LIFE CYCLE ASSESSMENT OF MULTI-GLAZED WINDOWS

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Declaration

I hereby declare that the work presented in this thesis was solely carried out by myself at Napier University, Edinburgh, except where due acknowledgement is made, and that it has not been submitted for any other degree.

Gillian Weir.

Gillian F. Weir (Candidate)

6.10.98

Date

Abstract

In 1987 the World Commission on Environment and Development proposed a reduction in per capita energy consumption of 50%. Increasing demands, and initiatives of this nature, produce a need for more reliable assessment methods, measurement tools and improvement regimes. Since the late 1960's Life Cycle Assessment (LCA) has become an increasingly important tool for engineers, technologists, scientists, designers, managers and environmentalists alike. LCA enables the effects which products, processes and activities have on local, regional or global environments to be assessed, adopting a holistic, or whole life approach to design methodologies.

The design of window systems has a large impact upon LCA results generated. Thermal performance properties influence energy consumption patterns throughout a lifetime of use, while appropriate use of materials, window positioning and size have a knock-on effect on lighting control functions and air conditioning demands. In developing countries, residential sectors account for between 20% and 30% of the total energy used (30% in the UK). Windows in dwellings alone account for 6% of the total UK energy consumption.

This thesis addresses an ongoing need to focus on sustainable development, using LCA as an assessment tool to develop a greater understanding of the window life cycle, and to highlight improvements which are necessary to lessen its environmental impact and make the processes involved more benign. To do this successfully requires that the demands of modern day living, and the comfort conditions expected, be incorporated into design criteria, whilst ensuring that the needs of future generations are not compromised by today's activities. Along with rising demands to improve efficiency and decrease energy consumption in buildings, comes an expectation for continual improvement in building interiors. To this end, both the aural and visual characteristics of window installations become paramount, in addition to the well researched thermal performance criteria.

Much research has focused on investigating the social and physiological benefits associated with improved interior environments. The correlation between worker satisfaction and performance has been well proven. If complete physical well-being is satisfied then an individual's mental well-being is less likely to be affected by the additional stressors of environmental dissatisfaction. An optimisation model has been developed, linking the thermal, aural and visual performance of varying window designs, such that an "advanced" window system is created.

Two outputs are generated from the model, which may be used to evaluate the "optimum" window design in terms of energy consumption and global environmental impact. Optimisation of energy consumption incorporates embodied energy, thermal performance and electric lighting demand, over the life cycle of a window. Global environmental impact optimisation is similar, but evaluation is based on energy generation, and greenhouse gas production. Finally, a flowchart for optimisation guides the user towards a glazing solution which offers sufficient noise attenuation, whilst minimising thermal losses and electric lighting demand. Each output provides a guide for design, leaving room for judgement, and is not intended to be followed definitively. Recommendations for improvements to manufacture systems and production of multi-glazed windows are offered, based on sustainable development criteria. Future research needs, which are necessary to minimise the total environmental impact resulting from multi-glazed window production, are also discussed.

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1. Introduction

Growing public awareness of environmental problems has led to increased green conservation and concern for the environment in recent years. The World Commission on Environment and Development in 1987 proposed a reduction by 50% of the per capita energy consumption [WCED, 1987]. Industry, business and the professions must respond to this demand, with engineers taking the lead in developing a safe and clean environment for future generations to enjoy without compromise. A million billion kilojoules of energy in the form of fuel is combusted daily, equivalent to eight billion tonnes of oil annually. Almost 90% of our energy comes from burning fossil fuels, which will eventually be exhausted [Emsley, 1994)]. Reliable assessment methods, measurement tools and improvement regimes provide the foundation to the development work required. Analytical measurements are the basis for many important business and management decisions. If these are wrong then decisions based on poor quality measurements will cost organisations money. Greek [1996] suggests that six basic steps could prevent problems in analysis; understanding the nature of a particular problem and applying the appropriate method to prevent it; validating the analytical method used; ensuring the competence of personnel involved; assessing independent bodies; being able to trace all results, and implementing formal quality systems. With regard to assessment of building construction, and in response to these expressed needs, the Chartered Institution of Building Services Engineers (CIBSE) has developed a policy statement on environmental matters which aims to contribute towards a sustainable environment. [BSJ, 1996]. The policy focuses on:

- provision of better information for decision making
- improved environmental awareness and education
- influence upon the location and physical characteristics of buildings to minimise impact
- minimising environmental consequences of the building construction process
- encouraging programmes to conserve resources
- evaluation of performance-in-use of new and refurbished buildings

In developed countries, energy consumption in residential sectors accounts for between 20% and 30% of the total energy used (30% in the UK [DTI, 1997]). Windows in dwellings alone account for 6% of the total UK energy consumption. This thesis addresses an ongoing need to focus on sustainable development, using Life Cycle Assessment as a tool to develop a greater understanding of the life cycle of multi-glazed windows, and to highlight improvements which are required to limit environmental damage. LCA is a systematic approach to assessment of environmental impacts associated with a product, process or activity, adopting a holistic, or whole life approach to design methodologies. To perform a successful LCA on any building component requires that the demands of modern day living, and the comfort conditions expected, be incorporated into design criteria, whilst ensuring that the needs of future generations are not compromised by today's activities. Switching our activities towards redressing the harm that our past and present activities impose upon the global environment, provides a strong way to revitalise the economy. The first objective for building in the 21st Century is to significantly reduce annual energy needs, driven by a whole-life or cradle-to-grave analysis.

This thesis focuses on design and selection of windows for office buildings. The examples selected and calculations presented are based around the commercial office environment. It is highlighted, however, that the methodology developed is applicable to any building type. Creating work environments which are efficient, productive and comfortable through glazing solutions demands a fine balance of design criteria. Much research has focused on investigating the sociological and physiological benefits associated with improved interior environments. Occupant performance in offices is of prime importance to building owners and the correlation between worker satisfaction and performance has been well proven. Alleviating discomfort is very important in maintaining building occupants' perceived level of productivity. The average perceived productivity loss for staff experiencing discomfort is -3.8%, whereas staff reporting no discomfort placed their productivity gain at +11.7%, a range of 15.5% [BSJ (1997)]. When the annoyance of noise is added to uncomfortable and relatively uncontrolled heating, cooling and ventilation conditions, then high dissatisfaction levels often prevail. If complete physical well-being is satisfied then an individual's mental well-being is less likely to be affected by the additional stressors of environmental dissatisfaction.

> *A higher quality environment leading to a healthier, happier and more productive staff, lower building energy and maintenance costs and an enhanced company*

image are amongst the most important potential benefits of green buildings. It has been suggested that a 0.5% increase in productivity is equivalent to a 50% saving in energy - productivity must thus be 100 times more important in financial terms than energy savings [Attenborough, 1996].

The architect and building services engineer is thus presented with a multi-disciplinary obstacle in the design of green buildings for the 21st Century. The need for high quality work performance and consistency in building occupant health and satisfaction demands that reliable and pleasant building interiors be provided. Distraction from thermal and visual discomfort, or annoyance due to noise disturbances must be avoided. Design and selection of windows used in buildings are therefore of prime importance.

Windows have changed more rapidly than almost any other building component in the past two decades. The best windows today insulate almost four times as well as the best commonly available windows of just two decades ago [Wilson, 1996]. Numerous advances in technology have made these energy improvements possible. However, the architect's and engineer's brief is further complicated by a need to conserve energy and materials now, such that the ability of future generation to provide for themselves is not compromised. This thesis aims to address this balance of interests, and to provide a reliable methodology by which windows may be designed and selected for use in sustainable buildings.

1.1 Research aims

The main aim of this research work is to provide a comprehensive and systematic methodology for the Life Cycle Assessment (LCA) of multi-glazed window designs used in sustainable buildings. To achieve this aim requires that several subsidiary objectives also be met. These objectives are as follows:

1.1.1 Provision of multi-disciplinary models to assess the performance of multi-glazed windows in terms of thermal, aural and visual design criteria.

1.1.2 Acquisition of inventory analysis data relating to each stage in the life cycle of a window, for effective resource management and impact assessment.

1.1.3 Development of dynamic optimisation models used to assess and compare window constructions in terms of their ability to meet tight design standards, minimise energy consumption over life, and limit the environmental burdens associated with all life cycle stages.

This research work further aims to identify window designs, which are currently available within the commercial marketplace, and which provide an optimal balance between stringent design criteria for improved building performance, and increasing economic, legislative and public pressure for improved commitment towards the environment and sustainability. It should be noted that only timber-framed window constructions are considered in this work. The same principles and method of analysis presented herein may be applied to any window construction. The scope of the work in this thesis did not permit in-depth analysis of more than one frame-type.

1.2 Methodology and structure

Due to the broad and comprehensive nature of the following research work, a wide and extensive literature review process was necessary to critically analyse preceding work, and to provide a foundation on which to build new research initiatives. Chapters 2-6 provide the main literature review input. The analysis that follows is the result of an extensive inventory analysis and impact assessment, contained within Chapter 4-7. Three comprehensive optimisation models were constructed using data developed throughout these analyses, and presented as a basis to the improvement analysis that follows in Chapter 9. Further potential imprcvements to the overall LCA process are considered, focused on sustainable initiatives, and a commitment to ongoing research.

Chapter 2 reviews the history of windows in architecture, and advances in fenestration made over recent decades. Multi-glazed window designs need to keep pace with a progressing world in which resources are finite and where there is growing demand to minimise waste, yet ever higher standards are expected within building construction. A methodology for Life Cycle Assessment of any building component needs to be dynamic and comprehensive in order to encompass this range of needs.

A definition of LCA and each stage involved is given in Chapter 3, showing the merits of such analyses, and possible shortcomings of the overall process. Current research work is discussed, and recent initiatives to establish recognised Ecolabelling schemes and Environmental Management Systems. The recently developed ISO14000 series is reviewed and the application of LCA techniques to BS7750: The Environmental Management Standard. A review of methods for environmental assessment is presented to compare and contrast the LCA technique with other current initiatives.

The structured approach of LCA provides the order to the work which follows in Chapters 4-9. The first stage, goal definition and scoping, follows a detailed planning procedure to define inclusion to and exclusion from the LCA, and to outline the method by which data is collected and processed. A full and systematic inventory analysis is followed by a thorough assessment of impacts associated with *processes and activities* throughout the window life cycle, termed impact assessment. Lastly, having identified impact sources and their magnitude, improvement strategies are sought, focused on reducing the overall environmental impact of the window life cycle. This is aimed at bringing the finished product into line with sustainable development criteria.

Acquisition of data to form the inventory analysis comes from all stages of the window life cycle, from raw material extraction to final disposal. There is no defined order to data collection, although the process is often simplified by following a sequential approach through the product life cycle. In the current LCA, the use phase has been considered before all other life cycle stages due to the large amounts of literature review which is integral to the analysis, and the nature of the optimisation work which follows. Chapters 4-6 extensively discuss the requirements associated with fenestration in modern building designs.

Criteria for the design of high performance windows is characterised by thermal, aural and visual considerations. An individual chapter is devoted to each of these criteria, following a similar structure in each case. Firstly, a detailed literature review to critically analyse the work of recent research initiatives is performed, and the importance of multi-glazed window design upon building occupant satisfaction, health and productivity is defined. Having highlighted the need for analysis and ongoing development, each literature review section is followed by a detailed analysis of technical performance.

With regard to thermal performance this takes the form of an energy consumption analysis, and a comparison of the convective heat input required to maintain conditions of comfort, using 24 different window constructions in building design. The same 24 window constructions are analysed with respect to their noise attenuation properties, providing a means by which to rate windows with regard to sound insulation. Visual analysis of the same window options provides a methodical approach to assessing the electrical energy consumed for artificial lighting within a building, given that a desired lighting level must be maintained for efficient task performance, and each window construction possesses different light transmission properties.

A range of 24 multi-glazed window designs is used as a common basis for comparison throughout each analysis in the thesis. A wide range of window constructions is used, aimed at providing basic information for common trends in construction. Four single glazed options are presented, in addition to various double and triple glazed window constructions, adopting single or double applications of low-emissivity coating. Four options in cavity infill gases are also presented for double and triple glazed options, to represent what is currently available within the commercial marketplace. These infill options currently include air and noble gases, Argon, Krypton and Xenon.

The inventory analysis of all other stages throughout the window life cycle, including raw material extraction, manufacturing processes, transportation, recycling and disposal is presented in Chapter 7. Each component part in the construction of a multi-glazed window is considered individually, including timber use, glass requirements, low-emissivity coating, production of inert gases, aluminium components, and ironmongery which is integrated into the window construction.

The methodology for impact assessment associated with each input to the window life cycle is also presented in Chapter 7. The global environmental impacts resulting from fuel production and use, transportation emissions, and other environmental impacts are presented and discussed.

In order to perform an effective improvement analysis, a systematic method is required to both qualify and quantify the impacts borne upon resource depletion, energy consumption and environmental impact as a result of changes to any part of the window life cycle. This qualification and quantification of impacts is used as the basis of comparison between different window constructions. A comprehensive optimisation of design parameters is therefore demanded. A multi-disciplinary approach is presented in Chapter 8, providing three computer models which the architect, designer or engineer may use to analyse the impact which design changes may have. Design changes may include material substitution, upgrading of manufacturing techniques or equipment, improvements in recycling, alterations to transportation systems, or possible building use changes. This list is not intended to be exhaustive. Use of the models provides vital information for environmental decision making, and resource planning, and allows the architect or engineer to make informed decisions with regard to window design and selection.

Having provided a methodology for window selection, such that the least energy intensive or most environmentally benign window may be selected from a range of alternatives, whilst keeping building user comfort and productivity at the fore of attention, consideration is given to the improvement analysis stage of the LCA. The improvement analysis presented in Chapter 9 considers both changes which could be made to the current life cycle of multi-glazed windows, and improvements which could be made to the overall LCA process. Quality of data and additional information which could be used to supplement that which is presented, are also discussed.

1.3 References

1. Attenborough, M., Green building: benefits and barriers, Part 2, Building Services Journal, May (1996).
2. BSJ, CIBSE policy on the environment: engineering the built environment for this and future generations Building Services Journal, p55, May (1996).
3. BSJ, Productivity linked to comfort claims report, Building Services Journal, April (1997).
4. Department of Trade and Industry, Digest of the United Kingdom Energy Statistics, HMSO, London, (1997).
5. Emsley, J., Energy and fuels, New Scientist, Inside Science, 68 January (1994)
6. Greek, D., It pays to get your sums right, Professional Engineer, April 24 (1996)
7. WCED, World Commission on Environment and Development, Our common future, Oxford Press, Suffolk, (1987).
8. Wilson, A., Windows: looking through the options, Environmental Building News, 5 (2), (1996).

2. Multi-glazed window design

2.1 Introduction

In recent years a greatly improved performance has been demanded of the building fabric in general, and of windows in particular. The need for improvement was emphasised by fuel price increases during the 1970's, and growing concern for the need to conserve the world's resources. Members of the Pilkington Technical Advisory Service wrote at the end of the 1970's that:

> *Advances in glass technology have made it possible to manufacture glass products that suit more stringent design requirements, but visual, environmental, and structural performances of the newer window glasses are necessarily complicated and the design techniques needed to make best use of products are not widely known [Turner, 1977].*

Relevant issues related to window designs were generally published separately until the late 1970's. Window functions were considered independently, and research was carried out on individual design functions. These functions include consideration of the window as a light, heat and sound filter, provision of a view, and a means of keeping out wind and precipitation. The architects brief was generally:

> *to create pleasant, comfortable, productive interiors, designed to keep running costs to a minimum.*

This brief is illustrated in Figure 2.1. Extensive research has focused for some years on comfort criteria and design of building components. Cena et al [1990] discussed the practical application of thermal comfort theory in homes and offices, while Fanger [1993] and Wyon [1996] performed numerous investigations to define more clearly the relationship between material selection and building user satisfaction. A number of studies to investigate the impact of different environmental stressors on work place performance have also been carried out by Ramsey [1995], Broadbent [1980], Cawthorne [1991] and others. Work has extended to investigate the combined impact of environmental stressors like heat, noise and glare. Research of this nature has been advanced in recent years by Oseland et al [1996], Clausen et al [1993] and Smith [1986]. These issues are explored in detail throughout chapters 4-6.

In the current building environment the original architect's brief is insufficient. To design buildings which are sustainable requires that consideration be extended to minimise energy and resource consumption over the entire life cycle of each building component, such that global, regional and local environmental impacts are removed as far as practically possible.

Progress has been made to collect individual design functions together. Loe & Davidson [1996] produced a methodology which provides a more holistic basis for window design and selection. This work is discussed in detail in Chapter 6. Numerous research activities have focused on frame design and material selection [Aschehoug, 1995], inert infill gases [Fernie & Muneer, 1996], transparent insulation options [Platzer, 1995], condensation frequency, [Muneer & Abodahab, 1998] and other advanced techniques. To date, however, no full LCA approach has been applied. Paul Sheerbart's ideas, expressed in 1914, would perhaps have been perceived as idealistic or impractical when he stated that:

> *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 a few windows, but through every possible wall, which will be made entirely of glass.*

The practicality of such constructions at the turn of the century would have rendered the structure uninhabitable. The cost of heating such a building would have been prohibitively large. Such designs were considered for application in temperate climates only. The technology to create such building structures in more northerly latitudes, and to thermally insulate them to an acceptable standard, now exists through the use of solar control glasses, low-emissivity coating, and inert cavity gases. Paul Sheerbart's statement was perhaps ahead of its time at the beginning of the twentieth century, but the underlying argument; that of considering the well-being and comfort of building occupants, is integral to today's design standards. Today the important relationship between glass and building construction still exists, but the history of architecture has since progressed.

2.2 Advances in window design

With the discovery of glass around 1000 BC, dawned a material which would become indispensable throughout the ages. Used extensively in window construction, car windscreens, lenses, bottles, flasks, fibreglass and many other applications, glass is part of our daily lives. Progress in glass technology over the past decades has seen large-scale changes, allowing for greater efficiency and improved quality. These changes have allowed for grand changes in architectural design, and are generally attributable to the development of the float glass process in the 1960's.

Innovations in glazing technology over the past few decades include glass coatings and films, inert infill gas options, advances in frame and spacer designs, laminated glass, and development of solar control glasses.

2.2.1 Low emissivity glazing coatings

Long wave radiation exchange between glazing panes may be restricted with the application of a thin layer of tin-oxide coating on the glass. Long wave radiation exchange accounts for about 60% of the total heat exchange across a glazing gap. Applying a single low emissivity coating (emissivity less than 0.2) to one glass surface, compared with a standard emissivity greater than 0.8 for uncoated glass, reduces the radiation exchange by approximately 75% [Button & Pye, 1993]. The resulting reduction in U-value allows for greater imagination in window design and fenestration in general. Larger areas can be glazed, allowing brighter rooms and spaces to be utilised, creating indoor environments which are pleasant and comfortable.

2.2.2 Inert gases

Several cavity gas options are currently available within the commercial market. A progression from air filled cavities to inert gas filled glazing units has created a demand for better quality seals, and new manufacturing technology, but the benefits to be gained are numerous. The introduction of Argon, Krypton and Xenon filled cavities allows for lower U-values and improved thermal performance of windows. Many manufacturers now produce Argon filled cavity windows as standard, such that air and heavier inert gases are produced on a special order basis. Fernie & Muneer [1996] investigated the energy, monetary and environmental costs associated with inert gas production and use. This research is discussed in detail in Chapter 7.

2.2.3 Solar control glasses

Modifications to the transmission, reflection and absorption properties of glazing make control of the solar transmittance properties of glass possible. Glass and glazing combinations can be specified by use of tinted glass products, which employ increased absorption properties, reflective coatings, employing increased reflectance and absorption techniques, and laminated glazings, incorporating blinds and louvres. Combinations of body tinted glass and reflective coatings can be incorporated into a single glass, allowing the architect and building engineer greater freedom in design and imagination.

2.3 Future Requirements

A number of codes, strategies, labelling procedures, and corporate initiatives have been developed within the last decade, aimed at fair, accurate and credible rating of window products. The Australian Nationwide House Energy Rating Scheme (NatHERS) [Ballanger et al, 1995], the New Zealand Window Energy Rating Scheme (WERS) [Ballanger et al, 1995], the US Primary Glass Manufacturers Council (PGMC) [Benney, 1995], the US National Fenestration Rating Council (NFRC) [Hogan, 1995], and the UK Advanced Glazing Industry Club (AGIC) [Robinson et al, 1995] are representative of increasing numbers of world-wide organisations. Whether based upon a star rating system, an energy monitoring and targeting basis, or simply provision of increased awareness and advice, none of the above initiatives reported to include Life Cycle Assessment techniques. There is certainly a need for increased understanding with regard to advanced window design applications, and any initiative to increase energy efficiency, and lessen environmental burden is to be encouraged, but progress should be approached with caution. Lawson, in an initial and very basic paper on Life Cycle Analysis of windows warns that an energy efficient technology is not necessarily an environmentally sound one, and that:

> *If ecological sustainability is the ultimate objective then Life Cycle Analysis and Ecological Accounting is necessary to achieve a more holistic evaluation of the environmental impacts of a new product or technology [Lawson, 1995].*

To take the design of building components, and in particular multi-glazed window construction into the next millennium requires not only holistic thinking and better planning, but practical, reliable techniques and procedures to ensure that finite resource consumption is optimised and waste of fossil fuels and raw materials is minimised. This thesis shall address the future design considerations of multi-glazed windows, such that we can continue to develop and use architectural imagination, but in a way which can be sustained, thus minimising environmental burdens and using finite resources to their best potential.

In 1994, an advanced Window Information System (WIS) was developed by Van Dijk and Bakker [1995] such that an information tool to determine thermal and solar characteristics of advanced windows could be made available in electronic format for building engineers and architects alike. The program is based upon the mind map shown in Figure 2.2. Additional criteria have been supplemented to consider the performance of windows more holistically; principally aural performance criteria. Each parameter illustrated in Figure 2.2 is restricted to window use and performance. No consideration is given to other stages of the window life cycle.

Using the principles of mind mapping, Figure 2.3 was generated to show the major design considerations necessary for a full Life Cycle Assessment. It is seen that the mind map illustrated in Figure 2.2 sits within the overall LCA mind map shown in Figure 2.3. It is not sufficient to design for performance only. Window design and performance is critical to building dynamics and environmental conditions, but remains just one stage in a full window life cycle. Figure 2.3 shows the rationale behind the development work contained within this thesis.

The overall objective of LCA is to quantify environmental burdens and identify means by which to improve products, processes and activities such that they are made more benign. This involves generating practical, effective strategies, aimed initially at the most environmentally damaging processes within the life cycle, and performing several LCA iterations, focused on continual improvement. Chapter 9, 'Improvement analysis and sustainable development', builds upon Figure 2.3 to offer a final mind map for multi-glazed window design criteria.

Life Cycle Assessment (LCA) is a technique which focuses on environmental solutions, and which ensures that no significant input to, or output from a system is ignored or over-looked. It's holistic nature is especially well-suited to the application of window design, since product use is considered to be as important as material procurement and manufacturing methods. Whereas it is naive to divorce economic considerations from any process which is market driven, LCA is not primarily an economic tool, and does not permit market forces to influence the outcome. LCA also lends itself to a changing technological environment. It is an ongoing process offering practical solutions in an evolving technical and monetary market place.

2.4 References

1. Aschehoug, O., Frame and edge-seal technology – an international state-of-the-art review, Proceedings of Window Innovations '95: State of the art window technologies for energy efficiency in buildings, p82-89, Toronto, 5/6 June, (1995).
2. Ballanger, J., Cassell, D., Prasad, D. and Lyons, P., The integration of window labelling in the nationwide house energy rating scheme (NatHERS) for Australia, Proceedings of Window Innovations '95: State of the art window technologies for energy efficiency in buildings, p300-308, Toronto, 5/6 June, (1995).
3. Benney, J.C., Fenestration tradeoff computer program, Proceedings of Window Innovations '95: State of the art window technologies for energy efficiency in buildings, p332-346, Toronto, 5/6 June, (1995).
4. Broadbent, D.E., Noise in relation to annoyance, performance, and mental health, Journal of the Acoustical Society of America, 68 (19), 15-17, (1980).
5. Button, D. & Pye, B. (editors), Glass in Buildings, Butterworth Architecture, Pilkington Glass Ltd., (1993).
6. Cawthorne, D., Buildings, lighting and the biological clock, The Martin Centre for Architectural and Urban Studies, University of Cambridge (1991).
7. Cena, K.M., Ladd, P.G. and Spotila, J.R., A practical approach to thermal comfort studies in homes and offices: discussion of methods and concerns, ASHRAE Transactions, 6 (2), (1990).
8. Clausen, G., Carrick, L., Fanger, P.O., Kim S.W., Poulsen, T. and Rindel, J.H., A comparative study of discomfort caused by indoor pollution, thermal load and noise, Indoor Air (3) 255-262, (1993).
9. Fanger, P.O., How to apply models predicting thermal sensation and discomfort in practice, International Conference Thermal Comfort: past, present and future, Building Research Establishment, 9-10 June, Garston, (1993).
10. Fernie, D. and Muneer, T., Monetary, energy and environmental cost of infill gases for double glazings, Building Services Engineering Research and Technology, 17 (1) 43-46 (1996).
11. Hogan, J., The use of NFRC ratings in US energy codes, Proceedings of Window Innovations '95: State of the art window technologies for energy efficiency in buildings, p309-324, Toronto, 5/6 June, (1995).
12. Lawson, W.R., Life cycle analysis of windows, Proceedings of Window Innovations '95: State of the art window technologies for energy efficiency in buildings, p325-331, Toronto, 5/6 June, (1995).
13. Loe, D. and Davidson, P., A holistic approach to lighting design, Energy Management, Sep/Oct pp16-18 (1996).
14. Muneer, T. and Abodahab, N., Frequency of condensation occurrence on double-glaring in the United Kingdom, Energy Conversion and Management, 39 (8) 717-726, (1998).

15. Oseland, N.A., Wargocki, P., Clausen, G. and Poulsen, T., Multiple factors: the interrelationship and effect of temperature, air quality and noise on perceived acceptability, Building Research Establishment Laboratory Report, (1996).
16. Platzer, W., Advanced glazing materials for daylight applications, Proceedings of Window Innovations '95: State of the art window technologies for energy efficiency in buildings, p553-562, Toronto, 5/6 June, (1995).
17. Ramsey, J.D., Task performance in heat: a review, Ergonomics, 38(1), 154-165, (1995).
18. Robinson, P.D., Hutchins, M.G., Lyons, P.R. and Ballanger, J.A., From laboratory to market place: a strategy for the successful application of advanced glazings, Proceedings of Window Innovations '95: State of the art window technologies for energy efficiency in buildings, p292-299, Toronto, 5/6 June, (1995).
19. Smith, A., Cognitive effects of noise, heat and other stressors, Proceedings of a workshop, June 11/12, National Academy Press, Washington, 114-128 (1984).
20. Turner, D.P. (editor), Window glass design guide, The Architectural Press Ltd. And Pilkington Brothers Ltd., London, (1977).
21. Van Dijk, D. and Bakker, L., Development of a European advanced window information system (WIS), Proceedings of Window Innovations '95: State of the art window technologies for energy efficiency in buildings, p337-347, Toronto, 5/6 June, (1995).
22. Wyon, D.P., Individual microclimate control: required range, probable benefits and current feasibility, Danish Technical University

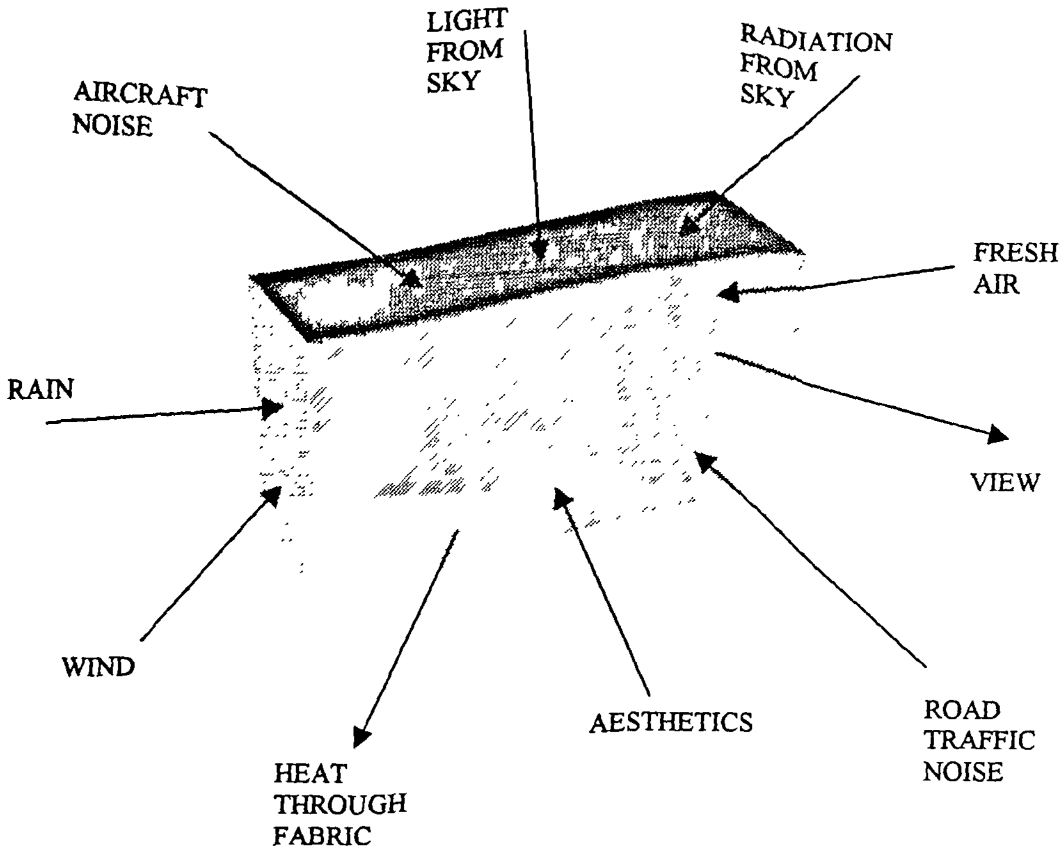

Figure 2.1 The architect's brief for window design [Turner, 1977]

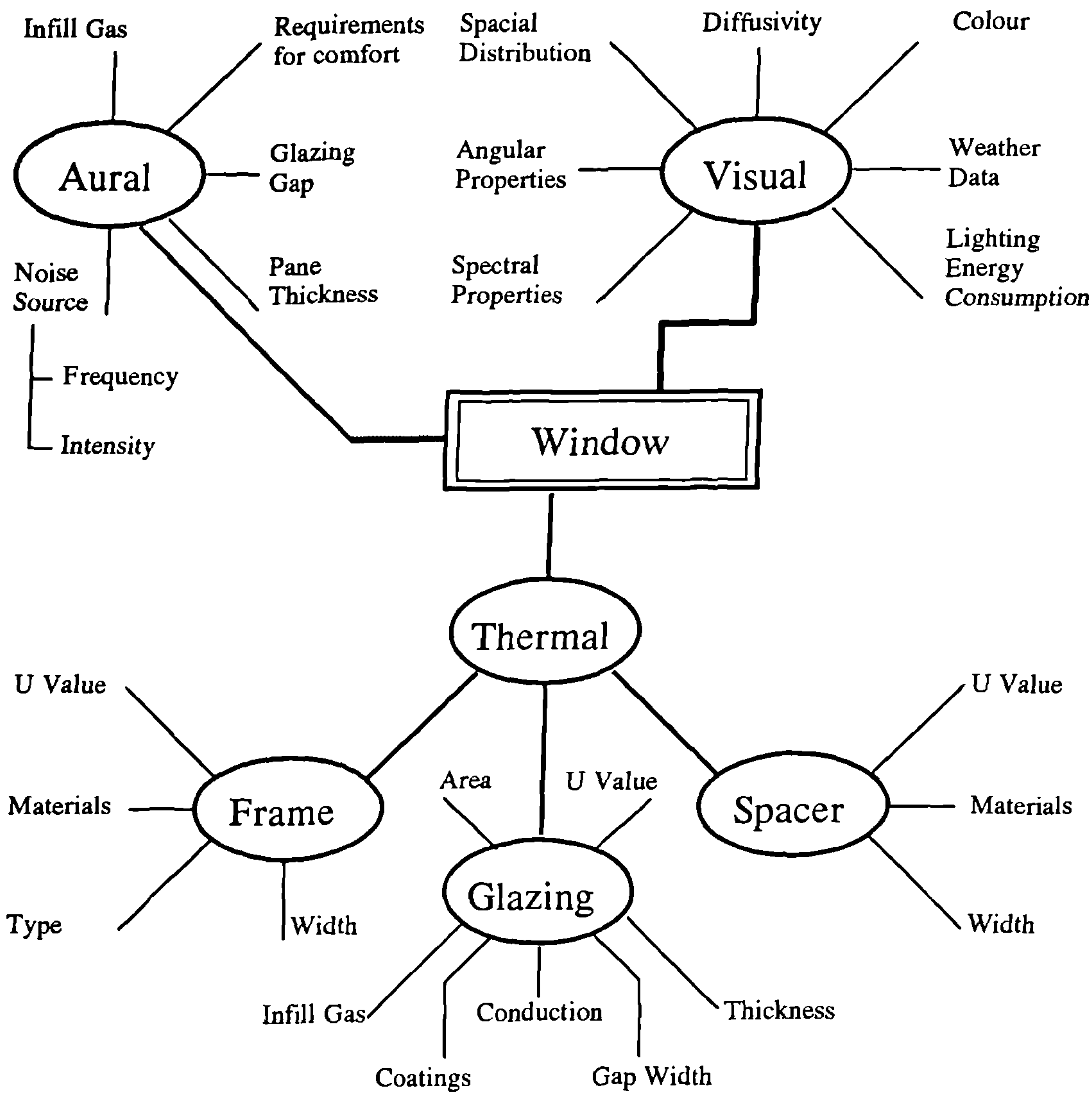

Figure 2.2 Mind map for thermal, aural and visual performance criteria (adapted from Van Diyk and Bakker, 1995).

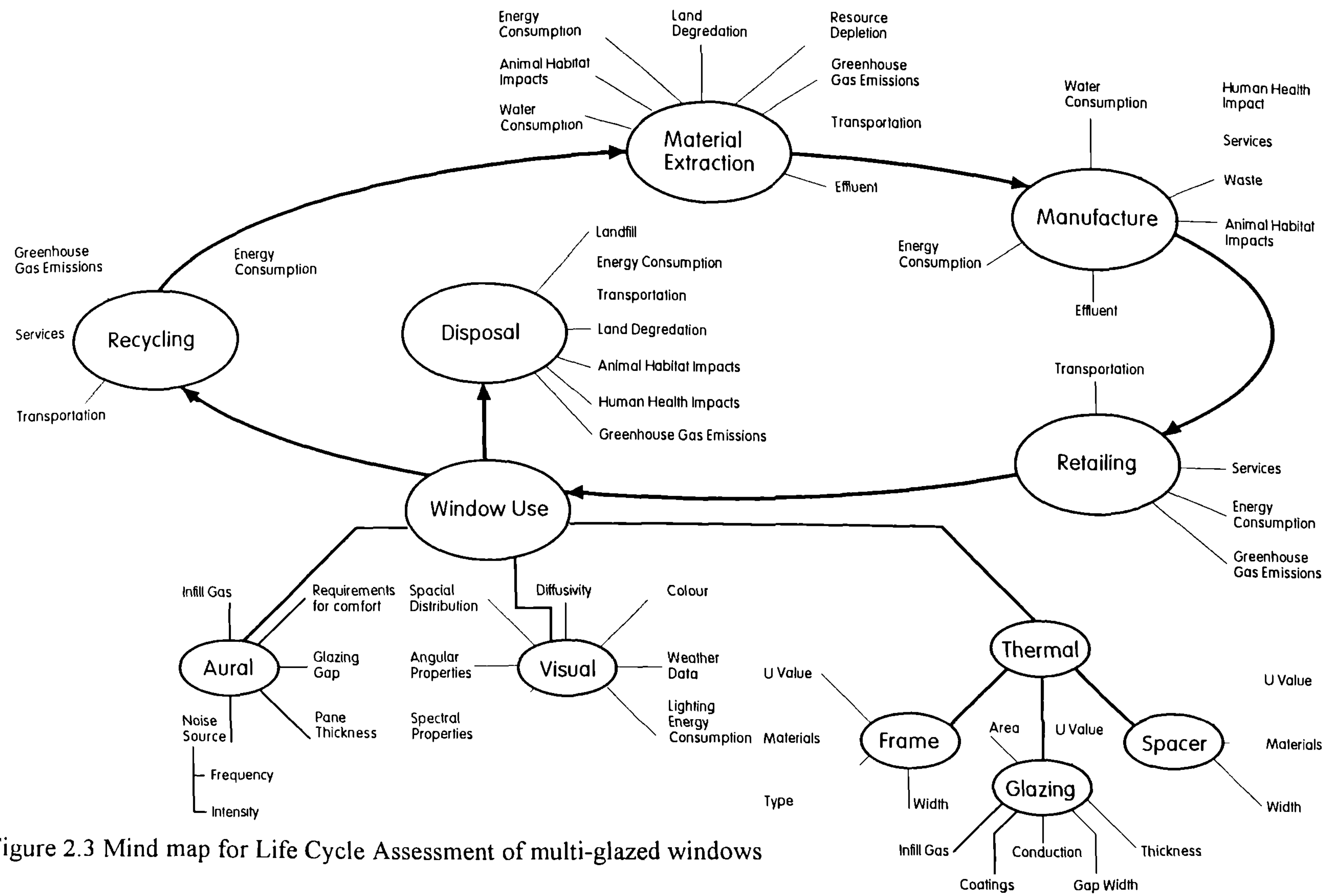

Figure 2.3 Mind map for Life Cycle Assessment of multi-glazed windows

3 Life Cycle Assessment

3.1 Definition

Since the late 1960's and early 1970's LCA has become an increasingly important tool for engineers, technologists, scientists, designers, managers and environmentalists. Environmental regulations have become increasingly stringent, forcing companies to include environmental impact factors in their production and operating decisions. During these two decades issues of energy efficiency and control of waste production and pollution came to the fore of public attention. Energy analyses became a common form of product and facility assessment, which latterly widened to encompass issues of material sourcing, emission loading and waste management. As knowledge and understanding of the environment increases more informed decisions are enabled, and environmental management policies will have greater influence.

LCA is defined as a systematic approach to assessment of the environmental burdens associated with a product, process or activity. By identifying and quantifying energy and materials used, and wastes released to the environment, opportunities to lessen environmental impact can be realised and implemented [Society of Environmental Toxicology and Chemistry, (SETAC), 1991]. The environment considered can be in terms of a local or regional environment, or wider as the global environment, depending on the nature and purpose of the investigation. The conditions under which a system exists, the circumstances which prevail, and those factors which influence change in a system, all define the nature of a particular environment. Impacts on the environment include effects on the atmosphere and the world's natural resources, in addition to human health factors, animal habitats, fuel depletion, noise pollution, and the availability of raw materials and primary fuel for the future. LCA takes a holistic view of the life cycle of a product, process or activity with a view to identifying those stages of the life cycle which are of the greatest detriment to the environment. It is necessary to consider the impact which raw material extraction, energy production, manufacturing processes, transportation needs and waste disposal requirements have on both social and natural environments.

LCA has had several names over the past decades. It has been known as Cradle to Grave Analysis, Eco-balancing, Terrotechnology and Material Flow Analysis. More recently a division has appeared between Life Cycle Inventory Analysis (LCIA) and Life Cycle

Assessment, whereby LCIA has developed as a methodology in its own right. F.R. Field III et al. [1994] states that LCA has become one of the most actively considered techniques for the study and analysis of strategies to meet environmental challenges, and concludes that it is one of the most promising approaches to integrate environmental knowledge and data into a framework for action. LCA gains its strengths from its basis in engineering and systems approach, and from the understanding that changes in technology cannot be qualified by improvements in single processes or activities. Only when a holistic approach to assessing all consequences of such a change is adopted can knowledge and understanding be widened.

Figure 3.1 illustrates the holistic approach of a Life Cycle Assessment study. The transportation effects must also be accounted for at each stage of the product life cycle, in addition to the underlying energy and material requirements of administration and work-force services. There are four main stages to an LCA:

3.1.1 Goal Definition and Scoping

The main purpose of the planning phase is to clearly define the investigation objectives, discuss product alternatives, realise system limitations, plan data collection strategies, and define environmental parameters and evaluation methods. LCA may be used for many different purposes, including the comparison of two products, identification of harmful stages in a product life cycle, new product development, allocation of process resources (both raw material and energy), categorising of research and development needs, or aggregation of total product environmental burdens. It is important to bare the purpose in mind while defining all other system parameters.

A system is defined as a collection of connected operations which together perform a defined function [Kirkpatrick, 1995]. System limitations may include such considerations as data availability, future environmental effects and technology development requirements. Before moving to the second stage (3.1.2 Inventory Analysis), a clear definition of investigation inclusions and exclusions, and the methods of data retrieval must be set out. The choice of system boundaries is crucial to the outcome of an investigation and can impact heavily on the conclusions made and actions which follow. If the choice of data generates a difference of 10%, the choice of system boundaries could easily affect the result by a factor of 2 or more [Erlandsson & Ödeen, 1994]. The following set of variable factors constrain the boundaries for most LCA's carried out, and define the boundaries of the investigation herein.

INCLUSIONS	**EXCLUSIONS**
• raw material extraction	• manufacture of capital equipment
• energy of manufacture	• maintenance of capital equipment
• packaging requirements	• manufacture of services
• transportation requirements	• maintenance of services
• in-use repairs & maintenance	• energy required to raise capital for production
• waste disposal and recycling	
• fuel production & use	
• energy generation	

3.1.2 Inventory Analysis

The inventory analysis is a methodical quantification of inputs and outputs. This is a measure of all matter which crosses the boundary defined in the planning phase, and shown in Figure 3.1. Energy, raw materials, air emissions, water-borne effluent and solid waste are both qualified and quantified at this stage. This may employ several different data acquisition methods, from direct measurements to database searches, surveys, questionnaires, analysis of historical data, theoretical calculations and individual interviews.

The inventory analysis will produce large quantities of information and data pertaining to the whole product life cycle. To enable comparisons and aggregation of data it is necessary to evaluate data on the basis of an equivalent function. This is termed the functional unit, and is usually expressed in units of mass, volume or energy consumption per unit output. e.g. the energy associated with the manufacture process may be expressed in kWh per unit output, or per 1000 unit output, whereas the waste generated from a process or activity may be expressed in m^3 or kg per unit output. A further consideration when defining the functional unit may be a time parameter. The expression of output from a system may only be understood when expressed in terms of the time period analysed. This becomes important when a product or service has a likely, or pre-set life, after which it is in need of upgrading or replacement. The resources consumed over a product life cycle are seldom constant with time. Manufacture, transportation, use and disposal consume varying amounts of energy and materials, depending upon the nature of the product, thus emphasising the need for a holistic approach to product design.

3.1.3 Impact Assessment

Impact assessment focuses on how the product affects the environment, and facilitates the interpretation and aggregation of data collected during the inventory analysis, presenting it in a more meaningful format for decision making. This requires a comprehensive approach to analysing how raw material use, energy generation, water production, effluent output, air emissions and solid waste affect the environment. The burden to the environment from any single process may be measured in terms of human health, animal habitat disturbances, noise pollution, changes in water quality or aesthetic changes to the environment. The effects analysed are assessed according to their direct impact in the present, and their possible future burden upon the environment. e.g. Raw material and fossil fuel consumption in the present can have effects on human health and animal habitats due to their extraction, transportation and burning, while their consumption influences the availability of these resources for the future. Impact assessment is a question of defining and characterising the consequences which result from the inputs and outputs quantified in the inventory analysis. The World Resource Foundation [WRF, 1995] considers LCA to be a vital, ongoing tool, in combination with the trend towards more open disclosure of environmental information by companies, and the desire by consumers to be guided towards the least harmful products. The WRF advise that LCA must, however, be used with care; the impact assessment of the inventory analysis should be approached cautiously with regard to subjective judgements.

3.1.4 Improvement Analysis

Improvement analysis involves decision making to reduce environmental burdens. This requires taking an objective view of the entire life cycle and assessing the environmental impacts which would result from changes made to the system. Product design changes, raw material substitutions, manufacturing process changes, improved waste management facilities, or suggested consumer use changes may thus result. There are many benefits associated with the incorporation of LCA into an organised environmental management system. These include the reduction of uncertainty with regard to environmental impact and the meeting of consumer requirements due to market demands for increased environmental awareness. A further benefit of establishing such as system, whereby waste and energy consumption are minimised, results in improved profitability [UETP-EEE, 1993].

3.2 Ecolabelling

The introduction of the European Community Ecolabelling scheme is an environmental initiative which aims to provide more comprehensive and higher quality information on the environmental burdens generated by products, processes and activities [Miller, 1994]. The scheme also aims to promote products which have reduced environmental impact during their entire life cycle, and has led, in part, to building specifiers demanding more information on the environmental consequences of building materials and products. The scheme is centred around LCA of environmental performance, and only those products which reach the set criteria will receive the label [Atkinson and Butlin, 1993].

The EC regulation on Ecolabelling operates around an indicative assessment matrix which is used to assess all levels of criteria when an Ecolabel is applied for and awarded. The scope of the assessment is often restricted to include only significant environmental impacts, as a full LCA would involve vast quantities of data, and lengthy evaluation periods. There is a danger in restricting impact assessment where differing views on the relative importance of elements must be accommodated. Ecolabelling must also include consideration of factors such as durability, maintenance and compatibility, as these factors cannot be easily assessed using the LCA tool [Atkinson, C. et al, 1994].

Hinks and Westland [1994] state that it is currently not possible to develop an Ecolabelling system which can accurately assess a product, process or activity without diluting the main political, social or economic factors. They argue that wide and shallow assessments, or deep and narrow analyses, which do not address subjective issues concentrate only on those issues which are easily quantified. Analyses of this nature could omit significant environmental impacts, creating a need for more in-depth investigations.

3.3 Environmental Management Systems

Environmental management is the corporate response to the growing concern about the state of the environment and the environmental effects caused by corporate activities. An Environmental Management System (EMS) is the overall framework for the actions that an enterprise takes to manage its environmental effects [UETP-EEE, 1993]. Stricter government legislation means that environmental management will become a prominent issue for organisational management in the future, much in the same way that quality management has come to the fore of attention [Griffith, 1995]. Environmental management takes into account the policies, strategies, procedures and practices that form the response of an organisation to its surrounding environment.

Environmental management systems exist to ensure legislative compliance with both present constraints and anticipated future constraints. Management systems and legislation were developed to minimise the risk and liability from environmental effects on human health of employees, surrounding inhabitants and animal habitats. To this end the reduction in use of raw materials and primary energy will bring about increased productivity and higher resource efficiency. Decisions to improve waste handling facilities will influence the quantity of waste produced and the associated handling costs. With higher efficiency, improved productivity and greater environmental awareness, organisations can boost their company image and attract higher quality workers.

3.3.1 The environmental management standard, BS7750

The British Standards Institute produced the first environmental management standard in 1992, identifying requirements for initiating, implementing and maintaining an environmental management system. According to BS7750, now ISO14000, the environmental policy of an organisation should incorporate a commitment to continual improvement in environmental performance, should be available for public consultation, and be understood at all employee levels within the organisation. The policy commits the organisation to reducing resource consumption and environmental effects of material and energy sourcing. In addition to this a commitment to reducing waste and pollution is required, whilst minimising the risk and health impairments to employees and surrounding inhabitants. A holistic approach should be adopted with regard to product design, encompassing the entire life cycle to ensure that minimal environmental burdens result from new product development.

Environmental assessments are recommended to include consideration of waste production and handling, use of land, water, energy and natural resources, and production of noise, odour, dust, vibration and visual impact.

The benefits of establishing an environmental management system are listed as follows:

- reduced risk to the environment and the health and safety of human and animal life.

- meeting current environmental legislation and anticipating future legislative constraints.

- minimising the risk of prosecution due to non-compliance, involving costly fines.

- personnel and resources are set in place to manage emergency situations, and to accommodate policy changes and additions.

- uncertainties in decision making and environmental impacts are reduced as personnel gain skills, and environmental assessments progress.

- public image is improved, asset value is increased and customer requirements are more easily met with a proactive response to environmental management. Investors will gain increased confidence in corporate activities.

- profitability is increased when waste output, energy input and resource consumption is minimised.

BS7750 was established to provide a defined structure for environmental management systems, giving guidance on regulations registers, documentation and record keeping, and providing a framework for auditing, programming and reviewing. Figure 3.2 shows the structure of the standard, and the general process for effecting an environmental management system. Each of the terms shown in Figure 3.2 is outlined below:

- Commitment refers to the provision and definition of personnel and financial resources for the execution of an environmental management system.

- The initial review establishes the current environmental status with regard to legislative requirements, registration of significant environmental parameters, assessment of existing environmental practices and the checking of previous non-compliance and its management.

- The environmental policy must be relevant to the products, services, activities and environmental consequences which result. It must be easily understood and implemented at all employee levels. The policy must also be committed to publishing all environmental objectives.

- The register of regulations must record all legislation and policy requirements which are relevant to the activities of the organisation. The organisation must establish procedures for examining the environmental effects of its products, processes and activities, and for recording all significant factors.

- Objectives and targets must be set for year-on-year improvement in performance. Particular attention should be paid to those areas which present significant risk to human health and well-being, and to the environment. Targets should be achievable with effort, and quantified in magnitude.

- The management programme designates responsibility to individuals for carrying out procedures, reviews and assessments, and achieving the targets set out in the environmental policy. The means by which these individuals are to do this, and the resources available must also be defined.

- The management manual is a permanent handbook for all levels of management and workers to refer to for guidance on the procedures documented, and individuals responsible for certain actions. It is also used by auditors to verify the environmental management system's existence.

- Operational control covers all the functions and activities which could have significant effects on the environment, and ensures that they are managed effectively and correctly.

- Audits refer to assessments made either by internal or external professionals to ensure system compliance, to effect corrective actions where necessary, and to highlight potential problems.

- Reviews should be performed at regular intervals to ensure that the management system is operating effectively, and that the required tasks are carried out by responsible internal personnel.

3.3.2 The role of LCA within an EMS

LCA requires to be backed up with a comprehensive environmental management system for it to be an ongoing and successful tool within an organisation. LCA is not a one-off, isolated exercise, but an on-going system of assessment. It is a tool which fits into the assessment strategy of an environmental management system. Together with economic assessments, input/output analyses and environmental audits, LCA completes the environmental assessment of products produced, processes required and activities executed within an organisational structure. This environmental assessment defines the policy statements made and improvement targets set. Policy makers and regulators see LCA as a tool that can guide the development of environmental policies and can provide a mechanism for enforcement of legislative procedures. For this reason LCA's are receiving greater consideration by industrial leaders and government legislators. The LCA tool does, however, fall short on several accounts for policy making.

- Firstly, LCA does not take account of the costs associated with alternative strategies, but focuses on environmental impact, health effects and resource consumption. For a complete and unbiased analysis, economic considerations must be viewed.

- Secondly, LCA's often produce large quantities of data, owing to extensive inventory analyses. This mass of data must be evaluated carefully, or the result may produce inefficient policies and decisions, or may be considered too difficult to process.

- Lastly, most LCA's performed to date have centred on existing products, processes or activities. The need for vast quantities of data to be collected during the inventory analysis stage makes it difficult for LCA to be used as a tool for assessing the environmental impact of future activities [F.R. Field III et al, 1994].

3.4 Review of assessment methods

Young and Vanderburg [1994] view the LCA of products essentially as the LCA of materials, and argue that both products and materials can be assessed according to their environmental impact. The approach of Young and Vanderburg is to define materials in terms of their intrinsic and extrinsic properties. Intrinsic properties are those that relate to the standard chemical and physical composition of a material. Extrinsic properties are dependent on the history experienced by a material, and are a product of prevailing circumstances. Embodied energy is a good example of an extrinsic property. The material inputs to two manufacture processes may be identical, but the energy required to produce the finished product may be very different. Another example is that of transportation. A material which has travelled a short distance to its destination will have a lower embodied energy than a similar material which has been hauled across a continent. All materials have three impact indicators: gross energy requirement (GER), global warming potential (GWP) and solid-waste burden (SWB). It was suggested that these properties could come to represent extrinsic environmental properties and could be useful for material selection guides. It was, however, concluded that GER, GWP and SWB are only indicators of potential impact, and since material profiles cover only material production, other phases of the life cycle must be included in the overall assessment.

A group of researchers lead by Dr Lave of Carnegie Mellon University [ENDS, 1995] has criticised the LCA methodology established by SETAC, published in 1991. SETAC believe that the inventory analysis stage is clearly defined, and well understood, with the most recent work being concentrated on improving the impact assessment stage of the analysis, and aggregation of differing environmental effects in particular. Dr Lave is now challenging the inventory analysis methodology, and suggests that the current investigation boundaries are restrictive. Focusing on the main material and resource suppliers may exclude smaller suppliers, who's input could significantly affect the outcome of the investigation. This could include the ignored effects of secondary suppliers, who supply the materials to primary suppliers manufacturing component parts. Lack of available capital or expertise may necessitate the purchase of component parts, where larger, more experienced companies would be in a position to manufacture their own. SETAC's guidance acknowledges that the secondary impacts should be included where they are likely to be significant. Dr Lave comments that the drawback appears where a boundary to the investigation has to be drawn at all.

Based upon an economic input-output system (EIO-LCA), the research team at Carnegie Mellon University have developed a new LCA approach. Economic changes in one industry will have a knock-on effect in both supplying industries, and competing industries and their suppliers. Models of this nature are used to estimate economic changes as a result of consumption pattern changes. The EIO-LCA models the environmental consequences of such changes in economic activity, but does however suffer from the same data quality problems. The same lacking in industry information, possible use of inaccurate or incomplete data and aggregation problems exist with this method also. One major fault of the EIO-LCA method is its inability to account for customer use patterns, the energy associated with the use phase and the disposal and/or recycling of materials at the end of the life cycle. These short-comings make this model's application inappropriate to the analysis of multi-glazed window production and use, since the performance of the windows in building situ is of prime importance to this investigation.

The Materials Systems Laboratory at Massachusetts Institute of Technology (MIT) have developed a scheme whereby engineering process modelling elements have been matched to elements of product design, materials, and manufacturing in order to generate tools to evaluate costs associated with production systems [F.R. Field III et al, 1994]. The purpose of the tools is to estimate the production costs of material and energy flows, capital requirements and production operations. With the use of such tools the economic consequences of policy decisions can be evaluated, and the future implications of new developments can be assessed, identifying possible limitations and benefits. Integrating economic analysis with environmental assessment can provide many advantages:

- The tools consider the technological implications of changes in materials, design and operating practices. The resulting technological changes and developments are accounted for when designing environmental strategies, which play a large role in decision analysis.

- The economic consequences of such technological developments are also considered, entering cost analysis as a variable into the strategic planning equation.

The pioneering development of researchers at MIT does not criticise the efforts of LCA investigations, but agrees that LCA is one of the most promising approaches to integrating environmental knowledge and data into a system for action. There is, however, a warning that LCA should not be used to evaluate single plans of action, where the consequences of such actions cause conflict between groups of decision makers. The underlying analysis could be of the highest quality, but if the conclusions drawn are controversial, then the assessment could lead to erroneous actions or poor policies. The role of LCA is to unambiguously present the consequences of each alternative, and provide a framework for negotiations.

3.5 References

1. Atkinson, C. J., and Butlin, R. N., Ecolabelling of building materials and building products, BRE Information Paper, IP 11/93.
2. Atkinson, C., West, J. and Hobbs, S., Life cycle assessment and ecolabelling of building materials, Materials session Paper 20, Proceedings of Building and the Environment International Conference, Building Research Establishment, 16-20 May (1994).
3. British Standards Institution (BSI), BS 7750 : Specification for Environmental Management Systems, (1992).
4. ENDS Report 248, A shot across the bows for life-cycle assessments, Environmental impact analysis No.40, September (1995), pp 19-21.
5. Erlandsson, M. and Ödeen, K., A study of system boundary problems in life cycle assessment, Materials session Paper 4, Proceedings of Building and the Environment International Conference, Building Research Establishment, 16-20 May (1994).
6. Field, F.R. III, J.A. Isaacs, and J.P.Clark, Life-Cycle Analysis of automobiles: a critical review of methodologies, Journal of Minerals, Metals and Materials Society, 46 (4), (1994), pp 12-16.
7. Griffith, A., Environmental Management Systems: an outline guide for construction industry organisations, Dept, Building and Real Estate, Hong Kong Polytechnic University, (1995).
8. Hinks, J. and Westland, P.R., Modelling the environmental impact of the life-cycle of building materials, Materials session Paper 25, Proceedings of Building and the Environment International Conference, Building Research Establishment, 16-20 May (1994).
9. Kirkpatrick, N., The application of life cycle assessment (LCA) to solid waste management practices, Warmer Bulletin, World Resource Foundation, November (1995).
10. Miller, A.J., Embodied energy in construction materials, Materials session Paper 23, Proceedings of Building and the Environment International Conference, Building Research Establishment, 16-20 May (1994).
11. SETAC - Society of Environmental Toxicology and Chemistry, (1991). - Full reference needs to be confirmed.
12. UETP-EEE: The Finnish Association of Graduate Engineers, Environmental assessment of products: a course on life cycle assessment, ed B. Pedersen, (1995).
13. WRF - World Resource Foundation, Warmer Bulletin Information Sheet, August (1995).
14. Young, S.B. and Vanderburg, W.H., Applying environmental life-cycle analysis to materials, Journal of Minerals, Metals and Materials, 46, (4), (1994), pp 22-27.

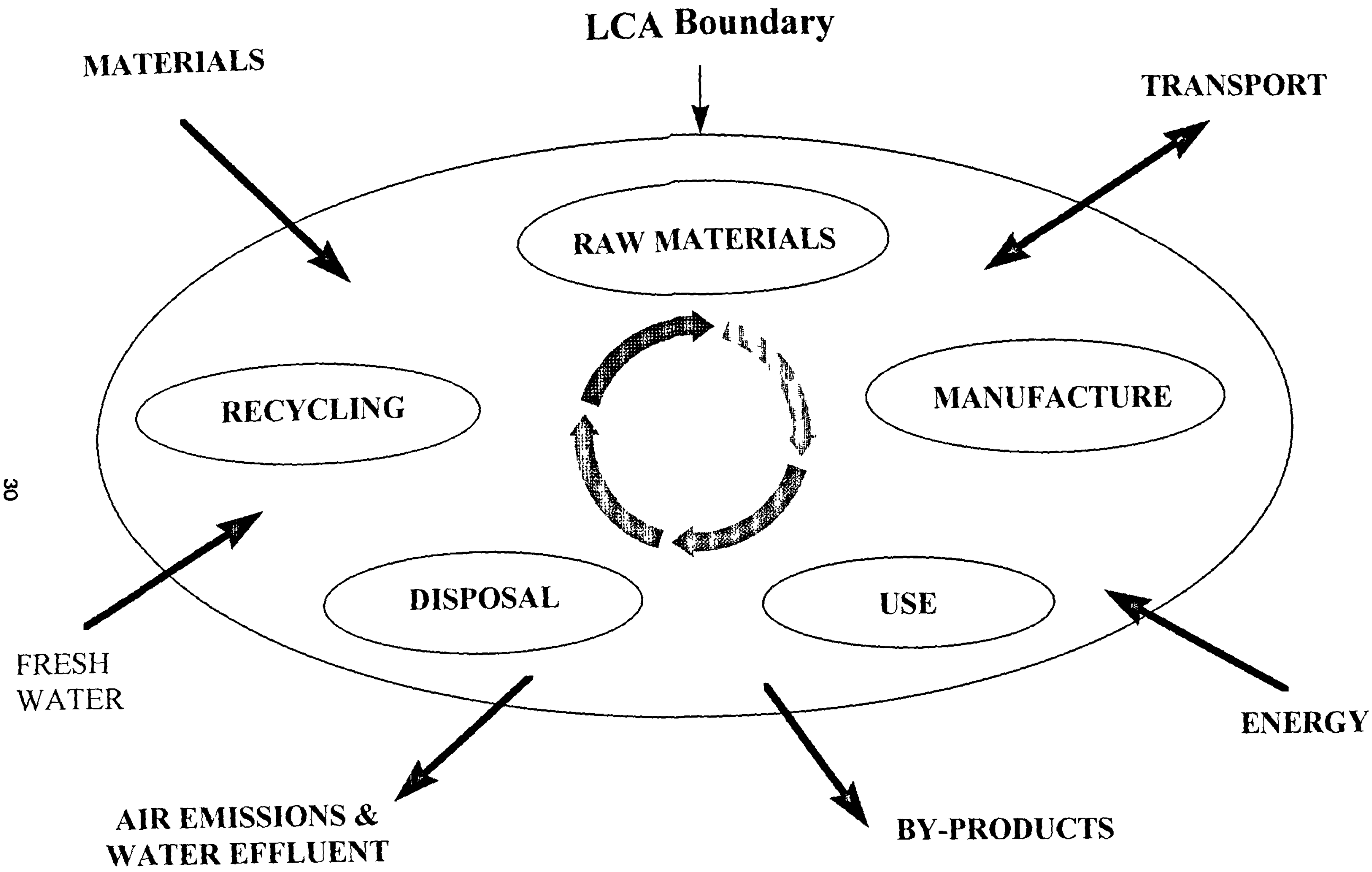

Figure 3.1 Input/output data requirements for a comprehensive Life Cycle Assessment

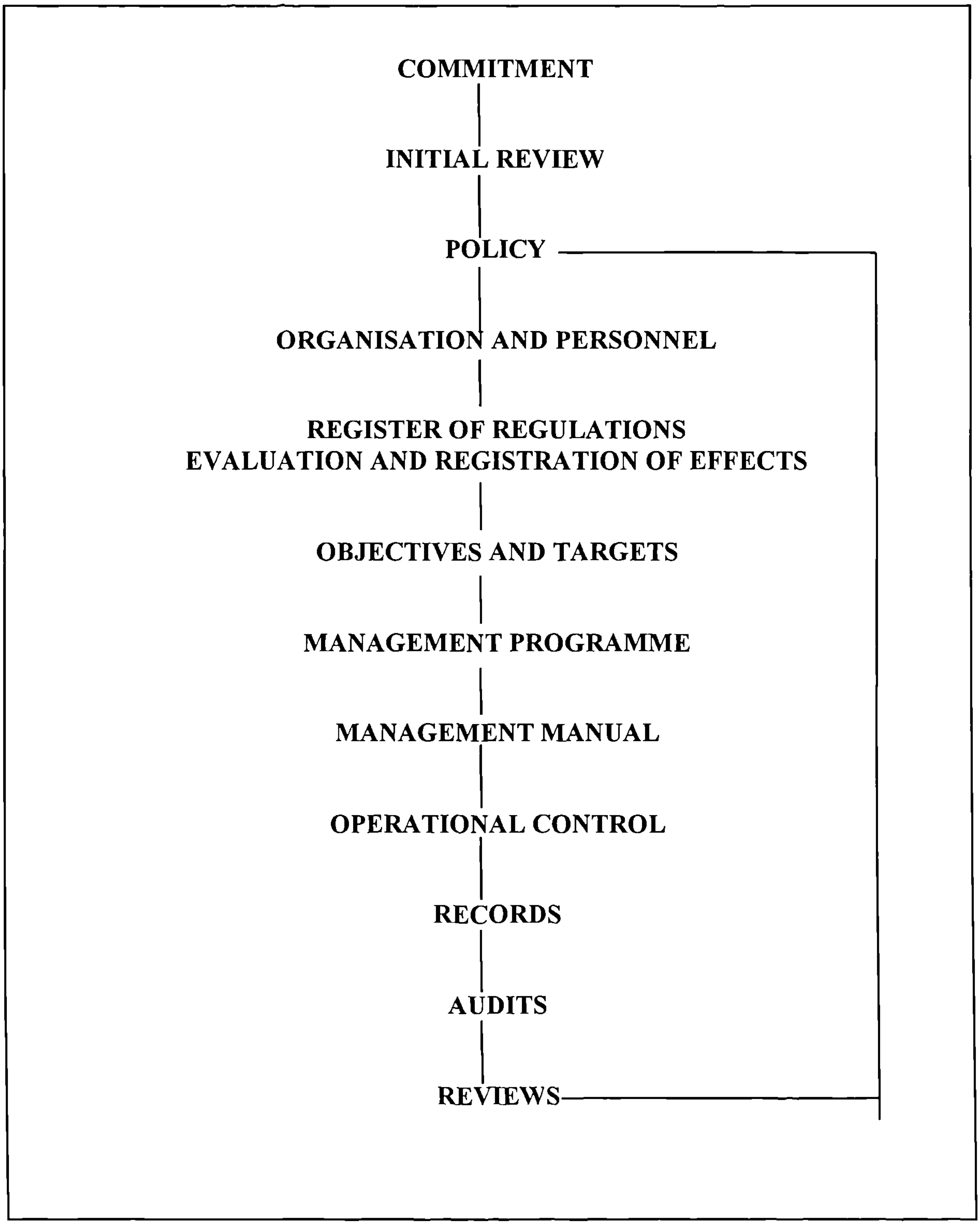

Figure 3.2 BS7750 specification for environmental management systems

4. Thermal analysis

4.1 Introduction

In any LCA, certain phases of the life cycle will be highlighted as having a greater or lesser impact on the environment than others. Raw material sourcing, manufacture, transportation and recycling/disposal of most products have the greatest impact on the environment, with little or no consideration being required for their general use. Windows differ greatly in their LCA. Their use phase impacts heavily on the environment. Window performance affects the indoor environment, building services operation, energy consumption of buildings and the well-being of occupants. For these reasons, no analysis would be complete without designing to optimise the well-being of occupants, whilst simultaneously minimising environmental impact generated from other phases of the life cycle.

Thermal insulating properties impact upon indoor air temperatures, draught sensation, and radiant temperatures, influencing energy use for heating and ventilation. A literature review of research related to such impacts is firstly undertaken to define problems associated with the thermal environment, and to discuss those aspects of the thermal environment which are less easily measured and quantified, e.g. work productivity losses due to thermal discomfort, draughts and radiant heating/cooling. These effects are no less important than measurable impacts, such as U-values, heat loss, and convective heat input loads. Analysis is undertaken to show the annual convective energy input associated with 24 different window constructions, for which an example calculation is presented, and the results displayed.

4.2 Literature Review

4.2.1 Thermal comfort analysis

When the complete physical well-being of an individual is satisfied, their mental well-being is less likely to be affected by additional environmental stressors, e.g. feeling cold, or sensation of draughts. The object of designing and selecting windows for use in office buildings is to maximise the comfort of occupants, and to limit the distraction associated with a poor thermal environment, thereby enabling more focused attention to work related tasks. In order to do this, a review of thermal comfort tools and design guidelines is required. A summary of recommendations is given.

The ASHRAE Handbook of Fundamentals [1977] defines thermal comfort in psychological terms as:

> *that condition of mind which expresses satisfaction with the thermal environment,*

and in physiological terms as:

> *a range of thermal conditions wherein most of our body energy is freed for productivity and minimum expenditure is required for adjustment to our surroundings.*

Thermal comfort analysis is a widely used tool in assessing the thermal well-being of building occupants. It is used in the design of building services and the modelling of building dynamics, but is also a subject of much debate between researchers, with respect, to the use of mathematical equations and application to field experiments [Bunn, 1993].

Professor Ole Fanger of the Technical University of Denmark has had a significant impact on environmental engineering throughout the last two decades, pioneering some of the first work in thermal comfort analysis, and is currently an influential decision maker in the development of standards. Fanger developed the general thermal comfort equation, used as the basis to ISO 7730 [1984], and identified skin temperature and sweat secretion as physiological parameters related to the sensation of comfort. For conditions of thermal comfort he developed regression equations to express both skin temperature and sweat secretion as a function of an individual's activity level. The general comfort equation derived by Fanger is a function of the clothing level of occupants, their level of activity, and their interior environment, as shown in Appendix A.

Bunn [1993] critically examined the work of Fanger to assess the application of thermal comfort theory in practical field investigations, in light of the fact that both ASHRAE standard 55 [1992] and the revised section of CIBSE Guide A1 [1988] extensively acknowledge Fanger's work. Bunn's review questions the ability of the thermal comfort and indoor air quality equations, derived under laboratory conditions, to simulate the comfort experienced by a building user. Responses to a recent proposal for a European

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Oseland, [1993] also questions the ability of the thermal comfort equation to match prevailing conditions in existing buildings. He found the comparison of a theory derived from thermal exchange physics and climate chamber results, with practical field results repeatedly incompatible. In one study he found that the neutral temperature based on the response of occupants was 2-4°C lower than that predicted by ISO 7730 [1984]. Personal factors of clothing level and activity are central to the argument; small changes in these values cause wide changes in comfort temperatures. The validity of standards based on theory and climate chamber results for use in field experiments is heavily questioned.

Cena et al, [1990] discussed the practical application of thermal comfort theory in homes and offices, for locations in the USA and Australia. The study highlighted several needs:

a) The social and behavioural influences on perception of the thermal environment need to be recognised, in addition to physical and physiological requirements.

b) A more accurate method for assessing the activity level of building occupants in field surveys. The evaluation of comfort bands is highly dependent on the assumptions which are made regarding a subject's clothing and activity level. Errors in estimation can lead to significantly variant thermal conditions.

c) When comparing assessments across varying climatic or socio-economic categories, it is important to allow for the influence of local conditions and behaviour norms on the perception of subjects, although Fanger maintains that these effects have no impact on design of comfort temperatures.

d) A standard methodology to enable comparisons between surveys in different locations and circumstances. Cena suggests that the methodologies outlined in

ASHRAE Standard 55 [1992], and ISO 7730 [1984] are not detailed enough regarding the collection of data and the methodologies for setting up field investigations.

Two very practical tools did however result from the development of thermal comfort analyses; Predicted Mean Vote (PMV) and Percentage People Dissatisfied (PPD).

4.2.2 Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD)

The PMV/PPD model was designed by Fanger [1970] to be a flexible tool, providing a range of comfort temperatures, found to be more useful than one optimal temperature value, and has been used for many applications:

- predicting optimal temperatures.
- design of radiant heating or cooling systems.
- comparison of energy economy in radiant and convective heating or cooling systems.
- analysis of the comfort consequences of applying new heating or cooling principles within buildings.
- use in computerised fluid dynamics to predict thermal sensation in occupied zones ventilated by various methods.

An explanation of PMV and PPD analysis is given in Appendix B.

As with the thermal comfort equations, PMV and PPD analyses have met with opposition from other research efforts. Humphreys and Nicol [1996] criticise the PMV model as inaccurate for situations where the clothing value differs from 0.6 Clo, since laboratory experiments were carried out on individuals wearing light clothing, equivalent to those worn in most offices. However, no reliable analysis has replaced Fanger's work to date.

Williams [1996] states that there is some level of disagreement over the application of PMV analysis to naturally ventilated buildings, and developed a different approach to assess the interior environment involving a multi-factorial satisfaction index. The aim of the index is to identify a satisfaction threshold so that dissatisfaction can be quantified. The index is based solely on the response of the occupant and their perception of temperature. The differences between expressed dissatisfaction, and Fanger's PPD for 8 buildings are shown in Figure 4.1. Large differences were found between Fanger's approach, and that of Williams, with up to 66% variance in PPD. Williams found no identifiable relationship between PPD and reported dissatisfaction expressed by occupants during field trials. As with ISO 7730 [1984] and ASHRAE Standard 55 [1992], selection of a maximum dissatisfaction level is required for each environmental variable. These levels are subjectively selected by the building manager, or the occupants themselves. With the information obtained Williams constructed building envelope diagrams as illustrated in Figure 4.2. A value for the maximum percentage of dissatisfied building occupants is attached to each interior environment parameter. The figure shows that dissatisfaction with room temperatures is more tolerable than dissatisfaction with other environmental parameters, but that a maximum of 20% dissatisfied occupants is acceptable. This limit is considerably higher than the +/- 5% recommended by CIBSE Guide A1 [1988] and ISO 7730 [1984]. Williams concluded that the satisfaction index is based on likability and acceptability. Unlike PMV/PPD analysis it is currently not possible to use this method as a predictive tool for building acceptability. Similarities may however arise between building types and allow generalities to be made. The analysis may also be applicable as a benchmarking tool for building performance.

4.2.3 Draughts

Draughts are a common source of complaint among office occupants, and are defined as unwanted local cooling of the skin caused by air movements. Ill-fitting windows are a potential source of draught, and design tolerances should limit air leaks to a minimum. Toftum [1994] carried out a field study of draught complaints within the industrial work environment, and concluded that it is essential for sedentary workers to feel thermally neutral or slightly warm, in order to minimise local discomfort due to draughts. Fanger [1988] analysed the effect of air turbulence intensity on sensation of draught, and found that air flows with high turbulence cause more complaints of draught than air flow with low turbulence, at the same mean velocity flow rate and air temperature. A model for draught risk was developed to predict the percentage of people dissatisfied due to draught, and is shown in Appendix C. Fanger recommends that the model be used for quantifying draught risk in spaces, and for development of air distribution systems with low draught risk.

Oleson et al [1979] exposed 16 subjects to four different vertical air temperature differences, between head and ankle level. It was found that less than 5-10% of people felt uncomfortable due to a temperature stratification of less than 3-4°C, and a dissatisfaction curve similar to that shown in Figure 4.3 was established. Thermal sensation votes indicated that dissatisfaction was attributed to warm head and/or cold feet. This agrees with the findings of Fanger [1986] who concluded that the head was the most draught sensitive part of the body. Fanger formed the relationships shown in Figure 4.4 for subjects at three temperatures and varying mean air velocity. Fanger's work shows that as lower mean air temperatures prevail, dissatisfaction increases at comparable mean air velocities.

4.2.4 Radiation effects

When the body is exposed to asymmetric radiation, discomfort effects are experienced because parts of the body will be too warm, while other parts are simultaneously too cold. Asymmetric radiation is caused by a cool or warm window, wall, or ceiling. Windows with high U-values have a lower internal surface temperature, and contribute to radiant cooling more than windows with lower U-values. Fanger [1986] examined the response of subjects to asymmetric radiation effects under controlled conditions using a climate chamber. Figure 4.5 shows the percentage of dissatisfied persons as a function of radiant temperature asymmetry. Radiant asymmetry from a warm wall caused less discomfort than from a cool wall. The converse was true for ceilings, where cool ceilings caused less discomfort than warm ceilings. Given that 5% of the occupants are uncomfortable, the following radiant temperature asymmetry values are permissible:

Cool wall	10°C
Warm wall	23°C
Cool ceiling	14°C
Warm ceiling	4°C

ISO 7730 states that radiant asymmetry at a cool wall should not exceed 10°C and should not exceed 5°C under a warm ceiling.

4.2.5 Discrepancies in thermal comfort theory

Discrepancies in thermal comfort theory is a long running argument which has its origin at the beginning of the 1900's, but which came to the fore of attention in the late 1960's with the progress of Fanger's work. Despite the longevity of the discussions, little has been accomplished to reconcile research findings. Parsons [1993] focused his research on psychological response analysis. Unlike the laboratory experiments and comfort equation analysis, the study of psychological responses to thermal environments is in its infancy; very little is understood about why people differ in their preferences. It is well accepted that the thermal environment affects psychological responses, but little is known about how to create environments that optimise mood and well-being. Many studies have proven that improvements in the indoor environment increase productivity, but no simple relationships between environment and productivity could be exacted. It was noted in several studies, however, that social factors dominated results significantly. The effects felt by building occupants are rarely identified as the cause of any one, or combination of environmental factors.

Canter [1985] described three types of psychological model: deterministic, interactionist *and transactionist. This approach is naive, but does aid understanding of the* problem.

- Deterministic models describe a situation where simple environmental parameters have specific consequences for the things we do and the way we feel. This leads engineers to design for specific temperature conditions to meet thermal comfort conditions and describes Fanger's thermal comfort equation well. The deterministic model follows on to behaviourism analysis, where environmental stimuli are identified as eliciting specific psychological responses.

- Interactionist models rely on the fact that behaviour is a function of the person, and the environment, and focuses on the interactions between the characteristics which a person brings to a situation, and the environment which they find themselves in.

- Transactionism relates to the goals and objectives which an individual brings to a situation, and the way in which these are affected by the social process of which the individual is a part.

Thermal sensation is a sensory experience, since it relates to how people feel. Parsons [1993] argues that it is not possible to define sensation in terms of physical or physiological terms. It is important to remember that sensation is how a person feels, not how the environment may be described. Thermal comfort is determined by the thermal condition of the body. Although the mechanisms behind some aspects of thermal comfort theory are not fully understood, it is generally accepted that area, position and duration of thermal stimuli, the existing thermal state of the individual, temperature intensity and changes in temperature stratification, all affect feelings of thermal comfort. To this end deterministic comfort temperature calculations are rendered impossible, since the pre-existing thermal sensation of individuals, the characteristics they possess, and the goals and objectives which they bring to a situation differ for each building occupant.

4.2.6 Health and Productivity

Numerous studies on the effects of heat stress on worker health and productivity have been carried out over the past two decades. Cortili et al [1996], Morris [1995] and Ramsey [1995] examined the effects of heat stress on human performance, but the effect of more moderate thermal environments upon development of fatigue, error rate, and dissatisfaction with the indoor environment is less easy to define. The work off Fanger, Nelson, Wyon, Meese et al, and others has widened understanding of physiological and psychological responses to mild heat stress. The relationship between this and other environmental stressors like air quality, noise and light is also better understood.

Fanger argues that it is very difficult to assess productivity in-situ. It would be most useful to be able to say that productivity would fall by a given percentage per 1°C deviation from the comfort temperature. This is, however, nearly impossible to measure accurately. If a decrease in productivity of 30-40% were noted, then assessment would be easier, and expensive heating, ventilation and air conditioning equipment is justifiable in terms of capital outlay. A change of just 2-3% is less easy to detect [Bunn, 1993].

There is little evidence to show that hot environments reduce cognitive ability, but moderately warm environments have shown detrimental effects upon vigilance tasks [Parsons, 1993]. This is almost entirely attributed to a drop in arousal level, although distraction due to discomfort does play a role. Where moderate environments become significantly warmer or cooler, arousal may increase, and productivity is raised.

> *Performance at a task will depend upon a person's arousal level compared with that for optimum performance. A task which is boring will be de-arousing, and a person will perform better if arousal can be raised to an optimal level by the stimulation caused by a stressor such as heat or cold. A warm environment however will reduce arousal level and hence performance at a vigilance task. If the task is demanding and arousing then thermal stress may over-arouse a*

person and performance will fall compared with that in a moderate thermal environment where arousal may be at an optimum for that task. [Parsons, 1993]

Nelson et al [1987] carried out experimental research to show that cool office temperatures delay the onset of fatigue and may benefit productivity to a limited extent. This creates a fine balance between the benefits of cooler offices, and the discomforts associated with them. Nelson's study produced results showing that the effects of fatigue can be lessened by creating conditions of comfort when the work tasks being carried out are of a routine and non-demanding nature. He found that productivity was higher in cooler conditions, and that fatigue developed more quickly in warm, comfortable environments. Individual mood was found to be better in a cooler environment, and concentration, vigour and activation were found to increase in cooler conditions. It is often difficult to relate laboratory, or test chamber conditions to real office situations, and it is questionable whether Nelson's results would be achieved over prolonged periods.

In a second experiment Nelson showed that warm temperatures induced sleepiness and that cooler air had the most significant effect on inhibiting sleepiness. Fatigue was also found to advance quickly after long exposures to warm temperatures, which was not found in cooler conditions. It was concluded that comfort is not the only deciding factor in setting thermal environment parameters. Cooler temperatures reduce fuel consumption, lessen environmental burdens and point toward a slower development of fatigue and sleepiness in individuals. Maintaining an office at 1°C cooler represented a saving of 5% in annual heating costs. With regard to northerly latitudes where the heating season is longer, and heating demands are higher, this saving could represent a significant sum of money. The essence of this statement questions whether excessive attention to thermal comfort can impact negatively on the competitive edge of a company. It was also found that cooler conditions are less likely to cause depressive feelings among workers. Anxiety, however, is not reduced by cooler temperatures, and aggressiveness can actually increase because individuals are less comfortable and are not working in an individual state of well-being.

Wyon [1975] investigated the performance of subjects clothed for comfort at two different air temperatures. Throughout an exposure period of 2.5 hours, each subject could adjust his/her thermal environment up or down to achieve comfort conditions. Subjects rated their own effort, arousal and fatigue, and the freshness of the air while performance tasks were carried out on numerical addition, memory recognition and cue-utilisation. No significant difference in performance of the tasks were highlighted, and the subjective responses to effort, arousal and fatigue remained reasonably constant. Subjects did express a preference for cooler air temperatures and higher clothing level rather than lighter clothing with higher air temperature, for reasons of air freshness. Average preferred air temperatures for 0.6 Clo value was 23.2°C, while the preferred air temperature at a higher Clo value of 1.5 was 18.7°C.

Grivel and Candas [1991] carried out tests on lightly clothed subjects in a climate chamber, while body and mean skin temperatures were recorded. For the first hour, the temperature was set at 25.1°C to allow body temperatures to stabilise. Over the next two hours subjects were allowed to set their preferred ambient temperature. Subjects spent approximately one hour seeking their preferred temperature, which tended to be unsteady in most cases. The overall preferred ambient temperature was 26.6°C. Time of day was found to have a significant effect on the preferred ambient temperature recorded. The difference between this study and numerous others carried out in climate controlled chambers, was that the subjects were not required to carry out any from of work task throughout the test period. For the first hour the only requirement was to subjectively assess the state of thermal comfort experienced. The next two hours were pre-occupied with determining the preferred ambient temperature. This is perhaps misleading, and potentially inapplicable to work-task functions, where movement and cognitive work tasks are required. In order to assess the impact on work tasks, productivity rating tests would be an advantage.

Meese et al [1984] carried out extensive experimental work to investigate the effects of moderate thermal stress on performance of factory workers. A large number of black and white, male and female factory workers were exposed to a series of low humidity temperatures. Two ranges of temperatures were used: a low temperature series, 6, 12, 18, 24°C and a high temperature series, 20, 26, 32, 38°C. Keeping clothing level constant for each of the two experimental ranges, the effect of temperature upon performance of factory simulated tasks was investigated.

Mean comfort votes versus air temperatures for the low temperature series, for all subjects, are shown graphically in Figure 4.6. The comfort vote is a five point scale, with 5 indicating 'comfortably warm' and 1 'uncomfortably cool. All subjects voted between 4 and 5 (comfortable and comfortably warm) at an air temperature of 24°C.

Meese found that the results obtained were in general agreement with the work of Fanger [1970]; around the comfort region there were few differences which could be attributed to sex or ethnic origin. Performance in the cold is likely to be affected by reduced dexterity and flexibility, loss of finger-tip sensitivity, lower muscle temperatures and distraction which occurs at very low temperatures (6 and 12°C). Conditions on the cool side of comfortable are often claimed to be beneficial for work. Meese found little evidence to support this claim, but states that a lower temperature (say 18°C) could help subjects to stay alert. A wide range of manual skills were found to be adversely affected by low air temperature, and the performance of most tasks were detrimentally affected by cold for all subject categories.

Mean comfort votes versus air temperature for the hot temperature series, for all subjects, are shown graphically in Figure 4.7. The same five point comfort scale was used as previous. The results of the study showed that many of the effects of heat on performance were beneficial. Nine out of ten tasks tested were significantly affected by temperature over the range, all showing an improvement in performance from 20-32°. Seven of the nine tasks showed a deterioration in performance at 38°C, with the remaining two showing no detrimental effect. All four subject categories expressed maximum comfort at 20-22°C.

Temperature has a strong effect on performance for subjects exposed to test conditions over an entire working day. For cold conditions the effects were significant enough to suggest factory building improvements to avoid low temperatures during winter months, and that capital spent on renovations could be easily reclaimed by resulting improvements in worker productivity. The authors also expressed that high performance ratings at 32°C may be at the expense of workers, who could suffer from the early onset of fatigue under real factory conditions.

In a review of thermal effects on performance, with regard to four test types, Wyon [1996] formed the following summary:

4.2.6.1 Thinking

Performance of mental tasks which require concentration are reduced by 30% at 27°C, when compared to performance at 20°C. Given that the group average neutral temperature is typically 21°C, it is assumed that individual performance is 100% at temperatures up to individual neutrality, decreasing linearly to 70% over the next 6°C, and remaining at 70% for higher temperatures.

4.2.6.2 Typing

Performance of routine and familiar office work like typing is assumed to 100% at temperatures up to individual neutrality, decreasing linearly over the next 4°C to 70%, and remaining at 70% for higher temperatures.

4.2.6.3 Skill

Performance of skilled manual work is assumed to be 100% at temperatures down to 6°C above individual neutrality, decreasing linearly with temperature to 80% at temperatures 12°C or more below individual neutrality.

4.2.6.4 Speed

Performance of finger movements is assumed to be 100% at temperatures down to 6°C above individual neutrality, decreasing linearly with temperature to 50% at temperatures 12°C or more below individual neutrality.

Figure 4.8 illustrates these effects graphically.

There is no general agreement about the impact of personal differences and individual variability upon thermal comfort rationale. There is published evidence that age, sex, race, personality, ability, fatigue, heart disease, and expectation all influence the effects of thermal comfort on performance and behaviour. Work by Humphreys & Nicol [1996], Bunn [1993], Fanger [1988] and others have not to date produced general agreement in research findings.

4.2.7 Summary

The above information, linking the thermal environment with comfort algorithms, satisfaction indices and productivity ratings cannot afford to be ignored when considering the design of building elements, and their impact on building occupants. It is, however, difficult to quantify specific effects which design changes make to building performance, and occupant comfort/productivity. Current research has not to date developed a "productivity algorithm" whereby a change in a particular building input parameter results in a defined loss/gain in worker productivity or occupant comfort. Work by Fanger et al has gone some way towards defining the relationship between performance indicators like thermal, aural and visual comfort. Fanger calculated that a 1dB drop in noise level is equivalent to a 3°C rise in temperature [Building Services, 1993]. This information is still, however, too basic to be applicable for use in optimisation analyses.

Research activities have arrived at a number of conclusions, often conflicting in nature, regarding the design of comfort equations, building indices and design algorithms. Three main problems are highlighted through the literature review above.

- Firstly, the approaches adopted by researchers trying to quantify the subjective elements associated with the indoor environment are very varied. This makes comparisons and correlations difficult, and results inconclusive. Some experiments are centred purely around subjective assessment of the environment presented [Grivel & Candas, 1991], while others are a measure of performance at simple job tasks [Nelson, 1987] and [Wyon, 1996].

- Secondly, results obtained experimentally, using laboratory equipment and test conditions, rarely correlate satisfactorily with field investigations [Bunn, 1993], [Oleson, 1993] and [Williams, 1996].

- Thirdly, the subjective nature of the exercise often means that differing results are obtained from similar experiments, using similar test conditions. Although Fanger [1970] maintains that there are no physiological differences in the response of humans to their environment, Canter's study on other influencing factors may go a long way to explaining the rift in results and opinions [Canter, 1985].

What is recognised, however, is that the design of building elements plays a major role in defining the nature of the thermal environment created within a building envelope. Windows are a focal point of thermal building design for many reasons:

- They are not static building objects. If the thermal environment is not satisfactory to the building user, then window apertures may be opened to vent excess heat.

- Radiant asymmetry from a warm window causes less discomfort than from a cool window. Given that no more than 5% of occupants experience discomfort radiant temperature, differences of 10°C for a cool window, and 23°C for a warm window are permissible.

- Selection of windows with poor U-values can significantly influence the running cost of a building, and impact upon convective heat input, ventilation rates, and air conditioning.

- Poorly fitting windows are a source of draught, causing asymmetric heating/cooling of occupants, influencing building services operation, and impacting upon monetary costs. Fanger [1988] found draughts to be more significant in thermal comfort analysis than prevailing air temperatures.

The above research findings, though varied in nature, allow the analyst to gain a better understanding of the mechanisms behind thermal comfort criteria, and provide good foundations for better judgement and improved decision making. Fanger summarises his research efforts thus:

> *thermal comfort is independent of air quality, but it is important to get the temperature and draught criteria right. More complaints are received about draughts than from the prevailing temperature level, and the predicted mean vote (PMV) gives a good indication of the range in which the building engineer should aim.*

Area, position and duration of thermal stimuli, the existing thermal state of an individual, temperature intensity, and changes in temperature stratification remain the major influences on thermal comfort.

Thermal comfort has been shown to conflict with performance rating tests, showing that higher temperatures hasten the onset of fatigue and feelings of depression, while lower temperatures raise awareness, and improve performance at general work tasks. Experiments which focus purely on thermal comfort show that higher room temperatures are preferred, while productivity and performance related tests illustrate that temperatures slightly below comfort levels produce better results, and delay the onset of fatigue.

Additionally, the thermal mass of a building structure impacts heavily on environmental temperatures achieved, and the perceived comfort of building occupants. Light building constructions have low thermal masses, short time constants and experience rapid temperature changes in response to prevailing outside temperatures. This increases the difficulty of maintaining a constant comfort temperature and building occupants experience a higher degree of discomfort. Heavy building constructions have a longer time constant and react to changes in outside air temperatures much more slowly, allowing tighter control of indoor conditions. The ability to control temperatures more accurately increases the comfort of building users.

The above literature review illustrates that research to date has not reached sufficient maturity to allow reliable algorithms describing the relationship between thermal environments and user comfort/productivity to be defined. To develop such algorithms was considered beyond the scope of this thesis. The information gained from the above literature review highlights the importance of getting thermal conditions right, and far from being excluded from the analysis which follows, it forms it's basis. The above review has provided the rationale for selection of a environmental temperature around which to base the following thermal analysis; a temperature which delays the onset of fatigue throughout the duration of a day, which minimises energy consumption used for space heating, and yet which provides sufficient comfort for workers such that attention is focused on work task performance, and not prevailing conditions.

4.3 Thermal analysis

The following analysis is centred around energy consumption used for space heating in a building, incorporating any given window construction with known thermal properties, rather than any quantification of productivity loss due to perceived discomfort. For completeness, solar transmission properties for a variety of window constructions are presented, both in tabular and graphical format, although the impact of solar heat gain to the space is not assessed. It is assumed that the space within a building is heated to a given environmental temperature for comfort throughout the heating season (1 October – 30 April), the windows are openable during summer months to provide natural ventilation, and that no artificial cooling is provided. To provide an in-depth analysis of solar heat gains to the internal space was considered to be beyond the scope of this thesis.

Single glazed window constructions offer very little resistance to heat loss since glass is a very poor insulator. Adding a second pane of glass, separated from the first by a cavity, offers additional resistance. Air and inert gases have low thermal conductivity and therefore increase the overall resistance of the window structure. The additional pane of glass also offers increased resistance to long wave radiation exchange.

Increasing the width of the cavity increases the resistance of the window structure. There is, however, an optimal cavity width which is dependant upon the type of gas used to fill the gap. Research carried out by Han [1996] identified the optimal gap to be 20mm for air, and 16mm, 12mm and 8mm for Argon, Krypton and Xenon gases respectively. Generally, smaller cavities are characterised by conductive heat transfer, while larger cavities are characterised by convective heat transfer. Gases with higher molecular weight have lower conductivity compared with air, and provide enhanced insulative properties. Addition of a third pane of glass further increases the window resistance by providing a second cavity. Heat transfer also occurs due to long wave radiation exchange between the internal pane and internal surfaces, and the external pane and the sky/surroundings. Coating the glass with a low-emissivity coating reduces this long wave radiation exchange. Mixed mode heat transfer through multi-glazed windows is illustrated in Figure 4.9.

The results of this analysis shall become one of four inputs to the final optimisation, whereby a glazing solution which maximises user comfort, whilst minimising global environmental impact, is sought.

To consider the energy analysis of a window in isolation of the building of which it is a part, would be both misleading, and of limited use. For this reason an example office, having dimensions and layout as shown in Figure 4.10, is used to compare the space heating energy requirement associated with each of 24 windows used in construction. Table 4.1 lists the construction and U-value of each window considered. The following assumptions are made regarding the office environment, location, orientation and construction:

- The office environment is maintained at an environmental temperature which is high enough to meet thermal comfort needs, yet low enough to inhibit the early onset of fatigue in workers. It is therefore reasonable to assume that under normal operating conditions, a setpoint temperature of 19°C is maintained, using building controls and/or energy management systems.

- Each window configuration is installed within a typical office setup, with office location and orientation, wall construction, and window sash and frame construction remaining constant across all permutations.

- The example office is on an intermediate floor of a building and has one external wall. It is surrounded above, below and on all internal sides by spaces at the same temperature.

The analysis is performed over a period of one year, using a recognised approach, and a typical one year sample data set from Meteorological (MET) office weather data. The spreadsheets developed are based upon weather data for Turnhouse in Edinburgh. Three years of hourly dry bulb temperature values were averaged over the heating period 1 October to 30 April, from 1990-1992, for operational hours of 8am to 6pm.

Dynamic computer models were developed to show the data used, and the calculations performed in evaluating annual space heating energy demand. The spreadsheets can be found on the enclosed compact diskette in directory CD/Program Folder/Thermal Analysis. Due to the size of the files created it was necessary to create several files, labelled as follows:

single.xls	all single glazed window data: 4mm, 6mm, 8mm and 10mm glazing.
Dnolowe.xls	double glazed window options with no low-emissivity coating: 4-20air-4, 4-16Ar-4, 4-12Kr-4 and 4-8Xe-4.
Dlowe.xls	double glazed window options with low-emissivity coating: 4e-20air-4, 4e-20air-e4, 4e-16Ar-4, 4e-16Ar-e4, 4e-12Kr-e4 and 4e-8Xe-e4.
Tplowe.xls	triple glazed window options with low-emissivity coating: 4e-20air-4-20air-e4, 4e-16Ar-4-16Ar-e4, 4e-12Kr-4-12Kr-e4 and 4e-8Xe-4-8Xe-e4.
Sndreduc.xls	Sound reduction glazing options: 6-12Air-6, 10-12Air-4, 10-12Air-6, 6-100Air-4, 6-150Air-4 and 10-200Air-6.

These example files contain only one day of data each to prevent files from becoming prohibitively large. To perform the analysis on a complete year of data, the formulae in all columns may be copied downwards, using MET office data contained within CD/Program Files/Thermal Analysis, with filename:

thermdat.xls dry bulb temperature data from MET office (1990-1992).

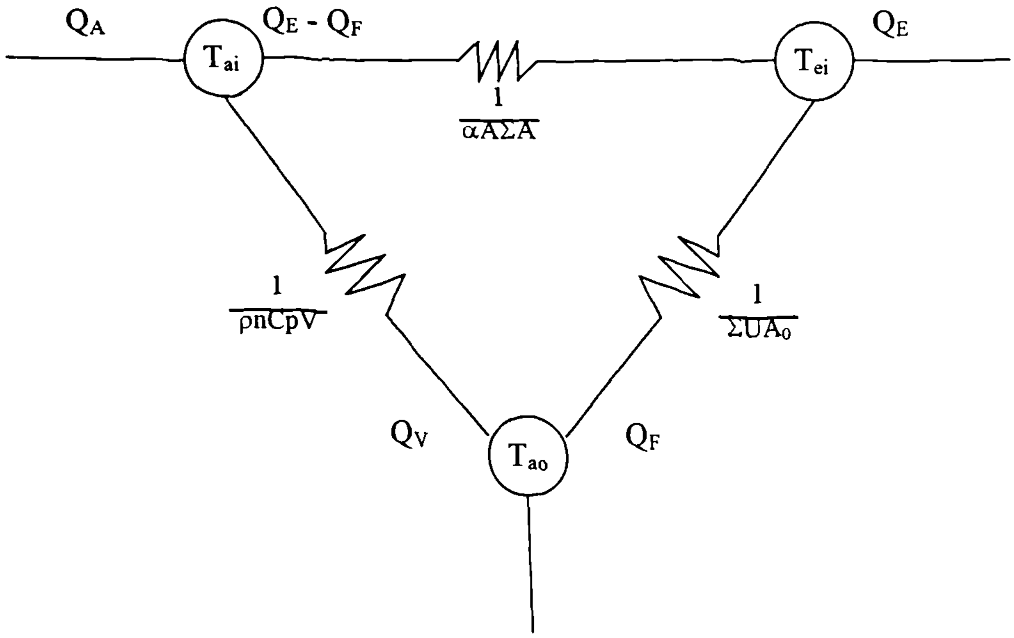
Within each of these working models, there is one worksheet per window type. The annual energy requirement associated with each window is calculated at the bottom of each sheet. A summary file lists all window types, their associated annual energy requirement in kWh and MJ, and illustrates these graphically. The summary file can also be found on the enclosed compact diskette in directory CD/Program Folder/Thermal Analysis, with filename:

Thermsum.xls Summary of all energy loss calculations.

4.3.1 Spreadsheet Use

1. Open selected file from CD/Program Folder/Thermal Analysis.

2. Enter user input values for room dimensions, window and wall areas (%), desired environmental temperature (°C), and wall thermal transmittance value (W/m^{2}K). Spreadsheet automatically calculates fabric losses, Q_F (W), ventilation losses, Q_V (W), and heat input Q_I, (W) at both air and environmental points, according to the steady-state energy network shown below:



$$Q_A + Q_E = Q_I = Q_F + Q_V$$

3. Results may be viewed for the 24 window constructions considered in this thesis in file CD/Program Files/Thermal Analysis/Thermsum.xls, on the worksheet labelled "graphical".

The flow diagram illustrated in Figure 4.11 shows what is required of the program user in performing the thermal analysis, and the stages involved in calculating the heat input required to maintain a given building at a pre-set environmental temperature.

4.3.2 Example Calculation

USER INPUT VALUES

Room length	13.4	(m)
Room width	6.8	(m)
Room height	2.5	(m)
Room Volume	227.8	(m^3)
Room surface area, A_s	283.2	(m^2)
Total facade area, A_o	33.5	(m^2)
Glazing area, A_{window}	60	(%)
Wall area, A_{wall}	40	(%)
Internal environmental temperature, T_{ei}	19	(°C)
Wall U-value, U_{wall}	0.5	(W/m^2K)
Air changes per hour, n	1.5	
Imaginary heat transfer coefficient	4.5	(W/m^2K)
window type	4-12Kr-4	
window U-value, U_{window}	2.54	(W/m^2K)

Columns B and C describe the window options available, and their U-values.

Columns D, E and F are automatically updated from the "user input values", and need not be edited.

Columns G, H and I are used to calculate the arm resistances on the steady state energy network diagram above.

Columns J to O are used to calculate the thermal loads for ventilation and fabric losses.

Column M gives the total heat load at the air point, and Column O gives the total heat load at the environmental point.

CALCULATION OF STEADY STATE RESISTANCES

fabric resistance

$\Sigma UA_0 = (A_{window} * U_{window}) + (A_{wall} * U_{wall})$ 4.1

$= (0.6 * 33.5 * 2.55) + (0.4 * 33.5 * 0.5)$

$= \underline{58.0 \text{ W/K}}$

ventilation resistance

$\rho n C_p V$ (taking ρC_p as 1200 J/m^{3}K) 4.2

$= 1.5/3600 * 1200 * 227.8$

$= \underline{113.9 \text{ W/K}}$

radiation resistance

$\alpha_a \Sigma A_s = 4.5 * 283.2$ 4.3

$= \underline{1274.4 \text{ W/K}}$

CALCULATION OF HEAT LOSSES

fabric losses

$Q_F = \Sigma UA_0 * (T_{ei} - T_{ao})$ 4.4

$= 58.0 * (19-0)$

$= \underline{1101.1 \text{ W}}$

internal air temperature

$T_{ai} = Q_F * (1/\alpha_a \Sigma A_s + 1/\Sigma UA_0) + T_{ao}$ 4.5

$= 1101.1 * (1/1274.4 + 1/58.0) + 0$

$= \underline{19.8°\text{C}}$

ventilation losses (air point)

$Q_{Vair} = \rho n C_p V (T_{ai} - T_{ao})$ 4.6

$= 113.9 * (19.8 - 0)$

$= \underline{2255.2 \text{ W}}$

ventilation losses (environmental point)

$Q_{Venv} = \rho n C_p V (T_{ei} - T_{ao})$ 4.7

$= 113.9 * (19 - 0)$

$= \underline{2164.1 \text{ W}}$

total heat loss (air point)

$Q_I = Q_{Vair} + Q_F$ 4.8

$= 2255.2 + 1101.1$

$= \underline{3356.3 \text{ W}}$

total heat loss (environmental point)

$Q_I = Q_{Venv} + Q_F$ 4.9

$= 2164.1 + 1101.1$

$= \underline{3265.2 \text{ W}}$

An example external air temperature of 0°C has been used in this calculation. The above calculation is executed for each hour of data input, and is summed over a period of one year. An example sheet from Dnolowe.xls is shown in Figure 4.12 to illustrate the layout of the calculation spreadsheets found on the enclosed compact diskette. The final output of this thermal evaluation model is shown graphically in Figure 4.13, and is discussed at length in Chapter 8.

By changing the user input values, or use of alternative weather data files, the model can be adapted to calculate space heating requirements for other locations and different building dimensions. Calculations can be performed for alternative window frame and glazing options, and by editing the indoor environment setpoint conditions, other building types can also be modelled.

4.3.3 Solar transmission properties

For completeness, solar transmission data for single, double and triple-glazed window properties are presented, both in tabular and graphical format. Two spreadsheets are used to evaluate solar transmission properties:

Soltrans.xls	evaluates diffuse solar transmission factors and direct solar transmission factors for angles of incidence 5°-85°.
Solsolve.xls	evaluates the equation of the direct solar transmission curve.

4.3.3.1 Spreadsheet Use

If solar transmission properties for a particular glazing construction are unknown, the Soltrans.xls spreadsheet can be used to evaluate the missing information using Procedure A below:

Procedure A

1. Open spreadsheet, Soltrans.xls from CD/Program Files/Thermal Analysis.

2. Select the first worksheet, "KL".

3. Table 1 is used to enter the construction of the window for which the solar transmission properties are required. L1, L2 and L3 describe the first, second, and third glazing panes in the construction, respectively. Refer to Table 2 and insert the appropriate values into cells B2, C2 and D2 to describe the glazing panes in the window construction. The KL value for each glazing pane is automatically

generated in cells B14, C14 and D14. Figure 4.14 illustrates a print-out of this worksheet.

4. If solar transmission properties are required for a single glazed window select worksheet "SGL"
   If solar transmission properties are required for a double glazed window select worksheet "DBL"
   If solar transmission properties are required for a triple glazed window select worksheet "TPL"

5. The diffuse and direct transmission values for the window construction are highlighted in green, and the direct transmission curve is shown graphically. Figure 4.15 illustrates a print-out from the "TPL" worksheet.

To evaluate the equation of the direct transmission curve, Procedure B is used:

Procedure B

1. Open spreadsheet, Solsolve.xls from CD/Program Files/Thermal Analysis.

2. Copy the direct light transmission values into column C. Column D contains calculated transmission values for the equation coefficients in cells H2 to H7, and Column E evaluates the difference between actual and calculated transmission values. Cell E11 gives the sum of differences.

3. Open the solver function within Excel, and minimise the sum of differences in cell E11 by changing the equation coefficient values in Cells H2 – H7. The computed values for a0 – a5 give the coefficients for the equation of the direct solar transmission curve. Figure 4.16 illustrates the spreadsheet layout.

A summary of solar transmissivity data for single, double and triple-glazed windows is given in Table 4.2. Direct solar transmission curves are presented graphically in Figures 4.17-19.

4.3.3 Synopsis

The dynamic computer models developed provide a tool for quick and simple thermal assessment of window constructions which was not previously available. Use of computer models for this purpose omits the need for time consuming calculations, and provides data which is often difficult to obtain. Used in conjunction with the solar transmission curves provided, a powerful and comprehensive method of analysis can be developed, which is building and location specific, providing detailed information for demanding design specifications.

It would appear, from studying Figure 4.13, that triple glazed window constructions which adopt the use of inert infill gases minimise annual convective heat input. Of the triple glazed window constructions available, Xenon filled windows, using two low emissivity glazing coatings (4e-8Xe-4-8Xe-e4), provide the highest thermal insulation value. The energy analysis at this point, is however, incomplete. The embodied energy associated with raw material acquisition and preparation, in addition to energy required for manufacturing, transportation, recycling, and final disposal must also be assessed. Further, the energy consumption associated with illuminating the building interior to an acceptable working standard must be considered. Light transmission properties for each window construction varies according to glass thickness and low emissivity applications. Energy consumption associated with artificial lighting is analysed in detail in Chapter 6.

In addition to aggregating total energy consumption over a complete window life cycle, it is important to consider the sources from which energy is obtained, and the impact which these have on the global environment, both now, and in the future. Impact assessment of energy consumption and use is detailed in Chapter 7.

4.4 References

1. ASHRAE Handbook of Fundamentals, Atlanta, Georgia, USA, (1977).
2. ASHRAE Thermal Standard 55: Thermal environmental conditions for human occupancy, ASHRAE, (1992).
3. Bunn, R., Fanger: Face to face, Building Services, June, 25-27 (1993).
4. BSJ, The Fanger Factor, Building Services Journal, September, (1997).
5. Canter, L., Psychological responses to environmental parameters: Deterministic, interactionist and transactionist models, Ergonomics, 28 (5) 731-747 (1985).
6. Cena, K.M., Ladd, P.G. and Spotila, J.R., A practical approach to thermal comfort studies in homes and offices: discussion of methods and concerns, ASHRAE Transactions, 6 (2), (1990).
7. CIBSE, CIBSE Guide Volume A1: Environmental criteria for design, (1988).
8. Cortili, G., Mognoni, P. and Saibene, F., Work tolerance and physiological responses to thermal environment wearing protective NBC clothing, Ergonomics, 39(4), 620-633, (1996).
9. Building Services, Technical File: What causes discomfort?, June (1993).

10. Fanger, P.O. and Christensen, N.K., Perception of draught in ventilated spaces, Ergonomics, 29(2) 215-235, (1986).
11. Fanger, P.O., Comfort limits for asymmetric thermal radiation, Energy and Buildings, Vol. 8, 255-236 (1985).
12. Fanger, P.O., How to apply models predicting thermal sensation and discomfort in practice, International Conference Thermal Comfort: past, present and future, Building Research Establishment, 9-10 June, Garston, (1993).
13. Fanger, P.O., Melikov, A.K., Hanzawa, H. and Ring, J., Air turbulence and sensation of draught, Energy and Buildings, Vol. 12, 21-39, (1988).
14. Fanger, P.O., Thermal comfort: analysis and applications in environmental engineering, McGraw-Hill Book Company, London, (1970).
15. Grivel, F. and Candis, V., Ambient temperatures preferred by young European males and females at rest, Ergonomics, 34 (3) 365-378, (1991).
16. Han, B., Investigation of thermal characteristics of multiple glazed windows, Ph.D. thesis, Department of Mechanical, Manufacturing and Software Engineering, Napier University, Edinburgh, (1996).
17. Humphreys, M.A. and Nicol, J.F., Conflicting criteria for thermal sensation within the Fanger predicted mean vote equation, CIBSE/ASHRAE Joint National Conference, (1996).
18. ISO, Moderate thermal environments – determination of the PMV and PPD indices and specification of the conditions for thermal comfort, International Standard ISO 7730, (1984).
19. Meese, G.B., Kok, R., Lewis. M.I. and Wyon, D.P., A laboratory study of the effects of moderate thermal stress on the performance of factory workers, Ergonomics, 27 (1), 19-43, (1984).
20. Morris, L.A., Practical issues in the assessment of heat stress, Ergonomics, 38(1). 183-192 (1985).
21. Nelson T.M., Nilsson, T.H. and Hopkins, G.W., Thermal comfort: advantages and deviations, ASHRAE Transactions, 93 (1) (1987).
22. Olesen, B.W., Scholer, M. and Fanger, P.O., Discomfort cause by vertical air temperature differences, Danish Building Research Institute, Copenhagen, (1979).
23. Oseland, N., UK design rules OK?, Building Services, June, 28-29, (1993).
24. Parsons, K.C., Human thermal environments, Taylor and Francis, London, Chapter *10: Interference with activities*, performance and productivity, 119-217, (1993)
25. Ramsey, J.D., Task performance in heat: a review, Ergonomics, 38(1), 154-165, (1995).
26. Toftum, J., A field study of draught complaints in the industrial work environment, 6th International Conference on Environmental Ergonomics, ICEE '94, Montebello, Canada, 252-253, (1994).
27. Williams, R.N., Predicting environmental dissatisfaction in UK offices, CIBSE/ASHRAE Joint National Conference, (1996).
28. Wyon, D.P. and Nilsson, I., Human experience of windowless environments in factories, offices, shops and colleges in Sweden, Building Resources Worldwide, Proceedings of the 8th CIB conference, 234-239 (1980).
29. Wyon, D.P., Fanger, P.O., Oleson, B.W. and Pedersen, C.J.K., The mental performance of subjects clothed for comfort at two different air temperatures, Ergonomics, 18(4), 359-374, (1975).
30. Wyon, D.P., Individual microclimate control: required range, probable benefits and current feasibility, Danish Technical University, Lyngby, Denmark, (1996).

Table 4.1 Window construction and U-value for 24 common window types

Window type	**Window Construction**	**U-value (W/m²K)**
Single	4mm	5.94
	6mm	5.91
	8mm	5.88
	10mm	5.81
Sound reduction	6*-12air-6	2.81
	10-12air-4	2.79
	10-12air-6	2.68
	6-100air-4	2.74
	6-150air-4	2.74
	10-200air-6	2.70
Double, no low-emmissivity	4-20air-4	2.74
	4-16Ar-4	2.63
	4-12Kr-4	2.54
	4-8Xe-4	2.49
Double, with low-emissivity	4e⁺-20air-4	1.58
	4e-20air-e4	1.44
	4e-16Ar-4	1.33
	4e-16Ar-e4	1.16
	4e-12Kr-e4	0.97
	4e-8Xe-e4	0.83
Triple, with low-emmissivity	4e-20air-4-20air-e4	0.83
	4e-16Ar-4-16Ar-e4	0.65
	4e-12Kr-4-12Kr-e4	0.52
	4e-8Xe-4-8Xe-e4	0.45

* refers to glass thickness

⁺ refers to low-emissivity tin-oxide coating ($\varepsilon = 0.12$)

Table 4.2 Solar transmissivity data for single, double and triple-glazed windows

A*	4+	6	8	10	4+4	6+4	6+6	10+4	10+6	4eo+4	4e+e4	4e+4+e4
0	0.86	0.83	0.80	0.78	0.75	0.72	0.70	0.68	0.66	0.63	0.53	0.46
5	0.86	0.83	0.80	0.78	0.75	0.72	0.70	0.68	0.66	0.63	0.53	0.46
10	0.86	0.83	0.80	0.78	0.75	0.72	0.70	0.68	0.66	0.63	0.53	0.46
15	0.86	0.83	0.81	0.79	0.75	0.72	0.70	0.68	0.66	0.63	0.53	0.46
20	0.86	0.83	0.81	0.79	0.74	0.72	0.69	0.68	0.65	0.63	0.53	0.46
25	0.86	0.83	0.80	0.78	0.74	0.72	0.69	0.67	0.65	0.62	0.52	0.45
30	0.86	0.83	0.80	0.78	0.74	0.71	0.69	0.66	0.65	0.62	0.52	0.45
35	0.85	0.82	0.79	0.77	0.73	0.71	0.68	0.65	0.64	0.61	0.51	0.44
40	0.85	0.81	0.79	0.76	0.73	0.70	0.67	0.64	0.63	0.60	0.50	0.43
45	0.84	0.81	0.78	0.75	0.71	0.69	0.66	0.63	0.62	0.59	0.49	0.41
50	0.83	0.80	0.76	0.74	0.70	0.67	0.64	0.61	0.60	0.57	0.47	0.40
55	0.81	0.78	0.75	0.73	0.67	0.64	0.62	0.59	0.57	0.55	0.45	0.37
60	0.79	0.75	0.72	0.70	0.63	0.60	0.58	0.55	0.54	0.51	0.42	0.34
65	0.74	0.71	0.68	0.67	0.57	0.54	0.52	0.50	0.49	0.46	0.38	0.29
70	0.67	0.65	0.62	0.60	0.48	0.46	0.44	0.43	0.41	0.39	0.32	0.24
75	0.57	0.55	0.52	0.51	0.38	0.36	0.35	0.34	0.32	0.31	0.25	0.17
80	0.42	0.40	0.39	0.38	0.25	0.24	0.23	0.23	0.22	0.21	0.17	0.11
85	0.23	0.22	0.21	0.21	0.12	0.11	0.11	0.10	0.10	0.09	0.08	0.04
90	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

* Incidence angle, degrees
+ Glass thickness, mm
o Tin-oxide low emissivity coating (ε = 0.12)

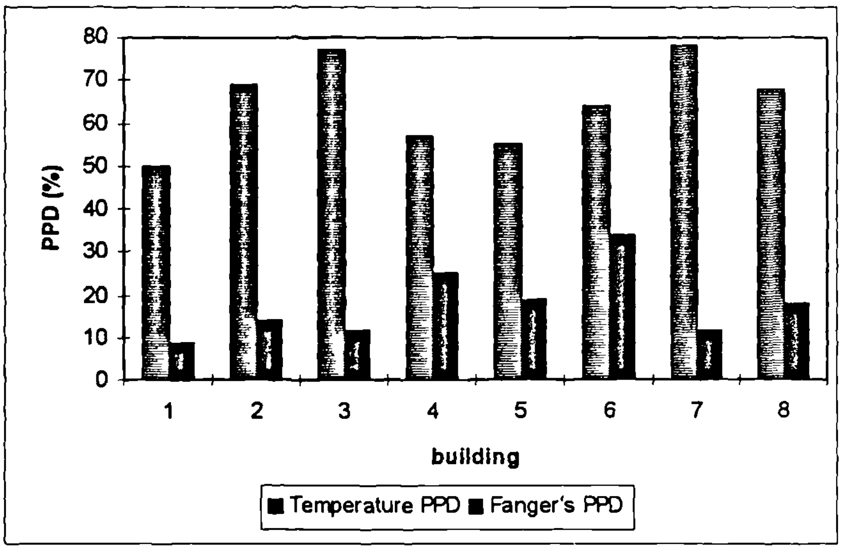


Figure 4.1 Field results of Williams' and Fanger's Percentage People Dissatisfied (PPD) models [Williams, 1996]

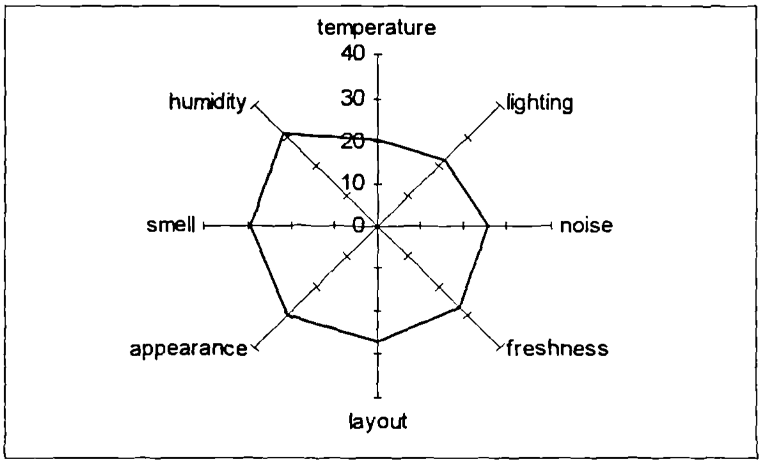


Figure 4.2 Average suggested building dissatisfaction envelope [Williams, 1996]

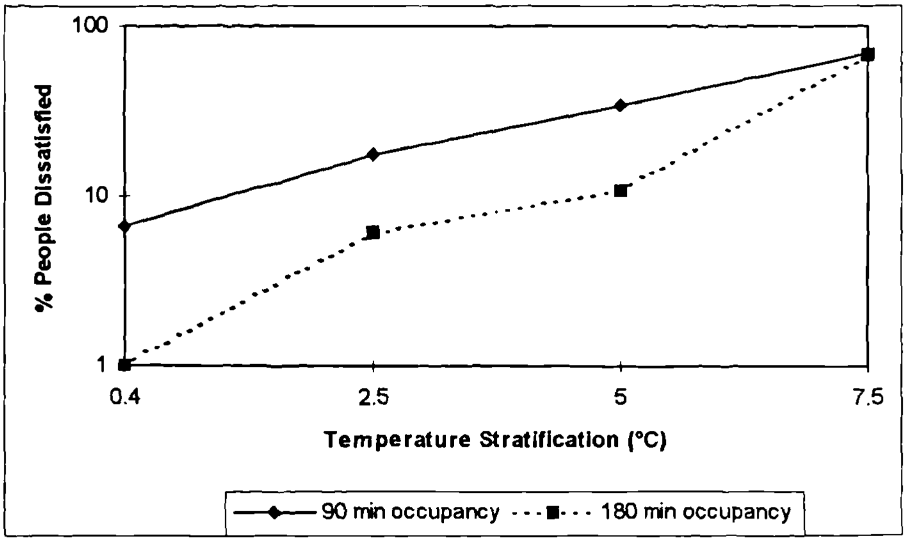


Figure 4.3 Subjective responses to local thermal discomfort [Oleson, 1979]

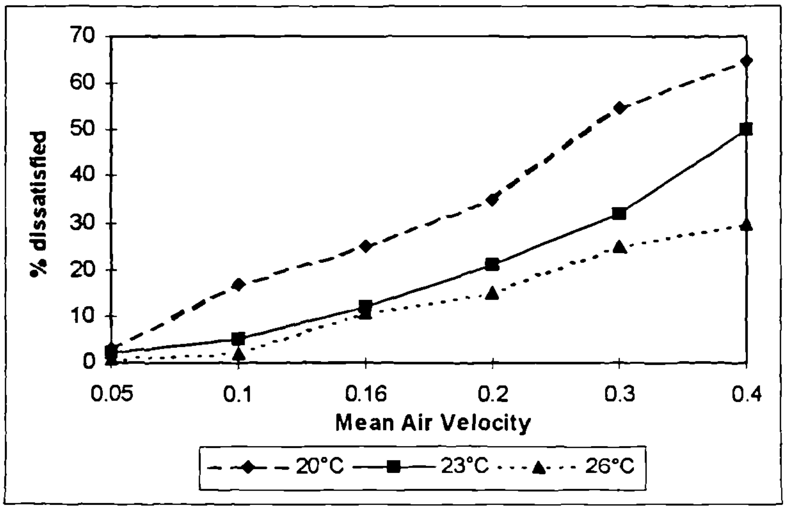


Figure 4.4 Percentage of dissatisfied people feeling draught as a function of mean air velocity at three different air temperatures [Fanger 1986].

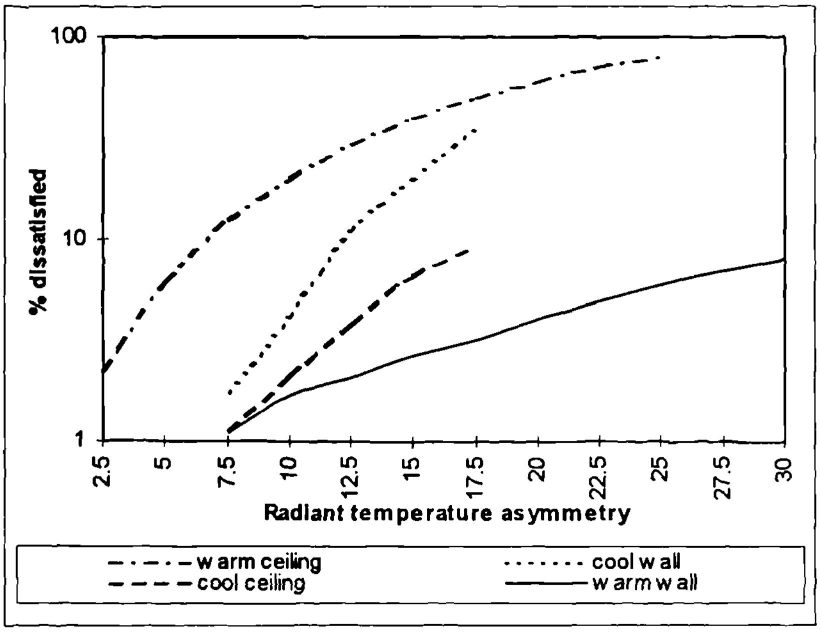


Figure 4.5 Percentage of dissatisfied persons as a function of radiant temperature asymmetry [Fanger, 1986]

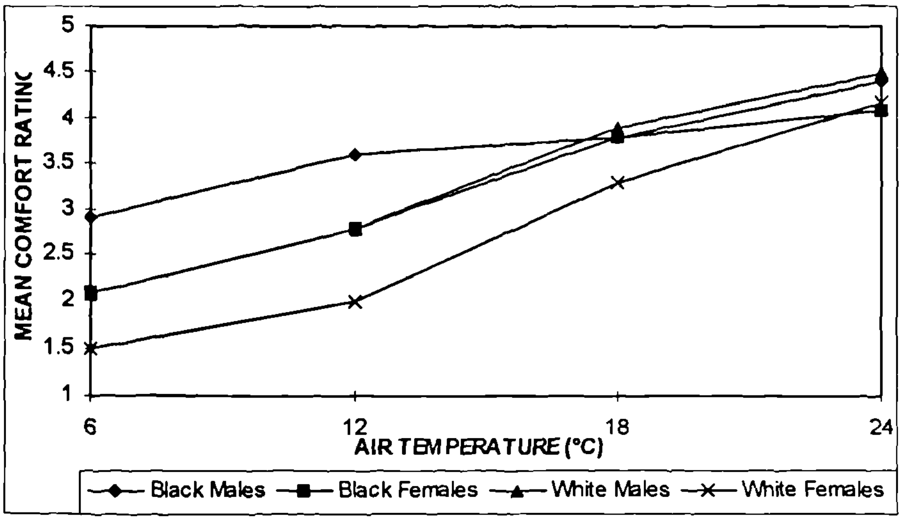


Figure 4.6 Mean comfort votes versus air temperature (cold series results) [Meese 1984]

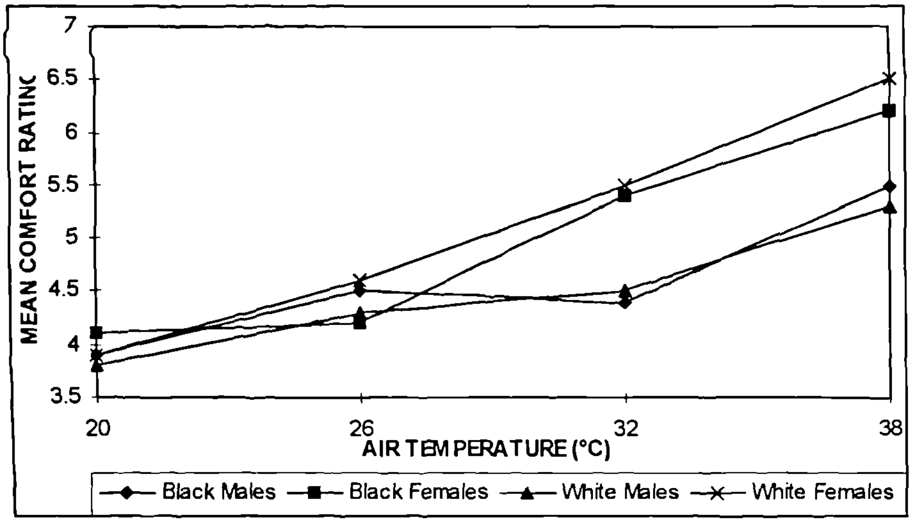


Figure 4.7 Mean comfort votes versus air temperature (warm series results) [Meese 1984]

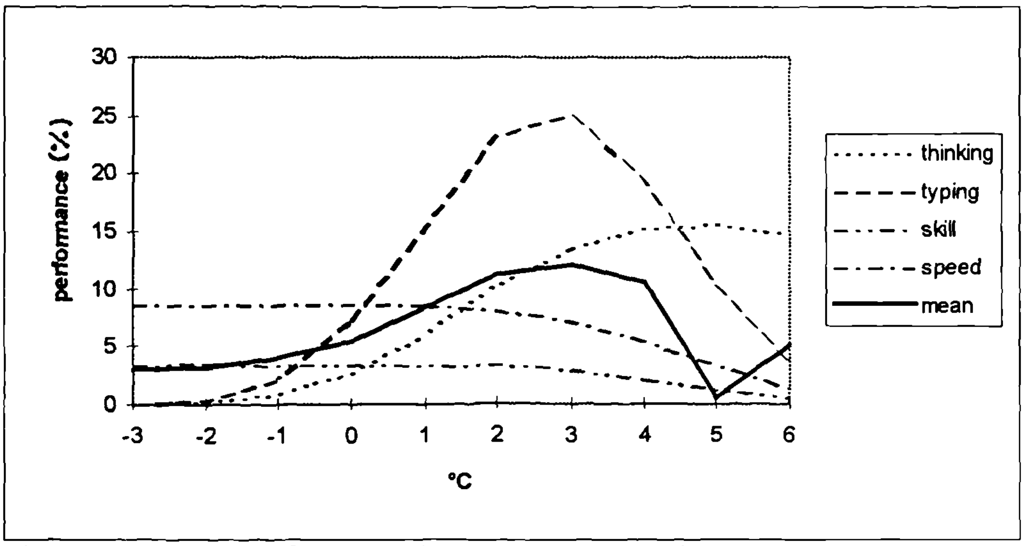


Figure 4.8 Deviation from comfort temperature against work performance for 4 tasks [Wyon, 1996]

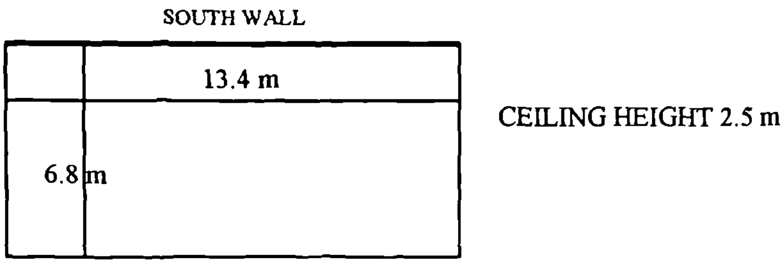


Figure 4.10 Example office dimensions and layout

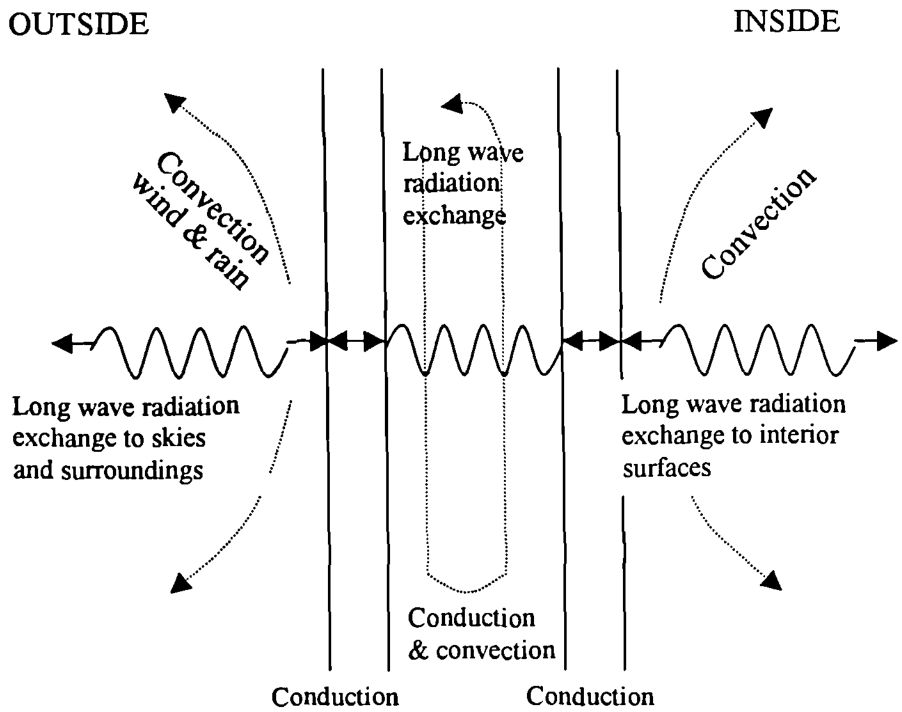


Figure 4.9 Mixed mode heat transfer through multi-glazed windows

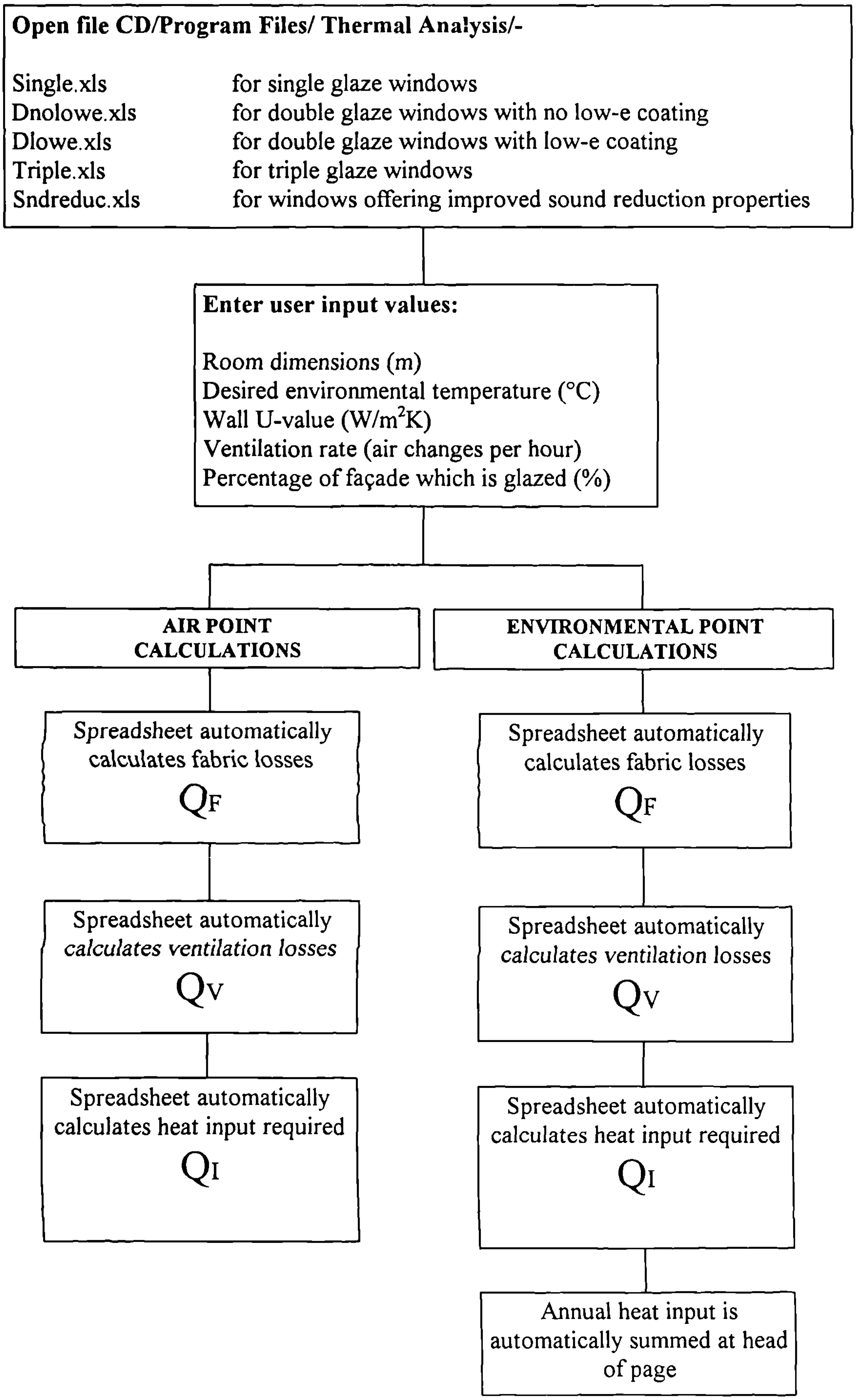


Figure 4.11 Flow diagram of thermal analysis calculations.

Thermal Modelling Spreadsheet	*4-12Kr-4*		*Annual Energy Input*	*14978.85*	*(MJ)*
User input values					
window U-value	2.54	(W/m^2K)			
Room length	13.4	(m)			
Room width	6.8	(m)			
Room height	2.5	(m)			
Office volume, V	227.8	(m^3)			
Surface Area, A_s	283.24	(m^2)			
Total Fascade area	33.5	(m^2)			
Glazing area %	60	(%)			
Wall area %	40	(%)			
Internal Environmental Temperature, T_{eo}	19	(°C)			
wall thermal transmittance	0.5	(W/m^2K)			
air changes per hour, n	1.5				

								Air Point			Environmental Point		
Month	Day	Hour	External environmental Temperature (°C)	ΣUA_0 (W/K)	ρnC_pV (W/K)	$\alpha_s \Sigma A_s$ (W/K)	Q_F (W)	Internal air temperature t_{ai} (°C)	Qv (air) (W)	Heat Input Ql (W)	Qv (env) (W)	Heat Input Ql (W)	Energy Input (kWh)
1	1	8	4.10	57.75	113.90	1274.58	860.53	19.68	1774.01	2634.54	1557.89	2418.43	2.42
1	1	9	4.43	57.75	113.90	1274.58	841.28	19.66	1734.32	2575.61	1523.04	2364.32	2.36
1	1	10	4.83	57.75	113.90	1274.58	818.18	19.64	1686.70	2504.88	1481.22	2299.40	2.30
1	1	11	5.53	57.75	113.90	1274.58	777.75	19.61	1603.36	2381.11	1408.03	2185.78	2.19
1	1	12	5.70	57.75	113.90	1274.58	768.13	19.60	1583.51	2351.64	1390.60	2158.73	2.16
1	1	13	6.03	57.75	113.90	1274.58	748.88	19.59	1543.83	2292.70	1355.75	2104.63	2.10
1	1	14	6.33	57.75	113.90	1274.58	731.55	19.57	1508.11	2239.66	1324.38	2055.93	2.06
1	1	15	7.03	57.75	113.90	1274.58	691.12	19.54	1424.76	2115.89	1251.19	1942.32	1.94
1	1	16	7.40	57.75	113.90	1274.58	669.95	19.53	1381.11	2051.05	1212.86	1882.80	1.88
1	1	17	7.27	57.75	113.90	1274.58	677.65	19.53	1396.98	2074.63	1226.80	1904.44	1.90

Figure 4.12 Example of thermal analysis computer model (taken from Drolowe.xls)

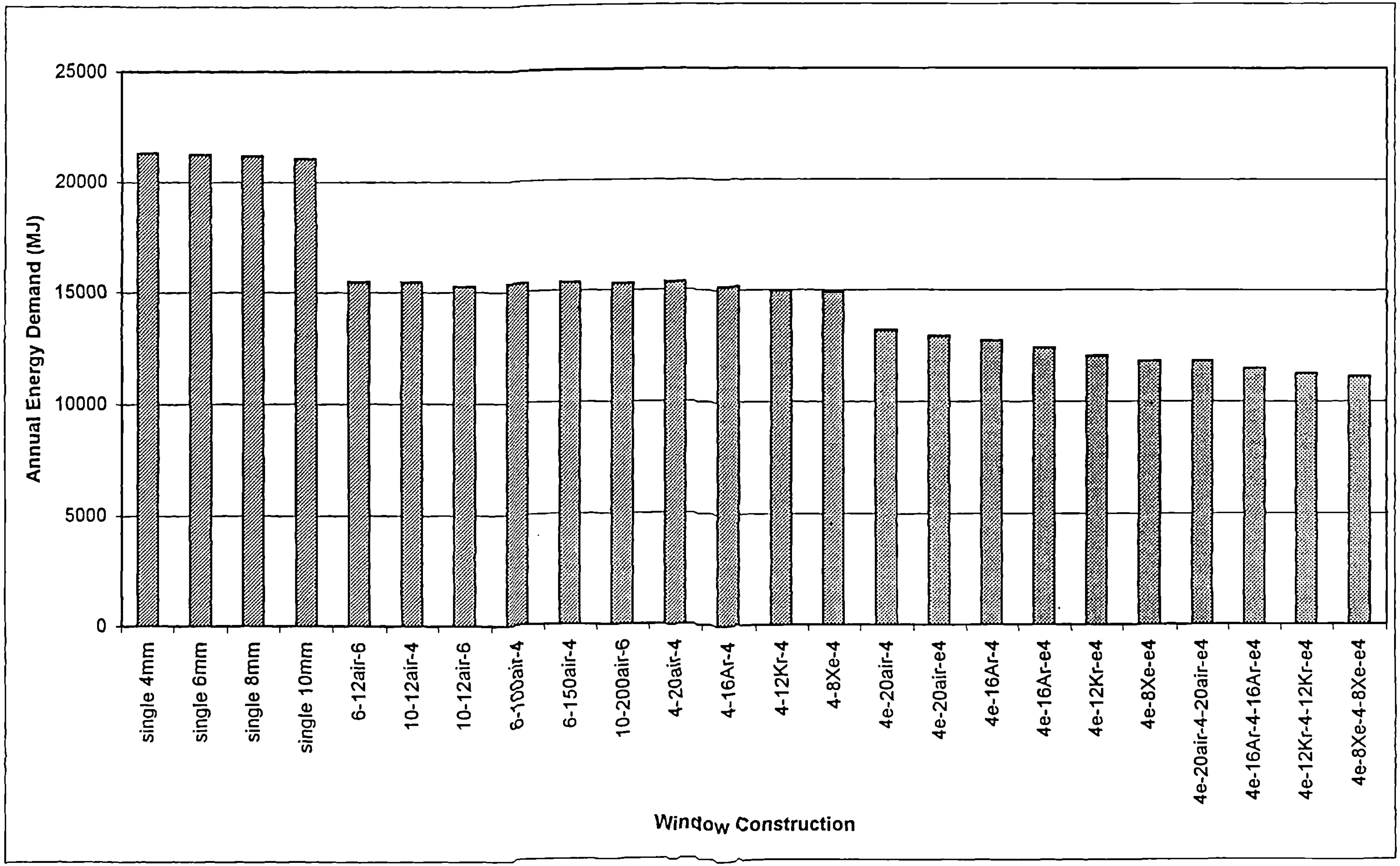


Figure 4.13 Annual space heating energy consumption for example office design incorporating 24 different windows in building construction

Table 1

	L1	L2	L3
glass	10	6	4e
T_0	0.78	0.83	0.72
μ	1.52	1.52	1.52
r	0.04258	0.04258	0.04258
A	0.916653	0.916653	0.916653
B	0.001813	0.001813	0.001813
g(-)	-649.035	-610.042	-702.985
g(+)	0.849808	0.904126	0.78459
KL	0.162745	0.100787	0.242595

Table 2

Glazing Thickness	Type	T_0 value	enter in B3, C3 or D3
4mm	no low-e	0.86	4
6mm	no low-e	0.83	6
8mm	no low-e	0.80	8
10mm	no low-e	0.78	10
4mm	with low-e	0.72	4e
6mm	with low-e	0.69	6e

Figure 4.14 Example layout of worksheet "KL" from spreadsheet "Soltrans.xls"

Diffuse		Direct	5	15	25	35	45	55	65	75	85
T1d	0.65374		0.728159	0.725863	0.720799	0.711711	0.695647	0.665607	0.60463	0.472433	0.195284
R1d	0.133529		0.067183	0.067148	0.067713	0.070622	0.080078	0.106144	0.173099	0.338407	0.713309
T2d	0.787538		0.862392	0.861566	0.85928	0.853804	0.840968	0.810746	0.738915	0.571044	0.229043
R2d	0.148366		0.077073	0.077137	0.077939	0.081338	0.091846	0.120347	0.193142	0.36968	0.740475
T3d	0.65374		0.728159	0.725863	0.720799	0.711711	0.695647	0.665607	0.60463	0.472433	0.195284
R2d	0.133529		0.067183	0.067148	0.067713	0.070622	0.080078	0.106144	0.173099	0.338407	0.713309
Z	0.949712		0.986314	0.986321	0.986088	0.984909	0.980809	0.967209	0.917892	0.728102	0.195915
T'd	0.354397		0.463598	0.460234	0.452738	0.439106	0.414928	0.371364	0.294294	0.175048	0.044584

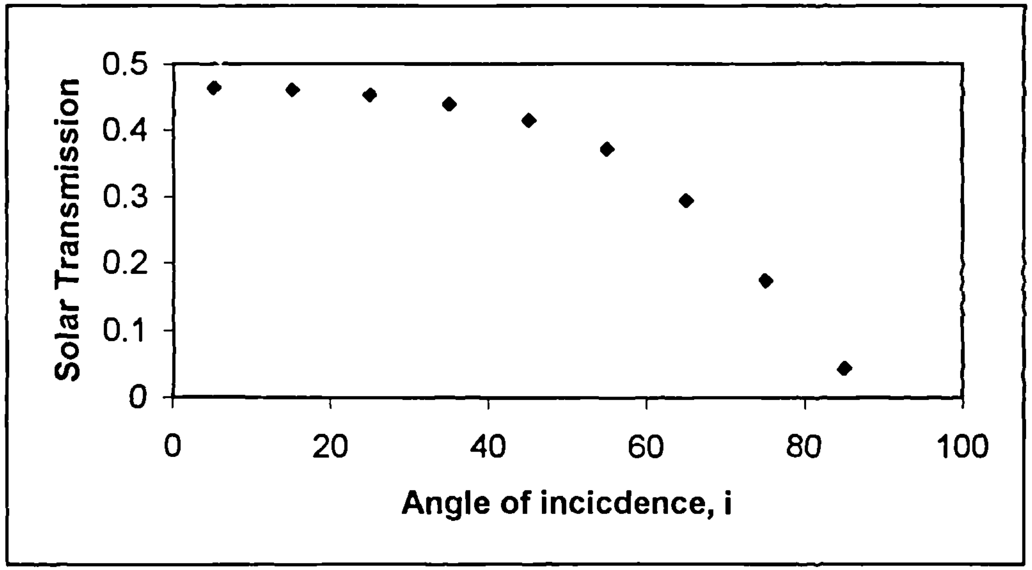


Figure 4.15 Example layout of worksheet “TPL” from spreadsheet Soltrans.xls

angle	Cos (angle)	Tranmission values	computed	difference
5	1.00	0.65847383	0.659399556	8.5697E-07
15	0.97	0.65847383	0.657198691	1.626E-06
25	0.91	0.65057928	0.651131297	3.0472E-07
35	0.82	0.639567491	0.63928885	7.7641E-08
45	0.71	0.617876572	0.617894732	3.2975E-10
55	0.57	0.574081042	0.574764238	4.6676E-07
65	0.42	0.485742	0.485066904	4.5572E-07
75	0.26	0.323136	0.323177927	1.7955E-09
85	0.09	0.098543706	0.098514782	8.3659E-10
			Sum of differences	**3.7907E-06**

	equation coefficients
a0	-0.012703362
a1	1.164679946
a2	1.785189583
a3	-6.319106423
a4	5.928956036
a5	-1.887394111

Figure 4.16 Example layout of spreadsheet "Solsolve.xls"

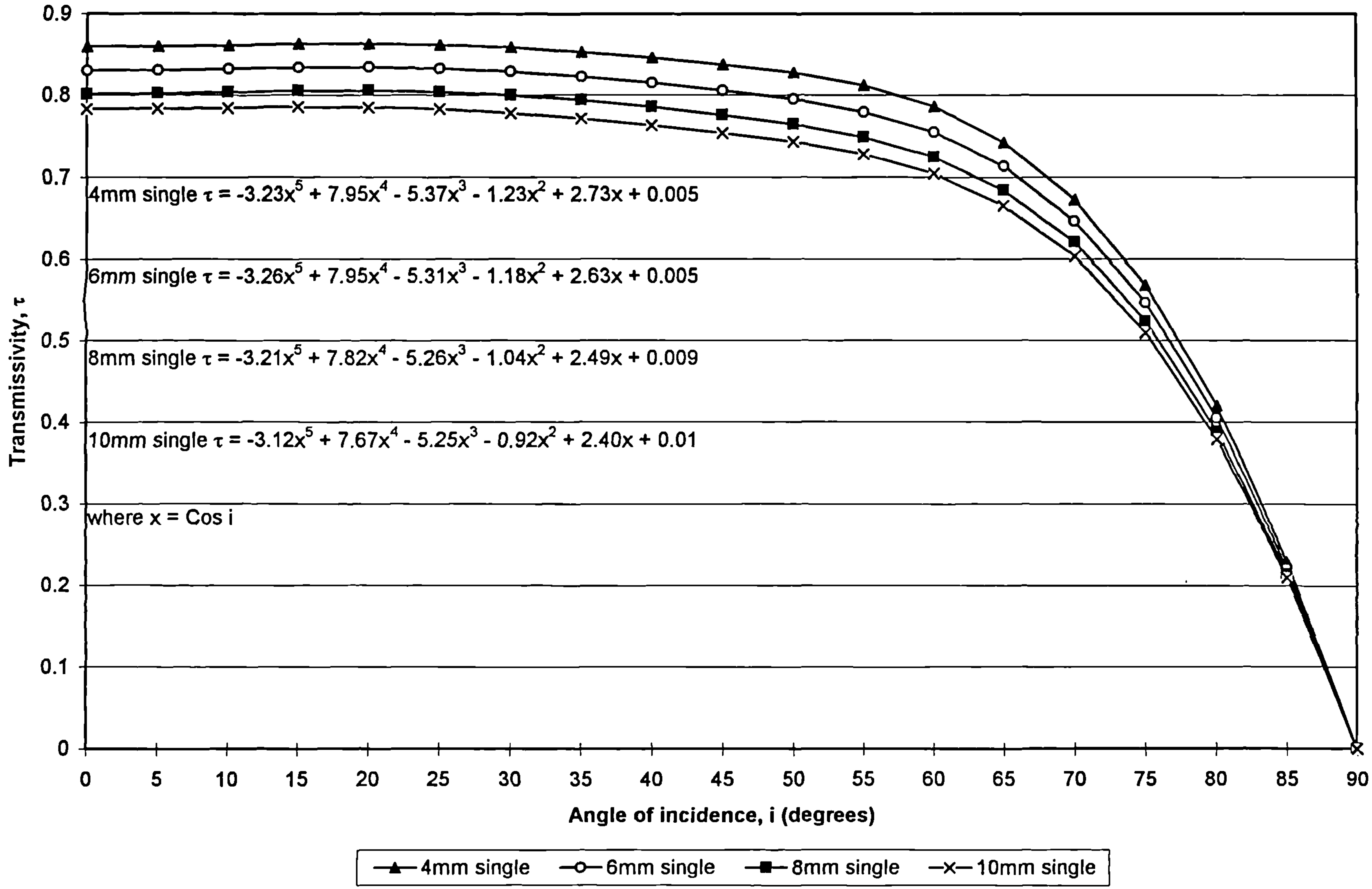


Figure 4.17 Solar transmissivity characteristics of single glazings

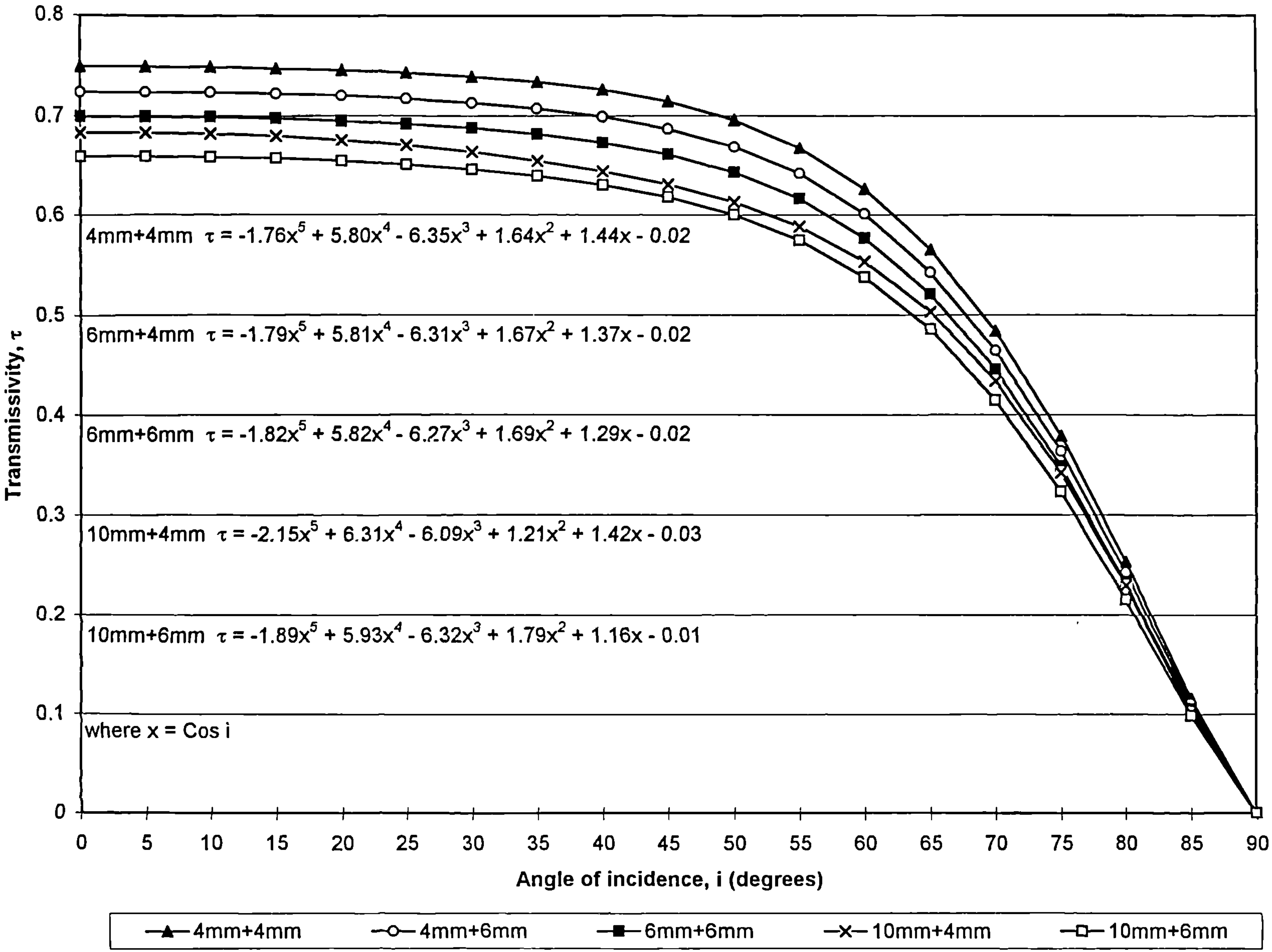


Figure 4.18 Solar transmissivity characteristics of double glazings

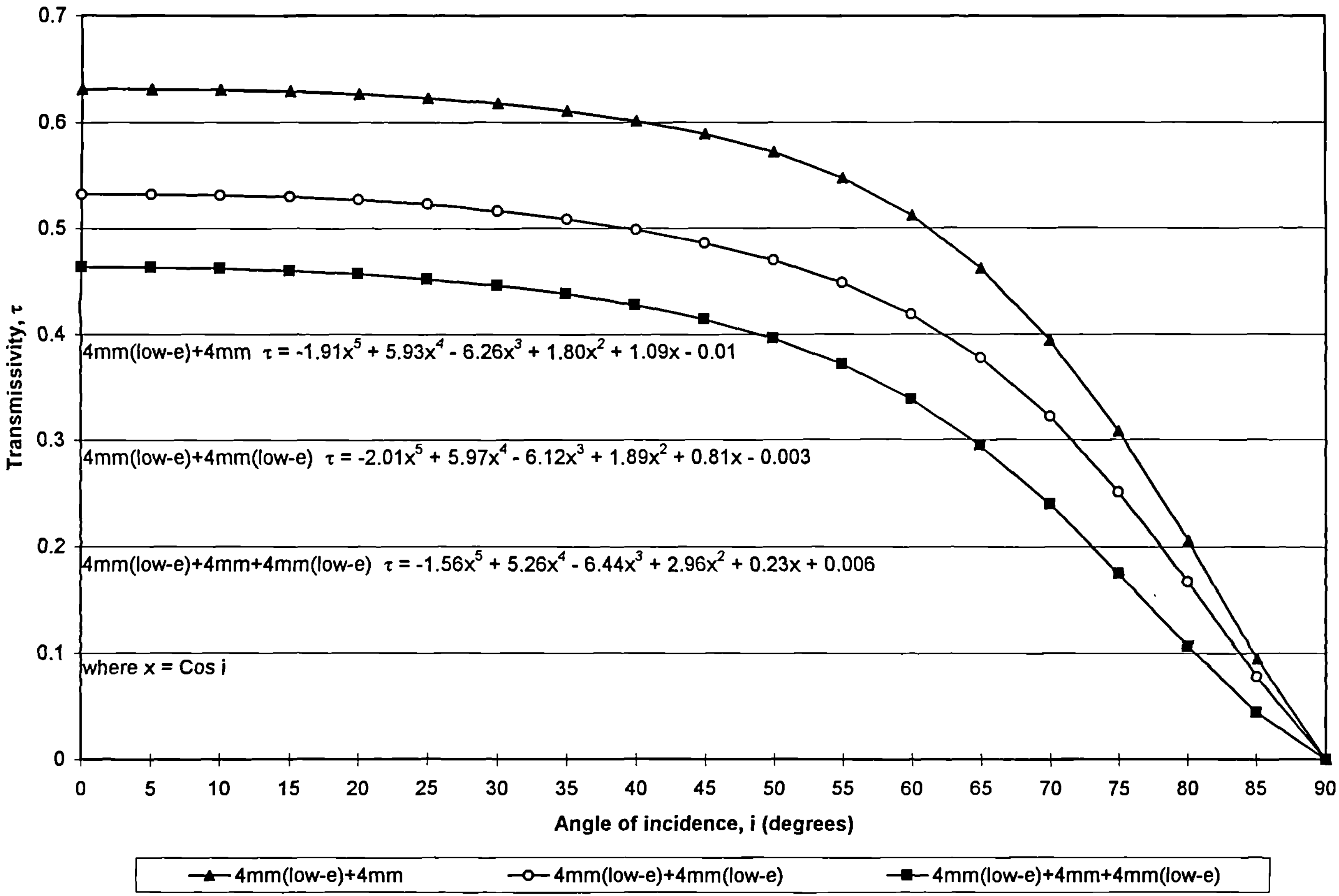


Figure 4.19 Solar transmissivity characteristics of double and triple glazings with low-e coatings

5. Aural Analysis

5.1 Introduction

It is clear to understand why a thermal analysis of window properties is included in a Life Cycle Assessment of windows. Energy consumption over a lifetime of use is significantly influenced by window thermal performance. It is less clear, however, to understand why an aural analysis should be included, as it has limited influence on material, energy or other resource consumption. No analysis would be complete, however, without designing to optimise the well-being of occupants, whilst simultaneously minimising environmental impact generated from the life cycle. If the well-being of building occupants is not at the fore of design criteria, the building, though well designed in terms of thermal performance, aesthetics and light transmission, will be unsatisfactory to its occupants. Work performance is heavily influenced by the working environment.

Sound is a form of wave energy. Noise is unwanted sound, and as such, may be described as pollution, evoking a need for corrective action. Noise pollution manifests itself in many ways, including hearing damage, communication disruption and the creation of unnecessary stress. Noise pollution may originate from transportation, industry, community life, and other sources. Annoyance very often occurs because the interference experienced by an individual is not the result of an action he or she benefits from, either immediately or directly.

Windows play an important role in attenuating exterior noise to an acceptable level for building occupancy. Achieving this is a function of three variables; the noise source, the receiver (the occupant) and the transmission medium (the window). Noise source variables concern the nature, composition and origin of the noise; receiver variables focus upon tasks and activities being performed by the building occupant; and window variables include the number and thickness of glazing panes, and the type of glass used. This chapter shall consider exterior noise sources which impact upon the interior environment, the effect they have upon health and productivity of building occupants, and how windows can be designed to act as appropriate filters to attenuate noise. Firstly, a thorough literature review of past and current research activities is presented, and then a computational analysis of window properties, and their ability to attenuate noise, is given.

5.2 Literature Review

5.2.1 Aural comfort

Attempts to apply the same comfort principles of thermal comfort analysis to building acoustics have been explored in the recent past. If the definition of thermal comfort is:

that condition where neither a warmer, nor cooler environment is desired,

then acoustic comfort can be paralleled as:

that condition where neither too quiet nor too noisy an environment exists.

Complaints about noise in the UK have increased dramatically over the last three decades. A survey carried out in England and Wales on 14,000 households between 1985 and 1987 showed that 14% of the adult population suffer from domestic noise annoyance. 11% of the subjects were bothered by road traffic noise, and 7% by aircraft noise. The increase in complaints received is a combination of several factors. Increased public awareness about entitlement to quieter environments, and a wider knowledge of complaints procedures account for some increase, but increases in general environmental noise levels also play a role.

There are thresholds of background noise level which should not be exceeded in order to establish conditions of comfort. Table 5.1 shows interior noise targets for some common building uses, while Figure 5.1 illustrates sound pressure and level for some typical locations.

5.2.2 Noise Sources

Most noise consists of a wide spectrum of frequencies. Before action can be taken to minimise the effect of noise, frequency levels and strengths must be identified. One of the dominant noise problems is traffic noise.

5.2.2.1 Road traffic noise

Road traffic noise is generally low frequency, and is a function of vehicle type, road surface, topography, and speed. Some typical road traffic noise levels are shown in Table 5.2. Road traffic noise decreases by approximately 3 dB(A) with each doubling of distance at right angles to the road. In terms of road traffic, noise exposure can be reduced by the following measures:

1. improved vehicle design.
2. improved road design; road surfacing.
3. provision of noise barriers, screens and earth embankments
4. traffic management schemes whereby lorries are re-routed and by-passes are constructed.
5. land use planning whereby road side land is used for non-domestic purposes.
6. improved sound insulation in buildings close to noisy roads [Adams and McManus, 1994].

This chapter will focus on solution No.6; improved sound insulation values of windows.

5.2.2.2 Rail Traffic Noise

Railway locomotive noise has a similar spectrum of frequency, although lectric trains have more emphasis towards middle frequencies, with higher frequencies decaying more quickly. Rail noise annoyance is generally more accepted than road traffic noise, despite higher noise levels, because it is more predictable and noise disturbance is shorter in period than the constancy of road traffic noise. The expression of rail noise is normally in terms of a 24 hour period since most traffic is regulated and time-tabled.. The noise levels associated with high speed, diesel passenger trains and freight trains, averaging 120 trains per day are shown in Table 5.3.

5.2.2.3 Aircraft Noise

Aircraft noise is a function of altitude, weather conditions, load and type of aircraft, with takeoff noise dominated by low frequencies, and landing with high frequency reverse thrust noise. In the past, noise in areas surrounding airports has been assessed using the Noise and Number Index (NNI). This is a composite of the number of aircraft movements, and the peak noises which they generate, and is generally plotted in contours around runways. NNI has since been replaced with L_{Aeq}, in accordance with International Standard ISO 1996/1 [ISO, 1996]. Table 5.4 shows the probable community annoyance due to aircraft noise at varying levels of NNI and L_{Aeq}.

Most conclusions concerning the ways in which people are affected by noise have been drawn from the results of subjective questionnaire based surveys which are used to assess the number of people affected by traffic noise and to what level. The problem of making definite conclusions from the surveys is that different types of noise have been assessed by different parameters; L_{Aeq}, L_{A10}, NNI, and different measurement locations. The type of questionnaire used is also highly variable.

5.2.3 Internal conditions

One problem experienced in assessing the exposure of an office worker to noise is that internally generated noise levels can often exceed those of external noise sources. Despite this, external annoyance may remain the focus of complaint, especially if the noise source is tonal or impulsive in nature. The building occupant has a greater element of control over noise generated internally, compared with external noise where no control is available. This difference has psycho-acoustic implications. The traditional way of accounting for tonal or impulsive noise was to add a penalty value to the measured dB(A). BS 4142 [1997] recommends a value of 5 dB(A) although this is regarded by some as inaccurate, as annoyance levels are so subjective in nature. A particular noise can cause annoyance at a level as much as 10dB below background levels, particularly where the noise is impulsive or tonal [Wilson et al, 1993].

Baker [1993] found that noise experienced by workers sitting just 2 meters from a window wall affected by traffic noise averaged 60dB. The background noise level in the office during unoccupied periods averaged 45-50dB. 70% of workers seated within 7 metres of the noise affected window wall found the external noise disturbance unacceptable. A study of all office occupants found that 48% of workers regarded the internal noise level as unsatisfactory.

The range of frequency covered by adult speech lies between 500-2000 Hz. Suppression of higher frequencies is crucial in maintaining privacy of conversation, since aural intelligibility relies on these most. In addition to developing Noise Criterion curves Beranek [1989] defined the speech-interference level (SIL). This enabled the influence of background noise levels on speech to be quantified. The average sound pressure level is calculated for three octave bands: 600-1200 Hz, 1200-2400 Hz and 2400-4800 Hz, covering most frequencies of speech. In the 1960's this was altered to three bands with centres: 500, 1000 and 2000 Hz, with a fourth centred at 4000 Hz added later. The average sound pressure level in the four bands is termed the Preferred octave Speech Interference Level (PSIL). The PSIL levels shown in Table 5.5 are suggested for good speech communication. Prevailing values much in excess of those listed will render normal speech unintelligible, except at very close distances. Table 5.6 lists sound level/distance relationships for speech intelligibility, in terms of background noise level in dB(A), and background NR, while Table 5.7 shows the quality of conversation at various background sound levels for telephone conversations.

5.2.4 Health and productivity effects

Numerous studies have been carried out to investigate the effect of loud noise on human health, or prolonged exposure to higher levels of noise on hearing ability. The effect of noise upon human health is variant and a function of personal susceptibility, and the nature, duration and location of the noise. The question of personal susceptibility is highly contentious, and was disputed by Smith and Stansfield [1986]. In the office environment, however, exposure to loud noises is generally not experienced, and the problem is associated with longer exposure to lower sound levels. At lower sound levels, more general physiological, psychological and social effects occur. The impact of more moderate intensity noise levels upon both human health, and work productivity is less well defined than for loud noise impacts. Difficulties in measurement and quantification of such effects mean that a relationship between noise discomfort and productivity loss is very difficult to develop. Studies to date have failed to identify any reliable formulation of the problem, but have led to a better understanding of its nature.

Sounds of only 20dB(A) engender increased alertness during sleep. From 35 dB(A) the time required to fall asleep increases and the duration of sleep falls. Noise exposure can lead to a number of symptoms being experienced, including headaches, nausea, fatigue, nervousness, accentuated irritability and aggressiveness, activity disruption, reduced concentration, reduced capacity for conversation, reduced work efficiency, increased accident risk, and feelings of isolation.

Smith & Stansfield [1986] studied the effects of aircraft noise on self-reported everyday errors. The results of the study highlighted two points. Firstly, a positive relationship was found between aircraft noise exposure and the frequency of occurrence of minor errors; e.g. errors of memory, attention and action. Psychologists suggest that information is handled on different processing levels, with higher levels controlling the actions of lower levels, and decision making criteria. Perception and memory are controlled by these higher processing levels. Environmental stressors like noise affect the operation of cognitive processes. Secondly, no correlation between sensitivity to noise and noise exposure was found, which contradicts the common belief that certain individuals are more sensitive to noise than others and experience exacerbated effects due to noise.

Interference with communication is one of the most common complaints of noise. In industry the interruption of communication can lead to inefficiency, and possible serious, or even fatal accidents. High noise levels render speech unintelligible, and can restrict the understanding of warning signals. Increased agitation or annoyance can also result, which could affect emotional responses, making people less reasonable than they might otherwise be. Noise which is insufficient to mask speech signals can, however, increase the difficulty of the listener, requiring more effort, especially in telephone communication. Holloway [1969] suggests that if non-masking noise can cause problems in speech intelligibility, then it is possible that difficulties can arise in other tasks performed simultaneously with listening. This implies that the person listening acts as an information processor of limited capacity.

These finding are paralleled in the work of Cohen and Lezak [1977]. Subjects in an experiment were asked to listen to a series of nonsense syllables which were later tested for memory recognition. As each syllable was given, a picture was shown. The subjects were told that the pictures were of no relevance. The subjects' memory for syllable recognition was no worse or better in conditions of quiet than for noise at 90 dB. When the memory for irrelevant pictures was tested, however, it was found to be significantly worse in conditions of noise. In summary, the main task of syllable recognition survived, but at the expense of ability to cope with a secondary task.

There are many processes involved in communication. Perception of speech received initiates the process, followed by understanding of the meaning of words used. The overall meaning of the conversation or message requires to be understood before a response or answer can be formulated. The task is further complicated if parts of the message need to be committed to memory. In some situations the listener may be expected to show their response to a question or statement. Thought process in forming an opinion, then selecting the correct words would be required, simultaneously to the process of listening. If, then, the communication process is made more difficult by disturbing noise levels, or conflicting messages in the background, conversation and thought processing becomes confused. In this respect unwanted sound can interfere with attention to a primary task; it is difficult for the listener to ignore conflicting messages. There is a need to interpret and understand noise signals, especially speech. Loudness of speech is also known to rise as difficulty in understanding increases. Adams and McManus [1994] summarised the effects on task performance and communication in four statements:

- *Noise may stimulate people; raise level of arousal and improve concentration and performance in relation to simple tasks.*
- *Noise, particularly loud or monotonous ambient noise may reduce arousal and have detrimental effect on performance.*
- *Loud noise is inherently annoying and distracting.*
- *Loud noise interferes with physiological mechanisms which are essential to complex task performance.*

Broadbent [1980] notes that due to psychological factors, there are several human responses to the same level of sound energy, and states that it is the meaning of noise, not only its intensity, which produces annoyance. One suggestion for differences in personal response is that expectations differ between individuals. Two noises may have the same sound energy level, but one may be found more annoying than the other if it is *expected* to be quieter. Another reason may be the nature of the noise; impulsive tones are generally more annoying than constant noises of the same sound energy level. Annoyance due to noise is often associated with psychiatric ill-health. Annoyance was defined by the World Health Organisation (WHO) as:

a feeling of displeasure evoked by noise.

Research on annoyance levels have acknowledged these problems, and conclude that a mechanical approach to improving acoustic environments cannot be adopted. Solutions to annoyance problems are often characterised by value, and not by scientific judgements.

Shultz [1978] did attempt to quantify annoyance levels by way of noise level. The results of his research on over 400 buildings, using 11 surveys are shown in Figure 5.2. Very few people are annoyed at noise levels below 45 dB(A). There is an increase in the number of people annoyed as the outside noise level rises above 60 dB(A). At 65 dB(A) approximately 25% of the population were highly annoyed. The wide spread in data points does, however, show the subjective nature of the study and highlights differences in personal opinion.

Broner [1978] noted that many studies have investigated the effects of infrasonic noise on people, yet the impact of low frequency noise on people had received little or no attention. Reports of nausea, disorientation, and general unpleasantness in response to infrasonic noise sources have gathered, where the unknown element of low frequency noise effects had been neglected. Man-made sources of noise at low frequency (20-100 Hz) include compressors, boilers, cars, ships and others. The focus of problems due to noise from these sources is annoyance, although responses to low frequency sound have varied from sleep disturbance to threats of suicide, in people who are otherwise disturbed. Individuals have reported annoyance due to the existence of low frequency rumble while others express a feeling of pressure on the inner ear. Broner states that apparent annoyance due to low frequency noise is more common that previously acknowledged, and the belief that loudness and annoyance are equivalent is incorrect. He also suggests that measures such as dB(A) cannot be used to predict annoyance levels.

Leventhall [1973] noted adverse effects on performance at noise levels lower than 80 dB(A), but that improvements in performance sometimes occurred at higher levels. This suggests that individuals are affected by the arousal effect, similar to that experienced in higher frequency noise.

The complete elimination of noise is not encouraged either, except in conditions where this is required for short periods, e.g. recording studios. Complete silence for prolonged periods can be very disturbing due to the effects of sensory deprivation and feelings of isolation. Noise within the workplace can be beneficial to efficient operation of machinery and equipment, as it gives an indication of the state of working order. Reasonable noise levels penetrating from the exterior can also be beneficial to work productivity.

5.2.5 Summary

Noise surveys and research activities vary in their method of assessment, numerical output and location type, making comparisons and broad conclusions difficult. Questionnaires are variant in sample size, type, content and results, while experimental studies differ in aim, location and type. Variant though the conclusions are, the following points summarise the findings of the above literature review, and reveal that attenuation of external noise sources to an acceptable level, via sound reducing glazing solutions is beneficial to work performance.

- Noise exposure can lead to a number of symptoms being experienced, including, headaches, nausea, fatigue, nervousness, irritability, aggressiveness, disruption to tasks, reduced concentration, reduced ability to converse, reduced efficiency, increased numbers of accidents, and feelings of isolation. All of these effects, whether directly, or indirectly, limit an individual's capacity to focus on a specific task, negatively influencing work performance and productivity.

- A direct relationship is confirmed between noise exposure and frequency of minor errors. This reduces the efficiency of work tasks performed, and may eventually lead to the occurrence of a serious error in instances where workers experience fatigue.

- Interference with communication is one of the most common complaints associated with noise. Disturbances in communications is both inefficient and dangerous.

- Where the noise disturbance in an environment is deemed unsatisfactory, the main tasks being carried out may remain unaffected, but at the expense of secondary tasks becoming inefficient, or containing errors. It may also lead to the early onset of fatigue in workers, reducing productivity and performance.

- A large number of factors influence noise perception, including personal health, personality, social habits and class, type of community, psychological well-being, and prejudice. It is therefore difficult to draw out firm conclusions relating noise and perceived aural comfort. What is certain, however, is that tonal, impulsive, loud and disturbing noises cause annoyance, which is detrimental to work task performance.

- Annoyance due to disturbance from noise sources is one of the most frequently received complaints. It cannot be measured using electronic equipment, and is only partially correlated with dB(A) measurements. Noises which are tonal or impulsive in nature are found to be most annoying.

- 70% of workers sitting within 7 metres of a window wall find disturbance from external noise sources to be unacceptable.

- Complete elimination of noise sources can be equally detrimental to work performance. Artificially suppressed acoustic environments could reduce arousal and distract concentration. An environment which is neither too noisy, nor too quiet, is optimal to work performance.

Adams and McManus [1994] conclude from a review of research techniques that the relationship between measured noise and noise level effects is extremely complex, and variant from person to person. There are a large number of influences on noise perception, including personal health, personality, social habits, social class, community type, psychological well-being, and prejudice.

There is a clear need to optimise the design of windows such that annoyance and disturbances caused by unwanted sound sources are minimised, whilst ensuring that thermal and visual qualities are not compromised in terms of occupant comfort and potential environmental impact. The analysis which follows was developed out of this need, and provides a method for assessing the sound attenuation properties provided by windows. When used in conjunction with the preceding thermal analysis in Chapter 4 and proceeding visual analysis in Chapter 6, a powerful tool for optimising the well-being and comfort of building occupants is developed.

5.3 Analysis

The following analysis is concerned with the noise that penetrates from the outside of a building (the source) to the working environment inside (the receiver), due to the attenuation properties of windows (the transmitting medium). The models presented herein are used to evaluate the noise attenuation properties for the same range of window constructions, listed in Table 4.1 (excluding triple glazed constructions), and for the same example office design and associated assumptions as considered in Chapter 4. The procedure for calculating aural performance of windows is illustrated using the flow diagram in Figure 5.3, and is discussed as follows:

1. Frequency dependent values of airborne sound insulation for each selected window configuration in the analysis is evaluated. This evaluation is a function of the number and thickness of window panes, cavity gap width and cavity gas type, as illustrated in Figure 5.4.

2. Frequency dependent airborne sound insulation values are converted into a single number characterising the acoustical performance for each window configuration.

3. Assessments and comparisons of constructions are simplified by the presentation of single number attenuation values in tabular and graphical formats.

This work presents a series of computer models for the calculation of the above properties, using the work of Pilkington [1995], Beranek [1992] and ISO Standard 717-1 [1996]. The models may be used to evaluate aural performance properties of any known single or double glazed window construction. A summary is given for single and double glazed windows considered in this work. The following method is not suitable for evaluating triple glazed window constructions. The mid pane in such windows causes acoustic coupling, and the attenuation value of the overall window is reduced due to vibration. The noise reduction achievable using a triple glazed window with two 8mm cavities is less than that for a double glazed window with a single cavity of width 20mm. It is assumed, therefore, that if noise attenuation is an important criteria in building design, that double glazed windows with a cavity greater than 50mm would be preferred over triple glazed options. To obtain data on triple glazed windows, the manufacturer should be approached for a detailed breakdown of sound insulation properties. By changing the prevailing noise spectrum and building construction details, the model can be adapted to calculate attenuation properties for other locations, varying noise sources and different building details. Calculations can be performed for any window/wall proportions or single/double glazed options.

The analysis is not sensitive to yearly data, or hours of occupancy, as with the thermal and visual analyses presented, but assesses the ability of window constructions to attenuate noise to an acceptable working level, whereby task operation is not detrimentally affected, and work performance is not compromised.

The final output of this analysis shall become the second of four inputs to the final optimisation presented in Chapter 8. The computer models are enclosed on CD/Program Files/Aural Analysis and are labelled as follows:

Aurcalc.xls Evaluates frequency dependent values of airborne sound insulation for each selected window configuration in the analysis

Aural.xls Converts frequency dependent airborne sound insulation values into a single number characterising the acoustical performance for each window configuration.

5.3.1 Spreadsheet Use

5.3.1.1 Aurcalc.xls

Frequency dependent values of airborne sound insulation may be calculated for any known single or double glazed window construction using the spreadsheet, Aurcalc.xls. There are two worksheets within the spreadsheet; a calculations worksheet, and a summary worksheet. Use of these worksheets is as follows:

Calculations Worksheet

- Select the worksheet labelled "calculations"
- For cavity gaps less than 50mm, enter the thickness of the first pane of glass in mm, in Cell B22, and the thickness of the second pane of glass in mm, in Cell B23. Enter the gas type in Cell B24.
- For cavity gaps between 50mm and 100mm, enter the thickness of the first pane of glass in mm, in Cell B32, and the thickness of the second pane of glass in mm, in Cell B33. Enter the gas type in Cell B34.
- For cavity gaps between 100mm and 150mm, enter the thickness of the first pane of glass in mm, in Cell B42, and the thickness of the second pane of glass in mm, in Cell B43. Enter the gas type in Cell B44.
- For cavity gaps between 150mm and 200mm, enter the thickness of the first pane of glass in mm, in Cell B52, and the thickness of the second pane of glass in mm, in Cell B53. Enter the gas type in Cell B54.
- Sound reduction values for the complete window, R are displayed for frequencies 125-4000 Hz.

Summary Worksheet

A summary of the single and double glazed window constructions considered in this thesis, and their associated frequency-dependent airborne sound insulation values, R, for frequencies 125-4000 Hz is given in the worksheet labelled "summary".

5.3.1.2 Aural.xls

Averaged values of sound reduction properties for each window are calculated for all frequencies using the spreadsheet labelled "Aural.xls". Use of this spreadsheet is as follows:

- Open the spreadsheet labelled "Aural.xls"
- Select the worksheet labelled "Computational"
- Select the window type for which sound reduction properties are required from the range of cells A39-K69
- Copy and paste the sound reduction values for each frequency to the cells E24 – K24.
- Select the worksheet labelled "Rw calculation"
- In the upper half of the spreadsheet, scroll along until the value under the heading "sum of unfavourable deviation" is as large as possible, but not exceeding a value of 10dB.
- Enter the corresponding value of dB by which the reference curve should be shifted into Cell F12.
- Cells B4 - B6 provide the Rw, C and Ctr values for the window selected.
- The worksheet labelled "summary" shows the Rw, C and Ctr values for all the window configurations included in the analysis.
- The worksheet labelled "Chart" shows these values graphically.

5.3.2 Example Calculation

Noise reduction values, R, for single glazing panes, and numerous double glazed windows are widely available through literature and manufacturers' brochures. Noise reduction values for windows employing heavy inert gases have not, however, been made generally available. Using the work of Beranek [1992] and Pilkington [1997], it was possible to develop a method by which the noise attenuation of such windows can be assessed. The analysis is based upon known, and published frequency dependent sound reduction values for single and double glazings. Manipulation of this data to provide frequency dependent sound reduction values for windows which do not possess published values, is based upon the acoustic velocity of the cavity gas, C_0, and the improved sound insulation achievable with increased cavity width. Beranek [1992] developed the following equation to define the sound reduction available through use of double glazed windows with gas filled cavities:

$R = R_1 + R_2 + R_{gas}$ where	R_1 is the sound reduction value of the first pane R_2 is the sound reduction value of the second pane R_{gas} if the sound reduction value of the cavity gas	5.1

and $\quad R_{gas} = 20 \text{ Log } \left[\frac{4\pi f \rho_0 C_0}{s'}\right]$ 5.2

where f is the frequency of the noise, ρ_0 is the density of the gas and s' is the dynamic stiffness of the gas, $s' = \frac{\rho_0 C_0^2}{d}$ 5.3

Following an in-depth analysis, it was found that the above equations, when used to evaluate the sound reduction capabilities of inert gases, produced misleading and erroneous results. Sound reduction values exceeding 80-100 dB frequently resulted for double and triple glazed windows. (Windows specifically designed to attenuate against external noise can provide up to 65 dB over limited frequencies). The relationship between sound reduction and the acoustic velocity of the gases was therefore used to further the analysis. Sound reduction due to the cavity gas, R_{gas} is a logarithmic function of C_0. Values of C_0 for air, Argon, Krypton, Xenon and SF_6 are presented below:

	C_0 (m/s)	Log C_0
Air	340	2.53
Argon	244	2.39
Krypton	169	2.23
Xenon	135	2.13
SF_6	128	2.11

No acoustic benefit is achieved through the use of Argon in place of air in window cavities [Pilkington, 1997], due to their similar C_0 values. For this reason Argon can be likened to air in acoustic calculations. Xenon was found to have a very similar C_0 value to the heavy gas Sulphur Hexafluoride, SF_6 (C_0 = 128 m/s), for which published data is available. Xenon was therefore likened to SF_6 for acoustic calculations. Performing a proportional analysis, based on acoustic velocity, it was therefore possible to interpolate between data values for air/Argon and Xenon/SF_6 to produce data for Krypton gas. Figure 5.5 illustrates the frequency dependent sound reduction values for each gas, present in a window with cavity gap less than 50mm.

To further manipulate this data to account for variance in cavity width, Figure 5.6 was used to adjust the sound reduction values generated for cavities less than 50mm wide. Generally, there is no noticeable benefit below a cavity width of 50mm. There is a sharp increase in sound reduction when the cavity width rises above 50mm. Little additional benefit is achievable with cavities wider than 200mm. In the following analysis it is assumed that no additional benefit can be achieved with cavities less than 50mm, while cavities between 50mm and 100mm provide an additional 8dB sound reduction, cavities between 100mm and 150mm provide an additional 11dB sound reduction, and cavities between 150mm and 200mm provide an additional 12dB sound reduction.

Building location inputs

Office Location		City Centre					
Room inputs							
Room length		13.4 m					
Room width		6.8 m					
Facade area		33.5 m^2					
Window area, A_{window}		60% = 20.1 m^2					
Wall area, W_{wall}		40% = 13.4 m^2					
window type		4-12Kr-4					
Glass Properties							
Sound reduction	f (Hz)	125	250	500	1000	2000	4000
	R (dB)	20	22	28	33	34	28

The first requirement is to evaluate the frequency dependent values of airborne sound insulation for a selected window design, in this case a double glazed, Krypton filled window with no low-emissivity coating. The Sound Reduction Index, R, is calculated for frequency values; 125, 250, 500, 1000, 2000 and 4000 Hz. An example calculation is presented for noise at 500 Hz.

The sound reduction, R, at 500 Hz for a window of similar construction with an air filled cavity, is known to be 25 dB, and for a Xenon filled cavity to be 45 dB. The sound reduction at 500 Hz for a Krypton filled cavity is known to lie between these two values, and can be calculated using the Log function of the acoustic velocities for these gases.

Since air is likened to Argon in acoustic performance, an average of the Log C_0 values for air and Argon is used, having a value of 2.46. Similarly Xenon is likened to SF_6 and an average Log C_0 value is used, having a value of 2.12. Krypton has a Log C_0 value of 2.23, almost exactly one third of the difference between Xenon and air. Using this proportional analysis it is possible to evaluate the sound reduction values at all frequencies in the noise spectrum considered. Frequency dependent sound reduction values for a double glazed window with two 4mm glazings, and a Krypton filled cavity of less than 50mm are thus:

Frequency	125	250	500	1000	2000	4000
R_{Kr}	23	23	38	50	59	42

A summary of the sound reduction values, R, for all single and double glazed windows considered in this thesis is shown in worksheet "summary" of Aurcalc.xls. The spreadsheet may be used to evaluate sound reduction values for any combination of glazing thickness, cavity gap, or cavity gas.

The second requirement is to convert the frequency dependent airborne sound insulation values, calculated above, into single numbers characterising the acoustical performance for each window configuration. Spreadsheet "Aural.xls" is used to perform this calculation.

The Sound Reduction Index, R, for a composite wall, incorporating a glazed area, is given by the following equation:

$$R = 10 \text{ Log } \frac{S}{\frac{S1}{10^{R1/10}} + \frac{S2}{10^{R2/10}}} \qquad 5.4$$

Where
- S is the area of the wall and window area together (m^2).
- S1 is the area of the masonry wall (m^2).
- S2 is the glazed area (m^2).
- R1 is the Sound Reduction Index of the masonry wall (dB).
- R2 is the Sound Reduction Index of the window (dB), as calculated.

R1 is taken for that of a masonry wall of minimum thickness 300 mm, and has frequency dependent values as follows:

F (Hz)	125	250	500	1000	2000	4000
R (dB)	40	45	53	59	64	67

R2 refers to those values calculated using the previous spreadsheet, "Aurcalc.xls"

Hence for noise at frequency 500 Hz,

$$R = 10 \text{ Log } \frac{33.5}{\frac{13.4}{10^{53\ 10}} + \frac{20.1}{10^{38\ 10}}}$$

$$= \underline{\underline{41 \text{ dB}}}$$

This calculation was repeated for all window constructions and noise frequencies (125-4000 Hz).

To evaluate the results of measurements made, or calculations performed (as above) in octave bands, the frequency dependent noise reduction values are compared to the relevant reference curve. The curve of reference values for airborne sound in octave bands is illustrated in Figure 5.7.

The sum of unfavourable deviations is evaluated for the measured/calculated data and the reference curve, as shown in Table 5.8.

An unfavourable deviation for a given frequency occurs when the result of a measurement or calculation is less than the reference value. Only unfavourable deviations are taken into account. The reference curve is shifted in steps of 1 dB towards the measured/calculated curve until the sum of unfavourable deviations is as large as possible, but not greater than a value of 10 dB. For the example curve above, the reference curve is shifted by 8 dB. The value, in decibels, of the reference curve at 500 Hz, after shifting it in accordance with this procedure, gives the Weighted Sound Reduction Index, R_w. In this example $R_w = 41$ dB.

Spectrum adaptation terms, given in dB, are added to the single-number rating (R_w) to take account of the particular sound spectra. The predominant outdoor noise source in city centre is traffic noise. For this reason a single adaptation term is calculated for traffic noise, C_{tr}, where:

$$C_j = X_{Aj} - X_w \qquad C_j \text{ is rounded to an integer} \qquad 5.7$$

where j is the index for the sound spectra, C and C_{tr}

X_{Aj} is the single number calculated in the above procedure (R_w)

$$X_{Aij} = -10 \text{ Log} \sum 10 (L_{ij} - X_i)/10 \quad \text{dB} \qquad 5.8$$

where i is the index for the octave bands 125 - 2000 Hz

L_{ij} are the levels given by the sound level spectra illustrated in Figure 5.8.

Therefore $C = X_{Atr} - X_w$

$= -10 \text{ Log } 0.0002 - 41$

$= 37 - 41$

$= \underline{\underline{-4 \text{ dB}}}$

and $C_{tr} = X_{Atr} - X_w$

$= -10 \text{ Log } 0.0006 - 44$

$= 32 - 41$

$= \underline{\underline{-9 \text{ dB}}}$

The single number quantity of the Krypton cavity filled double glazed window selected is hence given as:

$$R_w (C{:}C_{tr}) = 41\ (-4{:}-9)\ \text{dB}$$

Single number quantities and adaptation terms for all single and double glazed window constructions considered in this thesis are summarised on worksheet "summary" of Aural.xls, and are shown graphically in Figure 5.9. An example worksheet from Aurcalc.xls is shown in Figure 5.10, and an example worksheet from Aural.xls is shown in Figure 5.11, to illustrate the layout of the calculation spreadsheets found on CD/Program Files/Aural Analysis.

5.3.3 Synopsis

The thermal analysis in the preceding chapter, and the visual analysis presented in the following chapter contribute directly to the energy optimisation necessary to perform the current LCA. The aural analysis presented above does not contribute in such a direct manner, but is no less important to the designer and architect in providing buildings which are pleasant and comfortable places to work, and which maximise employee productivity. As previously mentioned, a building which provides excellent thermal and visual conditions, and which places a minimal burden upon the global environment throughout its life cycle, is of limited use if the aural performance is such that work tasks are compromised and building users are dissatisfied. The above models provide an efficient and simple-to-use procedure for aural performance which was not previously available, and which could significantly reduce the time required to design complex glazing specifications.

5.4 References

1. Adams, M.S. and McManus, F., Noise and Noise Law: A practical approach, Wiley Chancery Law, London, (1994).
2. Baker, N.V., Thermal comfort evaluation for passive cooling: a PASCOOL task, Proceedings of the 3rd European Conference on Architecture, 103-106, (1993).
3. Beranek, L.L. and Ver, I.L. (editors), Noise and vibration control: Principles and applications, John Wiley and Sons (1992).
4. Beranek, L.L., Balanced noise-criterion (NCB) curves, Journal of the Acoustical Society of America, 86 (2), 650-664, (1989).
5. Broadbent, D.E., Noise in relation to annoyance, performance, and mental health, Journal of the Acoustical Society of America, 68 (19), 15-17, (1980).
6. Broner, N., The effects of low frequency noise on people: a review, Journal of Sound and Vibration, 58 (4), 483-500, (1978).
7. British Standards Institution BS 4142, Rating industrial noise affecting mixed residential and industrial areas, (1997).
8. British Standards Institution BS 8233, Code of practice for sound insulation and noise reductions of buildings, (1987).
9. Cohen, S. and Lezak, A., Noise and attentiveness to social cues, Environment and Behaviour, 9, 407-422, (1977).
10. Glass and noise control, Pilkington Glass Products, CI/SfB (31), July (1995).
11. Glass and noise control: Technical Bulletin, Pilkington Glass Products, CI/SfB (31), May (1997).
12. Holloway, C., Noise and efficiency: the spoken word, New Scientist, 1 May, (1969).
13. International Standard ISO 1996/1, Acoustics: description and measurement of environmental noise, (1996).
14. Leventhall, H.G., Man made infrasound, its occurrence and some subjective effects, Proceedings of the Colloquium on Infrasound, Centre National de la Recherche Scientifique, Paris, September, 129-152, (1973).
15. Shultz, T.J., Synthesis of social surveys on noise annoyance, Journal of the Acoustical Society of America, 64, 377-405, (1978).
16. Smith A. and Stansfield S., Aircraft noise exposure, noise sensitivity, and every day errors, Environment and Behaviour, 18 (2), 214-225, (1986).
17. Wilson M., Nicol, F. and Singh, R., Measurements of background noise levels in naturally ventilated buildings, associated with thermal comfort studies: initial results, Proceedings of the Institute of Acoustics, Vol. 15, Part 8, (1993).

Table 5.1 Interior noise targets. Extracted from BS 8233: 1997

Location	Recommended Maximum L_{Aeq} Level (dBA)
Dwellings	
Bedrooms	30 - 40
Living Rooms	40 - 45
Offices	
Private / small conference rooms	40 - 45
Large Offices	45 - 50
Educational	
Classrooms (15-35 people)	40
Classrooms (>35 people)	35
Music / Drama spaces	30
Health & Welfare	
General Wards	55
Small Consulting Rooms	50
Diagnosis Rooms	45

Table 5.2 Road traffic noise levels (Pilkington, 1995)

Situation	**Noise Level dB(A)**	
	L_{A10}	**L_{Aeq}**
20 m from busy motorway average speed 62 mph grassed terrain	80	77
20 m from busy main road average speed 31 mph paved	70	67
20 m from busy main road average speed 31 mph screened by houses	60	57

Table 5.3 Rail traffic noise levels (Pilkington, 1995)

Distance from Track	**Noise Level dB(A)**
open grassland terrain	L_{Aeq}
25	67
50	64
100	59
200	54

Table 5.4 Aircraft noise levels (Pilkington, 1995)

NNI	**L_{Aeq} (12 hour)**	**Probable *Community* Annoyance**
35	57 +/- 4	Low
45	66 +/- 4	Moderate
55	75 +/- 4	High
60	80 +/- 4	Very High

Table 5.5 Suggested maximum PSIL values for effective communication

Room Type	**Max. acceptable PSIL (dB)**
Small private office	45
Conference room	30-35
Concert hall	25
Bedroom	30
Living room	45
Classroom /Lecture theatre	30

Table 5.6 Sound level/distance relationship for speech intelligibility [Adams & McManus, 1994]

Background sound level dB(A)	**Background (NR)**	**Max. distance for intelligibility (m)**
48	40	7
53	45	4
58	50	2.2
63	55	1.2
68	60	0.7
73	65	0.4
77	70	0.2
over 77	over 70	too noisy for speech

Table 5.7 Background sound levels for telephone conversations

Quality of conversation	**Sound level dB(A)**	**NR**
Satisfactory	58	50
Slightly difficult	68	60
Difficult	82	75
Unsatisfactory	over 82	over 75

Table 5.8 Unfavourable deviation evaluated from measured/calculated data and reference values for airborne sound reduction in octave bands

Frequency	Reference Curve	Measured/Calculated Data	Unfavourable Deviation
125	**36**	**20.98**	**15.02**
250	**45**	**30.96**	**14.04**
500	**52**	**48.4**	**3.6**
1000	**55**	**60.89**	**0**
2000	**56**	**66.81**	**0**
		sum	**32.66**

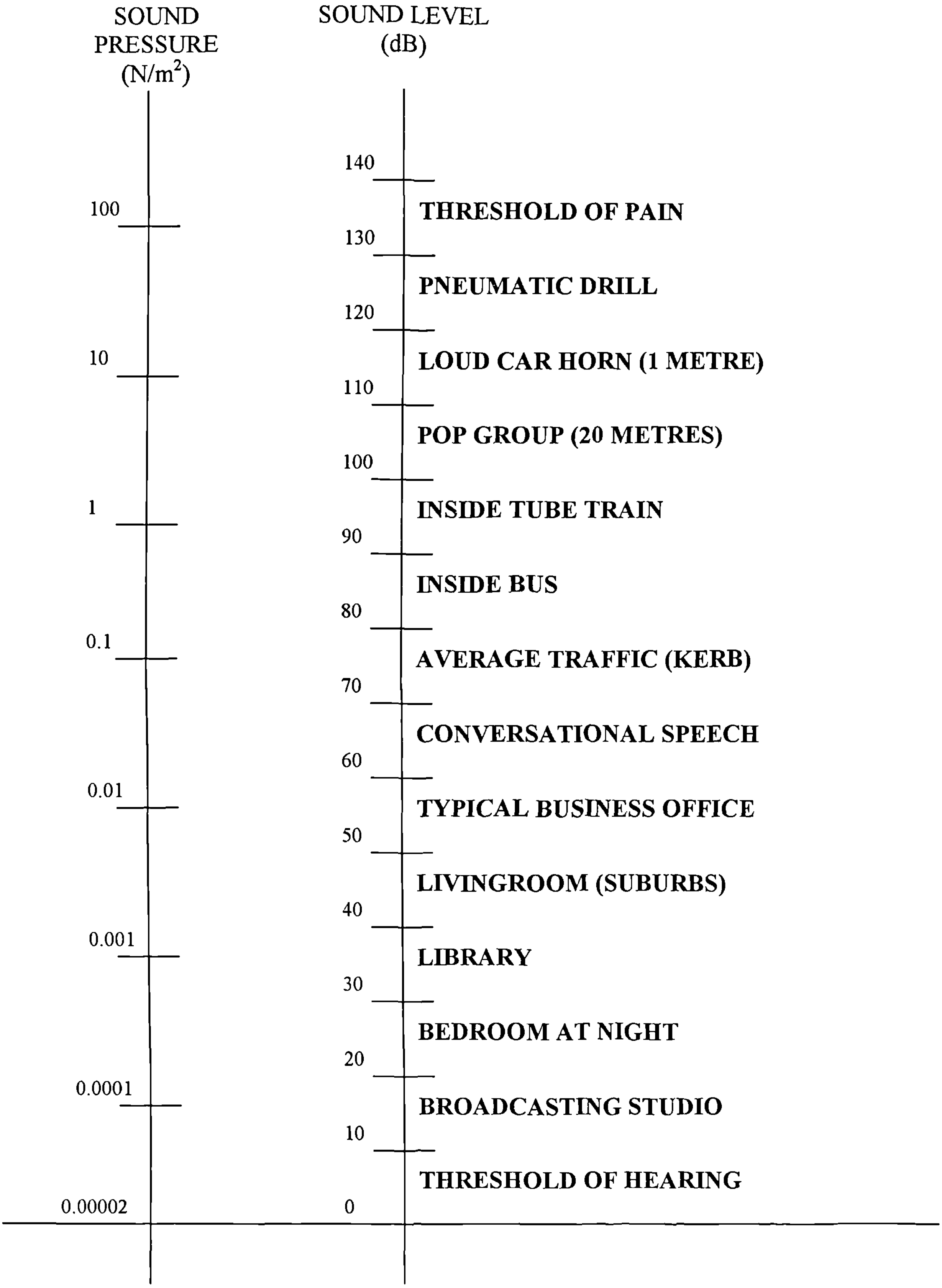


Figure 5.1 Sound pressure and level

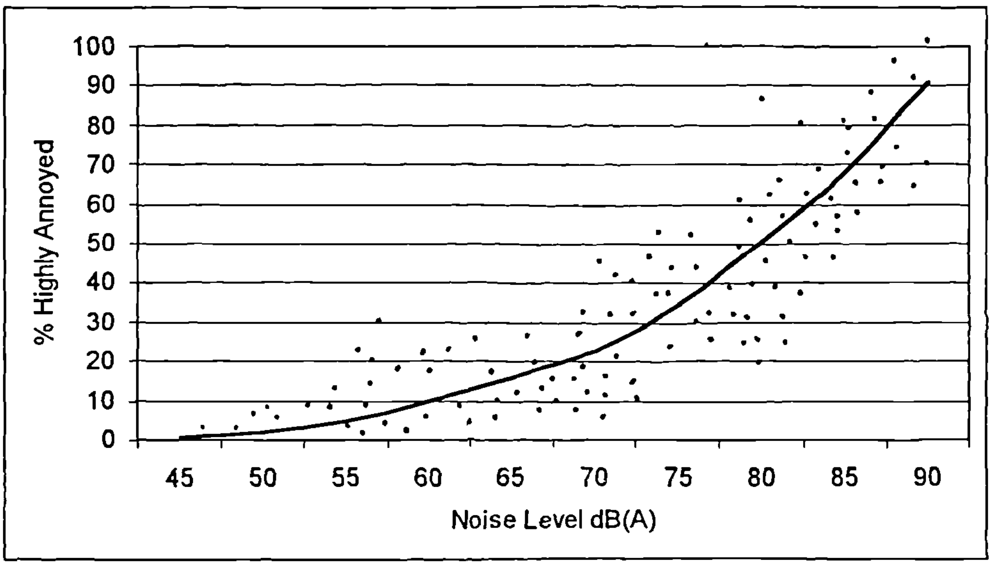


Figure 5.2 Percentage of survey sample reporting to be highly annoyed at various noise levels [adapted from Shultz, 1978].

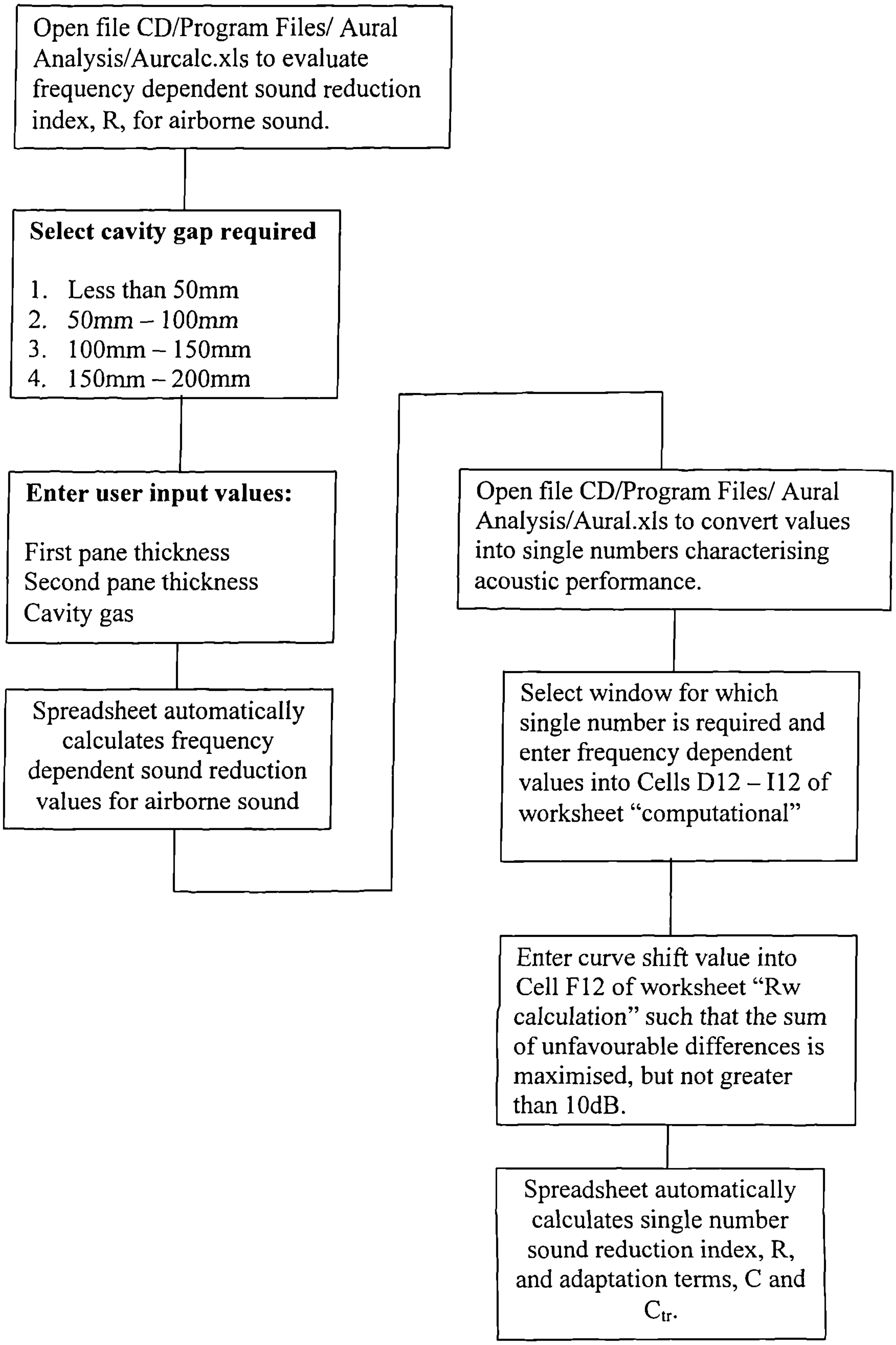


Figure 5.3 Flow diagram of aural analysis calculations.

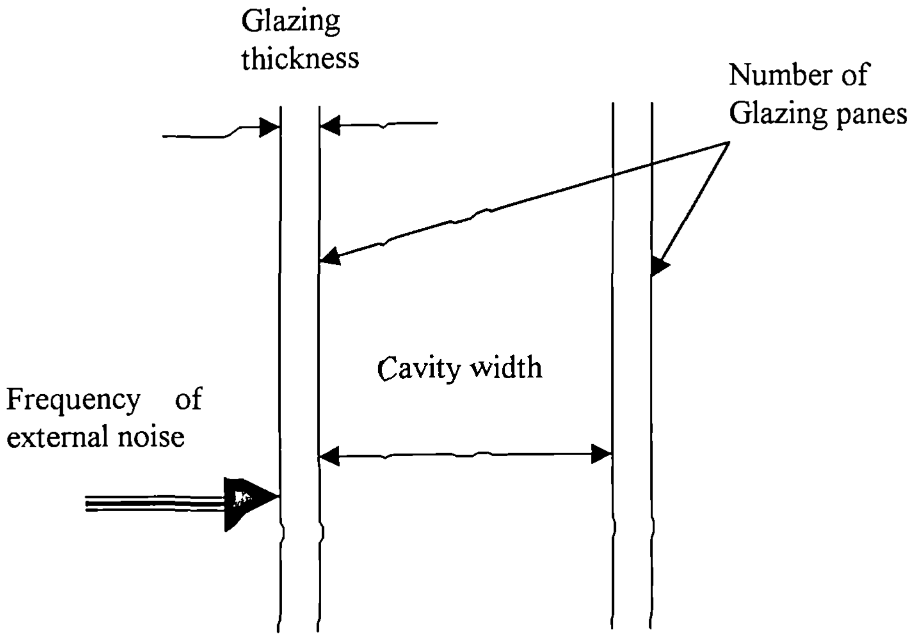


Figure 5.4 Factors influencing sound transmission through windows

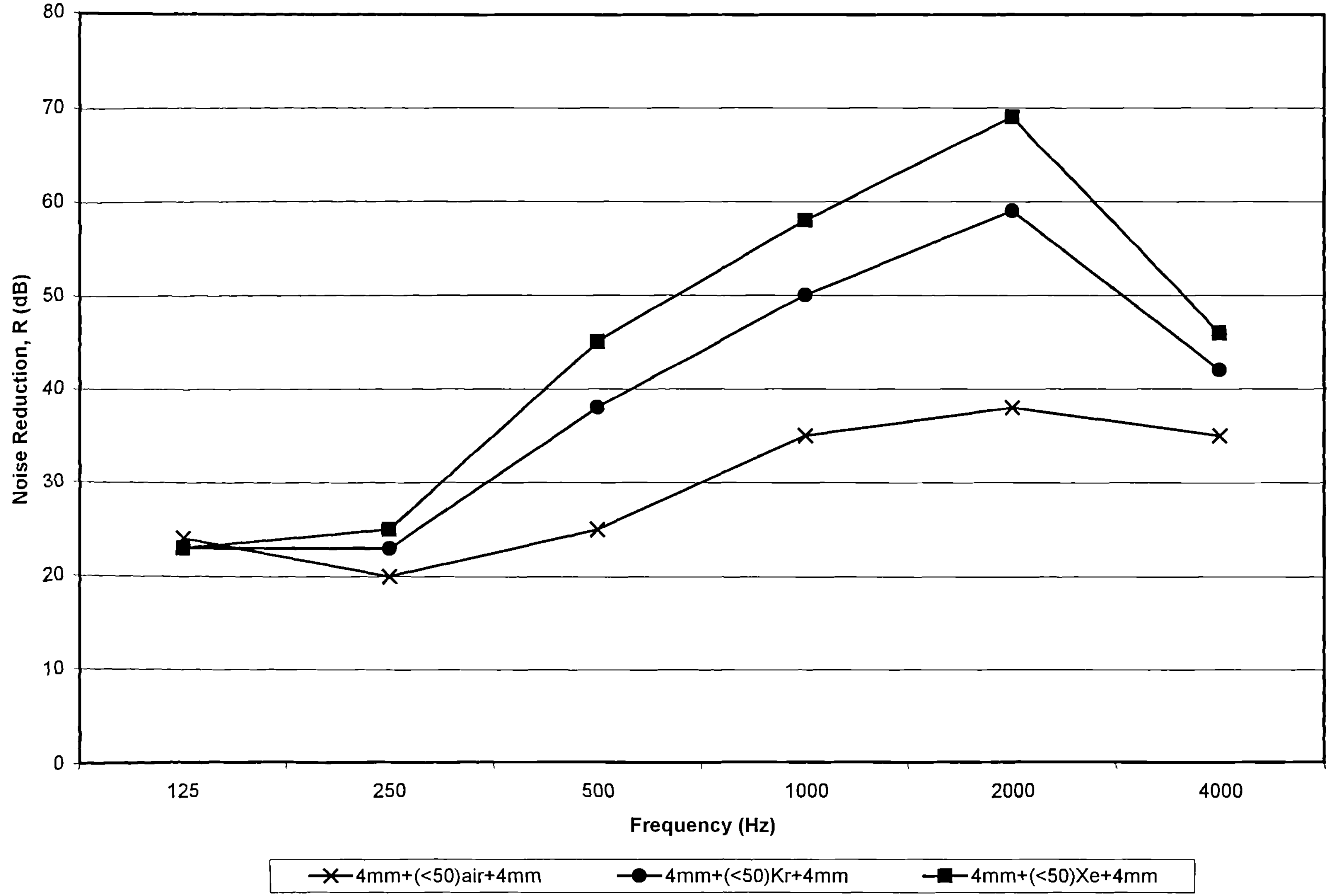


Figure 5.5 Frequency dependent sound reduction values for double glazed windows incorporating two 4mm glass panes, and a cavity of less than 50mm

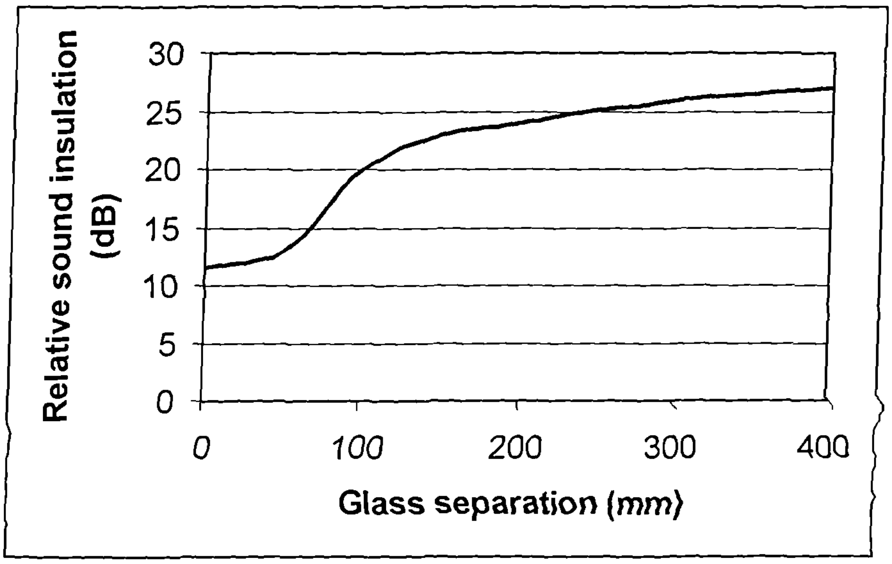


Figure 5.6 Relative sound insulation with increased air space width

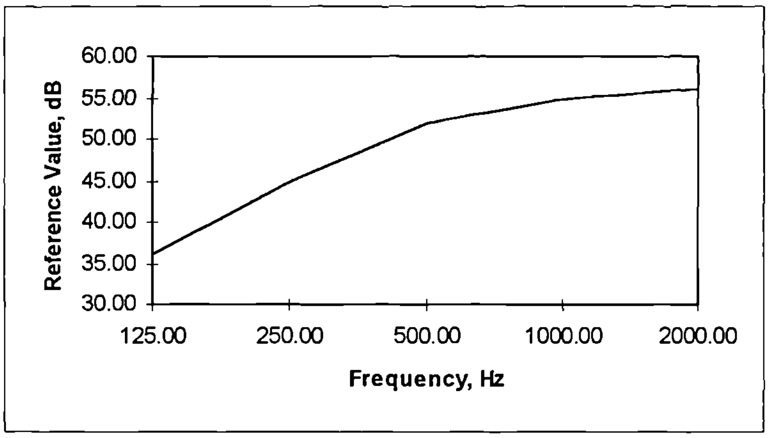


Figure 5.7 Reference values for airborne sound reduction in octave bands [ISO 717-1: 1996].

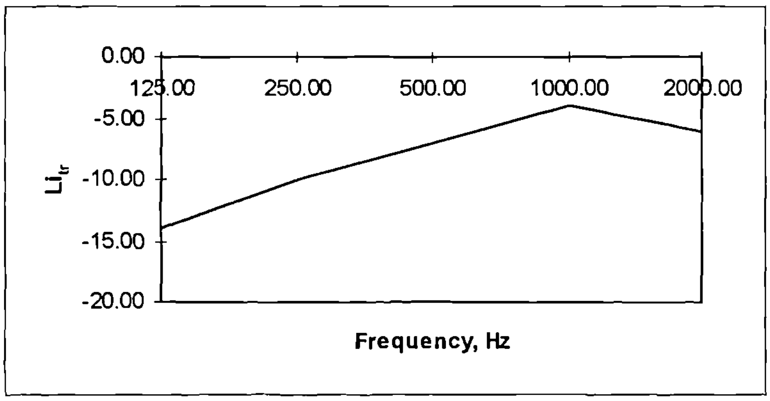


Figure 5.8 Spectrum to calculate C and C_{tr} [ISO 717-1: 1996]

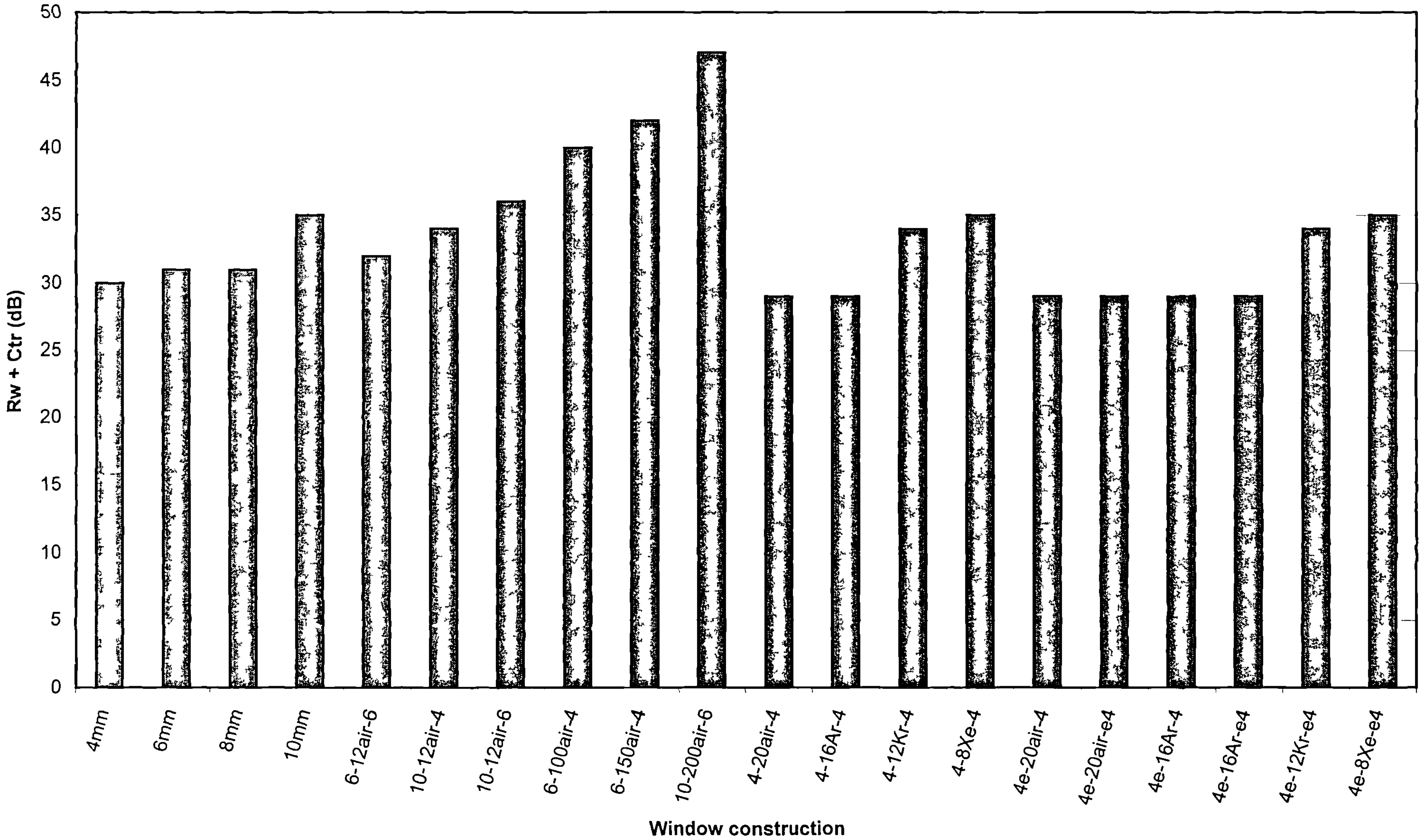


Figure 5.9 Single number values characterising acoustic performance for single and double glazed window constructions, based on the example office design presented.

glazing thickness (mm)	Frequency (Hz) 125	250	500	1000	2000	4000
4	20	22	28	33	34	28
6	20	24	31	35	29	36
8	24	27	30	32	28	38
10	26	27	34	35	36	44
19	28	32	37	37	46	54
4mm+(<50)air+4mm	24	20	25	35	38	35
4mm+(<50)Kr+4mm	23	23	38	50	59	42
4mm+(<50)Xe+4mm	23	25	45	58	69	46
6mm+100air+4mm	26	34	44	56	53	52
6mm+100Kr+4mm	31	31	46	58	67	50
6mm+100Xe+4mm	31	33	53	66	77	54
6mm+150air+4mm	29	35	45	56	52	50
6mm+150Kr+4mm	34	34	49	61	70	53
6mm+150Xe+4mm	34	36	56	69	80	57
10mm+200air+6mm	35	46	46	46	56	65
10mm+200Kr+6mm	35	35	50	62	71	54
10mm+200Xe+6mm	35	37	57	70	81	58
for cavity gap less than 50mm						
enter first pane thickness in mm	4	[4, 6, 8, 10, 19]				
enter second pane thickness in mm	4	[4, 6, 8, 10, 19]				
enter cavity gas	xenon	[air, Argon, Krypton, Xenon, SF_6]				
base case from above table (excluding contribution from glazing)	-17	-19	-11	-8	1	-10
R value for first glazing pane	20	22	28	33	34	28
R value for second glazing pane	20	22	28	33	34	28
R value for complete window	23	25	45	58	69	46

Figure 5.10 Layout of worksheet "calculations" in spreadsheet "Aurcalc.xls"

Composite Calculation								
Window Type	**as selected**	**Facades area**		**33.5**	(m^2)			
Wall Type	**300mm (min) masonry**	**Window area %**		**80**				
		Wall area %		**20**				
Noise Frequency			125Hz	250Hz	500Hz	1KHz	2KHz	4KHz
Façade area		S (m^2)	33.5	33.5	33.5	33.5	33.5	33.5
Wall area		S1 (m^2)	6.7	6.7	6.7	6.7	6.7	6.7
Wall area Sound Reduction Index (SRI)		**SRI1 (dB)**	40	45	53	59	64	67
Window area		S2 (m^2)	26.8	26.8	26.8	26.8	26.8	26.8
Window area Sound Reduction Index (SRI)		**SRI2 (dB)**	23	23	38	50	59	42
(copy values from table below for selected window type)								
Given the above values the overall Sound Reduction Index for the façade construction is as follows:-								
Façade Sound Reduction Index (SRI)		**SRI=**	**23.9**	**24.0**	**38.9**	**50.8**	**59.6**	**43.0**

Figure 5.11 Layout of "Computational" worksheet in spreadsheet "Aural.xls"

6 Visual analysis

6.1 Introduction

Good lighting in a building may be defined as the provision of "adequate" light, in the right place, at the right time, enabling occupants to perform tasks in comfort, to a high degree of efficiency, without suffering eye strain or fatigue. Guidelines have been in place for many years to aid designers in the provision of sufficient lighting. What is less well documented is the definition of "adequate" lighting. Use of appropriate luminaires, lighting control strategies, energy saving schemes, exploitation of daylight, and the impact which environments have upon building occupants must be considered in the standard of service provided.

As with the approach taken to analyse the thermal and aural indoor environments, a thorough literature review is presented to discuss the impact which visual environments have on building occupant satisfaction and work performance, before a numerical analysis is executed. Firstly, subjective factors associated with space lighting design are assessed, and secondly, a computational method of comparing window constructions is devised. Windows which permit light to enter an office space in a manner which is comfortable and satisfactory to its occupants, and which help create environments which permit maximum work productivity to be achieved, are sought.

6.2 Literature Review

> *"Lighting can be seen as balancing those things which are objective and can be measured relatively easily, against those which can be described as subjective and cannot be measured using conventional means, and can be used to describe features of lighting appearance which can affect human mood and sentiment" Loe & Rowlands [1996].*

Where natural light through windows is exploited to a maximum, subjective benefits can be enjoyed by building users, including:

- views to the exterior environment
- first-hand knowledge of weather conditions
- perception of time
- a sense of orientation

- relaxation for the eyes
- a feeling of more space
- explanation of exterior noise
- improved room characteristics

6.2.1 Provision of windows

British Standard BS 8206: Part 2 [1992] states that:

> *"an interior which looks gloomy, or does not have a view of the outside, where this can reasonably be expected, will be considered unsatisfactory by the users".*

There is little doubt that people prefer to work by daylight and to enjoy a view, when given a choice [CIBSE, 1984]. Windowless rooms, which lack direct exterior views, are generally disliked, but should be compensated for by having views into glazed areas which are made attractive with plants and activities.

Wyon [1980] summarised from his study on human experience of windowless environments that,

> *"it is difficult for people in a position to take windows and the daylit environment for granted, to analyse what it is they appreciate about this environment."*

He concluded that people deprived of a daylit environment were thought more able to subjectively assess the relative benefits and importance of windows. A general trend shown up in his study was that workers with less interesting jobs noticed the absence of windows most.

Wyon also found that attitudes towards windows were dominated by daylight and view considerations. Figures 6.1 and 6.2 show the results of Wyon's study. Figure 6.1 shows the attitudes towards environments, with and without windows, of five different building users. The attitude of the individual toward rooms with windows is consistently more positive than rooms without windows.

When asked open-ended questions about the advantages of windows, the most common spontaneous responses were those that mentioned daylight, weather information and fresh air. Figure 6.2 shows the percentage of shop, office and factory workers who mentioned the above three advantages. Wyon found that workers with windows were significantly more positive at being able to see sunshine and wind, predict weather and estimate temperatures. More than 40% of all workers in rooms with windows mentioned daylight as an advantage, while only 30% of workers in windowless environments mentioned this. When asked open ended questions on the disadvantages of having windows, the same group of subjects most commonly mentioned direct solar overheating, draughts and distraction in decreasing order of frequency.

Loe and Davidson [1996] noted the difference in recovery rates of patients in a hospital in Pennsylvania. Having received similar treatment, it was recorded that patients who looked out to a view of trees recovered 10% faster than those patients who looked out to a brick courtyard. This suggests the importance of windows, views and daylight in influencing human mood and well-being, as well as improving recovery rates in patients.

Employees who work in windowless control rooms for long periods of time, monitoring and handling control equipment and panels, often suffer from psychological stress and fatigue. Sato [1989] suggests that a pleasant working environment can play an important role in alleviating this. Collins [1975] stated that people prefer to work in daylight conditions, given that they are in a condition of thermal comfort, and glare does not cause visual discomfort.

6.2.2 The CSP Index

The Comfort, Satisfaction, Productivity (CSP) index was an attempt by Bean & Bell [1992] to produce an indicator of the effectiveness of lighting installations, as perceived by workers in an office. The index is produced by interrelating the physical parameters associated with the lighting to produce one single figure of merit for the installation, and assumes that there are three elements which contribute to the effectiveness of the visual environment:

- Visual Comfort - the level of comfort that exists in relation to the brightness, size and position of luminaires, and the brightness of the background.

- Visual Satisfaction - The level of satisfaction which exists regarding the appearance of people and objects, and the brightness of the walls and partitions.

- Visual Performance - the level of performance which exists due to the flux density distribution at the task area and the spectral quality of the light source.

Even if the lighting on the working plane is sufficient for the tasks required, the effectiveness of the installation is reduced if the worker suffers from eyestrain and headaches when they look up from the task because of excessive light source brightness. The CSP index is generated from a notional measure of visual effectiveness, related to the visual quality solid illustrated in Figure 6.3.

The CSP Index is given by $$Q_i = 3 \times \frac{CSP}{C+S+P} \qquad 6.1$$

C, S and P have a maximum value of 10, and hence the index is limited to a value between 0 and 100. The highest index value is obtained when C = S = P.

Application of the index is dependent on setting suitable optimum values for C, S and P against which to compare the installations, and establishing relationships between different lighting factors. For example, how important is colour rendering relative to lighting uniformity? Bean and Bell carried out studies based on 650 workers in 44 offices throughout the UK to relate the probability that workers would be satisfied with their visual environment. The results of the study are shown in Figure 6.4. The poor lower line represents those workers who were dissatisfied with the visual environment, while the upper satisfied line represents those workers who were happy with their environment. The results of the study can be summarised as follows:

- For CSP index values lower than 25, up to 50% of office staff are likely to be dissatisfied with the lighting.

- The minimum lighting requirements set out by the CIBSE Code for Interior Lighting [1984] would produce an index of about 35, giving a satisfaction level of 80%.

- When the index value rises above 60, 95% of office workers can be expected to be satisfied.

The CSP index was designed to be used in conjunction with the CIBSE Code [1984], and not instead of, or in competition with, but has come head to head with opposition from other lighting technologists. Perry et al [1996] set up experiments to validate Bean and Bell's work, and to extend the database derived in the CSP index. After recording images for installations with known CSP data, and examining scene information, correlations were made with the CSP data, and the hypothesis that subjective responses to the luminous environment depend on information content was tested. A true hypothesis would lead to the development of a quality index based on objective measurements. The results of Perry et al's work showed a poorer correlation than that reported in Bean and Bell's work. The conclusion of Perry et al's study may be summarised in the following statement:

"subjective responses do not correlate with objective measurements."

6.2.3 The holistic approach

Loe and Rowlands [1996] discuss six basic elements which define an efficient lighting design framework, providing a holistic approach to the appearance of the visual environment, whilst incorporating both art and science aspects:

- architectural integration: inclusion from earliest design stage
- visual amenity: colour, contrast and content of lit environment
- capital and operating costs of installation
- installation and maintenance
- energy efficiency of installations
- visual function: satisfaction in terms of task requirements

It is stressed that lighting design is not a post-construction methodology A holistic approach to building design is critical in maximising perceived satisfaction, and specifically, good daylighting design is inseparable from good architectural design. It should be considered from the earliest stage [Energy in Architecture, 1993].

6.2.4 Energy efficiency and visual comfort

In an analysis of energy consumption and lighting satisfaction, Zeguers and Jacobs [1997] developed a methodology whereby the classification of lighting installation comfort, perceived by building users, was possible. The concern focuses on tighter and more stringent laws with respect to energy consumption in buildings, but which do not consider the satisfaction or comfort relating to the indoor environment. The methodology encompasses 6 criteria for assessing lighting comfort:

1. Office size - 1/2 person room, or large open plan office
2. Lighting type - lamps, high frequency luminaires, or conventional lighting
3. Screening quality
4. Installed power
5. Switching type - individual control, control per room, control per building
6. Use of additional saving schemes e.g. daylight saving, presence detection

Weighting factors are attached to each of the criteria, and the sum of the weighted factors yields a judgement value, which is used as a rough guide, not a guarantee. Ziguers and Jacobs state in their work that research is still arbitrary and in its infancy. No field study examples were found to validate their work.

6.2.5 Lighting control

Use of artificial lighting within the building envelope consumes up to 60% of the total energy utility within commercial buildings [Littlefair, 1990]. Optimising the use of daylight in buildings can make a significant difference to energy consumption in buildings. Application of current best practice can significantly reduce lighting energy consumption; examples have demonstrated savings typically in the range of 30-50% [BRECSU, 1993]. Energy consumption is lowered directly, as result of reduced use of artificial lighting and indirectly, due to reduced cooling requirements resulting from the use of fewer luminaires.

Several different lighting control mechanisms are available today which could make significant in-roads into reducing energy consumption of lighting demands. Four lighting control strategies are discussed herein:

6.2.5.1 Manual controls

Manual control is the most basic and common control type used. For maximum efficiency, controls should permit individual switching of rows, and luminaires should be positioned in rows, parallel to windows. For the highest level of control, each luminaire should have its own switching mechanism. The expense of providing this level of control often rules this possibility out. The efficiency of manual lighting controls is dependent on the accessibility of switches.

6.2.5.2 Time controls

If the working hours of a building and its occupants are known and regular, then timing controls ensure that lights are not left on for long periods in unoccupied areas. This type of control strategy does not, however, allow for control of lighting when daylight illuminance is sufficient to supply some of the light to the working plane and could lead to higher rates of accidents if individuals are required to enter unlit areas where lighting is outwith their control, or enter a building section outwith the control pre-set hours.

6.2.5.3 Daylight linked controls

It is common practice in buildings without lighting controls to switch artificial lighting on in the morning when daylight levels are insufficient to provide the required luminosity, and to leave lights on throughout the day, even when daylight illuminance rises to meet, and even exceed, the illuminance level that artificial lights were designed for. Photo-electric lighting controls guard against use of artificial lighting when daylight is of sufficient illuminance. In interiors where large differences in daylight factor exist it may be necessary to provide individual control to separate rows of luminaires.

On-off photo-electric lighting controls operate by switching luminaires off when daylight illuminance is sufficient to provide the required lighting level on the working plane, and on when daylight illuminance levels fall below the critical level. Figure 6.5(a) shows the operation of on-off control lighting systems. There is no variation in the light output from luminaires, and when daylight falls to an insufficient level, the full lighting load is applied.

Top-up controls work in a similar way to on-off controls i.e. they respond to the availability of daylight. Controls are available to vary the output of luminaires so as to top-up the daylight when it fails to meet the designed level of artificial lighting. This means that artificial lighting is never fully on unless daylight illuminance falls to a negligible level. As daylight levels change throughout the passage of the day, artificial lighting output rises and falls to keep the lighting level from the two sources constant. Figure 6.5 (b) shows the operation of top-up control lighting systems. The light output from luminaires is variable and dependant upon daylight availability.

Energy consumption for both on-off control and top-up control is calculated from the proportion of the working year that lights will be on, multiplied by the lighting load controlled. Separate calculations are required for each zone in a building. Figure 6.6(a) shows the percentage of a working year (0900 - 1730 daily) that lights would be switched off, using on-off control. Figure 6.6(b) shows the percentage of the working year for which the equivalent full load is off, using top-up control. Equivalent load refers to all periods when output from lighting is less than maximum. [BRE, 1985]

Christoffersen [1995] founded a study to investigate the advantages and consequences of replacing artificial lighting with available daylight. To this end an analysis of natural daylight, artificial light and lighting control strategies with energy and thermal performance of buildings was carried out. The purpose of the study was to assess the scope for reducing lighting and heating energy requirements with the use of lighting control systems, and variation in window size and U-value.

Simulations carried out under laboratory conditions for a window to floor area ratio of 0.15 showed that by use of daylight as work surface illuminance, between 27% and 62% of general lighting energy could be saved. With the use of on-off control, or dimming control strategies, relative to a reference point in the centre of a room, saving potentials of 50% and 62% respectively were achievable. And even though the daylight level at the back of the room was lower, daylight provided savings of 27-46% of lighting energy consumption. Lowering the consumption of energy from lighting will reduce internal loads from the lighting system, but will, however, increase the need for heating within a building. Taking this increased heating load into account, total energy savings of 12-19% were still achievable. Christoffersen found that window/floor area ratios much above 25% significantly reduced the net energy savings for buildings, accounting for the increase in heating load, but that window/floor area ratios around 25% allowed quality daylight to be transmitted, yet maintained potential for larger overall energy saving due to reduced lighting loads.

Christoffersen extended the analysis to investigate the influence of window size on energy savings. Energy savings for window to floor area ratios of 0.15, 0.25 and 0.4, are illustrated in Figures 6.7 and 6.8. The reduced potential for saving with increased window size shows that there is an optimal window size for maximised energy saving. It is also evident that choice of control system is important. These findings are valid only for the test laboratory investigated, and the author warns that results should not be uncritically transferred to general contexts.

6.2.5.4 Occupancy controls

In building areas which are infrequently occupied, or which are occupied intermittently throughout the day, there is a high likely-hood that artificial lighting could be left on for long periods where this is not necessary. To combat this, the use of occupancy controls can ensure that energy consumption is reduced. Infra-red sensors are commonly used for these applications. The positioning of sensors is of key importance to this type of control [Lynes and Littlefair, 1990], as serious accidents could result from non-operational lights, due to poor sensor positioning. Building users could also become very dissatisfied with lighting control strategies if they were not compatible with building use and work tasks (e.g. the building user does not want to have to wave his/her arms around in order to switch lights on in remote areas). The most appropriate lighting control strategy for a situation will depend on the occupancy type and pattern. Occupancy ranges from multi-occupant to very low occupant numbers, and is generally related to the frequency of which a space is entered or exited.

A mains switching infra-red lighting control system was installed in Lloyds in 1981 [EEO, 1981] during a major refurbishment exercise. The system is a combination of localised manual switching, time-base switches and photo-electric controls. The use of infra-red sensors minimised the control wiring required, offsetting the additional cost of equipment. Energy monitoring to test the efficiency of the system, via computer logging, was carried out by the Building Research Establishment, and revealed that 32% estimated savings were achievable with the system, compared to conventional switching systems. An analysis of staff attitudes towards the system was carried out by the London School of Economics, and revealed that the system was considered generally acceptable by the majority of staff.

Glennie et al [1992] developed a novel lighting control system, termed IMaging CONtrol (ImCom), as an attempt to improve the effectiveness of lighting systems by reducing energy consumption, increasing space utilisation and meeting the needs of human occupants. ImCom uses image acquisition with a Charge-Coupled Device (CCD) camera and imaging board, and image interpretation with a personal computer. The system also uses a multi-channel control element to activate peripheral lighting hardware. The system has three main capabilities:

- lights are co-ordinated with room occupancy
- electric lights are reduced in response to daylight
- electric lighting levels are adjusted to suit the needs of different tasks.

The system would, however, be very expensive due to the large amounts of software required. If the building has several rooms which need to be controlled, the expense of CCD cameras would render the system unfeasible. The additional financial outlay would lengthen the pay-back period associated with this installation, and the additional maintenance of such equipment would also need consideration.

6.2.6 Other design criteria

Originally visual comfort was considered to be:

> *"the provision of adequate illuminance levels required for a specific task, while minimising the stimuli from the surrounding environment."*

It may now be considered as:

> *"the clear reception of visual messages from the visual environment" [CECD, 1993].*

Studies in psychology and ergonomics have revealed that more interesting environments can have beneficial effects on work productivity. At least 80% of all information used by an individual in the work place is obtained visually [Lyons, 1983]. Without adequate and suitable lighting, workers are handicapped. Poor quality lighting conditions can contribute to low production rates and inferior quality work, resulting in low productivity. Decisions made to spend money on improving lighting conditions are not simply legislative, but impact significantly on the economics of labour requirements.

The need to design for the physiological requirements of lighting is the keystone to lighting recommendations in the CIBSE Code for Interior Lighting [1984]. Less well understood, documented and quantified is the need to design for psychological responses to, or social effects of, lighting design.

In a study carried out by The Harris Research Centre, subjects were asked open-ended questions to describe factors promoted by well designed buildings. The results of the survey are shown in Figure 6.9. The most frequently mentioned design aspect (43% of subjects) was an attractive setting with good visual stimulus, colours and windows. Ranking almost as important as this was good morale and contented members of staff, mentioned by 41% of subjects. Around 15-19% of subjects also mentioned good surroundings which are conducive to work, increased productivity and motivation, and improved communications with closer staff contact. Less commonly mentioned (less than 3%) were factors such as reduced stress, better health, management and economic issues, reduction in complaints, less absenteeism, more privacy, and less distraction. These factors could be considered the results of creating a well lit building with good surroundings, attractive visual stimuli and improved communications.

The impact of lighting quality on building occupants can produce a variety of responses.

> *"Light can create a psychological mood of delight or melancholy, or one that is stimulating or soporific" [Loe & Davidson, 1996].*

Poor lighting can cause headaches, eyestrain, and general feelings of discomfort. When experienced for prolonged periods of time discomfort leads to loss of concentration, need for longer and more frequent breaks, higher error rates and increases in the required time to complete tasks. Both short duration, high irradiance exposures and long duration, low irradiance exposures can be harmful [CIBSE, 1984]. A study of workers in the US revealed that eye strain is the most prevalent health complaint reported, affecting 44% of all office workers [Harris, 1989]. These effects lead to reduced productivity, lower efficiency and higher costs for employers.

A study carried out by Wilkins, [1989] showed a decrease in headache occurrence with increased levels of daylight. In a further survey carried out on office workers, 41% of occupants reported that the lighting gave them headaches, or affected their eyes. It was also shown that the occurrence of headaches in offices decreased as the height of the office above the ground increased, due to increased contribution of daylight to the working plane. In a later study, Wilkins [1993] reported that several characteristics of lighting, both natural and artificial, can be detrimental to health. Glare, in addition to flicker, low frequency magnetic fields, ultra-violet emissions and luminous variations can affect the health and well-being of occupants. Glare effects are well documented, while research into other effects is still in its infancy, with few firm conclusions to date.

6.2.7 Glare

Glare occurs when one part of an interior is much brighter than the general brightness of the interior [CIBSE, 1984], and is most commonly caused by luminaires and windows. There are two ways in which glare can cause annoyance. The first is in impaired vision, more commonly termed disability glare, and the second is in causing discomfort, termed discomfort glare. These two effects can occur independently, or simultaneously. Disability glare is caused by an area in the line of sight which has a much higher luminance than the object of regard, and manifests itself in the creation of after-images, or in making certain details of an object difficult to detect due to reduction in contrast. Discomfort glare can be caused by a source of high illuminance, low background illuminance, or glare from a source very close to the line if sight. Most discomfort glare can be controlled with careful selection of luminaires and their position, and use of high reflectance finishes on ceilings and upper walls.

Most paper-based office tasks are performed on a horizontal surface, and parallel to the plane of office lighting, presenting few glare problems. The introduction of computers in the last decade has, however, created many problems [Hedge, 1995]. Reflected glare from luminaires or badly positioned screens can impair vision and reduce productivity. Significant problems are encountered where there is a need to perform both paper based and computer based tasks within close proximity. Paper based tasks require a higher ambient illuminance than computer based tasks, which generate their own luminous characters, and are not dependent on sufficient background illumination.

Boubekri [1992] studied the effect of window size on sunlight presence and glare. He notes that the discomfort glare of sunshine can compete with the positive psychological effects of sunlight. A survey carried out in 9 UK schools showed that 47% of teachers complained of thermal and/or visual discomfort from the sun, and that teachers were more tolerant towards the sun than pupils. Boubekri found that window size accounts for less than 30% of variation in perceived glare. Figure 6.10 shows that perceived glare rises from 1.4 to 4.65 as the window area increases from 20 to 50% of the wall area, and then decreases as the window size increases beyond 50%. The occupant experiences discomfort when the perceived glare value rises above a value of 4. Perceived glare is in the tolerable range, except when the window size is 40-55% of the wall area. The reason for this may be summarised as follows:

small windows	glaring source is small and perceived sensation is not disturbing
medium windows	a high contrast between glare source and surrounding.
	adjacent wall leads to a higher perceived glare level.

large windows though the glare source is large, the contrast between the source and the surroundings is small, raising the adaptation level of the eye and reducing the glare sensation and the level of discomfort.

6.2.8 Seasonal Affective Disorder

Seasonal Affective Disorder (SAD), sometimes referred to as winter depression, is a cyclical disorder which is characterised by depression during winter months, with recovery during summer months. SAD is thought to affect about 5% of the population [Blehar, 1989]. It is estimated that about ½ million people suffer badly from the disorder in Britain. Depression has been associated with the shortening of the day, and exposure to artificial light has proved to be an effective anti-depressant [Partonen, 1994]. For over 60 years the effects of cyclical disorders have been noted in patients, but until recently had not been recognised as a listed disorder. In 1987 SAD was first included in the American classification of psychiatric disorders [O'Brien et al, 1989]; it is neither a psychosomatic nor imaginary illness. Light is the dominant factor for controlling the quantity of melatonin secretion in the brain. Melatonin is a serum produced in the pineal gland nocturnally, and acts as a timing mechanism for humans and animals. Secretion of melatonin is suppressed by the experience of bright light. This acts as a waking up process in the morning, but on dark winter days the light level retards this process. For complete secretion of melatonin to take place humans require bright light of intensity >2500 lux, [Checkley et al, 1993]. The human circadian cycle has a natural period of 24.5 to 28 hours, and unless this period is reset by sufficient light levels at the correct time of day, then physiological functions will retard in relation to temporal time [Cawthorne, 1991]. The time and level of exposure to light influences many physiological processes within the body. Bright light in the morning has been shown to advance the melatonin secretion rhythm, whereas light in the evening can cause a phase delay. This delay occurs in people who suffer from SAD as well as in healthy people, although the effect may be substantially greater in SAD patients. Light regulates sleep/wake cycles, body temperature, blood cortisol, food and water consumption, hormonal and other physical processes. Cycles which operate on a 24 hour period are called circadian and are controlled by stimuli, termed zeitgebers, in the surrounding environment. Light is one such stimulus, and has the greatest influence on circadian cycles.

SAD has been shown to affect many cognitive processes, including long and short term memory, decision making skills, pattern recognition, spatial recognition, visual memory and visual learning [O'Brien et al, 1993]. Motivation and ability to process information could also be affected in patients. Over 50% of sufferers complain of carbohydrate craving, increased appetite, weight gain and a need for increased sleep [Checkley et al, 1993].

SAD is one disorder which may be treated without the use of pharmacotherapy. An alternative is phototherapy, where the use of bright artificial light is used to suppress melatonin secretion. The photoperiod is described as the interval between the earliest and latest exposure to light in a 24 hour period [Winton et al, 1989]. In the case of a winter day this photoperiod is significantly shorter than that in the summer months. Light treatment is therefore applied in the morning and evening to extend the photoperiod in winter. Laboratory and field studies have shown that exposure to light is critical both in terms of duration and intensity. Humans require illumination of 1000 - 2500 lux for at least one hour in the day for maximum melatonin suppression to take place [Eastman, 1990]. Depending on the season, weather and location, an average day will produce daylight ranges between 500 and 10,000 lux. The maximum circadian phase shift which results from light experience would require 4000 - 10,000 lux for 3-5 hours in the day. The required illumination intensity for treatment of SAD falls between the range for maximum melatonin suppression and maximum circadian phase shifting. Cawthorne reports that recent medical evidence points toward an optimum of bright light greater than 2500 lux in the morning, proceeded by regular indoor light levels ranging between 100 and 500 lux throughout the duration of the working day. This would maintain the synchronisation between circadian and temporal time nearly as efficiently as the outdoor lighting environment.

Espiritu et al [1994] investigated the daily illumination exposure which a randomly selected sample of middle aged San Diego inhabitants experienced. Subjects wore a monitoring device on the wrist, which recorded illumination levels and rest/activity levels throughout the day. An average subject received illumination above 1000 lux for only 4% of the observation time, equating to approximately 58 minutes of daylight per day. On average, 50% of each day was spent in illumination levels between 0.1 and 100 lux. The conclusion of the report supported the hypothesis that many Americans do not receive adequate light exposure to maintain optimal mood.

Throughout the working day an individual spends the majority of time working indoors, experiencing low levels of illumination. This time may be broken up by short periods outdoors during the lunch and other breaks, or located next to window areas. Cawthorne proposed that this effect could alter the timing of a building occupant's circadian cycle. He also noted that if a combination of building design, lighting design and occupant behaviour pattern produced a lighting schedule which either advanced or retarded the cycle sufficiently to alter mood, cause drowsiness, disturb sleep patterns, or induce earlier onset of fatigue, then the well-being of that occupant would be adversely affected. These changes need not be large to be noticeable, and could be incremental with time. This effect could contribute to sick building syndrome by creating desynchronised circadian cycles with temporal time. At the very least this effect could make building occupants more sensitive to other building attributes, including thermal comfort, noise levels, and air quality.

The amount of information conveyed in low illuminance, homogeneous environments is very limited, and has been recognised to have significant influence on psychological well-being. Healthy indoor environments are created with the use of varied lighting intensities and use of daylighting wherever possible. Scenes with high frequency of contrast convey more information than those with low frequency of contrast. It is clear, then, that buildings with larger glazed areas have a higher Daylight Factor (DF), and admit more quality light into the indoor environment, increasing perceived visual comfort, improving the health and well-being of occupants, and potentially increasing task performance and work productivity.

6.2.9 Daylight Factor (DF)

Daylight entering a room is made up from direct sunlight, light diffused through the sky, and light reflected from the ground and from external surfaces. The measure of daylight within a room is characterised by the Daylight Factor (DF) and should be high enough to ensure that daylight can replace artificial lighting for at least part of the working day. The equation for DF is shown in Appendix D. When an average DF is 5% or more, the interior will be perceived as well daylit and there will be no need for continuous artificial lighting throughout the day. When the DF falls below 2%, however the interior will seem badly daylit.

Cawthorne [1991] carried out a study of occupants in three different building structures in Cambridge to assess the effect that design had on the timing of illuminance received by building occupants. The buildings represented a cross-section of designs, based on their window to floor area ratio, including a laboratory with high average DF, an office with medium average DF (control building) and a deep plan office with low average DF. In the first assessment the high average DF laboratory was compared to the control building, and in the second assessment the deep plan office with low average DF was compared to the control building. In each assessment the analysis was based on the results of ten days data. One subject for each of the ten days, in each of the buildings was required to wear a light dose meter strapped to the forehead for the entire working day. This ensured that an accurate measure of the illuminance perceived by the eyes was measured. Behaviour patterns throughout the day were recorded, including information on timing of lunch and coffee breaks. To generate information for an average building occupant in each building design, the data over the ten day assessment period was averaged. Figures 6.11, 6.12 and 6.13 show the received illuminance for each building design for the average occupant.

The average perceived light level in the high DF laboratory was 2.46 times greater than the medium average DF office, while the low average DF deep plan office was 0.26 times the level of the medium average DF office. The low average DF deep plan office has very few peaks and troughs to its profile, and can be likened to a homogeneous lighting environment. The high average DF laboratory has a very varied profile, representing more closely the lighting environment experienced outdoors.

6.2.10 Illuminance

Designing for sufficient daylight penetration in building structures is critical to building operation, as is the supply of adequate lighting levels to the working plane. Recommendations given in the CIBSE Code for Interior Lighting [1984] for illuminance levels are consistent with the rule that no working space which is to be continually occupied should have an illuminance level of less than 200 lux on the working plane, while offices are generally designed to an illuminance level of 500 lux. The gradual use of computers is bringing down this requirement to a value of 300 lux.
Poor task performance is one indisputable effect of insufficient or unsuitable lighting levels. Higher illuminance levels can ensure higher quality work, reduction in fatigue and improved productivity. The quality of lighting improves steadily with illuminance level, but saturates at about 800 lux. Figure 6.14 illustrates this law of diminishing returns.

6.2.11 Summary

Research related to daylight quality and its effects on perceived comfort, work performance and general productivity is variant in nature. Lighting quality is characterised by many factors, including, quantity, content and contrast. It is dependent upon window size, construction and transmission properties, room characteristics, finishes applied to walls, ceilings and floors, building aspect, location and architecture, and ultimately, must be suited to the tasks being carried out, and the comfort of building occupants.

There are a number of conclusions which may be drawn from the preceding literature review:

- People prefer environments with windows and daylight conditions [Wyon, 1980] and [Collins, 1975], and may recover from operations and illness more quickly in environments which are daylit, and which afford an exterior view [Loe and Davidson, 1992].

- The average person receiving more than 1000 lux from natural daylight for less than one hour per day, is not receiving sufficient levels to maintain optimal mood. A typical office worker could spend 50% or more of their time in environments of 0.1 – 100 lux [Espiritu, 1994]. This could be improved by re-thinking the office environment, and building construction.

- Buildings with low Daylight Factor create environments with homogenous lighting, having little contrast and holding limited interest for the occupant, whereas buildings with high Daylight Factor transmit more quality daylight, creating conditions likened to those found externally, maintaining optimal mood conditions for longer [Cawthorne, 1991].

- It is recognised that a holistic approach to lighting design is required to provide environments which are pleasing to the eye, comfortable for the occupant, and which do not limit work productivity [Loe & Davisdon, 1996]. The CSP index [Bean & Bell, 1994] places equal importance on the comfort, satisfaction and productivity associated with the lit environment. This, although heavily criticised by Perry et al [1996], emphasises the importance of considering all design aspects of lighting.

- One unwanted aspect to the presence of windows, is the generation of disability glare and discomfort glare. The impact of these can be minimised by appropriately sizing glazing areas in a façade, avoiding window proportions of 40-55% [Boubekri, 1992]. Discomfort glare occurs, however, when contrasting fields of brightness and darkness exist. Use of large window areas avoids this.

- On a window/floor area ratio basis, Christoffersen [1995] found that ratios much above 25% significantly reduced net energy savings for buildings, but that window/floor area ratios around 25% allowed quality daylight to be transmitted, maintaining potential for larger overall energy saving due to reduced lighting loads.

- Improvements in daylight penetration to the indoor environment, where properly managed can significantly lessen energy consumption on artificial lighting systems, and where employed with lighting control strategies can improve building performance [Zeguers and Jacobs, 1997].

Research on the provision of daylight, and its impact on work performance and productivity is still in its infancy. It is therefore difficult to produce confident relationships between daylight level and improvements/detriments to work output and quality. What is clear however, is that people prefer daylit environments and enjoy the benefits associated with windows. Occupants who are contented with their environment find it easier to channel their attention to work tasks; distraction is reduced and work productivity is increased. Exploiting daylight to a maximum has a knock-on effect on electrical load patterns, benefiting the environment through reduced energy consumption and associated emissions from fossil fuel combustion. The following analysis will focus on this benefit, providing a method by which annual electricity consumption for artificial lighting may be calculated for two strategies; top-up and on-off lighting control.

6.3 Analysis

Using the information gained from the above literature review, a visual analysis model is presented to evaluate the energy consumption associated with artificial lighting provided in buildings. For a given building and lighting design layout and load, the energy consumption used for artificial lighting may be assessed. The model calculates energy consumption associated with two different lighting control strategies (on-off and top-up lighting control) for each of the 24 window constructions considered in this thesis, and listed in Table 4.1. Each window construction is considered for the same example office design, and associated assumptions as used in the thermal and aural analyses, detailed in Figure 4.9.

To do this requires that the light transmitted through windows, onto the working plane within a building structure, is assessed. The extent to which light is transmitted through windows is a function of the optical properties of the material used. Glass may be modified to enhance or limit light transmission, primarily by changing the reflectance, or absorption of materials. Reflectance occurs when the glazing surface reflects an incident beam of light. Reflections can be direct, diffuse, or a mixture of both. Absorption defines that part of the incident light which is lost in the body of the glass. Transmittance describes the fraction of the direct incident radiation only that is transmitted through the glass, and is defined as that part of the incident light remaining after reflectance and absorption. Increasing the thickness and number of glazings therefore increases the fraction of the incident light which is absorbed, or lost in the glass structure. Similarly, addition of low emissivity coatings impacts upon the reflective properties of the glass. Cavity gas, however, does not influence the transmission of light, so no separate analysis is required for air and inert gas filled cavities. Figure 6.15 illustrates the transmission, reflectance and absorption of incident light through window structures.

The BRECSU guide for energy efficient lighting in offices states that in assessing lighting installations, the monitoring period should cover a full range of lighting conditions, ideally over at least half a year from summer to winter or vice versa [BRECSU, 1993]. The analysis given is performed over a period of one year, and is given for each of three years; 1990, 1991 and 1992 using MET office weather data for Turnhouse in Edinburgh. Irradiation values were extracted from weather files from 1 January to 31 December, throughout 1990-1992, for operational hours of 8am to 6pm.

A number of assumptions are made with regard to lighting control strategies within the office environment, as follows:

- Occupants do not override the lighting controls.
- Dimming control is linear in nature and does not employ step functions.
- Both lamps and control units are suitably maintained to ensure good performance.

- Building occupants do not object to gradation in daylight/artificial light throughout the passage of a day.

The final output of the visual analysis model shall become the third of four inputs to the final optimisation, the results of which are discussed in Chapter 8. By changing the user input values, or use of alternative weather data files, the model can be adapted to calculate energy consumption for other locations and different building constructions. Calculations can be performed for other window proportions, glazing options and daylight factors, and by editing the required lighting level and electrical load other building types can also be modelled.
The spreadsheets contained in CD/Program Files/Visual Analysis show the data used, and the calculations performed in evaluating the annual artificial lighting energy consumption for each of the window constructions considered, based on the level of natural daylight transmitted onto the working plane. The files are labelled as follows:

Vis1990.xls	lighting load calculations based on 1990 weather data
Vis1991.xls	lighting load calculations based on 1991 weather data
Vis1992.xls	lighting load calculations based on 1992 weather data

In the above example files, the annual energy consumption for top-up and on-off lighting control strategies is limited to one day of MET office data to minimise disk space occupied. To perform the analysis over a complete year, the formulae in all columns may be copied downwards using the data contained within:

Visdata.xls	Global irradiation values for Turnhouse (1990-1992)

A summary file lists all window types, their associated annual energy consumption in kWh and MJ, and illustrates these graphically. The summary file can also be found on CD/Program Files/Visual Analysis with filename:

Vissum.xls	Summary of annual artificial lighting energy consumption for top-up and on-off control strategies

The evaluation of lighting loads for both control strategies is dependent upon the light transmission qualities associated with each window construction. For each window type, a transmission curve for direct beam illuminance, based on the angle of incidence of the sun, and a transmission factor for diffuse illuminance is required.

Two further spreadsheets are used to evaluate these properties for each window construction.

Vistrans.xls	evaluates diffuse light transmission factors and direct light transmission factors for angles of incidence 5°-85°.
Vissolve.xls	evaluates the equation of the direct light transmission curve.

6.3.1 Spreadsheet Use

If window light transmission properties for a particular glazing construction are unknown, the Vistrans.xls spreadsheet can be used to evaluate the missing information. Use of the Vistran.xls spreadsheet is identical to the solar transmission spreadsheet developed in Chapter 4, Soltrans.xls. The spreadsheets are identical except for the replacement of solar transmission values with light transmissions values in Table 2 of the "KL" worksheet. Please refer to Procedures A and B in Chapter 4.

Both Procedures A and B were carried out for each window configuration in the study. Daylight transmissivity data for single, double and triple-glazed windows, which was not previously available, is presented in tabular format in Table 6.1, and in graphical format in Figures 6.16-18. Data produced was entered into a single spreadsheet to evaluate the lighting load for top-up and on-off lighting control. A separate spreadsheet was developed for each of three years of MET office data; Vis1990.xls, Vis1991.xls and Vis1992.xls. All three spreadsheets are identical in layout:

Columns A to E show the month, day, hour, minute and horizontal global irradiation from the MET office measured data file.

Columns F to BU are extracted from two spreadsheets, which are the work of Muneer [1997].

Columns BV to EY extend Muneer's work to evaluate the internal illuminance on a horizontal plane, given the transmission properties of the windows in question, where:

- Columns BV to BZ evaluate the beam irradiation, illuminance and luminous efficacy.
- Columns CA to CV evaluate the light transmission factor, given the angle of incidence.
- Columns CW to DG evaluate Daylight Factor, "r", and internal illuminance, given the transmission factor of the window.

- Columns DH to DR evaluate the lighting deficit between natural daylight transmitted through the glazing, and the design illuminance for top-up control strategies.
- Columns DS to EC evaluate whether the natural daylight transmitted through the glazing is sufficient, or whether electric lighting is required, for an on-off lighting control strategy.
- Columns ED to EN evaluate the lighting load for a top-up lighting control strategy, given the full load power of the lighting installation.
- Columns EO to EY evaluate the lighting load for an on-off lighting control strategy, given the full load power of the lighting installation.

The flow diagram illustrated in Figure 6.19 shows what is required of the program user in performing the visual analysis, and the stages involved in calculating the annual electricity consumption for artificial lighting under top-up and on-off lighting control strategies.

6.3.2 Example Calculation

Building location inputs

Latitude	default 55.95
Longitude	default 3.2
Aspect	default 270° due North
Slope	default 90°
Albedo	default 0.24
Ground reflectivity (ρ_g)	default 0.24
Diffuse/ground reflected angle of incidence, (i)	default 60°

Room inputs

Room length	13.4 m
Room width	6.8 m
Window area, A_{window}	50%
Daylight Factor, (DF)	default 2%
Required lighting level	default 500 lux
Lighting load	default 19W/m^2
window type	4-12Kr-4
date	7th July 1991, 13:30

Calculation of Beam Irradiation, E_{eb}

$$E_{eb} = \text{Horizontal Global Irradiation - Horizontal Diffuse Irradiation} \quad 6.2$$
$$= 299 - 293$$
$$= \underline{\underline{6 \text{ Wh/m}^2}}$$

Calculation of Beam Illuminance, E_{vb}

E_{vb}	=	Global Illuminance - Diffuse Illuminance	6.3
	=	40847 - 38155	
	=	2692 lux	

Calculation of Beam Efficacy, K_b

K_b	=	E_{vb} / E_{eb}	6.4
	=	2692 / 6	
	=	448.7 lm/W	

Calculation of Transmission factor at angle of incidence, T_i

If i > 90°, T_i = 0

If i < 90°, T_i = $a_0 x^5 + a_1 x^4 + a_2 x^3 + a_3 x^2 + a_4 x + a_5$

where $a_{0\text{-}5}$ = coefficients of transmission curve

x = Cos i = Cos (55.2) = 0.57

= [-1.7071 * $(0.57)^5$] + [5.7121 * $(0.57)^4$] - [6.2909 * $(0.57)^3$] + [1.4899 * $(0.57)^2$] + [1.6162 * 0.57] - 0.0206

= 0.72

Calculation of Diffuse Transmission factor, T_{60}

calculated, using spreadsheet "Vistrans.xls" T_{60} = 0.68

Calculation of Daylight Factor, D.F.

Procedure as shown in Appendix D D.F. = 2.59

Calculation of r

r	=	D.F. * 0.01 / (0.396 + 0.5 * ρ_g)	6.5
	=	2.59 * 0.01 / (0.396 + 0.5 * 0.24)	
	=	0.05	

Calculation of Internal Illuminance on a horizontal plane, E_v

If i < 90 E_v = r (T_i (Beam Slope Irr * Beam Luminous Efficacy) + T_{60} (Sky Diffuse Slope Irr * Sky Diffuse Luminous Efficacy) + T_{60} (Ground reflected Slope Irr * k_g))

= 0.05 (0.72(2.1 * 448.7) + 0.68(120.3 * 130.2 + 35.9 * 86))

= 671.4 lux 6.6

If i > 90 E_v = r (T_{60} (Sky Diffuse Slope Irr * Sky Diffuse Luminous Efficacy) + T_{60} (Ground reflected Slope Irr * k_g)) 6.7

Calculation of Lighting deficit, L_D

If E_v < Design Illuminance, L_D = Design Illuminance - E_v
If E_v >= Design Illuminance, L_D = 0
for example calculation, E_v > Design Illuminance, therefore $L_D = 0$

Calculation of Lighting load for top-up lighting control strategies, $W_{top\text{-}up}$

$W_{top\text{-}up}$ = Lighting Full Load * L_D / Design Illuminance
= 0.63 * 0/500
= $\underline{\underline{0}}$ W

Where the Lighting Full Load is calculated at 19 W/m^2, according to good practice [BRECSU, 1993].

Calculation of Lighting load for on-off lighting control strategies, $W_{on/off}$

If L_D > 0 $W_{on/off}$ = Lighting Full Load
If L_D = 0 $W_{on/off}$ = 0

For example calculation, $L_D = 0$, therefore $W_{on/off} = 0$

6.3.3 Summation over yearly period

Lighting loads are calculated for each hour of data represented, for each window construction. The total energy consumption associated with each window construction is summed over the full data set.

An example sky condition for 7th July at 13:30 has been used in this calculation. A similar calculation was carried out for each hour of occupation (8am to 6pm) throughout the year for 1990, 1991 and 1992, using sky data from Turnhouse in Edinburgh. The total energy consumption for artificial lighting was summed for each window construction, each lighting control strategy, and each year included in the analysis The average annual electrical energy consumption for each window construction is shown in Figure 6.20. An example sheet from Vis1991.xls is shown in Figure 6.21 to illustrate the layout of the calculation spreadsheets found on CD/Program Files/Visual Analysis.

6.3.4 Synopsis

Improvements in lighting conditions seem an obvious answer, but is often one of the last considerations for optimising workplace performance. The capital costs associated with improving lighting systems, and the running costs for higher illuminance levels may be high, but this is only a fraction of the total business cost for a company. In relation to the vast sums spent on employee salaries and expenses, attention to lighting gives way to good performance return from investment in staff. Use of artificial lighting controls, which minimise electrical energy consumption through exploitation of daylight, offsets the cost of additional installation and capital costs. The above computer models, as with the thermal and aural analysis models, provide easy to use tools for engineers and designers, reducing the need for time consuming calculations, and collating data and information that was previously not available. Use of the above models, in conjunction with the daylight transmissivity data and curves presented, will ease decision making in both window design and selection.

6.4 References

1. Bean, A.R. and Bell, R.I., The CSP index: a practical measure of office lighting quality as perceived by the office worker, Lighting Research and Technology, 24(4) 215-225, (1992).
2. Blehar M.C. and Rosenthal, N.E., Seasonal affective disorders and phototherapy, Guildford Press, New York (1989).
3. Boubekri, M., Effect of window size and sunlight presence on glare, Lighting Research and Technology, 24(2) 69-74 (1992).
4. BRECSU – OPET, for the Commission of the European Communities Directorate-General XVII for Energy, Energy efficient lighting in offices, (1993).
5. BRE Digest 272, Designing for natural and artificial lighting, BRE (1985).
6. British Standard Institution (BSI), BS8206 : Part2, Lighting for buildings: Code of practice for daylighting, (1992).
7. Cawthorne, D., Buildings, lighting and the biological clock, The Martin Centre for Architectural and Urban Studies, University of Cambridge (1991).
8. Checkley, S.A. et al, Melatonin rhythms in seasonal affective disorder, British Journal of Psychiatry, Vol. 163, 332-337 (1993).
9. Christoffersen, Daylight Utilisation in Office Buildings, PhD Thesis, SBI Report 258, Danish Building Research Institute (1995).
10. CIBSE Code for Interior Lighting, Yale Press Ltd, London (1984).
11. Collins B.L., Windows and people: a literature survey: psychological reaction to environments with and without windows, NBS Building Science Series 70 (1975).
12. Daylighting in Architecture: a European Reference Book, Commission of the European Communities Directorate-General XII, ed. Baker, N., Fanchiotti, A. and Seemers, K., James and James, Brussels, (1993).
13. Eastman, C.I., Natural summer and winter sunlight exposure patterns in seasonal affective disorder, Physiology and Behaviour, Vol.48, 611-616 (1990).
14. Energy efficiency demonstration scheme report, An advanced lighting control system using mains signalling and remote infra-red) reset in a refurbished office building, Energy Efficiency Office, (1986).
15. Energy in Architecture: the European passive solar handbook, Batsford for the Commission of the European Communities, B.T. Batsford Ltd, London, (1993).
16. Espiritu, R.C. et al, Low illumination experienced by San Deigo adults: association with atypical depressive symptoms, Biological Psychiatry, 35(6) 403-407 (1994).
17. Glennie, W.L., Thukral, I. and Rea, M.S., Lighting control: feasibility demonstration of a new type of system, Lighting Research and Technology, 24 (4) 235-242, (1992).
18. Harris, L. and associates, Office Environment Index, Steelcase Inc., Grand Rapids (1989).

19. Hedge, A., Sims Jr, W.R. and Becker, F.D., Effects of lensed-direct and parabolic lighting on the satisfaction, visual health, and productivity of office workers, Ergonomics, 38 (2) 260-280 (1995).
20. Littlefair, P.J., Predicting annual lighting use in daylit buildings, Building and Environment 25(1) 43-54 (1990).
21. Loe, D. and Davidson, P., A holistic approach to lighting design, Energy Management, Sep/Oct pp16-18 (1996).
22. Loe, D. and Rowlands, E., The art and science of lighting: a strategy for lighting design, Lighting Research and Technology, 28 (4), 153-164, (1996).
23. Lynes , J.A. and Littlefair, P.J., Lighting energy savings from daylight: estimation at the sketch design stage, Lighting Research and Technology 22(3) 129-137, (1990).
24. Lyons, S.L., Management guide to modern industrial lighting, 2nd edition, Butterworths, London, (1983).
25. O'Brien, J.T., Sahakian, B.J., and Checkley, S.A., Cognitive impairments in patients with Seasonal Affective Disorder, British Journal of Psychiatry, 163, 338-343, (1993).
26. O'Brien, J.T. and Checkley, S., Seasonal affective disorder, The Practitioner, Vol. 233, 1575-1578 (1989),.
27. Partonen, T., The shortening of the photoperiod may alter gene expression in winter depression, Medical Hypothesis, Vol.42, 13-14 (1994).
28. Perry, M.J., Canter, D.J. and Manzano, E.R., Validation of the CSP lighting quality index and other physical correlates, CIBSE National Lighting Conference, 84-91, (1996).
29. Sato M., Inui M., Nakamura Y. and Takeuchi Y., Visual environment of a control room, Lighting Research and Technology, 21(3) 99-106 (1989).
30. Wilkins A.J., Fluorescent lighting, headaches and eyestrain, Lighting Research and Technology, 21(1) 11-18 (1989).
31. Wilkins A.J., Health and efficiency in lighting practice, Energy, 18(2) 123-129 (1993).
32. Winton, F. et al, Effects of light treatment upon mood and melatonin in patients with seasonal affective disorder, Psychological Medicine, 19(3) 585-590 (1989).
33. Wyon, D.P. and Nilsson, I., Human experience of windowless environments in factories, offices, shops and colleges in Sweden, Building Resources Worldwide, Proceedings of the 8th CIB conference, 234-239 (1980).
34. Zeguers J.D.M. & Jacobs, M.J.M., Energy saving and the perception of visual comfort, Proceedings of Lux Europa, (1997).

Table 6.1 Daylight transmissivity data for single, double and triple-glazed windows

A*	4+	6	8	10	4+4	6+4	6+6	10+4	10+6	4e°+4	4e+e4	4e+4+e4
0	0.89	0.87	0.85	0.84	0.80	0.78	0.77	0.76	0.74	0.76	0.72	0.64
5	0.89	0.87	0.85	0.84	0.80	0.78	0.77	0.76	0.74	0.76	0.71	0.64
10	0.89	0.87	0.85	0.84	0.80	0.78	0.76	0.76	0.74	0.76	0.71	0.64
15	0.89	0.87	0.85	0.84	0.80	0.78	0.76	0.76	0.74	0.75	0.71	0.64
20	0.89	0.87	0.85	0.84	0.80	0.78	0.76	0.75	0.74	0.75	0.71	0.64
25	0.89	0.87	0.85	0.84	0.79	0.78	0.76	0.75	0.73	0.75	0.71	0.64
30	0.89	0.87	0.85	0.84	0.79	0.77	0.76	0.75	0.73	0.75	0.70	0.63
35	0.88	0.86	0.84	0.83	0.79	0.77	0.75	0.74	0.72	0.74	0.70	0.63
40	0.88	0.86	0.84	0.83	0.78	0.76	0.74	0.73	0.72	0.73	0.69	0.62
45	0.87	0.85	0.83	0.82	0.77	0.75	0.73	0.72	0.70	0.72	0.68	0.60
50	0.86	0.84	0.82	0.81	0.75	0.73	0.71	0.70	0.69	0.70	0.66	0.58
55	0.84	0.82	0.80	0.79	0.72	0.70	0.69	0.68	0.66	0.68	0.63	0.55
60	0.82	0.80	0.78	0.77	0.68	0.66	0.64	0.63	0.62	0.63	0.59	0.50
65	0.77	0.75	0.73	0.72	0.61	0.60	0.58	0.58	0.56	0.57	0.54	0.44
70	0.70	0.68	0.66	0.65	0.52	0.51	0.50	0.50	0.48	0.49	0.46	0.36
75	0.59	0.57	0.56	0.55	0.41	0.40	0.39	0.39	0.37	0.38	0.36	0.26
80	0.44	0.43	0.41	0.41	0.28	0.27	0.26	0.26	0.25	0.26	0.24	0.16
85	0.24	0.23	0.23	0.23	0.13	0.12	0.12	0.12	0.11	0.12	0.11	0.07
90	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

* Incidence angle, degrees

+ Glass thickness, mm

o Tin-oxide low emissivity coating ($\varepsilon = 0.12$)

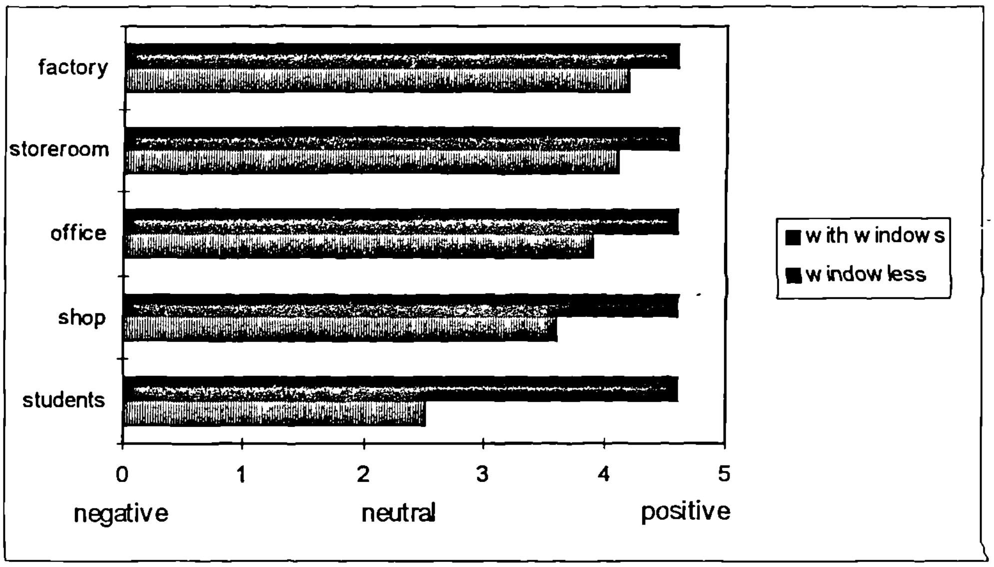


Figure 6.1 Attitudes towards environments, with and without windows [Wyon 1980]

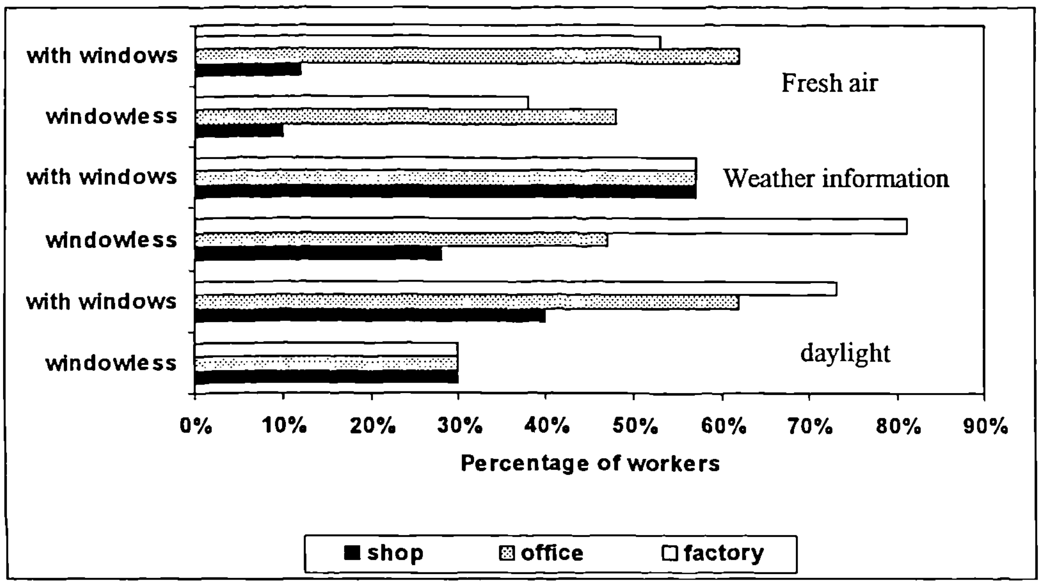


Figure 6.2 Percentage of shop, office and factory workers mentioning fresh air, weather information and daylight as advantages of windows [Wyon, 1980]

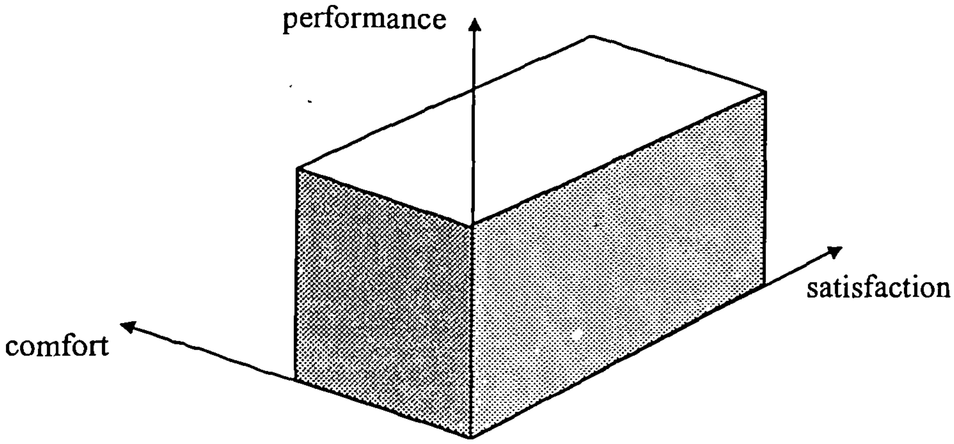


Figure 6.3 The visual quality solid - CSP index [Bean and Bell, 1992].

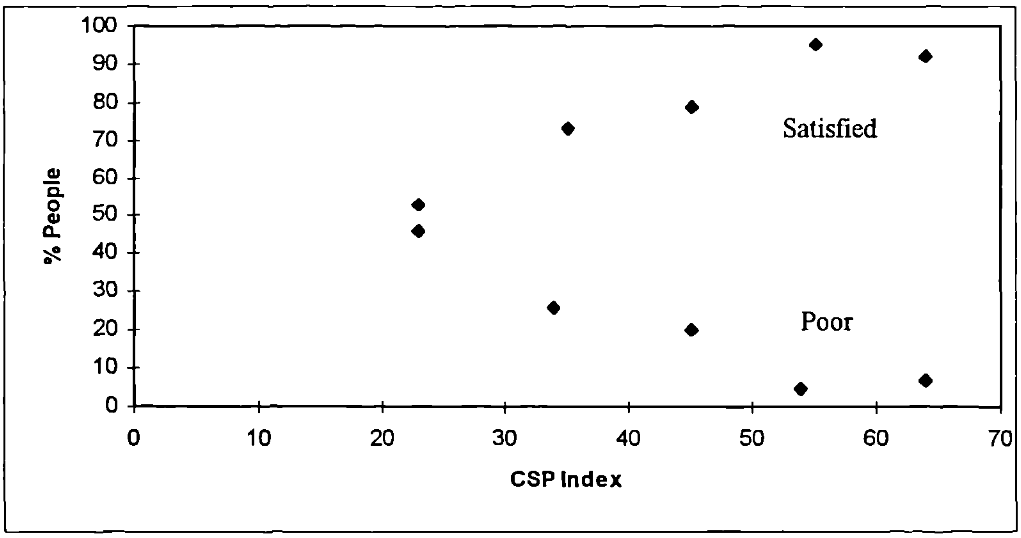


Figure 6.4 Perceived glare [Bean & Bell, 1992]

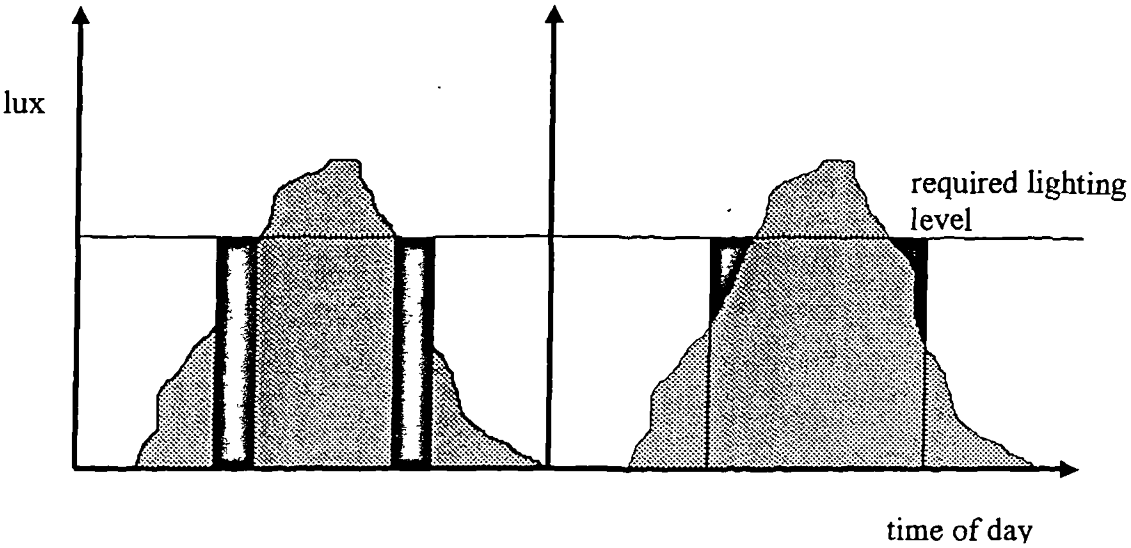


Figure 6.5(a) On-off control strategy Figure 6.5(b) Top-up control strategy

lighting 'ON' time, and lux level of light supplied

lighting level provided by natural daylight

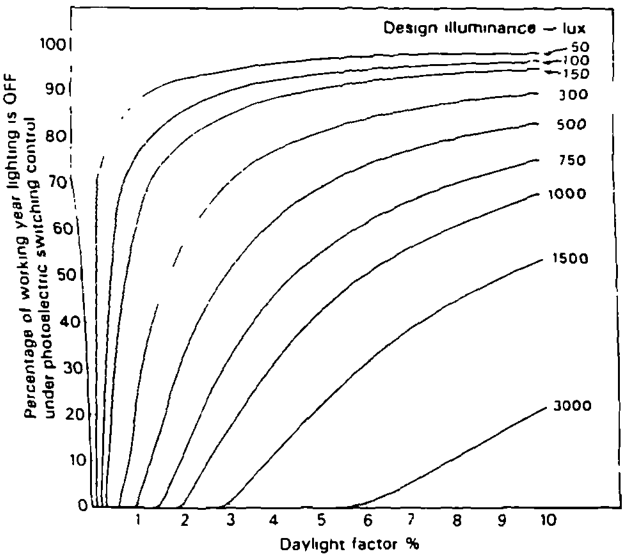


Figure 6.6(a) Lighting operation under on-off control [BRE, 1985].

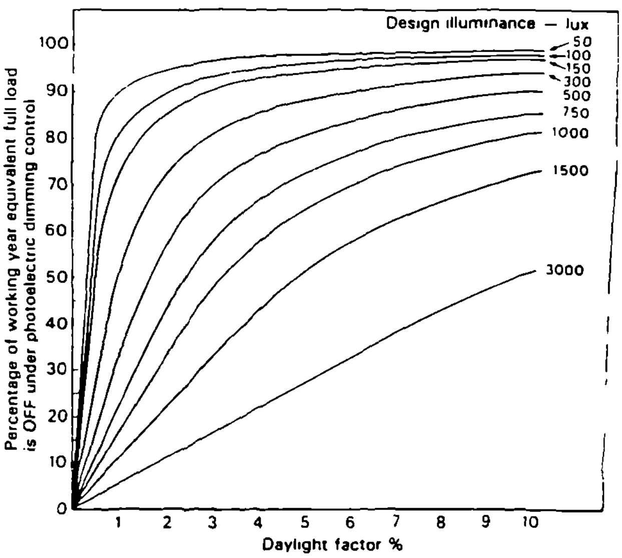


Figure 6.6(b) Lighting operation under top-up control [BRE, 1985].

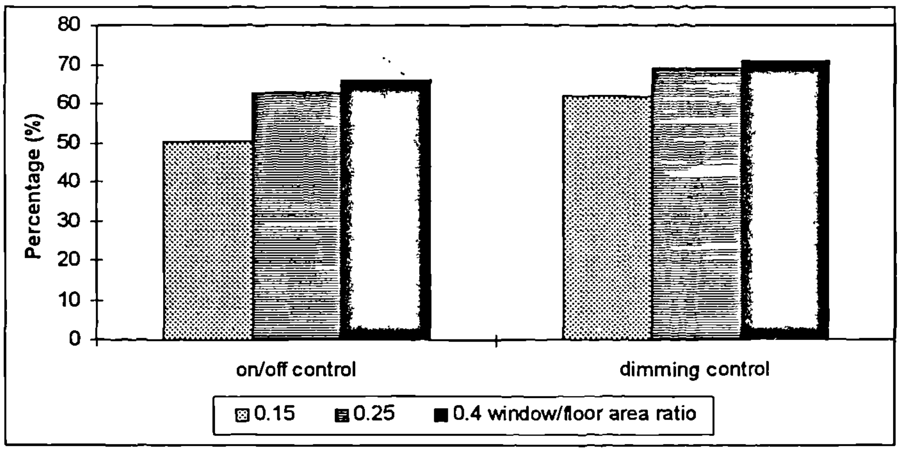


Figure 6.7 Gross energy savings due to reduced lighting load for varying window/floor area ratios [extracted from Christoffersen, 1995]

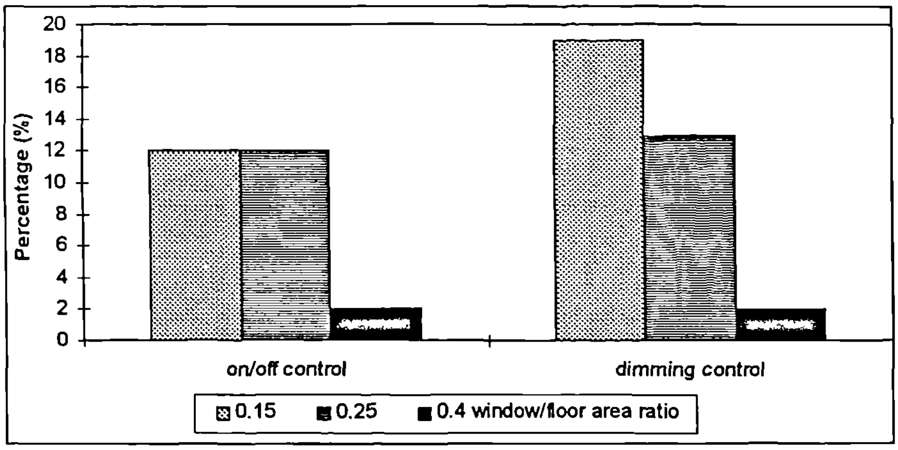


Figure 6.8 Net energy savings for building, accounting for increased heating load [Christoffersen, 1995]

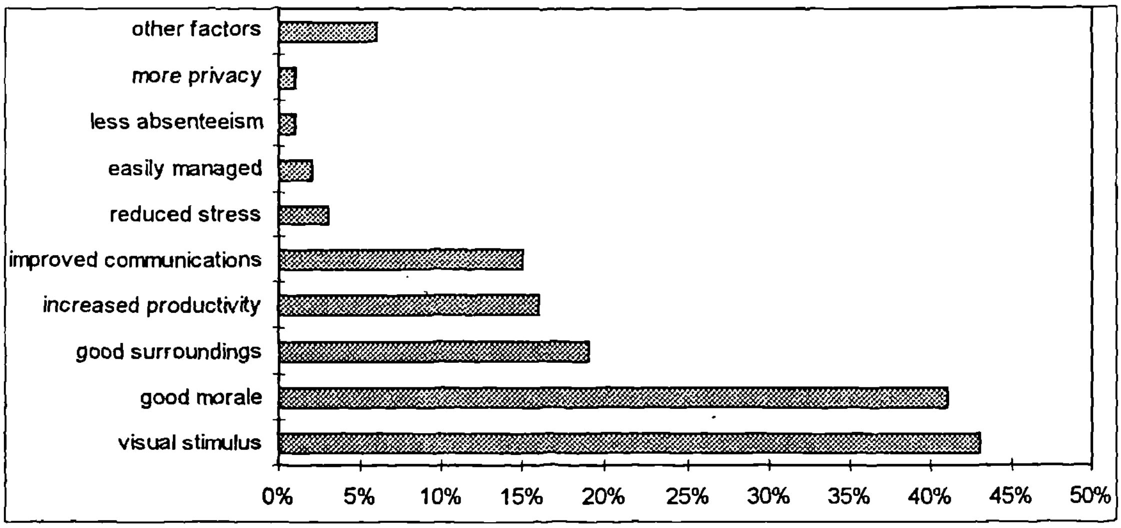


Figure 6.9 Factors promoting well-designed buildings [Richard Ellis, 1994]

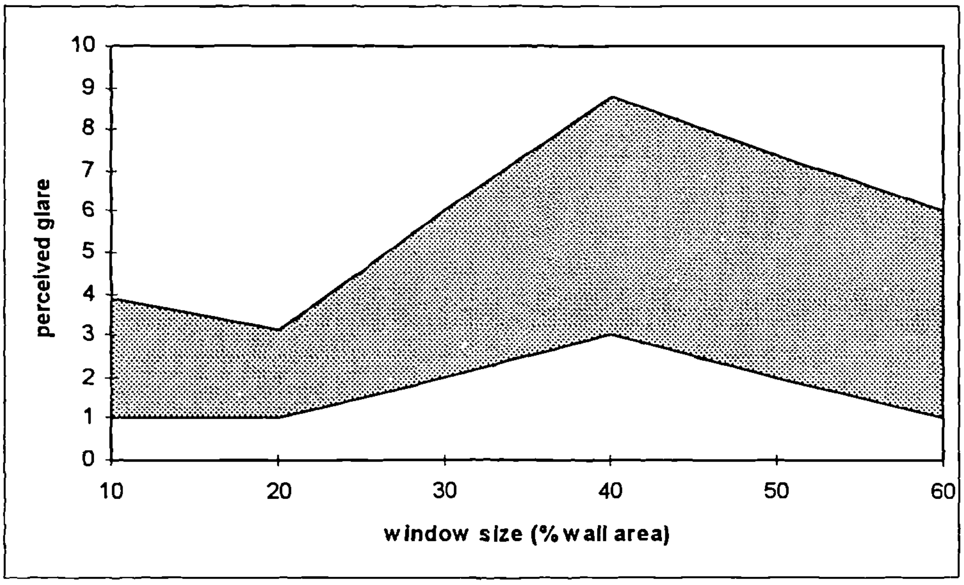


Figure 6.10 Predicted variation of perceived glare with window size. The window is viewed from a perpendicular distance of 2.75m [Boubekri, 1992]

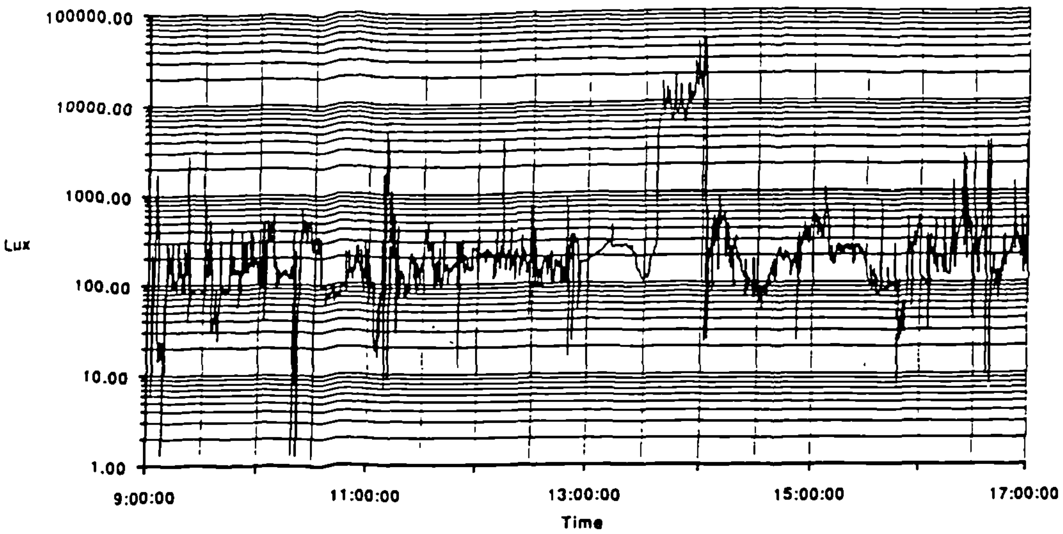


Figure 6.11 Typical light exposure trace from an individual in a medium average daylight factor building.

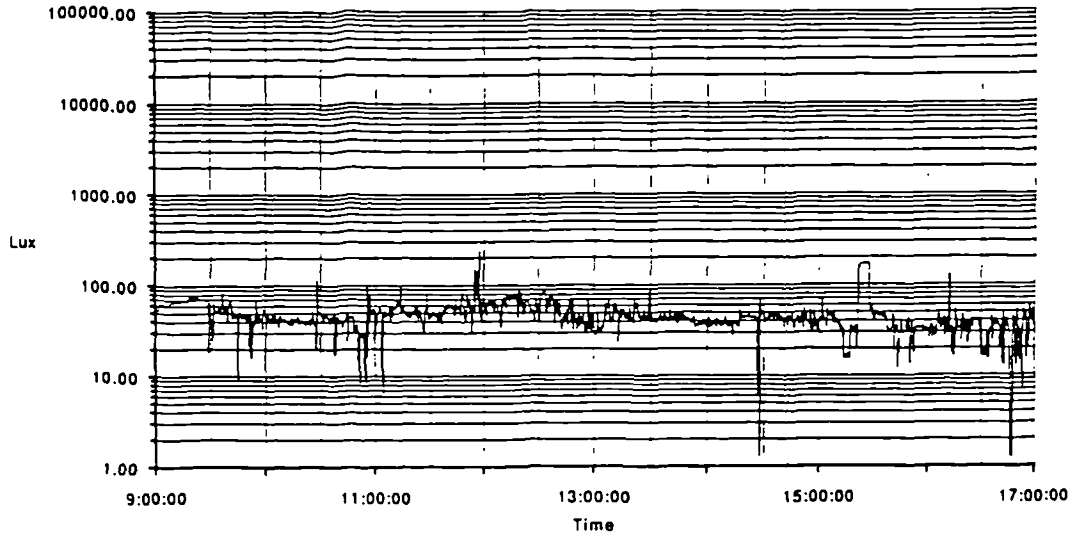


Figure 6.12 Typical light exposure trace from an individual in a low average daylight factor building.

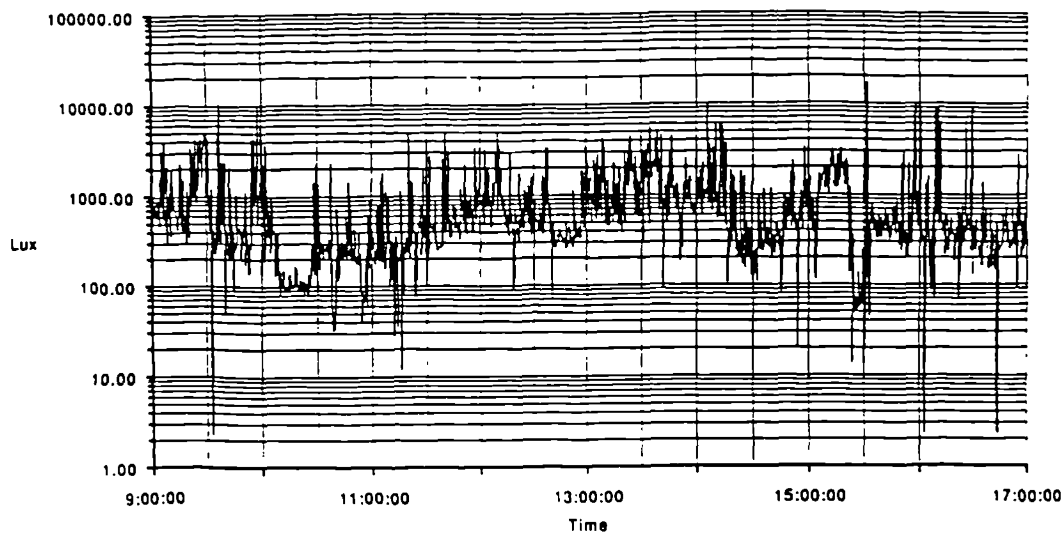


Figure 6.13 Typical light exposure trace from an individual in a high average daylight factor building [Cawthorne, 1991].

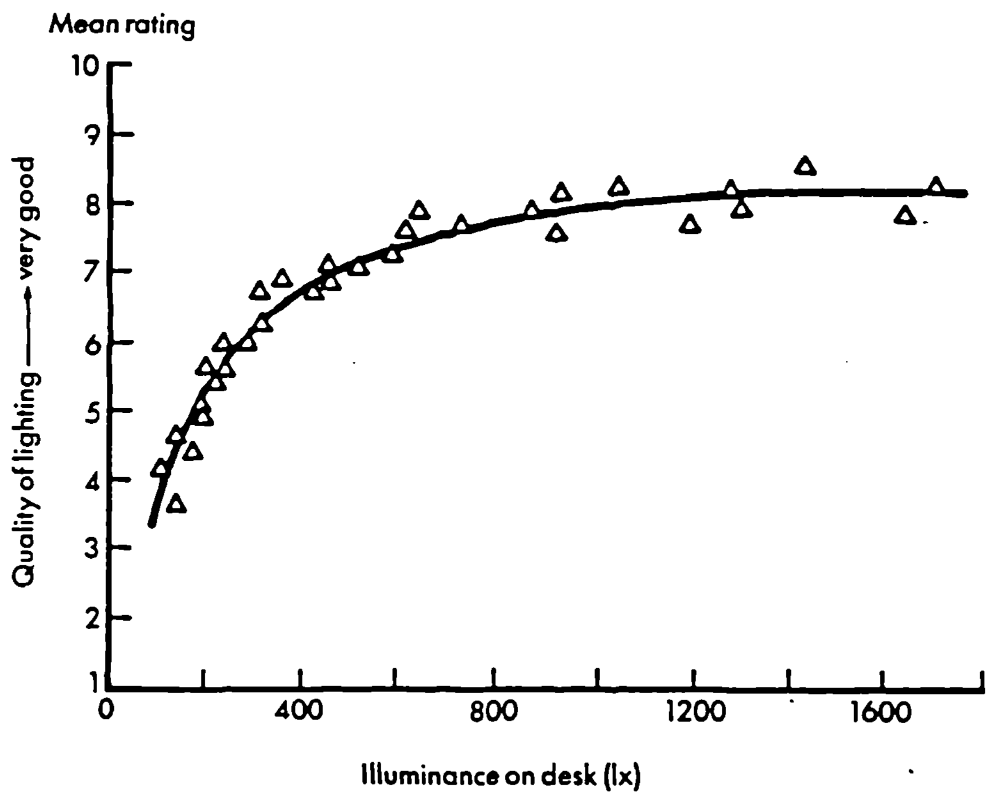


Figure 6.14 Law of diminishing returns on task illuminance and lighting quality

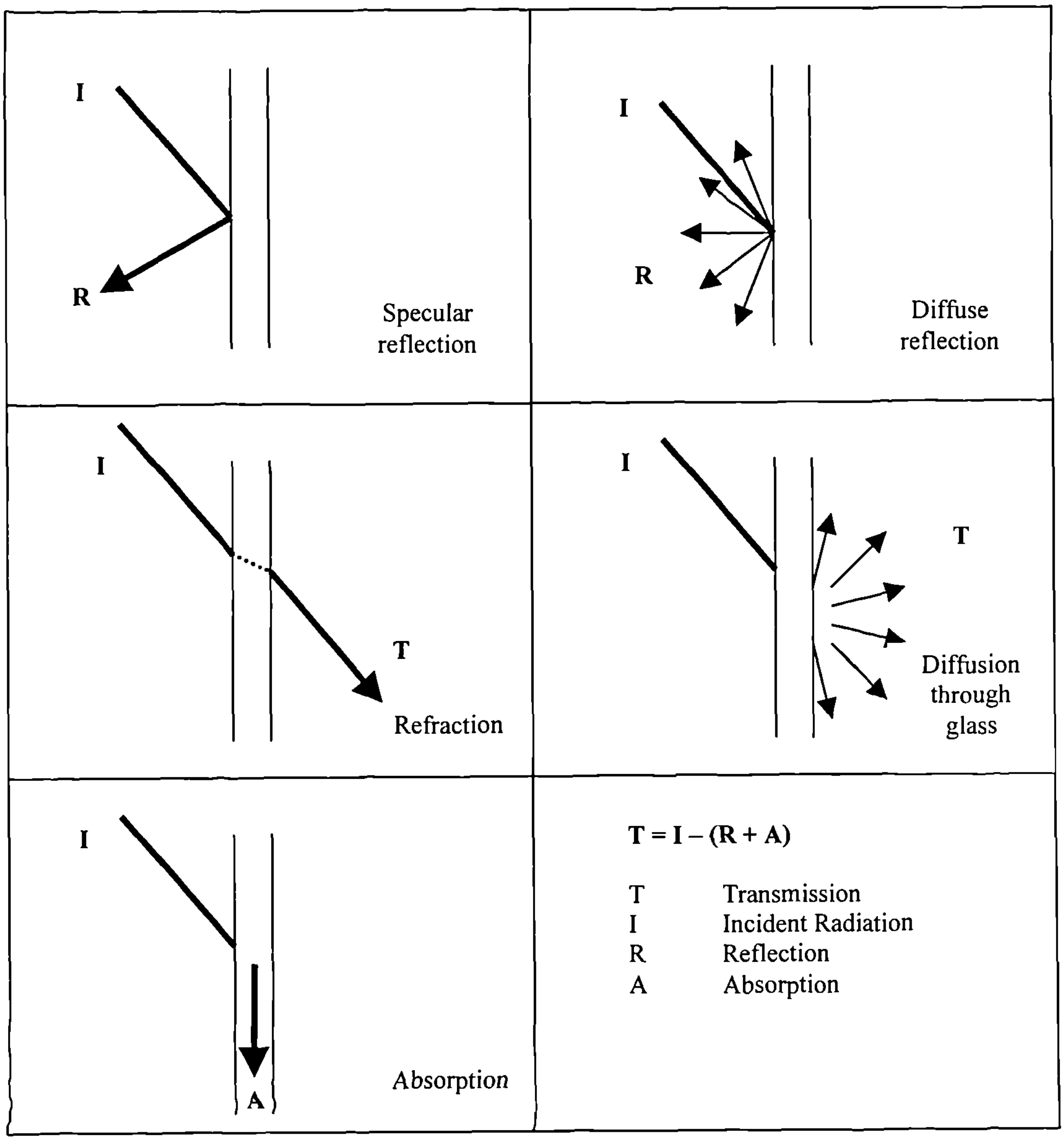


Figure 6.15 Transmission, reflectance and absorption of incident light

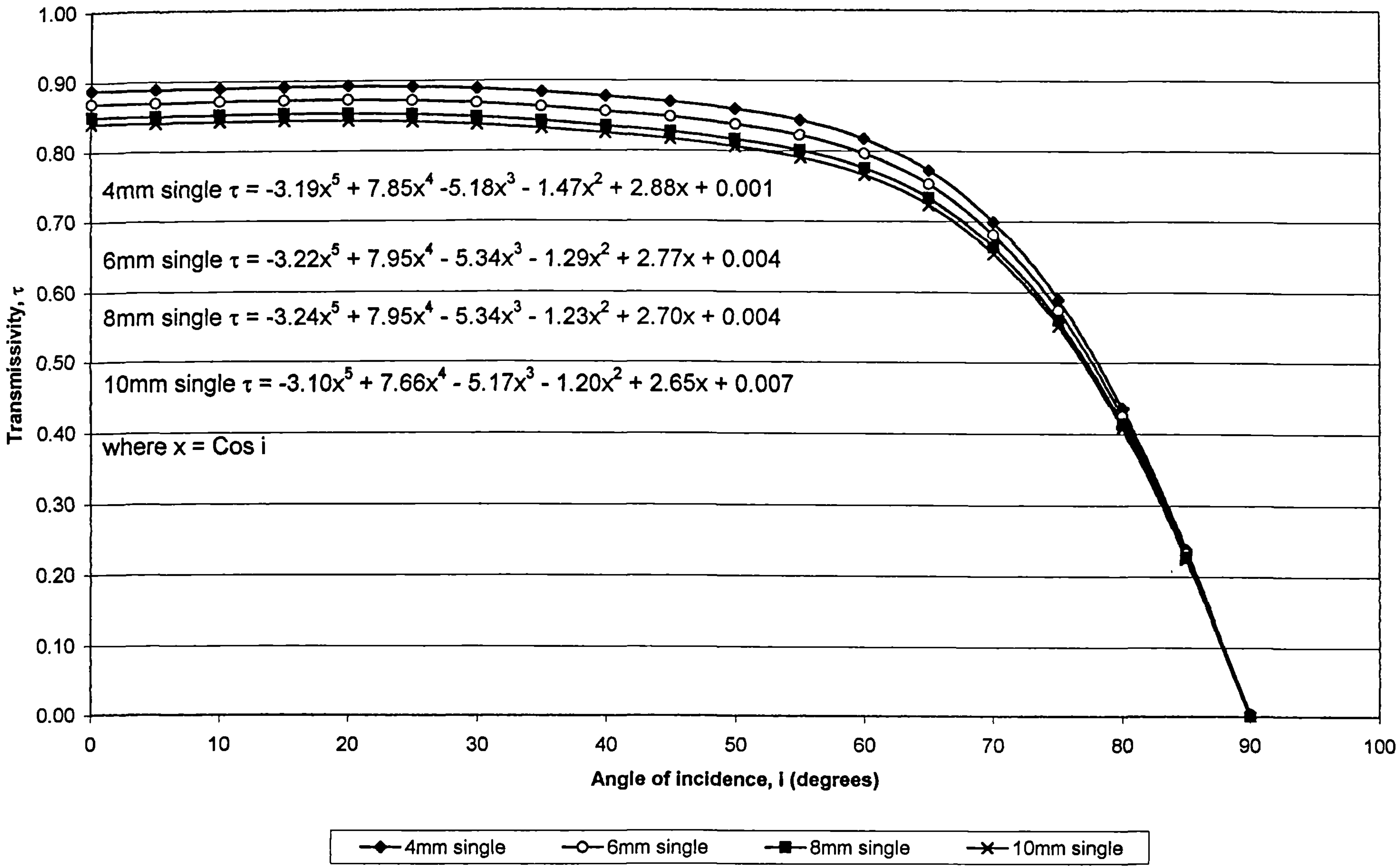


Figure 6.16 Daylight transmissivity characteristics of single glazings

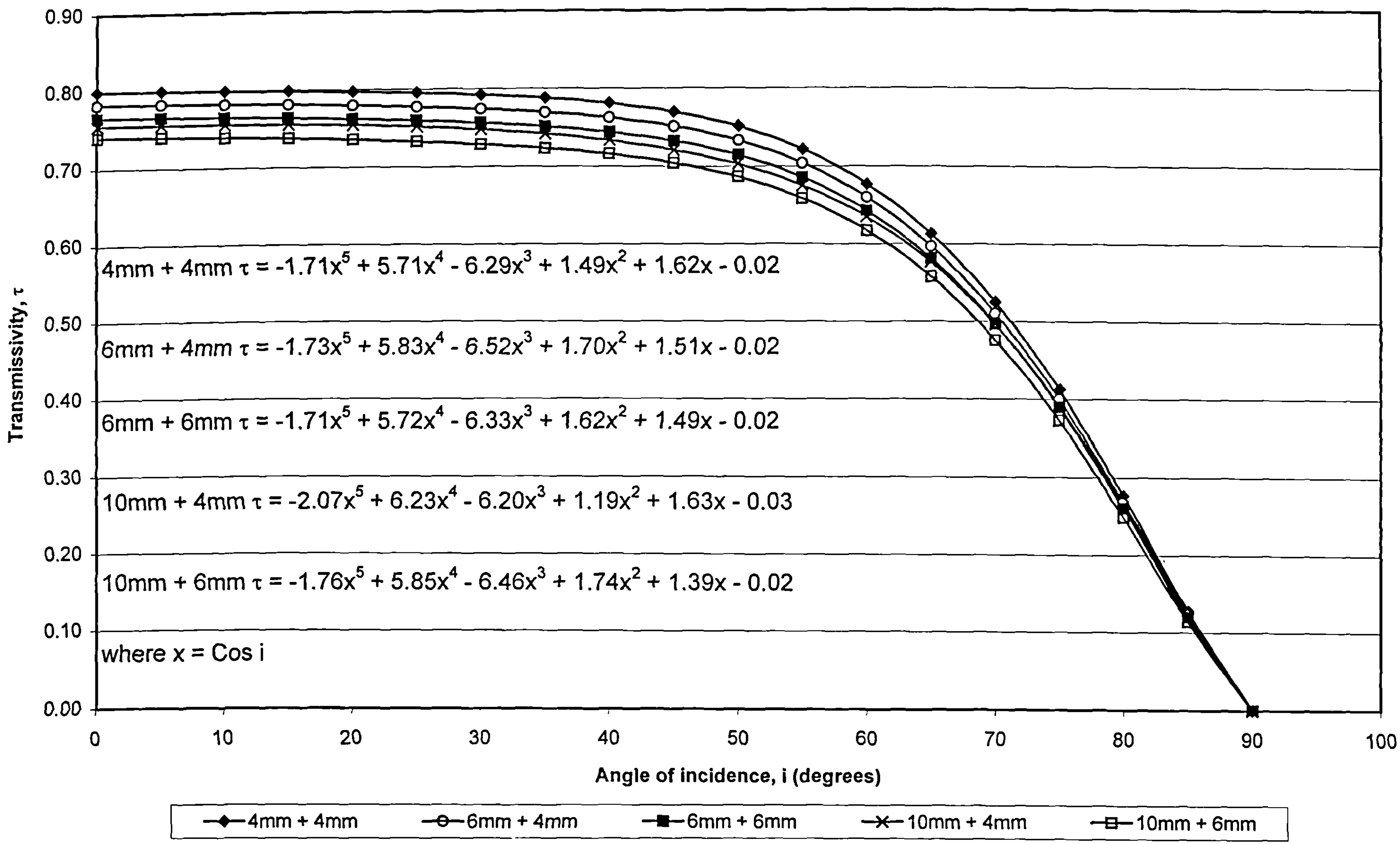


Figure 6.17 Daylight transmissivity characteristics of double glazings

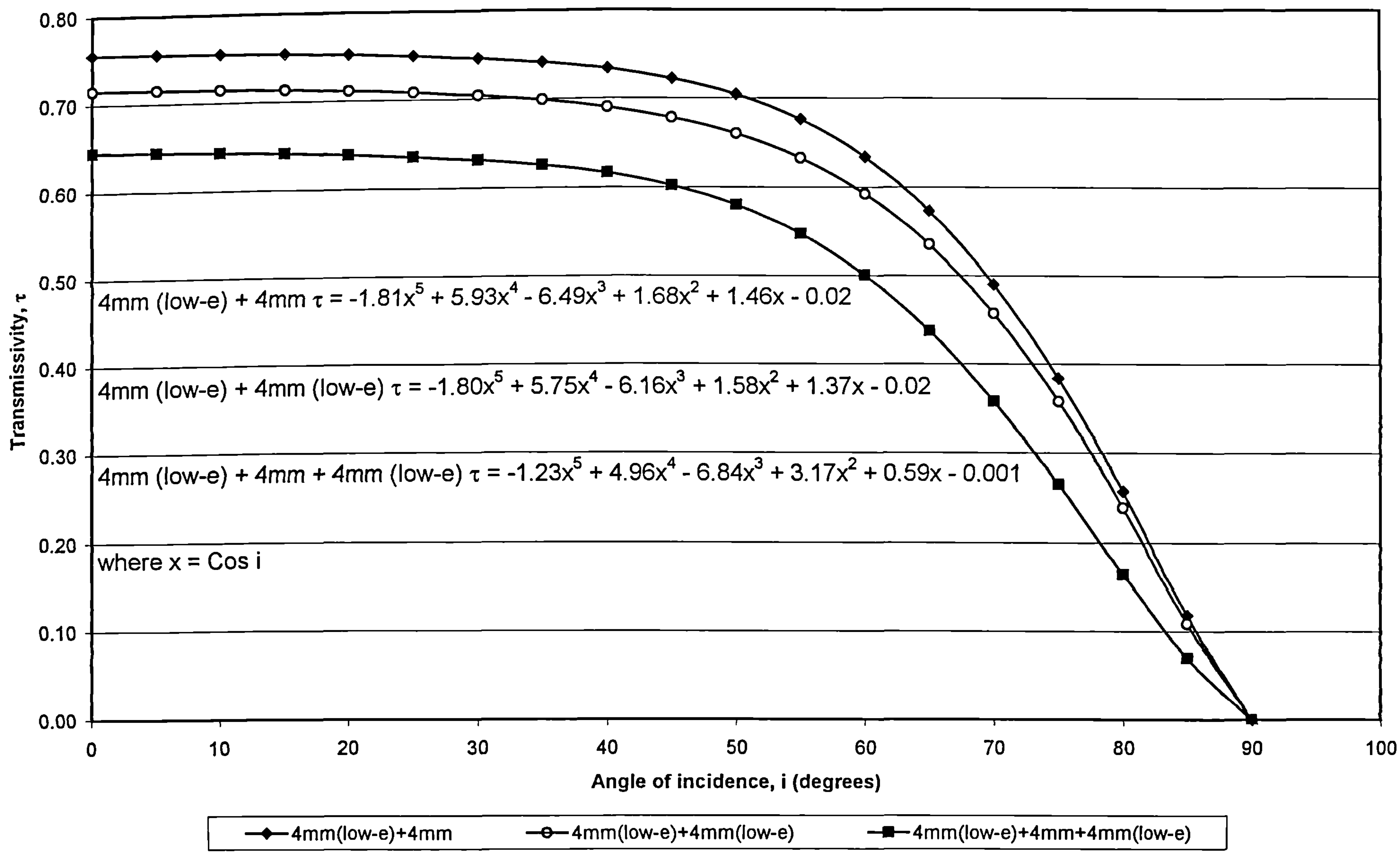


Figure 6.18 Daylight transmissivity characteristics of double and triple glazings with low-e coatings

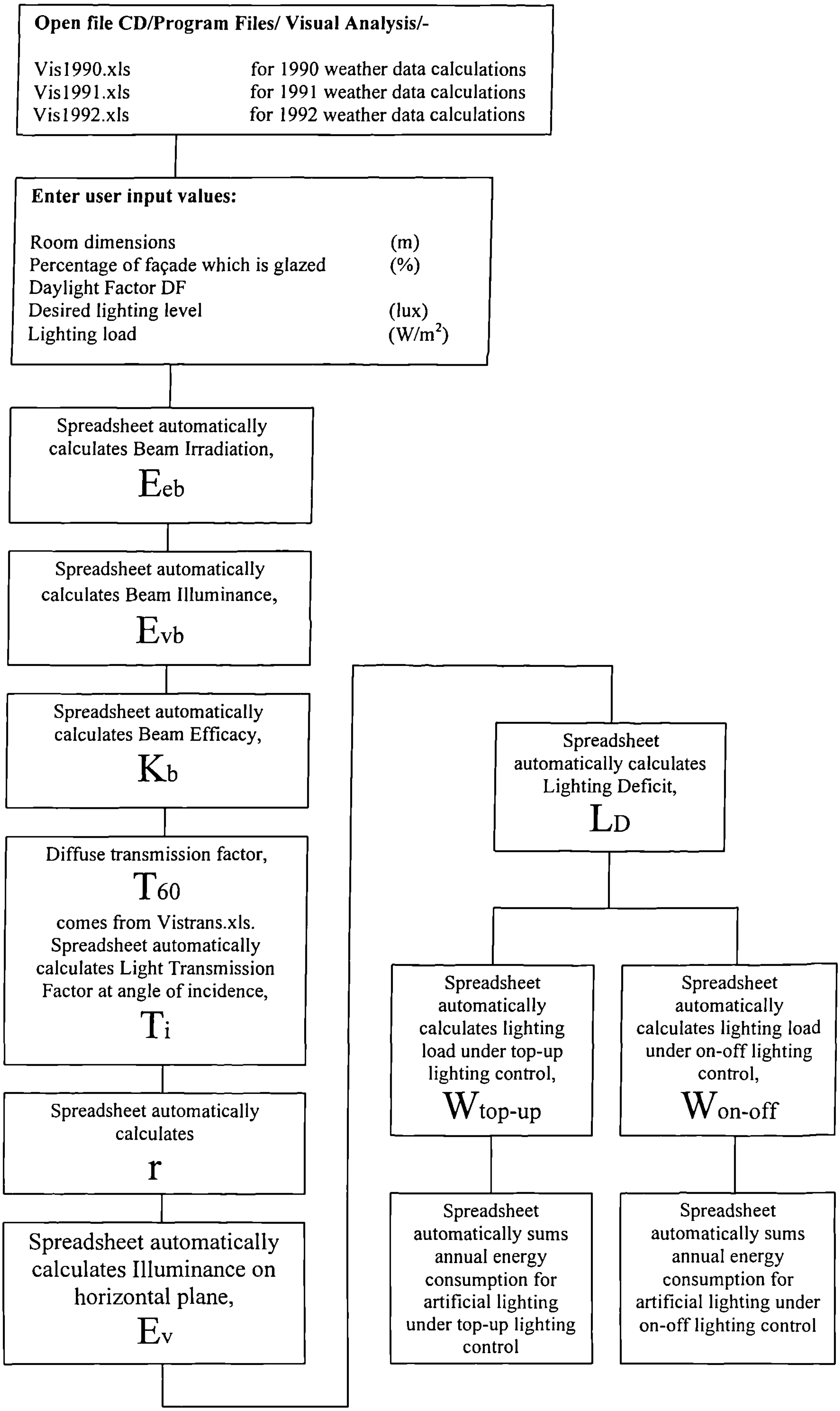


Figure 6.19 Flow diagram of visual analysis calculations

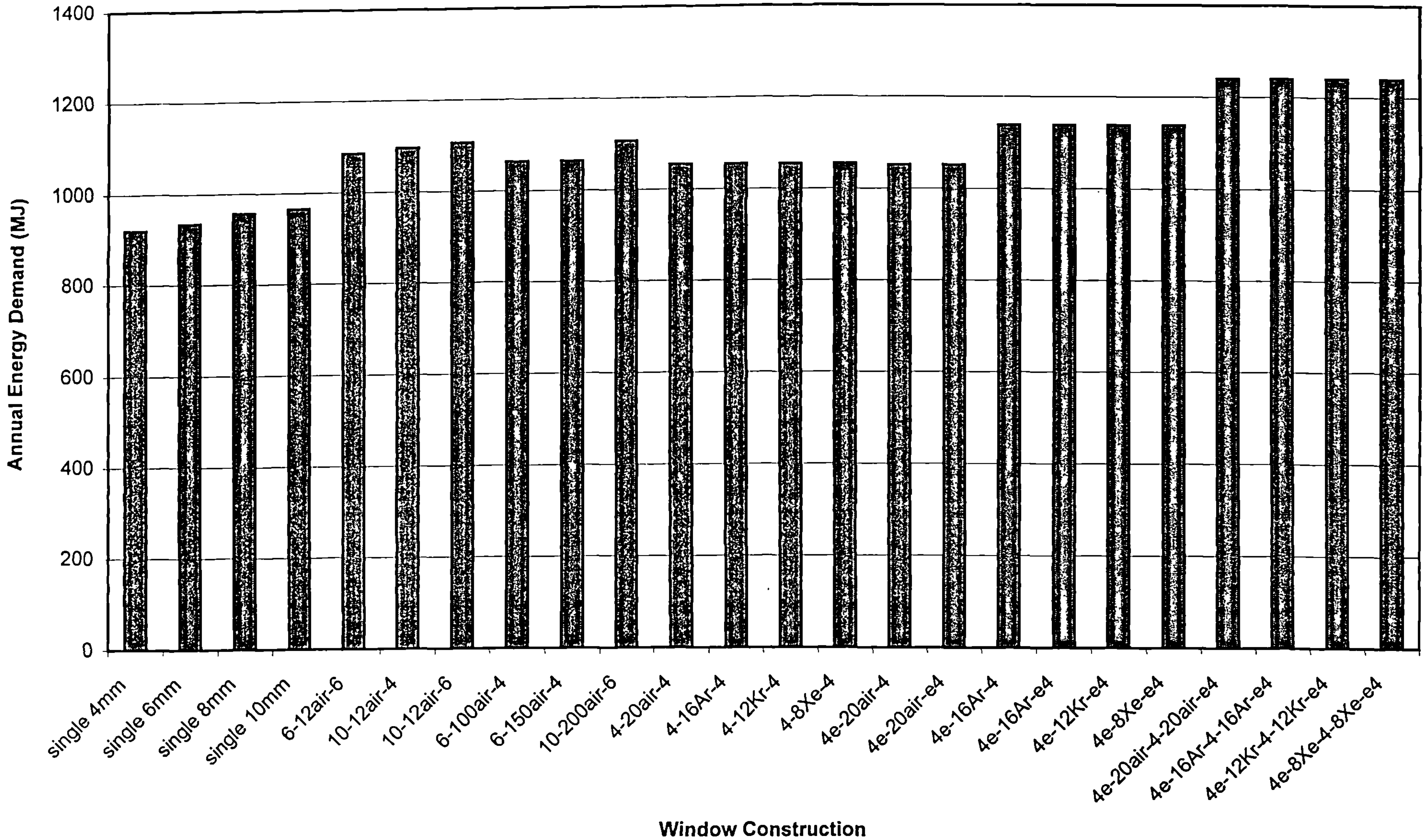


Figure 6.20 Annual energy demand for artificial lighting under top-up lighting control strategy, incorporating 24 different windows in construction (window area 60% of example office façade)

Window Area	20.10	
kg (lm/W)	86	
Ground reflectivity (rg)	0.24	
Diffuse/ground reflected angle of incidence, i		60
Cos i		0.5
Room surface area		283.2
Average surface reflectance		0.4
Angle in vertical plane, Q		45

Transmission Curve Coefficients

0.001	0.114	0.004	0.007	-0.021	-0.017	-0.018	-0.029	-0.017	-0.019	-0.001
2.88	1.058	2.702	2.645	1.616	1.513	1.488	1.633	1.393	1.37	0.585
-1.467	3.362	-1.232	-1.196	1.49	1.699	1.616	1.191	1.736	1.575	3.168
-5.179	-7.664	-5.338	-5.173	-6.291	-6.515	-6.325	-6.199	-6.456	-6.161	-6.837
7.846	4.389	7.949	7.659	5.712	5.829	5.718	6.231	5.846	5.751	4.963
-3.193	-0.378	-3.235	-3.102	-1.707	-1.726	-1.713	-2.071	-1.763	-1.8	-1.233

Direct Light Transmission Factors

0.82	0.80	0.78	0.77	0.68	0.67	0.65	0.64	0.63	0.60	0.51

Daylight Transmission Factors

Beam Irradiation Wh/m2	Beam Illuminance (lux)	Beam Luminous efficacy (lm / W)	Clear Glass 4mm Ti	T60	6mm Ti	T60	8mm Ti	T60	10mm Ti	T60	4-air-4 Ti	T60	6-air-4 Ti	T60	6-air-6 Ti	T60	10-air-4 Ti	T60	10-air-6 Ti	T60	Low-e Glass 4e-12air-4e Ti	T60	4e-air-4-air-4e Ti	T60
0.0	0	0.0	0.00	0.82	0.00	0.80	0.00	0.78	0.00	0.77	0.00	0.68	0.00	0.67	0.00	0.65	0.00	0.64	0.00	0.63	0.00	0.60	0.00	0.51
0.0	18	450.1	0.00	0.82	0.00	0.80	0.00	0.78	0.00	0.77	0.00	0.68	0.00	0.67	0.00	0.65	0.00	0.64	0.00	0.63	0.00	0.60	0.00	0.51
0.2	90	450.1	0.00	0.82	0.00	0.80	0.00	0.78	0.00	0.77	0.00	0.68	0.00	0.67	0.00	0.65	0.00	0.64	0.00	0.63	0.00	0.60	0.00	0.51
0.3	144	450.1	0.00	0.82	0.00	0.80	0.00	0.78	0.00	0.77	0.00	0.68	0.00	0.67	0.00	0.65	0.00	0.64	0.00	0.63	0.00	0.60	0.00	0.51
0.3	126	450.1	0.34	0.82	0.29	0.80	0.33	0.78	0.32	0.77	0.20	0.68	0.20	0.67	0.19	0.65	0.19	0.64	0.18	0.63	0.16	0.60	0.12	0.51
0.2	108	450.1	0.73	0.82	0.65	0.80	0.69	0.78	0.68	0.77	0.56	0.68	0.54	0.67	0.53	0.65	0.52	0.64	0.50	0.63	0.48	0.60	0.39	0.51
0.2	108	450.1	0.85	0.82	0.83	0.80	0.80	0.78	0.79	0.77	0.72	0.68	0.71	0.67	0.69	0.65	0.68	0.64	0.66	0.63	0.64	0.60	0.55	0.51
0.1	45	450.1	0.88	0.82	0.86	0.80	0.83	0.78	0.82	0.77	0.78	0.68	0.76	0.67	0.74	0.65	0.73	0.64	0.71	0.63	0.69	0.60	0.61	0.51
0.0	0	0.0	0.89	0.82	0.86	0.80	0.85	0.78	0.84	0.77	0.79	0.68	0.77	0.67	0.76	0.65	0.75	0.64	0.73	0.63	0.71	0.60	0.63	0.51
0.0	0	0.0	0.89	0.82	0.86	0.80	0.85	0.78	0.84	0.77	0.80	0.68	0.78	0.67	0.76	0.65	0.75	0.64	0.74	0.63	0.71	0.60	0.64	0.51
0.0	9	450.1	0.00	0.82	0.00	0.80	0.00	0.78	0.00	0.77	0.00	0.68	0.00	0.67	0.00	0.65	0.00	0.64	0.00	0.63	0.00	0.60	0.00	0.51
0.2	99	450.1	0.00	0.82	0.00	0.80	0.00	0.78	0.00	0.77	0.00	0.68	0.00	0.67	0.00	0.65	0.00	0.64	0.00	0.63	0.00	0.60	0.00	0.51
0.9	396	450.1	0.00	0.82	0.00	0.80	0.00	0.78	0.00	0.77	0.00	0.68	0.00	0.67	0.00	0.65	0.00	0.64	0.00	0.63	0.00	0.60	0.00	0.51
1.7	783	450.1	0.00	0.82	0.00	0.80	0.00	0.78	0.00	0.77	0.00	0.68	0.00	0.67	0.00	0.65	0.00	0.64	0.00	0.63	0.00	0.60	0.00	0.51
1.3	594	450.1	0.34	0.82	0.29	0.80	0.32	0.78	0.32	0.77	0.20	0.68	0.20	0.67	0.19	0.65	0.19	0.64	0.18	0.63	0.17	0.60	0.11	0.51
1.1	513	450.1	0.73	0.82	0.65	0.80	0.69	0.78	0.68	0.77	0.55	0.68	0.54	0.67	0.52	0.65	0.52	0.64	0.50	0.63	0.48	0.60	0.38	0.51
0.7	315	450.1	0.85	0.82	0.83	0.80	0.80	0.78	0.79	0.77	0.72	0.68	0.71	0.67	0.69	0.65	0.68	0.64	0.66	0.63	0.64	0.60	0.55	0.51
0.1	45	450.1	0.88	0.82	0.86	0.80	0.83	0.78	0.82	0.77	0.78	0.68	0.76	0.67	0.74	0.65	0.73	0.64	0.71	0.63	0.69	0.60	0.61	0.51
0.0	18	450.1	0.89	0.82	0.86	0.80	0.85	0.78	0.84	0.77	0.79	0.68	0.77	0.67	0.76	0.65	0.75	0.64	0.73	0.63	0.71	0.60	0.63	0.51
0.0	0	0.0	0.89	0.82	0.86	0.80	0.85	0.78	0.84	0.77	0.80	0.68	0.78	0.67	0.76	0.65	0.75	0.64	0.74	0.63	0.71	0.60	0.64	0.51
0.0	9	450.1	0.00	0.82	0.00	0.80	0.00	0.78	0.00	0.77	0.00	0.68	0.00	0.67	0.00	0.65	0.00	0.64	0.00	0.63	0.00	0.60	0.00	0.51
0.2	90	450.1	0.00	0.82	0.00	0.80	0.00	0.78	0.00	0.77	0.00	0.68	0.00	0.67	0.00	0.65	0.00	0.64	0.00	0.63	0.00	0.60	0.00	0.51
0.7	306	450.1	0.00	0.82	0.00	0.80	0.00	0.78	0.00	0.77	0.00	0.68	0.00	0.67	0.00	0.65	0.00	0.64	0.00	0.63	0.00	0.60	0.00	0.51
1.3	585	450.1	0.00	0.82	0.00	0.80	0.00	0.78	0.00	0.77	0.00	0.68	0.00	0.67	0.00	0.65	0.00	0.64	0.00	0.63	0.00	0.60	0.00	0.51
1.4	639	450.1	0.34	0.82	0.29	0.80	0.32	0.78	0.32	0.77	0.20	0.68	0.19	0.67	0.19	0.65	0.19	0.64	0.18	0.63	0.17	0.60	0.11	0.51
0.9	423	450.1	0.72	0.82	0.65	0.80	0.69	0.78	0.68	0.77	0.55	0.68	0.54	0.67	0.52	0.65	0.52	0.64	0.50	0.63	0.48	0.60	0.38	0.51
0.6	279	450.1	0.84	0.82	0.83	0.80	0.80	0.78	0.79	0.77	0.72	0.68	0.71	0.67	0.69	0.65	0.68	0.64	0.66	0.63	0.63	0.60	0.55	0.51
0.6	252	450.1	0.88	0.82	0.86	0.80	0.83	0.78	0.82	0.77	0.78	0.68	0.76	0.67	0.74	0.65	0.73	0.64	0.71	0.63	0.69	0.60	0.61	0.51
0.1	36	450.1	0.89	0.82	0.86	0.80	0.85	0.78	0.84	0.77	0.79	0.68	0.77	0.67	0.76	0.65	0.75	0.64	0.73	0.63	0.70	0.60	0.63	0.51
0.0	0	0.0	0.89	0.82	0.86	0.80	0.85	0.78	0.84	0.77	0.80	0.68	0.78	0.67	0.76	0.65	0.75	0.64	0.74	0.63	0.71	0.60	0.64	0.51
0.0	9	450.1	0.00	0.82	0.00	0.80	0.00	0.78	0.00	0.77	0.00	0.68	0.00	0.67	0.00	0.65	0.00	0.64	0.00	0.63	0.00	0.60	0.00	0.51
0.4	180	450.1	0.00	0.82	0.00	0.80	0.00	0.78	0.00	0.77	0.00	0.68	0.00	0.67	0.00	0.65	0.00	0.64	0.00	0.63	0.00	0.60	0.00	0.51
1.8	828	450.1	0.00	0.82	0.00	0.80	0.00	0.78	0.00	0.77	0.00	0.68	0.00	0.67	0.00	0.65	0.00	0.64	0.00	0.63	0.00	0.60	0.00	0.51
2.3	1053	450.1	0.00	0.82	0.00	0.80	0.00	0.78	0.00	0.77	0.00	0.68	0.00	0.67	0.00	0.65	0.00	0.64	0.00	0.63	0.00	0.60	0.00	0.51
1.8	828	450.1	0.34	0.82	0.29	0.80	0.32	0.78	0.32	0.77	0.20	0.68	0.19	0.67	0.19	0.65	0.19	0.64	0.18	0.63	0.17	0.60	0.11	0.51
0.8	360	450.1	0.72	0.82	0.65	0.80	0.69	0.78	0.68	0.77	0.55	0.68	0.54	0.67	0.52	0.65	0.52	0.64	0.50	0.63	0.48	0.60	0.38	0.51
1.1	486	450.1	0.84	0.82	0.83	0.80	0.80	0.78	0.79	0.77	0.72	0.68	0.71	0.67	0.69	0.65	0.68	0.64	0.66	0.63	0.63	0.60	0.55	0.51
0.3	144	450.1	0.88	0.82	0.86	0.80	0.83	0.78	0.82	0.77	0.78	0.68	0.76	0.67	0.74	0.65	0.73	0.64	0.71	0.63	0.69	0.60	0.61	0.51

Figure 6.21 Example visual analysis calculation sheet from Vis1991.xls spreadsheet

7 Inventory analysis and impact assessment

7.1 Introduction

The inventory analysis stage of a Life Cycle Assessment was defined in Chapter 3 as a methodical quantification of resource inputs and outputs; all matter crossing the LCA boundary. To ease comparison of inputs/outputs and computer modelling processes, a functional unit is required. The functional unit herein, is expressed in terms of energy, as Joules per unit output (J/window). This allows all material inputs and manufacturing energy requirements to be assessed on a common basis.

The impact assessment stage is based upon the evaluation of each input/output in terms of impact upon the global environment. Impact assessments can be calculated for each potential impact on the environment. A complete Environmental impact assessment requires data and information on many different pollution effects; effects which are known and quantifiable, and effects which are unknown and the subject of ongoing research. The impact assessment is limited to the effects which energy generation and consumption have on greenhouse gas emissions, in terms of electricity production and transportation fuels, bearing in mind the energy structure prevalent in the UK today.

A review of inventory analysis findings is presented and an impact assessment is given, based on the inputs and outputs detailed in the inventory analysis.

7.2 Inventory analysis

The major source of data for this research is a result of a detailed audit of manufacturing processes at the window production plant of Nor-Dan Windows, based in Moi, Norway. This was completed during the early months of 1996. A variety of data collection methods were used. Energy monitoring equipment was used to measure energy use throughout the factory. Interviews were set up with key personnel from various departments within the factory, and suppliers. Historical records were investigated, and where no information was available, calculations were performed.

There are six basic window types produced, each having a possibility of more than six finishes. Each window construction is available in an infinite range of dimensions, including irregular shapes for individual projects. The basic construction for each window begins with a timber frame and sash, designed and milled to a high quality, ensuring a good fit with minimal insulative losses. With so many products being manufactured in one factory, it was not possible to analyse each construction permutation. As a result, a single window construction was chosen, using a popular size of 1.2m by 1.2m. The window selected accounts for the largest production output (over 50% of total production), described as a three handle tilt and turn window. The Nor-Dan manufacturing plant contains 23 halls of production processes, each requiring machinery power, lighting, heating, services, transportation and raw material distribution.

Inventory analysis and impact assessment result in large volumes of data being produced. The analysis was sub-divided into sections, and these are presented below.

7.2.1 Materials

7.2.1.1 Timber

The timber used in the window manufacturing process is 100% softwood, and is obtained from organised, well established tree management programs in Scandinavia (Finland 30%, Norway 30%, Sweden 40%), whereby two trees are planted to replace the felling of one. Timber used in construction and manufacture is processed to a variety of finishes, possessing variable energy contents. Table 7.1 shows the energy content for some popular forms of timber used in construction.

Methods for evaluating the energy content of materials are numerous and varied. Research work from other sources has shown energy contents which are both higher and lower than the data values shown in Table 7.1. The data in Table 7.1 is the product of research by Buchanan and Honey [1994] and allows for the energy consumption of machinery and machinery production, including the energy required to raise capital for production. Analysis by West et al [1994] produced data for indigenous softwood which considers transportation, material extraction, processing and manufacture. This work derived an energy content of 2.6 GJ/m^3. Further studies by Hollinger & Hunt [1990], Halliday [1991] and Dinesen and Trabergy-Borup [1994] derived values of 0.51 GJ/m^3, 1.77 GJ/m^3, and 4.03 GJ/m^3 respectively. These values are widely dispersed due to variations in data collection. The working boundaries, as set out in the planning phase of an LCA, must be kept central to all decision making in the analysis. Manufacturing methods can be widely variant in nature, incorporating many differences in procedures, machinery and available technology. Work by West et al [1994] was found to be most closely related to the aims and boundaries of this investigation, and hence an energy content of 2.6 GJ/m^3 of softwood timber is used in this analysis.

Allowing for material waste within the milling processes, and given the window dimensions and type analysed, a total mass of 37 kg of timber is used (Frame 14.94 kg, Sash 10.01 kg, Waste 12.05 kg). The density of softwood varies greatly, according to the water content in the timber, but an average of 500 kg/m^3 is used. This gives an energy content for the timber component, exclusive of machining, of 192.4 MJ.

Timber arriving at the factory site is 70% pre-cut to the correct length, and is transported directly to the storage hall. Non-standard timber lengths account for approximately 30%, and must be cut to size. For the sash, timber must pass through a laminating process where two or three sections of timber are glued and compressed together. Therefore, to complete the analysis for the embodied energy of timber, a contribution for the glue used in laminating must be added. Buchanan and Honey [1994] estimated that 0.5 kg of glue is required per square meter of laminate surface. 25% of timber laminated involves one layer of glue, and two sections of timber, while the remaining 75% requires 2 layers of glue and three sections of timber. Each layer covers an area of 0.07 m^2. Therefore, taking into account that only 30% of sashes are laminated, an average of 0.04 m^2 of glue is applied to each sash. Expressing this in mass terms gives 0.02 kg of laminate glue. The glue is assumed to have an energy intensity of 160 MJ/kg, which equates to 2.94 MJ per sash.

The total embodied energy for timber sash and frame materials used in the manufacture of one window, is thus 195.3 MJ.

7.2.1.2 Aluminium

The processes involved in cutting and assembling the aluminium components for window construction involve minimal quantities of energy. The main consideration for material consumption and energy use comes at the aluminium manufacturing stage. The process of manufacturing aluminium components from raw bauxite is a highly energy intensive, multi-stage procedure. The most energy intensive stages in the procedure include the crushing of raw bauxite, electrolysis of alumina, to produce soluble aluminium, and the casting of ingot. The process of producing aluminium from raw bauxite is illustrated in Figure 7.1. The final processing is carried out in the window factory, whereby lengths of formed aluminium are cut to size. All other processing is carried out at the aluminium production plant. Again, the energy content of aluminium production is much debated. Buchanan and Honey [1994] quote a content of 130 MJ/kg for general aluminium, while Saito & Shukuya [1995] quote a content of 502.5 MJ/kg for pressed and finished aluminium window frames. Work by Young & Vanderburg [1995] produced data for both primary and secondary aluminium. Primary aluminium is produced from raw bauxite. Secondary aluminium is produced from recycled aluminium. The gross energy requirements of primary and secondary aluminium are 225 MJ/kg and 50 MJ/kg respectively.

Aluminium is used for many different purposes in the window construction. Profiles are fitted along the bottom edge of the sash to protect the timber from water penetration. The window opening mechanism, various sections of the ventilation grills, and the glazing unit spacer are also made of aluminium to ensure a light weight design. The total mass of aluminium used in a standard window of 1.2 m by 1.2 m was calculated to be 2.3 kg, and the total waste from each process was calculated to be 0.32 kg. A breakdown of aluminium use and waste is shown in Table 7.2.

Waste aluminium generated in the manufacturing of windows (0.306 kg per window) is not discarded, but sold to a metal merchant for recycling as secondary aluminium. The total energy input required to produce and process the aluminium for one window, assuming that 100% primary aluminium is used, is estimated to be 517.5 MJ. UNIDO [1989] estimate that 27% of the world's total aluminium production comes from recycling aluminium. This percentage is likely to be lower for building materials due to design for long life-spans in construction components. If the assumption is made that 27% of the aluminium used is recycled, then the energy intensity for the aluminium used in the window is 408.8 MJ.

7.2.1.3 Glass

The production of large glass panes supplied to the factory is also an energy intensive process. West et al [1994], Saito & Shukuya [1995], and Dinesen and Trabergy-Borup [1994] report the energy content per kg of sheet glass manufactured to be 13 MJ/kg, 16.9 MJ/kg, and 18.6 MJ/kg respectively. There is less discrepancy between these values than for aluminium and timber. This is perhaps because the technology used is standardised, and fewer differences between manufacturing methods exist. Again, the work of West et al [1994] was found to be compatible with the aims of this research, and an energy content of 13 MJ/kg of sheet glass was used.

An energy and material analysis for the glass sheet manufacturing was carried out. The mass of glass required for a double-glazed unit of 1.1 m^2 was calculated to be 21.2 kg in the finished product. A small amount of material is wasted due to breakages, and small offcuts which are not able to be used. This amounts to approximately 5.5% of the total glass utility. Taking this into account means that the average glass consumption for one unit is 22.26 kg, possessing an energy content of 289 MJ.

7.2.1.4 Infill gas

The production of double-glazed windows is typically limited to the use of air and Argon gas in glazing cavities, although a limited number of manufacturers produce windows with a wider range of gases. In this analysis three cavity gases are investigated, and compared to the use of air:

- Argon
- Krypton
- Xenon

Argon, Krypton and Xenon are all present in the atmosphere, and production of the pure gases is a process of separation from the other components present. Table 7.3 shows the percentage content of gases in air. Trace gases include water vapour, Hydrogen, Ozone, methane, carbon monoxide, Helium, and Neon. The process of separating inert gases from air is shown in Figure 7.2.

The equipment required for the separation of gases from the air has a power rating of 12 MW. This is the only equipment required for extracting Argon gas. Krypton and Xenon, however, require the operating of a crude Krypton/Xenon column, consisting of a reactor (4 kW), heater (10.8 kW), flash vaporiser (4 kW), liquid oxygen pump (2.3 kW), and purification column (2.4 kW). The actual yield of gas from the column is between 31% and 54%. Production rate data is based on an average yield rate of 42%. Table 7.4 shows the yield volume per hour, energy consumption rate for extraction and the specific energy consumption per litre of gas produced.

A window measuring 1.2 m by 1.2 m has a glazed area of 1.1 m^2, and a cavity gap of 20 mm, 16mm, 12mm and 8mm, for air, Argon, Krypton and Xenon respectively. The volume of air and inert gas required to fill each cavity is hence 22 litres, 17.6 litres, 13.2 litres and 8.8 litres respectively. The energy requirement to produce Argon, Krypton and Xenon gases to fill this gap is hence 11.85 kJ, 508.5 MJ and 4.50 GJ respectively.

7.2.1.5 Low emissivity glazing coatings

A full energy and material use audit was undertaken during May 1996 of the low emissivity (low-e) coating process at Pilkington Glass in St Helens, England. This analysis required the quantification of all inputs to and outputs from each process involved.

Float glass is produced 24 hours a day, requiring a weekly input of 5000 tonnes of materials. The annealing lehr works at a speed of 870 metres per hour. The glass ribbon produced is 3.56 metres wide, and can be produced in a variety of thickness. The gross area of glass produced is 3097 m^2/hour [Liggett, 1996]. The net yield of glass, allowing for breakage and trimming of the glazing edges has been accounted for in the calculations, but cannot be published for reasons of confidentiality. Details of the energy analysis are as follows :

Natural Gas load	3165 kW	Energy input	1.7034 kWh/m^2 low-e coating
Electrical load	783 kW	Energy input	0.4214 kWh/m^2 low-e coating
Total load	1148 kW	Total input	2.125 kWh/m^2 low-e coating

Therefore, for the production of low-e coating for a window measuring 1.1 m2, the energy content is 2.34 kWh per pane, or 8.42 MJ per pane.

Natural gas is used to supply the incineration plant, installed to execute thermal oxidation of fumes generated in the coating process.

7.2.1.6 Components

A number of components are assembled into the window construction; handles, security mechanisms, seals and ventilation grills are fitted to the completed sash and frame. All components are bought in as finished products, requiring minimal processing on the factory site. The mass of all components fitted to a standard window construction were weighed in order to assess the embodied energy content of materials. Table 7.5 lists the mass of materials used, and associated embodied energy values. The total embodied energy of materials used for components was calculated to be 143.76 MJ.

7.2.2 Manufacturing processes

The manufacture of a double-glazed window unit takes the form of five main processes. The energy associated with each of these processes was analysed, and is presented below.

7.2.2.1 Timber sash and frame

Energy monitoring equipment was used to measure the average no load machinery power, average operational power and power factor for each piece of machinery involved in the line. Production schedules were closely monitored, and an average percentage was calculated for the split between time spent running on no load, and the functional time that each machine runs on operational load. Each machine is left running on no load for a large percentage of the day (average > 50%) There are a number of reasons for this. Machine tools have to be changed, different window sizes have to be done in batches and require different timber dimensions, and the machinery often needs reset, due to wood jamming or falling off the line.

The moulding lines are an energy intensive sequence of mills and saws which profile timber. Milling is required to shape each sash and frame for ironmongery and accessories. Figure 7.3 shows the final outcome of all timber, and the percentage of timber entering the factory which is wasted.

All the sawdust produced from these lines is extracted via a comprehensive network of ducts and fans. No timber is wasted in the production process. Three uses are made of the wood offcuts and sawdust by-products :

- sawdust and small wood offcuts are combusted in furnaces for factory heating.
- sawdust is sold to neighbouring farmers to improve soil quality.
- larger wood offcuts are sold to factory workers for domestic heating.

The final two stages of production for the sash and frame include assembly and impregnation. All timber components are impregnated with a white spirit based solution, which soaks into the timber pores, and slows down the process of decay in the timber, lengthening the window lifecycle. All timber sections are enclosed in a designated chamber, and a vacuum is created. The preservative tank is then opened and the chamber is filled. The vacuum is maintained for a few minutes before a discharge pump is operated and the vacuum is lost. The loss of vacuum ensures that each timber pore is filled with preservative. The chamber is then emptied of preservative, and a new vacuum at a higher pressure is created over a longer period of time. A final discharge completes the impregnation process, and the timber remains within the drying chamber for 1-2 days. All the stages of manufacture, including the timber impregnation, have been taken into account when considering energy content of the windows.

The average energy consumption for the manufacture of one sash and one frame were estimated to be 16.9 MJ and 16.3 MJ respectively.

7.2.2.2 Glazing units

The production process for the manufacturing of sealed glazing units is shown in Figure 7.4 The first task in the glass production procedure is to plan the cutting schedule. Glass sheets are precision cut on large, programmed cutting tables. Secondly, the edges around low-e coated glass sheets are ground to ensure that the adhesive seals the unit adequately. Glass panes are then washed to remove dirt and dust particles from the interior of the unit. An aluminium spacer is fitted to separate the glazings, and is kept in place by a butyl compound. Before the unit is sealed it is filled with inert gas. Finally, the unit is sealed with a butyl compound, and is ready for assembly into the window sash and frame.

Three phase energy monitoring equipment was used to analyse the energy consumption of the glazing unit production line. The average real power load for the entire process line was found to be 132.1 kW. Based on a 12.5 hour working day, and 230 working days in the year, this gives an annual energy consumption of 1367 GJ. The output from the glazing department averages 228022 finished units per year, and an allocation of 6 MJ per finished window was estimated.

7.2.2.3 Aluminium profiling

Once delivered to the factory, the cutting machinery for aluminium uses very little energy, and has a load power of approximately 4 kW. This gives an annual energy input of 26.5 GJ, or 0.2 MJ per finished window. It is clear that the energy of aluminium production from raw bauxite is of a greater concern.

7.2.2.4 Painting and finishing

There are two halls used for painting and finishing within the factory. Energy monitoring equipment was used to measure the average machinery load for both paint line machinery and heat recovery equipment. Both painting halls are run 12 hours a day, for 230 days of the year. To calculate the energy associated with painting and finishing one window unit, an average load for machinery and equipment, and associated energy consumption was evaluated on an annual basis.

Hall No.1	Paint station load	29.92 kW
	Heat recovery unit	35.76 kW
Hall No.2	Paint station and heat recovery	63.06 kW
Total load		128.74 kW

For operational periods of 12 hours daily for 230 days in the working year, the annual energy consumption of painting and finishing equipment is 1279 GJ. In previous calculations it was sufficiently accurate to average this energy consumption over total window production in order to evaluate an energy consumption value per unit output. For the painting and finishing lines this would be incorrect. A proportion of window units leaving the factory are painted and finished on site, while other units have special finishes, depending upon client requirements.

Production output of the selected tilt and turn window during the period 1993-95 averaged 50.93% of total production, while an average of 65% of these windows are painted and finished on the factory premises, equivalent to an average of 48630 window units annually. Using these estimations, an energy consumption value of 8.71 MJ per window unit was calculated.

7.2.2.5 Assembly

Once all the window components have been manufactured, painted and finished, they are sent to the assembly area to complete the production process. The assembly area is not an energy intensive process, and as such was measured as one entity using three phase energy monitoring equipment. The assembly area was found to have a reasonably consistent load of 36.9 kW, and is operational for 8 hours daily, over 230 working days per year. The total energy consumption for assembly line work was calculated to be 244.44 GJ per year. For an average total production output of 146899 windows per year, this is equivalent to 1.66 MJ per window unit.

7.2.3 Administration and services

Administration and services needs are accounted for in the factory as a separate, but necessary issue. For the product to be produced, marketed and sold there must be administration personnel, a design team, factory workers, and management. To sustain a workforce requires services, heating, lighting and materials. Each of these has implications for energy consumption and material use. They are not easily subdivided into manufacturing stages, and must be accounted for in a unit overhead. Included in these are the factory services of administration, technical design, heating, lighting, and weekend and night-time loads. Energy consumption during night-time and weekends is significant, accounting for a large proportion of total energy consumption throughout the factory. The load is attributed to the large drying machines, used to reduce the moisture content of timber arriving in the factory, and overnight electrical charging of machinery, and stand-by heating facilities. The average power load, annual energy consumption, and energy consumed per window is shown in Table 7.6. A summary of all manufacturing processes and the energy requirement for each is given in Table 7.7.

7.2.4 Packaging and transportation requirements

Finished windows are grouped and transported to clients in order batches. They may be stored on site for a period of time until an order is completed, or until the client's request date. A limited number of standard window sizes and constructions are also stored on site. When orders are ready for release they are sent to the packing department.

7.2.4.1 Packaging requirements

Windows units are packaged together in groups of 2-6 windows and are transported to clients on wooden pallets, wrapped securely in cling film plastic covering, and then a harder plastic sheet to seal the windows in a protective casing for transportation.
8662 kg of polyethylene wrapping is used annually, equivalent to an average of 0.06 kg per window for a production output of 146,899 windows per year. Polyethylene wrapping has an energy content of 112 MJ/kg [Buchanan & Honey, 1994], equivalent to 6.60 MJ per window transported.

Approximately 19000 timber pallets are used annually. An average pallet weighs 3.06 kg. This equates to 58,264 kg of timber used for pallets annually. Some of the pallets are produced from waste wood, while others are specifically manufactured for packaging purposes. A large percentage of pallets are returned for re-use in packaging, or are employed on the factory floor. Assuming that 25% of the pallets used are produced from new timber each year, this equates to 14,566 kg of new timber annually. With an energy content of 2.6 GJ/m^3 for softwood timber, the gross energy content for new timber in pallets 75,743.2 MJ per year, equivalent to 0.52 MJ per window for a production output of 146,899 windows per year.

7.2.4.2 Transportation requirements

Assessing transportation requirements throughout a product life cycle demands detailed inventory analysis information based on the source and destination of all materials, fuels and components. In addition, information on the final destinations of finished products requires to be known, and the means by which they are transported. Different modes of transport have varying energy consumption implications. Table 7.8 lists the energy consumption associated with various modes of transport, for given distances, and loads.

Materials are sourced from a number of locations and countries throughout the world. Raw bauxite for the production of aluminium is shipped 12,000 km from Argentina, while timber is transported by rail from Norway, Sweden and Finland. Glass sheets are bought from a variety of locations, depending upon market availability, currency changes and manufacturing needs. Components are sourced from all over Europe, again according to market and currency variations.

Accurate evaluation of energy consumption used in transporting materials to the factory would require thorough analysis and reliable data on market sourcing and transportation systems. This was considered beyond the bounds of this thesis. An estimation of transportation requirements associated with the main material sourcing for the production of one window unit is shown in Table 7.9. Energy of transportation of materials was estimated to be 64.65 MJ.

Finished window units are manufactured for a number of countries, and are transported via different modes of transport. The average percentage breakdown of window units per country is illustrated in Figure 7.5. Destinations in Norway, Denmark, Sweden, Germany and Holland are handled by one conveyor from factory to site; packaged window units do not leave the container until delivered on site. This method of conveying finished products significantly lowers the occurrence of breakages, which are wasteful on materials, time and energy. Deliveries to the UK, however, are made in a series of manoeuvres. Firstly, units are transported by road to Stavanger, where they are transferred to a shed, prior to shipping. Orders are shipped to Aberdeen once per week. Units are again stored before being transported, by road, to site. The number of handling exercises involved with this transport system means that breakages are a more common occurrence.

It is not cost effective to transport windows in individual units, but the functional unit of this research work is measured in MJ/window unit, and to this end, on a mass basis, the transportation analysis is the same. Therefore, for a tilt and turn window, weighing 37.5

kg, to be transported from the factory to an Edinburgh city centre site location, the energy consumption of transportation was evaluated as follows:

80 km by road, Moi – Stavanger	0.304 MJ/kg	11.4 MJ
525 km by ship Stavanger – Aberdeen	0.03 MJ/kg	1.13 MJ
200 km by road Aberdeen – Edinburgh	0.76 MJ/kg	28.5 MJ
Total		41.03 MJ

7.2.5 Use, maintenance, disposal and recycling

7.2.5.1 Use

Implications for window use have been discussed at length throughout chapters 4, 5 and 6. Models were developed, based upon literature review of current and past research, aimed at creating productive environments in terms of thermal, aural and visual function.

7.2.5.2.Maintenance

Maintenance and repairs are kept outwith the investigation boundaries for all stages of production, including machining, lighting, services and transportation. During the product use phase, however, maintenance and repairs are of importance, as the length of useful life for a window is a direct function of the treatment it receives whilst in-situ. There are a number of influencing factors which define the durability of a window unit. These factors include cleaning, frame protection, repairs, prevailing weather conditions, condensation, insects and fungi. Table 7.10 describes these influences in more detail.

Methods for reducing maintenance frequency include the application of aluminium cladding. This adds 296MJ of embodied energy to the overall window energy content, approximately 20% of total embodied energy of materials, but extends the length of useful life of the window.

7.2.5.3 Disposal

Waste handling and management must also be considered in a thorough LCA. When a product reaches the end of its useful life it is tempting to focus attention on its successor, or to forget that the product requires disposing of, and/or recycling. Ninety five percent of household, commercial and industrial wastes end up in landfill sites, accounting for around 20% of the total waste produced in the UK [Jones, 1993]. Alarmingly, this equates to eight tonnes of waste per person annually. After more than 5 decades of profligate use of resources and badly managed waste disposal, attention has been turned to reduction of waste at source, re-use, recycling and use of waste to generate energy. These four management solutions, in addition to environmentally sensitive disposal of waste, form the framework of sustainable development, with the emphasis on reducing waste at source. The Scottish Office Development Department produced a planning policy guideline on waste management in March 1996, which is heavily focused on sustainable development solutions [Scottish Office, 1996]. A Best Practicable Environmental Option (BPEO) that provides the most benefit, or least damage to the environment as a whole is sought. Research is ongoing and coincides well with the aims of LCA. The need to plan for disposal and recycling in the product conception phase is emphasised, and remains the only sustainable solution in the long-term.

7.2.5.4 Recycling

During the past decades there has been considerable interest in recycling products and materials. Public awareness campaigns have raised the issue, enabling consumers to make more informed decisions about disposal and recycling of household and commercial waste. Bottle banks, paperless offices, textile reuse, newspaper reclaims and other initiatives make the public more aware of recycling capabilities, and place each community member in a position of responsibility. Beyond the issue of personal responsibility, corporations and industries have a responsibility too. Reuse and recycling of demolition and construction waste is no exception. However, little progress has been made in the practical implementation of research findings and government recommendations. The BRE carried out a recent research program to demonstrate the reuse and recycling of materials [Hobbs & Collins, 1997]. It was found that around 96% by volume of the waste generated from the demolition of an existing building was reusable or recyclable. Only a small percentage (4%) was sent to landfill sites. In the construction industry, the largest proportion of embodied energy for a given product is predominantly in material extraction and processing. To reuse materials omits this embodied energy in new constructions, whilst recycling of materials significantly reduces environmental impact.

Embodied energy of materials for a double-glazed window, in this research, was found to be of the order 1464.5 MJ (excluding choice of cavity gas and low-emissivity coatings); approximately 85% of total energy consumption used in extracting raw materials, manufacturing and transportation. Reuse, or recycling, of window units would therefore show significant benefits in terms of material sourcing, and energy generation and emissions. However, no on-going construction activity could be found to support this initiative to date. Transportation of waste to processing centres remains a stumbling block to recycling initiatives, and development work to find reliable, economic markets for recycled materials is in its infancy.

A summary of all energy requirements involved in the extraction of materials, manufacture of finished window units, packing and transportation of both materials and finished products is illustrated in Figure 7.6. This summary of inventory analysis data forms the basis to the impact assessment which follows.

7.3 Impact assessment

Impact assessment focuses on how the product affects the environment, and facilitates the interpretation and aggregation of data collected during the inventory analysis. This requires a comprehensive approach to analysing how raw material use, energy generation, water production, effluent output, air emissions and solid waste affect the environment. The burden placed upon the environment from any single process may be measured in terms of human health, animal habitat disturbances, noise pollution, changes in water quality or aesthetic changes to the environment. The effects analysed are assessed according to their direct impact in the present, and their possible future burden upon the environment. e.g. Raw material and fossil fuel consumption in the present can have effects on human health and animal habitats due to their extraction, transportation and burning, while their consumption influences the availability of these resources for the future. Impact assessment is a question of defining and characterising the consequences which result from the inputs and outputs quantified in the inventory analysis.

The concept of economic optima was developed over a century ago and has pervaded decision making since. Derision of optimality aimed at making one person or group better off without placing another person or group at disadvantage. Environmental impact assessment (EIA) methodologies are numerous and varied; ranging from cost-benefit and effectiveness analyses, opportunity cost and travel cost approaches, and hedonic pricing and contingent valuation techniques, to ecological evaluations and the development of mathematical matrices. Not all methodologies are applicable to each EIA, but they are centred around economic analysis and monetary assessment. It is naive to erase monetary consideration from an LCA exercise, since all products, processes and activities exist and function within the commercial environment, but it is important to remember that all LCA's focus on environmental parameters, and as such are not an economic, but environmental, appraisal technique.

> *"EIA is essentially about optimising resources through an allocation of all resources, to achieve a balance between sustainable development and environmental protection" [Gilpin, 1995]*

A methodology to maximise occupant comfort and work productivity within the indoor environment, whilst minimising global environmental impact is sought. Chapters 4-6 detailed interior thermal, aural and visual requirements for occupant well-being, and developed models to quantify window unit performance. The following impact assessment exists, therefore, to quantify global impact from the production of each window unit construction, based on the above inventory analysis data. It is, however, based purely upon quantifiable environmental impacts, principally greenhouse gas generation associated with electrical energy production. It is acknowledged that there are numerous impacts which are less easily quantified, namely:

- Human health effects due to noise pollution, loss of visual amenity and air pollution.
- Damage to natural habitats in terms of flora and fauna.
- Natural resource depletion, and lack of attention to sustainable development criteria.

7.3.1 Fuel production and energy generation

The main environmental impact throughout the window lifecycle is from electricity production and burning of natural gas. Emissions generated as a result of producing 1 MJ of electricity in the UK, and from burning natural gas, are listed in Table 7.11.

The generation of NO_x is the result of two different processes in the combustion of fossil fuels. Oxidation of atmospheric nitrogen is one source, forming nitric oxide, often referred to as thermal NO due to its highly temperature dependent nature. The other source is from nitrogen chemically bound in the fuel. Natural gas contains approximately 0.1% nitrogen by weight. At very low nitrogen contents the chemical NO_x becomes insignificant, with the main contribution from thermal NO_x. The emission of NO_x from the combustion of natural gas is highly dependent on the conditions present during combustion. Temperature and availability of excess air are the main influencing factors. Under normal working conditions, this equates to 52.06 mg/MJ, which is negligible in comparison to the 12.24g NO_x emitted from the generation of 1 MJ of electricity.

The environmental impact, assessed in terms of carbon dioxide, nitrous oxides and sulphur dioxide, generated as a result of material extraction and manufacture is based on inventory analysis data. For each MJ of energy generated, for simplicity, the environmental impact was calculated on a UK plant mix basis. In reality, each material used in the window construction should be assessed at the point of location. To do this would, however, render the results of this thesis too location, or country specific. The impact assessment associated with window use is presented in Chapter 8: Optimisation.

7.3.2 Transportation emissions

Research work by Buchanan & Honey [1994] and Walsh [1992] were used to evaluate emissions generated for various modes of transport on a distance and load basis. Table 7.12 shows the quantities of carbon dioxide, carbon monoxide, nitrous oxides, and hydrocarbons which result from road, rail and ship transport. For the distances and loads listed above, the generation of greenhouse gas emissions, as a result of transportation of materials and finished window units, was evaluated. The results are illustrated in Table 7.13.

7.3.3 Other environmental impacts

The primary environmental objective of LCA is to reduce total impacts and health risks caused by the development of products, processes and activities. LCA seeks to minimise resource depletion, reduce pollution as a result of development and activities, support environmental equity and develop realistic, effective economic solutions.

Through reduced resource consumption, the impacts associated with extraction of resources, and the energy embodied in machinery and activities to mine, transport and process materials is reduced. Not only do larger areas of natural habitats remain intact, but energy consumption and the need for fuel production is reduced. The decision to exploit any given resource efficiently impacts on a chain of sub-resources and processes.

> *"Pollution may be defined as any unwanted by-product created as a result of human activity" [EPA, 1993].*

The primary concern is to limit pollution at source, rather than managing consequences at a later date.

Just as inequity in resource distribution over the earth's surface exists, creating areas which are rich in indigenous resources, and areas which suffer resource deprivation, so pollution is unevenly distributed. Geographical and political boundaries create differences in acceptable standards and best practices. This imbalance frequently places countries, areas or groups of people at disadvantage, while other countries, areas or groups of people benefit directly from the same course of action. Environmental inequity is not only a function of location, but also of time. Resource depletion and environmental impact in this century will limit the options available to future generations.

> *"Products should be designed to balance human resources, natural resources, and capital in order to achieve pollution prevention, resource conservation, and ecosystem sustainability" [EPA, 1993].*

Without a sustainable attitude to development, the environment will be become heavily polluted, resource deficient and ecologically damaged. The results of this will be to reduce choice, compromise future developments and limit economic growth. The burden on the economy of cleaning up a degraded environment would be debilitating. The only solution is to limit pollution at source.

The inventory analysis and impact assessment model presented in this research is limited to quantifiable effects of resource consumption, energy generation and transportation energy consumption. To consider each possible environmental impact on land, air and water quality, directly attributable to the production of double-glazed windows, would require in-depth research into ecological sustainability, and was considered beyond the bounds of this thesis.

7.4 Inventory analysis and environmental impact model

The results of the preceding research work are summarised, and used to develop a working model through which the material and energy requirements of each single window unit can be assessed. The above analysis was based on a window size of 1.2m by 1.2m, for ease of measurement and analysis, but is of little use unless findings can be interpolated for other dimensions. The model therefore allows the user to calculate material requirements, energy content and greenhouse gas emissions for 24 different window constructions of any given size. A summary of embodied energy content, incorporating material extraction, manufacturing, associated services, and transportation for each of 24 window constructions of dimensions 1.2m by 1.2 m is given in Figure *7.7. Total CO_2 emissions produced as a result of electricity* generation and transportation energy consumption for the same 24 window constructions is given in Figure 7.8.

The model can be found in CD/Program Files/Inventory, under filename Windata.xls. There are 4 worksheets within the spreadsheet:

Inventory	Calculates all energy requirements of materials, manufacture, administration, factory services, packing and transportation for any given size of window.
Inventory Chart	Bar chart of total energy demand for each window construction.
Impact	Calculates the associated greenhouse gas emissions for electrical and transportation energy associated with the inventory.

Impact Chart Bar chart of total greenhouse gas emissions for each window construction.

7.4.1 Spreadsheet Use

1. Open spreadsheet, Windata.xls from CD/Program Files/Inventory.
2. Select the first worksheet, "Inventory."
3. Insert window height and width in Cells C2 and C3.
4. All calculations of energy content and emissions generated are automatically performed within the spreadsheet.

The flow diagram illustrated in Figure 7.9 shows what is required of the program user in performing the inventory analysis and impact assessment, and the stages involved in calculating the embodied energy of materials and processes, and the associated greenhouse gas production resulting from fuel combustion, electricity production and transportation.

The above model, and hence Figures 7.7 and 7.8, provide information on the embodied energy and resulting CO_2 emissions of material extraction and preparation, manufacturing and transportation only. At first glance it would appear that Xenon filled glazing units are highly energy intensive products, and are therefore very damaging to the environment. Interpretation of results at this stage should be approached with caution, as the excellent thermal insulating properties which these units possess are currently excluded from the analysis. Only when a holistic approach is adopted, and the complete aggregation of energy consumption over an entire window lifecycle is made, can the final assessment of total energy consumption and greenhouse gas emissions be concluded, and thus, decisions regarding pending improvements be executed.

7.5 References

1. Beggs, C.B., Ice thermal storage : impact on the United Kingdom carbon dioxide emissions, Building Services Engineering Research and Technology, 15 (1) 11-17, (1994).
2. Buchanan, A. and Honey, B., Energy and carbon dioxide implications of building construction, Energy and Buildings, (20), 205-217, (1994).
3. CCW, Countryside Council for Wales, Energy policy and perspectives for the Welsh Countryside,(1992).
4. Dinesen, J. and Trabergy-Borup, S., An energy life cycle assessment model for building design, Danish Building Research Institute, Proceedings of the first international conference on buildings and the environment, CIB 16-20 May, (1994).
5. EPA – Environmental Protection Agency, Life cycle design guidance manual: Environmental requirements and the product system, Cincinnati, (1993).
6. Fernie, D. and Muneer, T., Monetary, energy and environmental cost of infill gases for double glazings, Building Services Engineering Research and Technology, 17 (1) 43-46 (1996).
7. Gilpin, A., Environmental Impact Assessment: cutting edge for the twenty first century, Chapter 3: EIA methodologies, Cambridge University Press, (1995).
8. Halliday, M., Feasibility of using timber for medium rise office structures, Research Rep. 91-3, Department of Civil Engineering, University of Canterbury, (1991).
9. Hanby, V.I., Combustion and pollution control in heating systems, Springer Verlag, London, (1994).
10. Hobbs G. and Collins, R., Demonstration of reuse and recycling of materials: BRE energy efficient office of the future, Building Research Establishment, IP3/97, (1997).
11. Hollinger , D. and Hunt, J., Anthropogenis emissions of carbon dioxide and methane in New Zealand, Journal of the Royal Society, New Zealand, 20 (4) 337-348, (1990).
12. Jones, P.T., Underlying trends in the UK waste sector, Waste: handling, processing and recycling, IMechE, Mechanical Engineering Publications Ltd., London (1993).
13. Liggett, P., Energy and emissions per square meter of Pilkington K glass, Pilkington Glass Products, (1996).
14. Saito, M. and Shukuya, M., Energy and material use in production of architectural windows for passive solar heating, ISES '95 Congress, Harare, Zimbabwe, (1995).
15. Scottish Office Development Department, National planning policy guideline, NPPG10: Planning and waste management, March (1996).
16. Shorrock L.D. and Henderson, G., Energy use in buildings and carbon dioxide emissions, Building Research Establishment Report (L7)(R3), (1990).
17. UNIDO – United Nations Industrial Development Organization, Industry and Development – Global Report 2989/1990, Vienna, (1989).
18. Walsh, M.P., Transport and the environment: local, regional and global challenges, The vehicle and the environment, Volume 1, Automotive Technology Serving Society, IMechE, Technical papers(1992).
19. West, J., Atkinson C. and Howard, N., Embodied energy and carbon dioxide emissions for building materials, Proceedings of the first international conference of building and the environment, CIB 16-20 May, (1994).
20. Young, S.B. and Vanderburg, W.H., Applying environmental life cycle analysis to materials, Journal of Minerals, Metals and Materials, 46 (4), (1995).

Table 7.1 Embodied energy content for popular forms of timber used in construction [Buchanan & Honey, 1994]

Timber type	**Energy content (MJ/m^3)**
Rough timber	848
Glulam timber	4500
Hardboard	20600
Softwood	15470
Particleboard	12900

Table 7.2 Estimate of total aluminium mass incorporated into one window construction.

Window component	**Aluminium mass (kg)**	**% Waste**	**Total aluminium mass (kg)**
Glazing unit spacer	0.241	3	0.248
Frame ventilation	0.159	17	0.186
Outer protection	1.421	17	1.663
Window mechanism	0.174	17	0.204
Total	**1.995**		**2.301**

Table 7.3 Percentage composition of air

Component	**Percentage**
Nitrogen	78
Oxygen	21
CO_2	0.03
Argon	0.9
Krypton	0.000114
Xenon	0.0000087
Trace Gases	0.069

Table 7.4 Yield rate and energy consumption for the production of inert gases [Fernie & Muneer, 1996]

Gas	Yield volume per hour (litres/hour)	Energy consumption rate (kW)	Specific energy consumption (kJ/litre)
Argon	900,000	168	0.672
Krypton	44.43	475.5	38500
Xenon	3.39	475.5	511400

Table 7.5 Materials and embodied energy of components

Material	Mass incorporated in frame (kg)	Mass incorporated in sash (kg)	Embodied Energy (MJ/kg)	Total Embodied Energy (MJ)
Zinc	0.736	0.106	68.4 *	57.6
Steel	0.0535	0.166	34.9 *	7.66
Plastic	0.027	0.045	160 *	11.5
Rubber	0.453	-	148 *	67.0
Total				**143.76**

* Extracted from Buchanan and Honey [1994]

Table 7.6 Average power load and energy consumption for non-machining requirements.

Energy use	Average power load (kW)	Annual energy consumption (GJ)	Energy consumption per window (MJ)
Administration	69.84	462.62	2.1
Technical design	57.37	380.02	1.7
Heating	49.40	1557.88	11.3
Lighting	255.85	3389.5	24.5
Night use	377.86	5005.89	36.2
Weekends	337.88	3036.05	21.9
Total			**97.7**

Table 7.7 Summary of energy content for manufacturing processes

Function	**Energy requirement per window (MJ)**
Timber sash and frame	33.2
Sealed glazing unit	6
Aluminium processing	0.2
Lighting and factory services	97.7
Total	**137.1**

Table 7.8 Energy consumption associated with various modes of transport for given distances and loads [Buchanan & Honey, 1994]

Mode of transport	Energy consumption (MJ/kg)
Road 30 km	0.114
Road 50 km	0.19
Rail 100 km	0.23
Rail 200 km	0.146
Rail 500 km	0.365

Table 7.9 Energy consumption associated with transporting materials to factory site

Material	**Source location**	**Average Distance (km)**	**Mode of Transport**	**Material Mass per window (kg)**	**Total Energy Consumption (MJ)**
Bauxite	Argentina	11,881	Ship	14.72	52.47
Aluminium	Norway	80	Road	2.3	0.05
Timber	Norway	100	Rail	11.1	2.55
Timber	Sweden	200	Rail	14.8	2.16
Timber	Finland	400	Rail	11.1	3.24
Glass	UK	600	Ship	21.2	3.82
Components	Norway	100	Road	1.59	0.36
Total					**64.65**

Table 7.10 Influencing factors on window unit durability

Influencing factors
Cleaning
Frequency with which window frames are washed
Substance with which the window frames are washed
Whether washed mechanically or manually
Frame protection
Frequency with which the frames are painted over a lifetime
Method of removal of old paint
Repairs
Hinge replacement frequency
Window pane replacement frequency
Handle replacement frequency
Part window frame replacement frequency
Length of use before replacement
Prevailing weather conditions
Precipitation level
Thermal and moisture expansion
Wind
Solar radiation
Air humidity
Other factors
Condensation
Fungi
Insects

Table 7.11 . Emissions generated as a result of producing 1 MJ of electricity in the UK, and from burning natural gas

	Emissions		
	CO_2	**SO_2**	**NO_x**
Electricity Generation (UK plant mix) *	0.2 kg	2.778 g	0.945 g
Natural Gas Combustion **	0.058 kg	-	4.02 mg

* [CCW, 1992], [Shorrock & Henderson, 1990]
** [Hanby, 1994], [Beggs, 1994]

Table 7.12 Transportation emissions per kg load, per km travelled.

Mode of transport	CO_2 (g)	CO (mg)	NO_x (mg)	Hydrocarbons (mg)
Road 30 km	0.279	16.7	2.65	2.04
Road 50 km	0.279	16.7	2.65	2.04
Road 100 km	0.169	10.1	1.61	1.23
Rail 200 km	0.054	3.24	5.13	0.39
Rail 500 km	0.054	3.24	5.13	0.39
Ship	0.027	1.62	2.57	0.20

Extracted from Buchanan & Honey [1994] and Walsh [1992].

Table 7.13 Greenhouse gas and hydrocarbon emissions generated as a result of transportation of materials and finished window units.

Material		CO_2 (kg)	CO (kg)	NO_x (kg)	Hydrocarbons (kg)
Bauxite	Transported to factory	472.2	28.3	45.0	3.50
Aluminium	Transported to factory	0.05	3.07×10^{-3}	4.88×10^{-3}	3.75×10^{-4}
Timber	Transported to factory	1.40	0.08	0.13	0.01
Glass	Transported to factory	0.34	0.02	0.03	2.54×10^{-3}
Components	Transported to factory	0.03	1.61×10^{-3}	2.56×10^{-4}	1.96×10^{-4}
Finished window units	Transported to site	2.64	0.16	0.07	0.03
Total		**476.66**	**28.56**	**45.24**	**3.54**

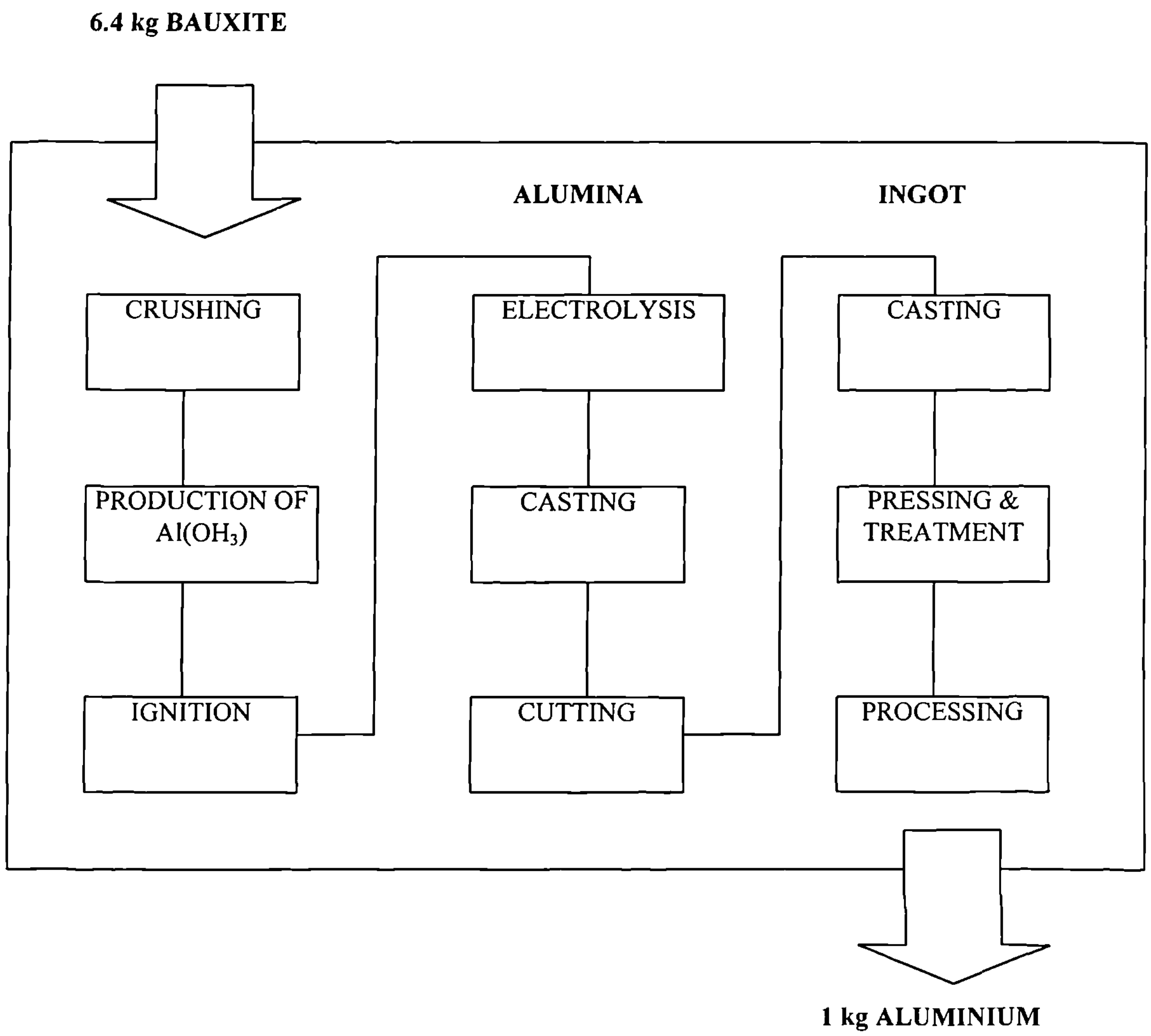


Figure 7.1 Production of Aluminium from raw bauxite [Saito & Shukuya, 1994]

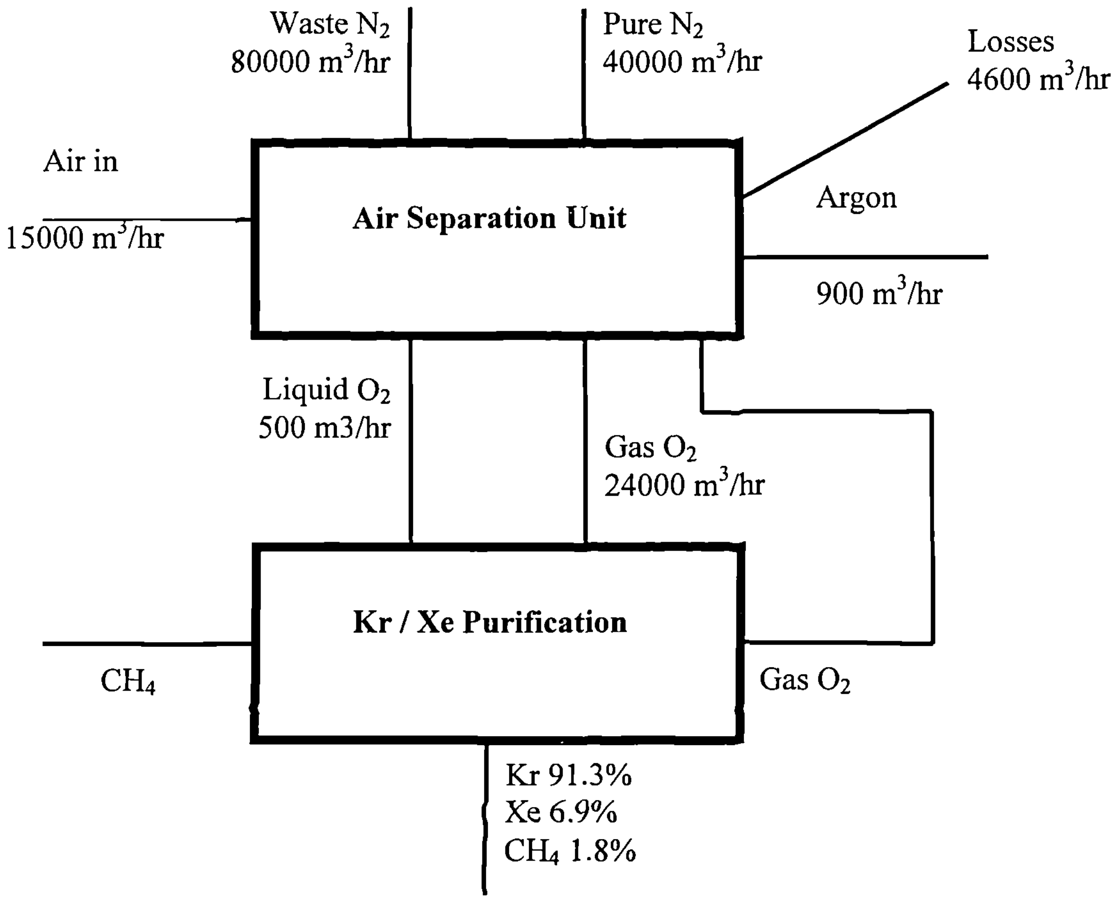


Figure 7.2 Gas production schematic for BOC Middlesburgh plant [Fernie & Muneer, 1996]

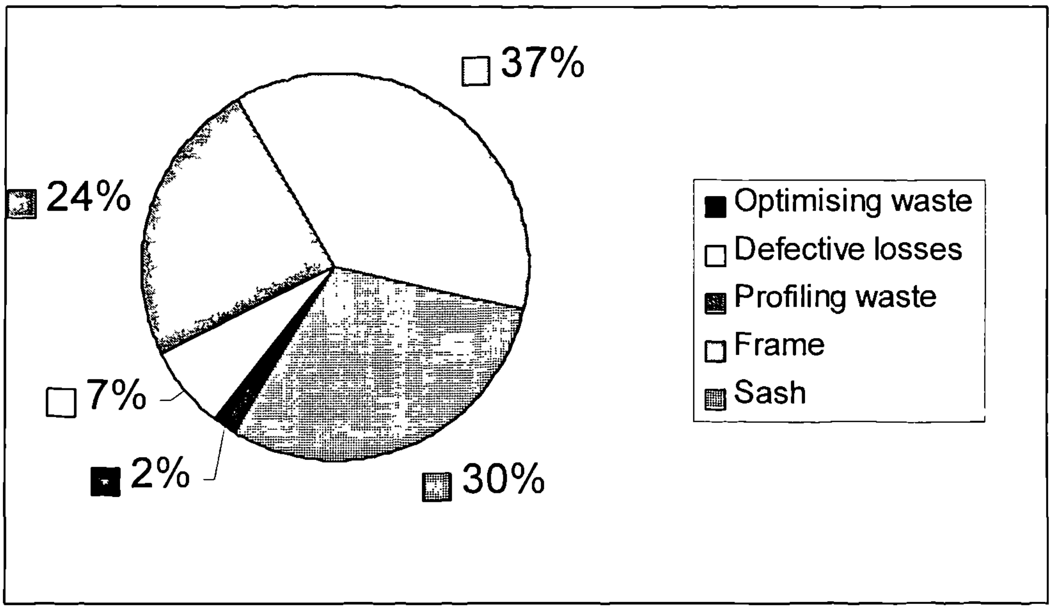


Figure 7.3 Timber use and waste within the manufacturing plant

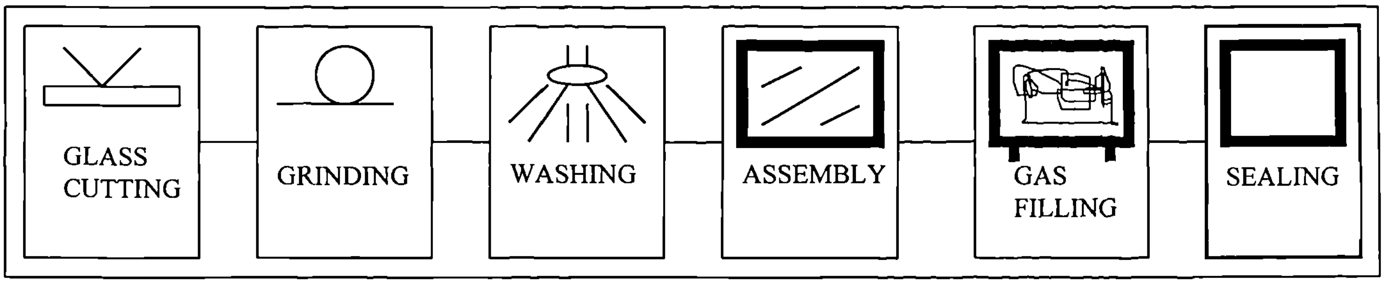


Figure 7.4 Sealed glazing unit production line process

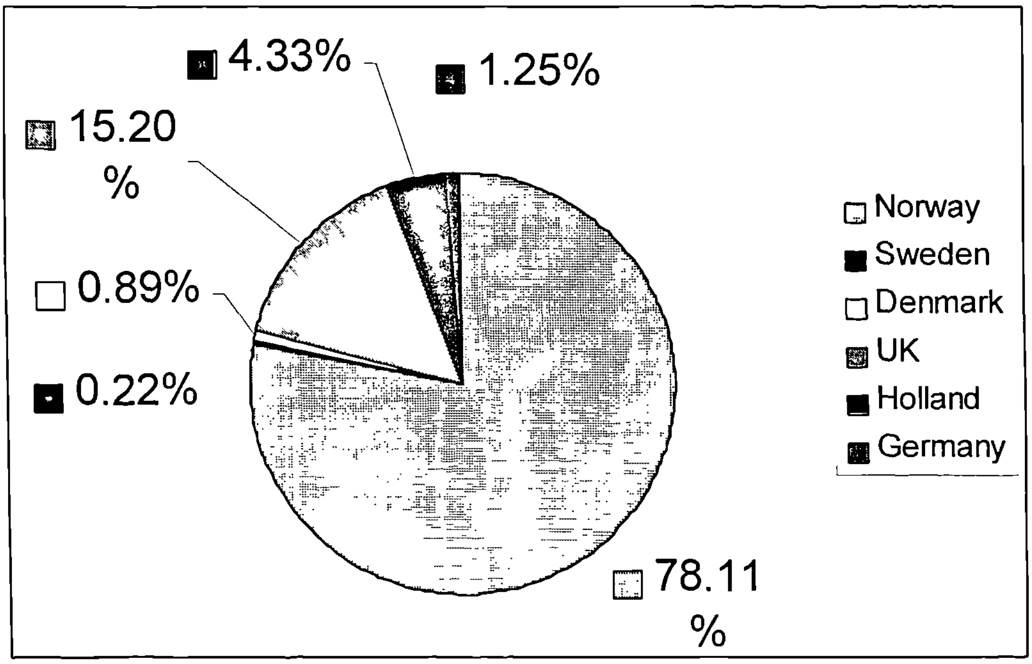


Figure 7.5 Sales and exports by country

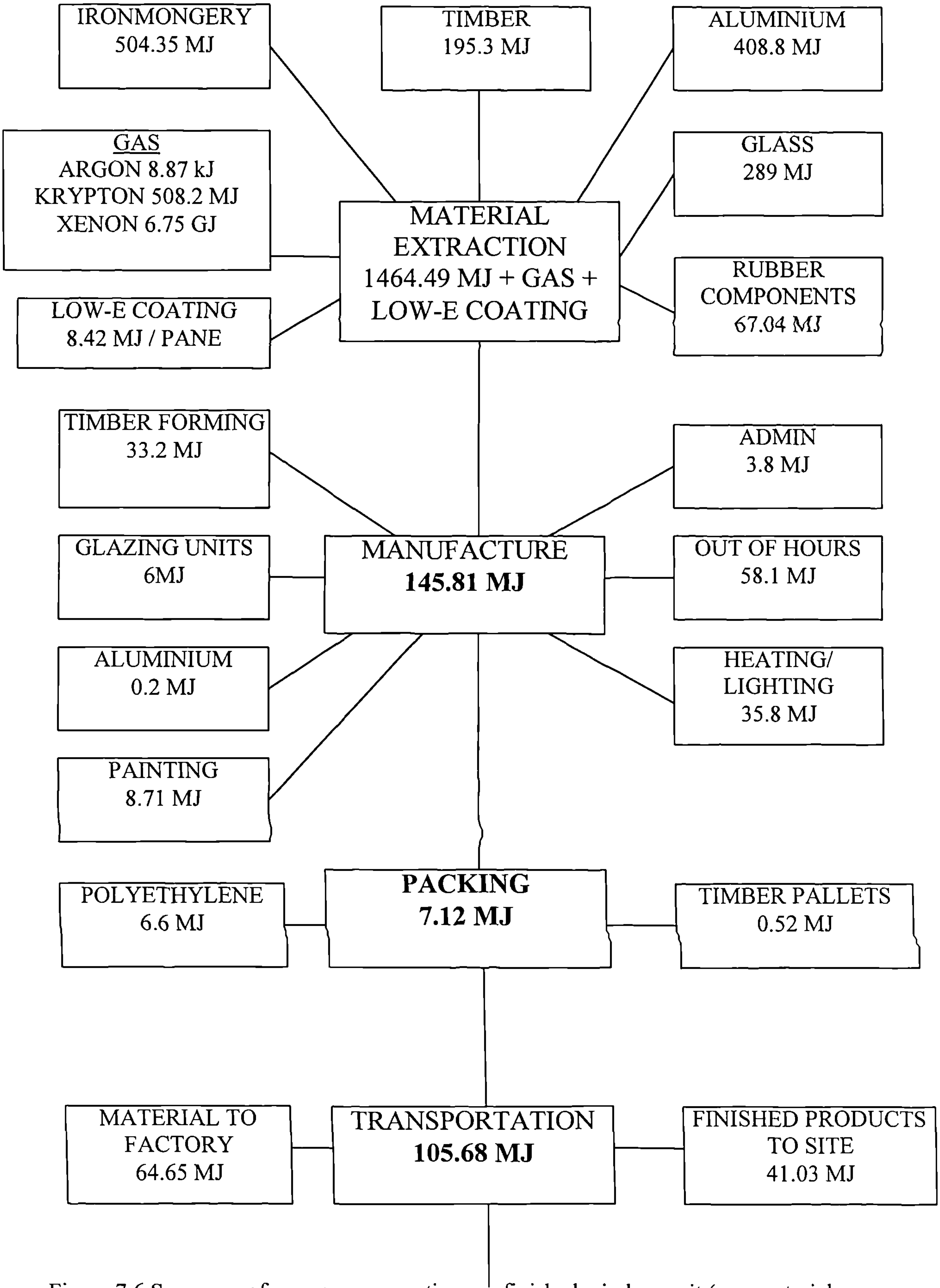


Figure 7.6 Summary of energy consumption per finished window unit (raw material extraction to site arrival) for a window measuring 1.2m by 1.2m.

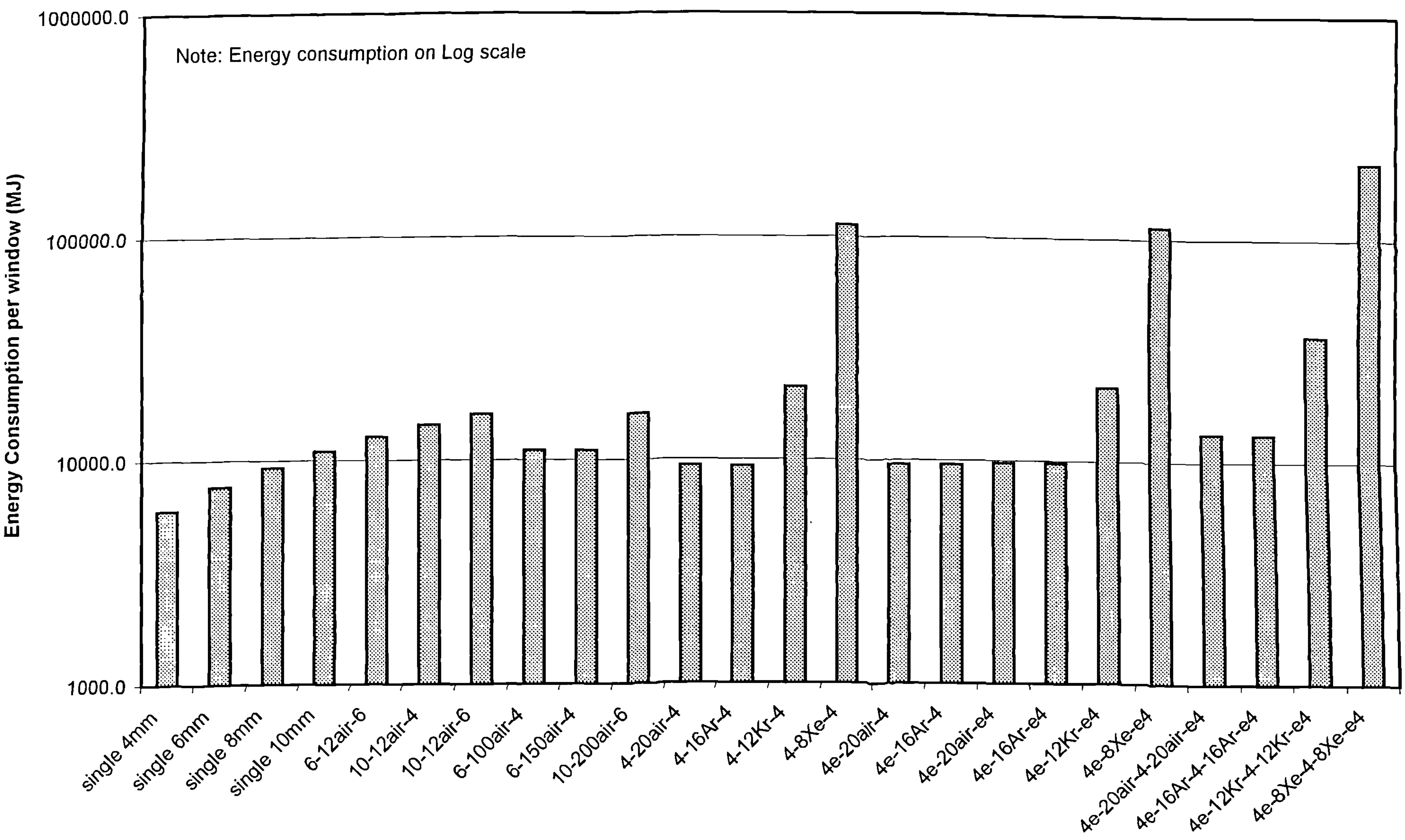


Figure 7.7 Summary of embodied energy content, incorporating material extraction, manufacturing, associated services, and transportation for 24 window constructions of dimensions 1.2m by 1.2 m

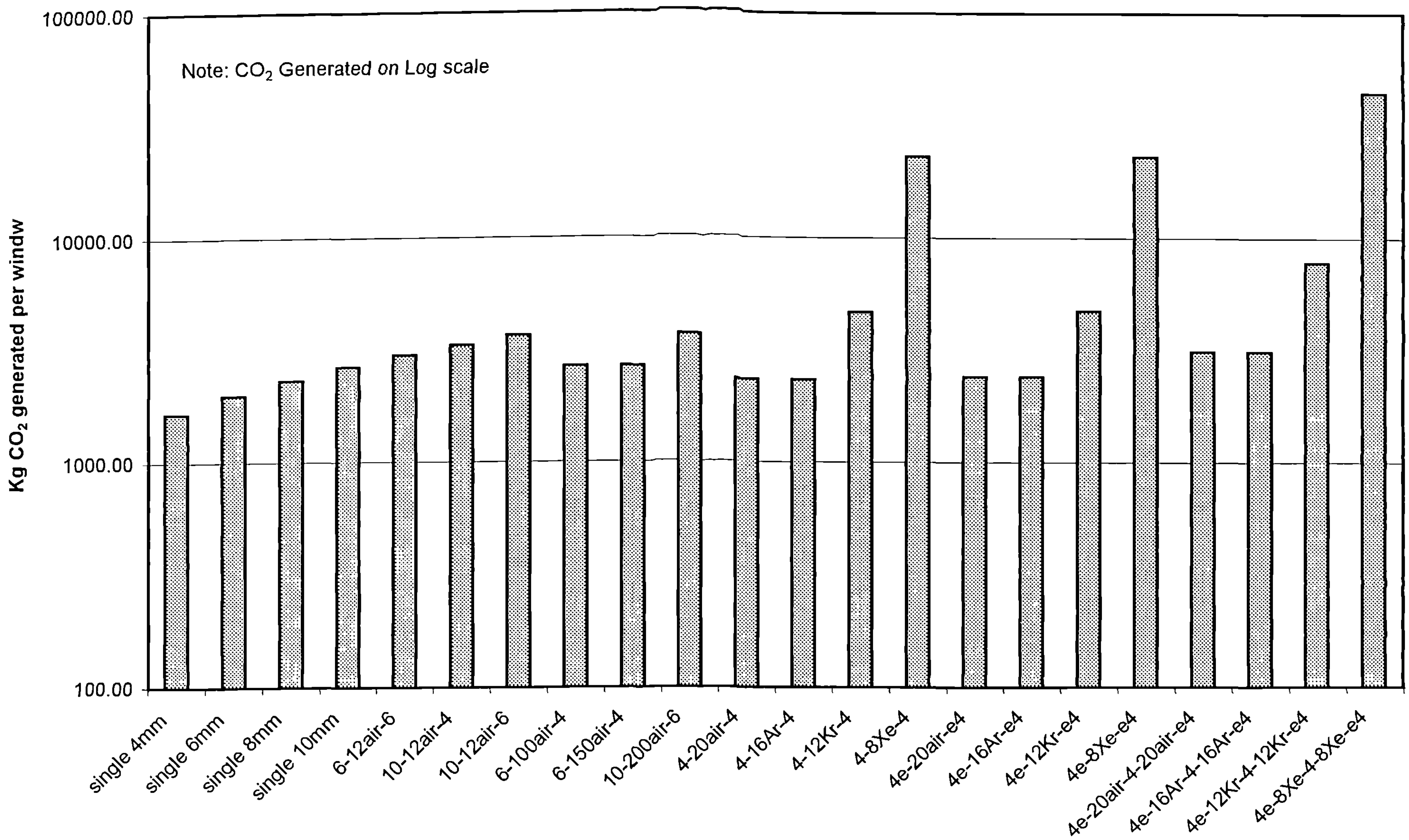


Figure 7.8 Total CO2 emissions produced as a result of electricity generation and transportation energy consumption for 24 window constructions

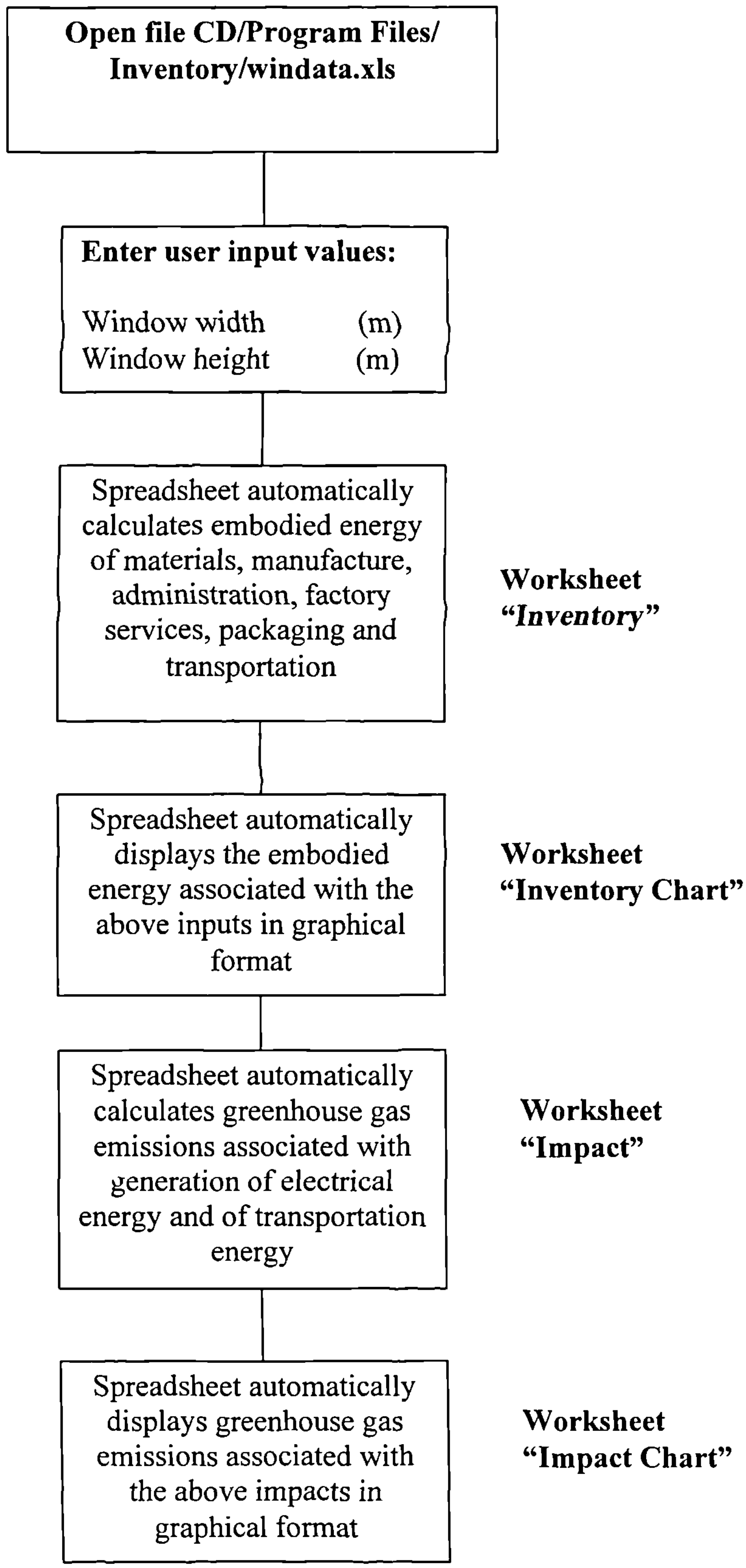


Figure 7.9 Flow diagram of inventory analysis and impact assessment calculations .

Chapter 8 : Life Cycle Optimisation

8.1 Introduction

The underlying objective behind a Life Cycle Assessment is to systematically quantify all inputs to and outputs from a given product, process or activity, and to assess environmental impacts resulting, with a view to identifying practical improvements which impose reduced environmental burdens. To this end, a method to assess and compare total energy consumption and environmental impact for any given window construction is sought. A sensitive approach is required, allowing advances in design and technology to pervade yet placing importance upon building user comfort. Within this approach, a focus on maintaining a sustainable environment for future generations is essential.

Creating working environments which are efficient, productive and comfortable through glazing solutions is a fine balance of design criteria. Designing to minimise space heating requirements and artificial lighting energy consumption, whilst minimising disturbance due to external noise, demands a methodology which allows the engineer to consider all possible construction permutations within the same framework. To graft sustainability criteria, which consider the full life cycle of products, processes and activities, into this same framework presents the engineer with a multi-disciplinary obstacle.

A full review of use implications for windows in buildings has been presented through Chapters 4-6, and three working models to represent thermal, aural and visual design criteria were developed. A comprehensive inventory analysis and impact assessment was also completed, and a working model to evaluate energy requirements and greenhouse gas emissions was developed in Chapter 7.

Using these four working models it is possible to develop a number of optima to aid the design engineer in appropriate selection of window configurations, which are location and building-use specific. Three optimisations are presented herein.

8.2 Energy consumption optimisation

Throughout the life cycle of a multi-glazed window there are implications for energy consumption. Material extraction, manufacturing, administration, packaging, and transportation, as considered through the inventory analysis phase of this LCA, are integral to any energy analysis. So, also, are those of design, use and reuse/recycling/disposal. It is possible, therefore, to construct an optimisation model to identify window configurations which minimise energy consumption over a full life cycle.

There are three main elements considered in the optimisation of energy consumption:

- Energy of material extraction, manufacturing, factory services, packaging and transportation, as derived in the inventory analysis.
- Energy associated with convective heat input to the internal space over window life, as a function of window thermal properties.
- Electrical energy associated with artificial lighting of the internal space over window life, as a function of window light transmission properties and lighting control strategy.

The models developed in Chapter 4 (thermal analysis), Chapter 6 (visual analysis) and Chapter 7 (inventory analysis) provide the input to the following energy consumption model. Care must be taken to ensure all inputs generated using these models are on a common basis, i.e. window size and glazed proportion. Spreadsheet 'energy.xls', located on CD/Program Files/Optimisation, is used to evaluate the total energy consumption over any given window life, for any defined window construction, including the embodied energy of materials, manufacture and transportation, in addition to the energy consumption associated with space heating, and artificial lighting.

8.2.1 Spreadsheet use

The inputs to the 'energy.xls' spreadsheet are generated from the thermal, visual and inventory models defined in chapters 4,6 and 7. By editing the input parameters to these base models, the energy consumption optimisation model may be applied to any given building design, location, or window specification.

The spreadsheet comprises 6 worksheets:

1. Inventory - a summary of embodied energy associated with the material sourcing and processing, manufacturing, packaging and transportation of 24 window configurations, as evaluated using 'inventory.xls'. Results are presented for window/ facade area proportions of 20%, 40%, 60% and 80%.

2. Thermal – a summary of annual space heating requirements associated with each window configuration and window/facade area proportion.
3. Visual - a summary of annual artificial lighting energy requirements associated with each window configuration and window/facade area proportion.
4. Totals – evaluation of total energy requirements associated with each window configuration over any given window design life.
5. Top-up chart – plot of total energy requirement over window design life, using a top-up lighting control strategy, for each window construction considered.
6. On-off chart – plot of total energy requirement over window design life, using an on-off lighting control strategy, for each window construction considered.

Results from each of the base models should be copied and pasted into the appropriate worksheets.

The window design life should be entered into Cell C1 of worksheet 'Totals'. The spreadsheet automatically sums the energy embodied in material, manufacture and transportation, with the energy associated with space heating and artificial lighting requirements over the window design life specified. A separate graph for buildings operating with top-up and on-off lighting control strategies is generated automatically, and can be viewed on worksheets 'Top-up' and 'On-off' respectively.

8.2.2 Energy optimisation example

Using the selected example office layout, a glazed area of $20.1m^2$ is required to achieve a glazed proportion of 60%. The total energy consumption associated with this glazing area, for each of 24 configurations, over a window life of 20 years, for top-up lighting control strategies, is illustrated in Figure 8.1. (Results for both top-up and on-off lighting control strategies are very similar. For simplicity, discussion of results is limited to the top-up control strategy only). If design criteria dictate that total energy consumption over the life of a window be minimised, the optimum window construction is 4e-12Ar-4-12Ar-e4 (triple glazed construction with 2 low-emissivity coatings and Argon gas cavity-fill). Total energy consumption for double and triple glazed options, using air, Argon or Krypton, and applying either one or two low-emissivity glazing coatings, are comparable for the above scenario. Single glazed options are excluded due to their poor insulative properties, and Xenon filled window configurations are prohibitively energy intensive due to the embodied energy of materials, primarily Xenon gas extraction from air. Contribution towards total energy consumption over window life, from materials, manufacture and transportation is minimal (1.1% -10.0%) for window constructions excluding the use of Xenon gas. The impact of Xenon gas alone on total energy consumption is, however, significant, accounting for 20.8% - 39.9% of energy consumption over window life.

8.2.3 Impact on energy consumption of low-emissivity coatings

Figure 8.1 also highlights the potential savings available, in terms of space heating energy consumption, by adopting use of low-emissivity glasses. Over a twenty year period, a saving of 54.5 GJ is achievable through the use of 2 low-emissivity coatings on a double glazed window having a 16mm Argon filled cavity. This represents an 18% saving in total energy consumption over window life, in return for an additional 91 MJ of energy input to manufacture materials (2.79 % of total embodied energy of materials, manufacture and transportation). Natural gas consumption associated with space heating is therefore reduced, and the environmental burden associated with greenhouse gas production is lowered. The impact on energy consumption of applying two low-emissivity coatings over a single coating is also seen. The benefit is minimal where glazing/facade area proportions are small, but more marked in larger glazing/facade area proportions. Applying a second low-emissivity coating requires materials, energy associated with production and transportation, and although thermal insulating properties are improved, light transmission is reduced, increasing the energy demand associated with artificial lighting. Applying just one low-emissivity coating to a double glazed, Argon filled window, increases the energy consumption over a 20 year window life by 4GJ, just 1.6% of total energy consumption, for a window/facade proportion of 60%.

8.2.4 Impact on energy consumption of inert gases

In terms of energy consumption, it would take many times the design life intended to justify the use of Xenon gas filled constructions. It is, however, impractical to expect any building element to consistently meet performance criteria over such a period. Design specification and quality of build are critical to the assumed useful life of a window; a specification is only as durable as its weakest component. To carry out an LCA with an unrealistic design life renders the results impractical for decision making purposes. Twenty years is considered to be a practical and realistic design life for a window construction.

8.2.5 Impact on energy consumption of window/facade area proportion

Several factors influence the output from the energy optimisation model. Window size and dimensions, and proportion of glazing in a facade, in addition to comfort parameters of preferred temperature and lighting lux level all impact on energy consumption throughout a lifetime of use. For conditions which differ from those assumed in this research, each of the underlying models can be edited to reflect any specific application, and the same optimisation technique applied.

Varying the window area proportion also impacts on the selection of optimum window design, in terms of energy consumption over the window life. Table 8.1 illustrates the change in optimal window design as window life is extended, and glazing proportion is increased. A window life greater than 20 years is considered impractical, but the longer window lives shown are there to illustrate the duration of time required to make certain construction optimal. As the percentage area of glazing in the facade increases, windows employing heavy inert gases require a longer window life to be optimal in terms of energy consumption. This is because the increased glazing area demands larger volumes of inert gas to be inserted in the glazing cavities. Extraction of inert gases, with the exception of Argon, as discussed in Chapter 7, is an energy intensive process. Figure 8.2 *shows, for a triple glazed* Xenon *filled window,* how the percentage of the total energy consumption attributed to space heating and materials is influenced as the percentage area of glazing in a facade increases. For larger glazed areas, the benefit of using heavy inert gases in glazing cavities are outweighed by the "cost" of embodied *energy of materials.*

Figure 8.3 displays the total energy consumption for the example office, for each window construction for window areas 20%, 40%, 60% and 80% of facade area, over a window life of 20 years, using a top-up lighting control strategy. For double and triple glazed window configurations, adopting the use of air, Argon and Krypton gases, with low-emissivity coatings, there is little difference in energy consumption when glazing area is varied. For single glazed configurations, variance is high between glazing proportions of 20% and 80%, highlighting the importance of good insulative properties in minimising space heating requirements. For heavy inert gas glazing configurations, the same large variance is attributed to the large embodied energy of gas production, despite the excellent insulative properties of the window constructions.

8.3 Global environment optimisation

Centred around the same framework as the energy consumption optimisation model, the global environment optimisation model considers greenhouse gas emissions which are generated as a result of energy consumption over window life. All electrical energy consumption is assumed to be based on the UK mix of generating plant, while all convective heat requirements are assumed to be met via natural gas fired central heating systems. Greenhouse gas emissions generated as a result of electricity generation in the UK, and of combusting natural gas were defined in Chapter 7, Table 7.11.

Spreadsheet 'global.xls', located on CD/Program Files/Optimisation, is used to evaluate the total greenhouse gas emissions generated over any given window life, for any defined window construction, including the procurement of materials, manufacture processes, and transportation, in addition to the emissions associated with the combustion of natural gas for space heating, and the generation of electricity for artificial lighting requirements.

8.3.1 Spreadsheet use

Inputs to the 'global.xls' spreadsheet are generated from the 'energy.xls' spreadsheet. The spreadsheet comprises 10 worksheets:

1. 20%E : total energy requirements over any given window design life for a window/facade area ratio of 20%.
2. 20%I : total greenhouse gas emissions over any given window design life for a window/facade area ratio of 20%.
3. 40% E : total energy requirements over any given window design life for a window/facade area ratio of 40%.
4. 40%I : total greenhouse gas emissions over any given window design life for a window/facade area ratio of 40%.
5. 60% E : total energy requirements over any given window design life for a window/facade area ratio of 60%.
6. 60%I : total greenhouse gas emissions over any given window design life for a window/facade area ratio of 60%.
7. 80% E : total energy requirements over any given window design life for a window/facade area ratio of 80%.
8. 80%I : total greenhouse gas emissions over any given window design life for a window/facade area ratio of 80%.

9. Summary – total CO_2, SO_2, NO_x, CO and Hydrocarbon emissions for each window/facade area ratio considered.
10. CO_2 chart – plot of total carbon dioxide emissions associated with each of 24 window constructions over specified window design life.

The window design life should be entered into Cell B2 of worksheets '20%E', '40%E', '60%E' and '80%E'. The *spreadsheet automatically updates worksheets, '20%I'*, '40%I', '60%I', '80%I', 'summary' and 'CO_2 chart'.

8.3.2 Global environment optimisation example

For a window/facade area proportion of 60% (based on the example office used in this study), total CO_2 emissions associated with each of 24 configurations, over a period of 20 years is illustrated in Figure 8.4. CO_2 emissions are sub-divided to show contribution from energy associated with material consumption, transportation, lighting and space heating. Similar results are borne out in this analysis as found in the energy consumption optimisation model above. Cavities filled with heavy inert gases possess excellent insulative properties, but the benefits of this are outweighed by the burden placed upon the environment of producing the materials required. If design criteria dictate that total greenhouse gas emissions over the life of a window be minimised, the optimum window construction is again 4e-12Ar-4-12Ar-e4. Window life influences the selection of optimal window configuration differently in terms of environmental impact than for energy consumption, as shown in Table 8.2. For a window life of 1-10 years, the optimal configuration is 4e-12Ar-e4. Variances in optimal window design between an energy based analysis and a global environment based analysis, result from the differences in energy generation for manufacturing, transportation, space heating and artificial lighting. Window designs which possess poor thermal insulating properties are characterised by a predominant energy requirement for space heating over window life. Window designs which are 'over-designed' to minimise thermal losses require energy intensive materials in construction, and are characterised by a predominant energy requirement in material sourcing and manufacture. If space heating requirements are met via combustion of natural gas, and all other energy requirements are generated using a typical plant mix of fossil fuels and renewable energy, then the emission profile for windows will vary.

Figure 8.5 illustrates how CO_2 emissions are influenced by increasing glazing/facade area proportions. The same general trend is seen in greenhouse gas generation as for energy consumption. Higher variance in emissions between small and large glazing proportions exist for both poorly insulated window constructions, and those which employ materials with high embodied energy values. Those constructions which show a more even profile between small and large glazing proportions depict appropriate use of materials over a practical window life.

8.4 Comparison of present results with other research work

Fernie and Muneer [1996], in an analysis of monetary, energy and environmental implications for infill gases used in high performance windows, discovered that maximum CO_2 saving over a 20 year period was achieved through use of double glazed window constructions, employing a 12mm Krypton filled cavity, and two low-emissivity coated glazing panes. Differences in analysis exist between Fernie and Muneer's study, and the research presented in this thesis. Work presented by Fernie and Muneer [1996] did not consider the use of triple glazed window constructions, and analysis was limited to windows of area $1m^2$ only. Window proportion as a percentage of facade area was not considered in the analysis, and no inclusion for energy consumption on artificial lighting was given. Embodied energy of materials was limited to inert gases only, and no input from other window materials, nor from transportation of products was given. The analysis presented in this thesis gives a more comprehensive assessment of energy consumption and greenhouse gas emissions resulting from the whole life cycle of multi-glazed window manufacture and use, but also contains limitations. No quantifiable impacts resulting from window maintenance, disposal and recycling has been presented due to lack of reliable data sources, and the infancy of building techniques to adopt recycling techniques in construction. Assumptions were made pertaining to the energy consumption and greenhouse gas emissions resulting from the production and use of windows which varied in size from the measurement standard (1.2m x 1.2m).

8.5 Comfort optimisation

A reliable and consistent methodology to select glazing solutions which maximise building user comfort in terms of thermal, aural and visual conditions, is sought. The development of a single model which derives an "optimum" solution in terms of occupant comfort at the push of a button is inappropriate in this application. The model for comfort optimisation, presented herein, is intended to be used as a guide, allowing the design engineer to employ professional judgement and building knowledge in window selection.

The comfort optimisation model is not as straight forward as the energy consumption and global environment models developed above, due to the number and complexity of variables involved. The flow sheet shown in Figure 8.6 was developed to aid the design engineer in selection of an optimum window configuration, meeting thermal, aural and visual comfort criteria, yet minimising energy consumption and greenhouse gas emissions. To make best use of the spreadsheet requires knowledge of the aural environment which is required by building occupants to maximise comfort and work performance. Building location information and prevailing external noise levels and frequencies are also required, such that an appropriate window sound reduction level can be derived. Selecting only those windows which meet aural performance criteria will provide the designer with a number of alternatives. These alternatives can then be assessed using the energy consumption and global environment optimisation models, developed above, in order to select an appropriate construction. In this way, adequate noise attenuation for a given location is provided, energy consumption over a life-time of use is minimised, and damage to the environment, in terms of greenhouse gas emissions, is limited as far as is practicable.

For large open plan office buildings the interior noise target level, extracted from BS 8233 [1997], is recommended to be a maximum of 45 –50 dB. If in an industrial environment the selection of sound reduction window configurations was necessary, and a noise attenuation value greater than 35dB was required, then construction alternatives, based on the 24 window configurations offered within this research, would be limited to specific noise reducing window designs, and Xenon cavity window constructions:

1. 10-12air-4
2. 10-12air-6
3. 6-100air-4
4. 6-150air-4
5. 10-200air-6
6. 4-12Xe-4
7. 4e-12Xe-e4
8. 4e-12Xe-4-12Xe-e4

for a window/facade proportion of 60%.

Restricting the energy and global environment optimisation models to the above alternatives, reveals that either the 6-100air-4 or 6-150air-4 construction is optimal in terms of both energy consumption, and greenhouse gas production, over a window life of 20 years, for both top-up and on-off lighting control strategies.

8.6 Constrained and unconstrained analyses

Model results presented throughout Chapters 4-8 were constrained to the same 24 window constructions in each analysis for ease of comparison and to provide uniform data on which to perform optimisation techniques. As previously stated, the models developed are universal, and can be used to calculate properties and optima for any given set of window configurations, building locations, styles and constructions. In practice, however, it is unlikely that any single window manufacturer will be able to provide such a diverse selection of window configurations from one a single manufacture plant. The provision of windows adopting 5 glazing options, from single glaze to triple glaze, with/without low-emissivity coating, and 4 gas cavity options, relies on a single manufacturer possessing capital, labour and machinery to invest in a number of production lines and techniques. It is possible to obtain such diversity from a number of manufacturers, but analysis is dependent upon consistent LCA data availability from each manufacturer considered, the resource and financial implications of which would prove prohibitive. A compromise is often the solution to such obstacles. An example of this is seen in considering the technological developments required to manufacture windows with a range of cavity gas options. For optimal thermal performance, and to minimise heat loss due to convection in glazing cavities, the choice of infill gas influences the glazing gap [B. Han, 1996]. For air filled cavities the optimal gap is 20mm, while for inert gases Argon, Krypton and Xenon the optimal gap is 16mm, 12mm and 8mm respectively. To manufacture each of these configurations relies on 4 dedicated production lines. Air and argon gas cavities are common in construction, but use of Krypton and Xenon is limited, resulting in production equipment lying idle. The solution, therefore, is to produce all cavity gas options with the same glazing gap of 12mm, thereby reducing capital equipment requirements. The impact on energy consumption and greenhouse gas emissions over window life of constraining all cavity gaps to 12mm is shown in Table 8.3.

Energy consumption over window life for all 24 configurations is increased when the glazing gap is compromised. Emission of CO_2 resulting from fossil fuel combustion is also increased for the majority of window configurations. Those window constructions which result in reduced levels of CO_2 being emitted, despite a compromise in window design, illustrate the balance between combustion of natural gas for space heating, and combustion of fossil fuels for electricity generation. Total energy consumption over window life which is most heavily influenced by materials and manufacture is predominantly a function of carbon dioxide emitted through fossil fuel combustion associated with the prevailing generating plant mix. Total energy consumption over window life which is most heavily influenced by space heating requirements is predominantly a function of carbon dioxide emitted through natural gas combustion. This highlights the importance of selecting appropriate use and quantity of materials in window design, and the need to optimise window design over a full life cycle, bearing in mind the building, location, occupant needs and building services prevalent.

8.7 References

1. BS 8233 British Standards Institution, (1997).
2. Fernie, D. and Muneer, T., Monetary, energy and environmental implications for infill gases used in high-performance window, Building Services Engineering Research and Technology, 17(1) 43-45 (1993).
3. Han, B., Investigation of thermal characteristics of multiple glazed windows, Ph.D. thesis, Department of Mechanical, Manufacturing and Software Engineering, Napier University, Edinburgh, (1996).

Table 8.1 Results of energy optimisation model for example office layout

Percentage of façade which is glazed	20%		40%		60%		80%	
Lighting control strategy	Top-Up	On-Off	Top-Up	On-Off	Top-Up	On-Off	Top-Up	On-Off
Window Life (years)	Optimum window configuration							
5	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4
10	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4
20	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4
30	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4
40	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4
50	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4
100	4e-12Kr-4-12Kr-e4	4e-12Kr-4-12Kr-e4	4e-12Kr-4-12Kr-e4	4e-12Kr-4-12Kr-e4	4e-12Kr-4-12Kr-e4	4e-12Kr-4-12Kr-e4	4e-12Kr-4-12Kr-e4	4e-12Ar-4-12Ar-e4
200	4e-12Kr-4-12Kr-e4	4e-12Kr-4-12Kr-e4	4e-12Kr-4-12Kr-e4	4e-12Kr-4-12Kr-e4	4e-12Kr-4-12Kr-e4	4e-12Kr-4-12Kr-e4	4e-12Kr-4-12Kr-e4	4e-12Ar-4-12Ar-e4

Table 8.2 Results of environmental impact optimisation model for example office layout [Optimisation based on CO_2 production only]

Percentage of façade which is glazed	20%		40%		60%		80%	
Lighting control strategy	Top-Up	On-Off	Top-Up	On-Off	Top-Up	On-Off	Top-Up	On-Off
Window Life (years)	Optimum window configuration							
5	4e-12Ar-e4	4e-12Ar-e4	4e-12Ar-e4	4e-12Ar-e4	4e-12Ar-e4	4e-12Ar-e4	4e-12Ar-e4	4e-12Ar-e4
10	4e-12Ar-e4	4e-12Ar-e4	4e-12Ar-e4	4e-12Ar-e4	4e-12Ar-e4	4e-12Ar-e4	4e-12Ar-e4	4e-12Ar-e4
20	4e-12Ar-e4	4e-12Ar-4-12Ar-e4	4e-12Ar-e4	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4
30	4e-12Ar-e4	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4
40	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4
50	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4
100	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4
200	4e-12Kr-e4	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4	4e-12Ar-4-12Ar-e4

Table 8.3 Impact on total energy consumption and CO_2 emissions of constraining cavity gap to 12mm, instead of optimal design gap (Air – 20mm, Argon – 16mm, Krypton – 12mm, Xenon – 8mm).

Window construction	Total Energy consumption over window life of 20 years (GJ)		**% difference**	Total CO_2 emitted over window life of 20 years (tonnes)		**% difference**
Glazing gap	optimal	12 mm		Optimal	12 mm	
Double glaze, no low-e, air cavity	335.02	337.89	**+0.86**	23.92	23.91	**-0.04**
Double glaze, no low-e, Argon cavity	330.92	332.32	**+0.42**	23.68	23.59	**-0.38**
Double glaze, no low-e, Krypton cavity	336.23	336.23	-	25.21	25.21	-
Double glaze, no low-e, Xenon cavity	402.35	439.52	**+9.24**	38.70	46.14	**+19.22**
Double glaze, 1 low-e coating, air cavity	292.50	301.88	**+3.21**	21.47	22.31	**+3.91**
Double glaze, 1 low-e coating, Argon cavity	283.21	290.34	**+2.52**	20.93	21.64	**+3.39**
Double glaze, 2 low-e coatings, air cavity	288.61	295.56	**+2.41**	21.48	21.72	**+1.12**
Double glaze, 2 low-e coatings, Argon cavity	278.21	283.32	**+1.84**	20.88	21.01	**+0.62**
Double glaze, 2 low-e coatings, Krypton cavity	279.43	279.43	-	22.18	21.18	-
Double glaze, 2 low-e coatings, Xenon cavity	342.59	379.76	**+10.85**	35.49	42.93	**+20.96**
Triple glaze, 2 low-e coatings, air cavity	270.68	274.96	**+1.58**	21.11	21.18	**+0.33**
Triple glaze, 2 low-e coatings, Argon cavity	263.97	266.80	**+1.07**	20.72	20.70	**-0.10**
Triple glaze, 2 low-e coatings, Krypton cavity	276.44	276.44	-	23.90	23.90	-
Triple glaze, 2 low-e coatings, Xenon cavity	409.81	485.27	**+18.41**	50.94	66.03	**+29.62**

Note: Total Carbon Dioxide emissions are a result of a mixture of energy sources - generation of electricity using UK plant mix, combustion of natural gas, and consumption of fossil fuels for transportation.

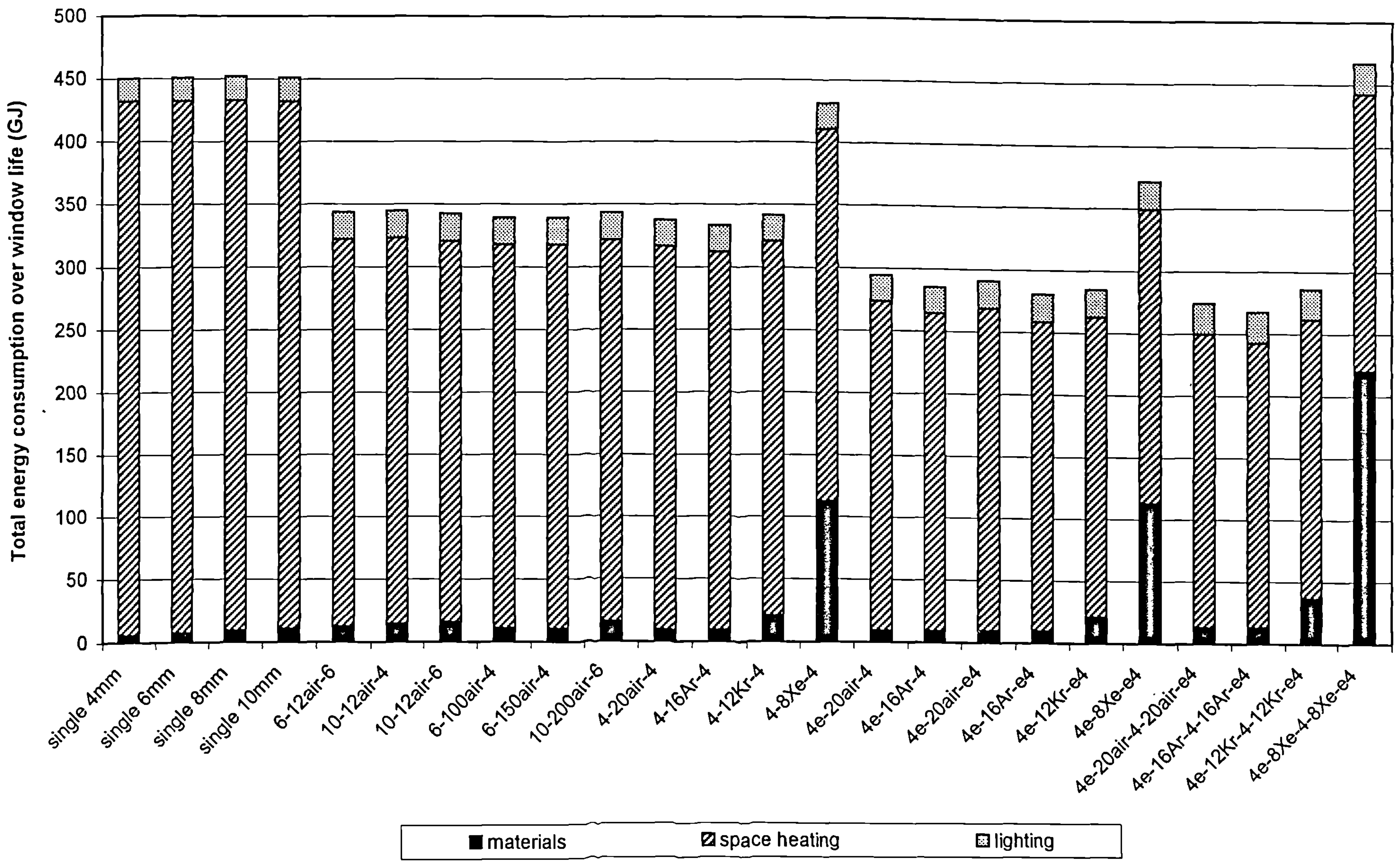


Figure 8.1 Breakdown of total energy consumption over window life for 24 window configurations (Window area 60% of façade/ Window life 20 years)

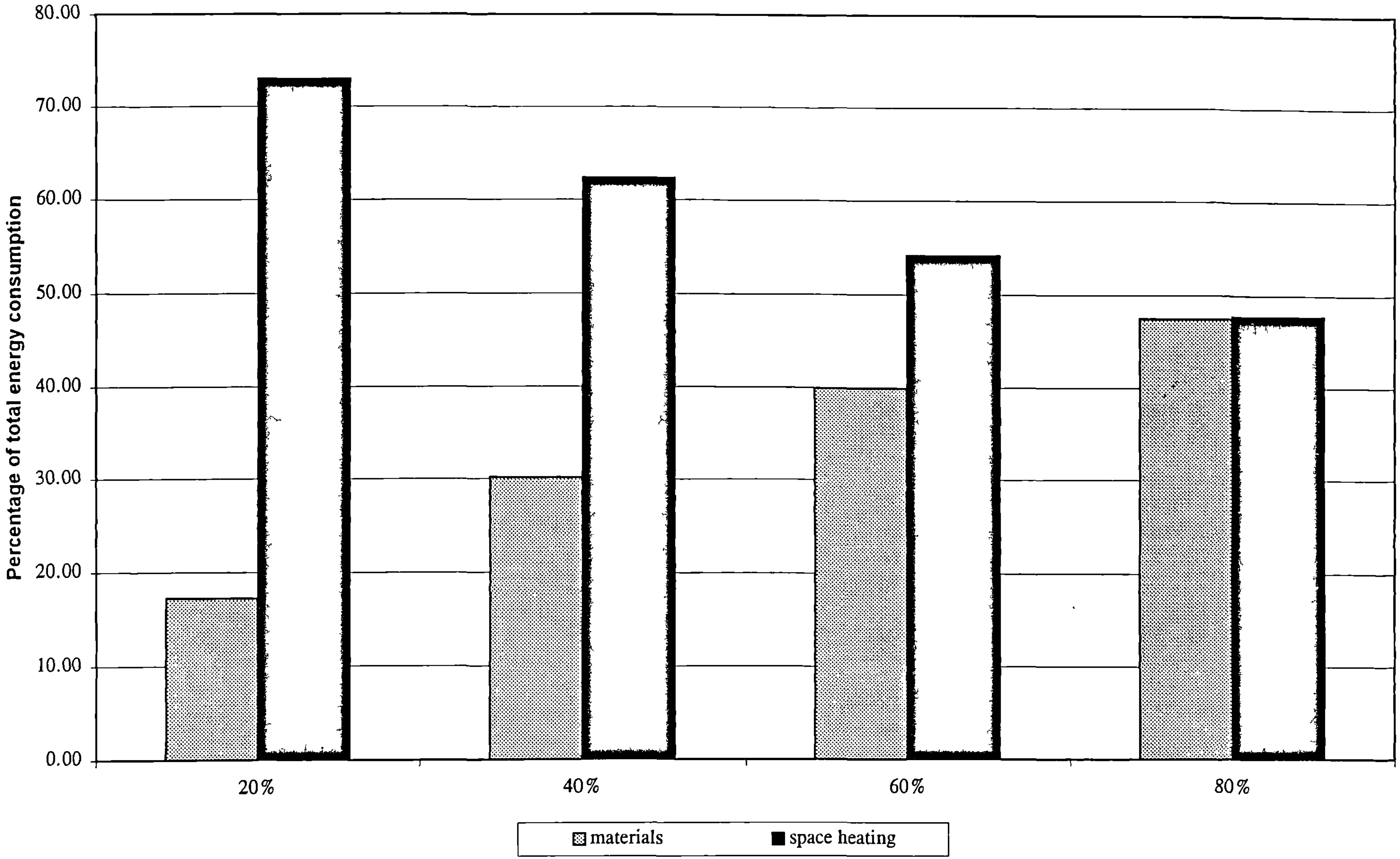


Figure 8.2 Percentage of total energy consumption, over window life, associated with space heating and materials, for varying window/façade area ratios (Window 4e-8Xe-4-8Xe-e4)

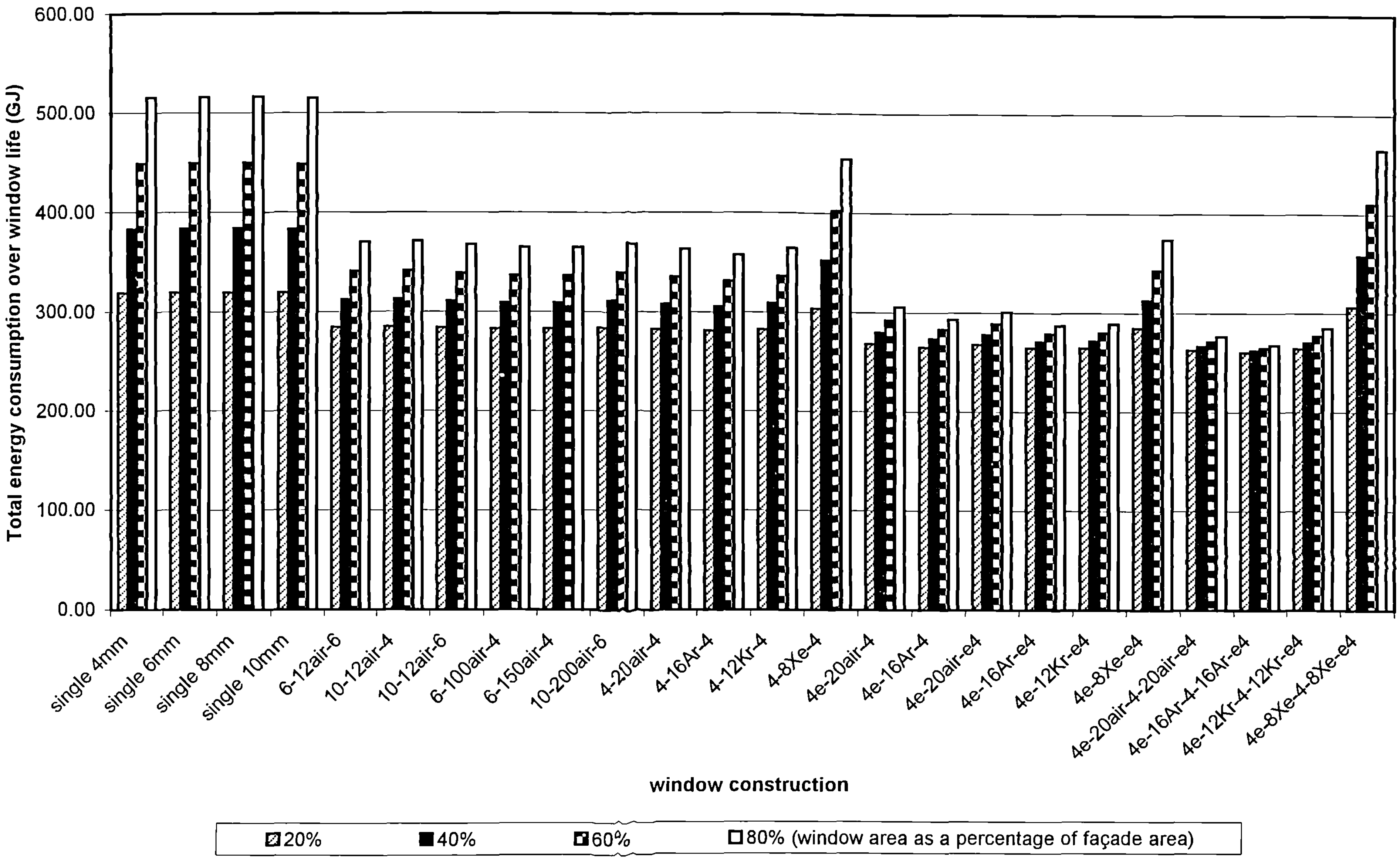


Figure 8.3 Total energy consumption over window life of 20 years (based on top-up lighting control strategy)

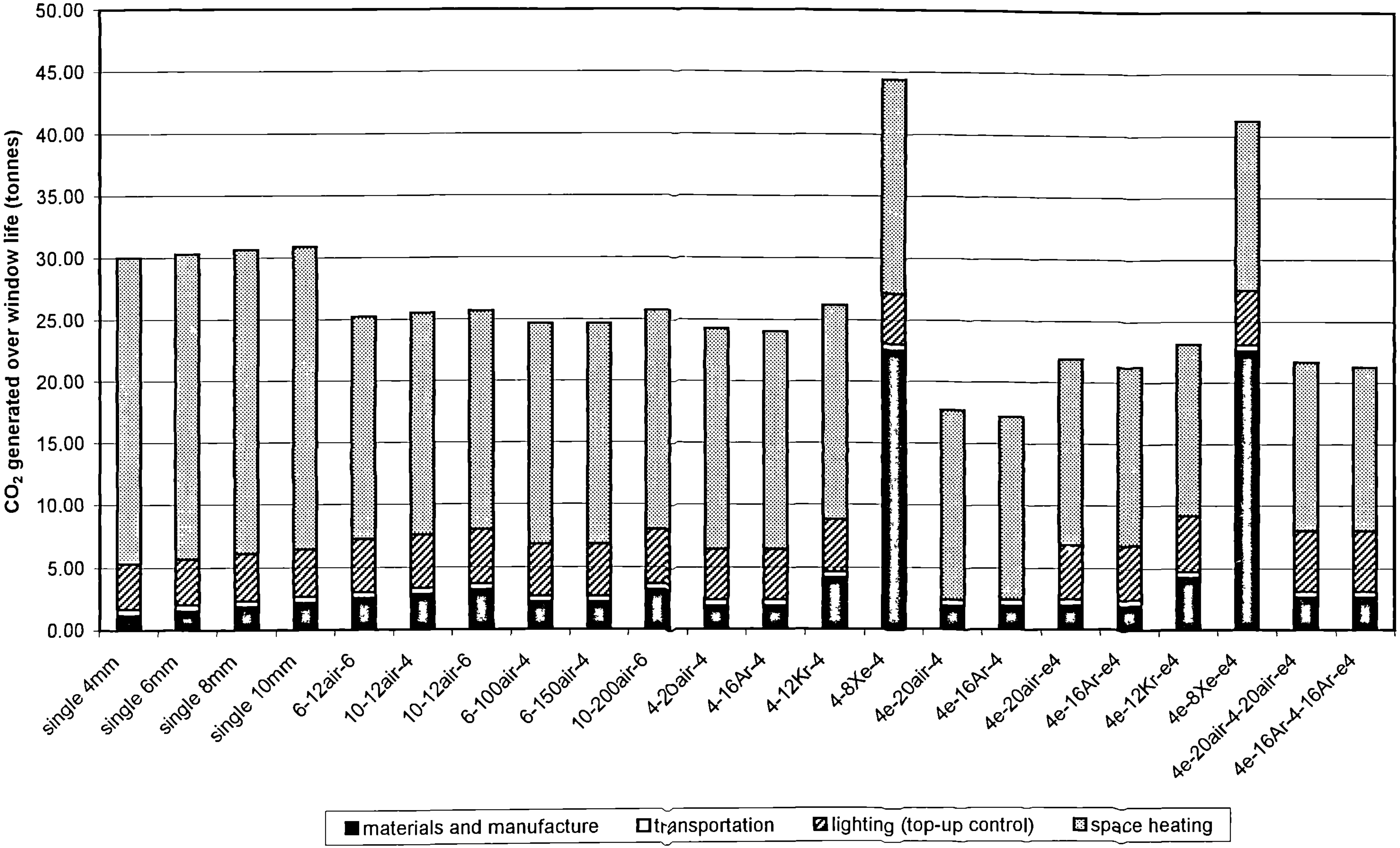


Figure 8.4 Total CO2 production over window life of 20 years (window area 60% of facade area)

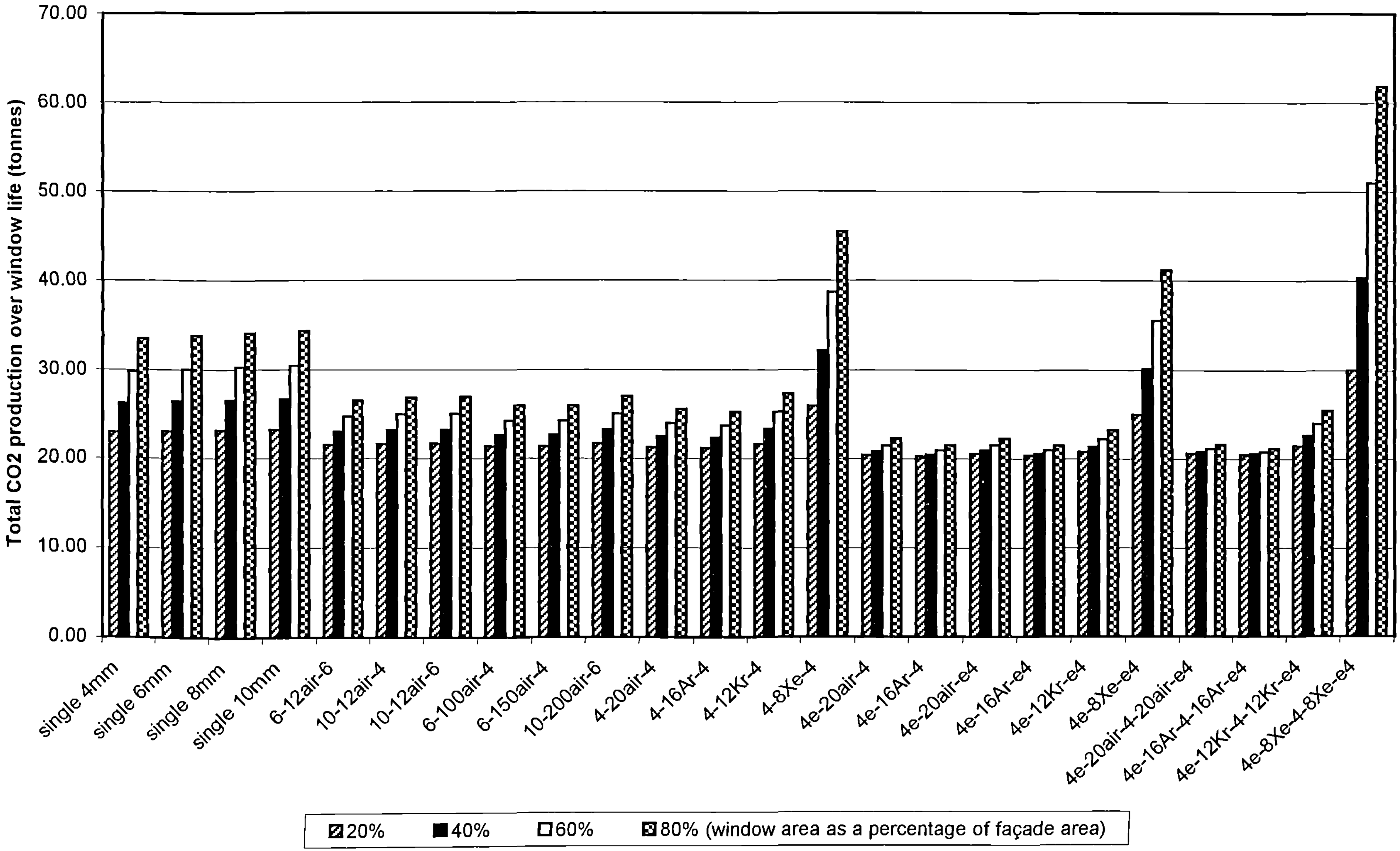


Figure 8.5 Total CO2 production over window life of 20 years for varying window/facade area ratios (based on top-up lighting control strategy)

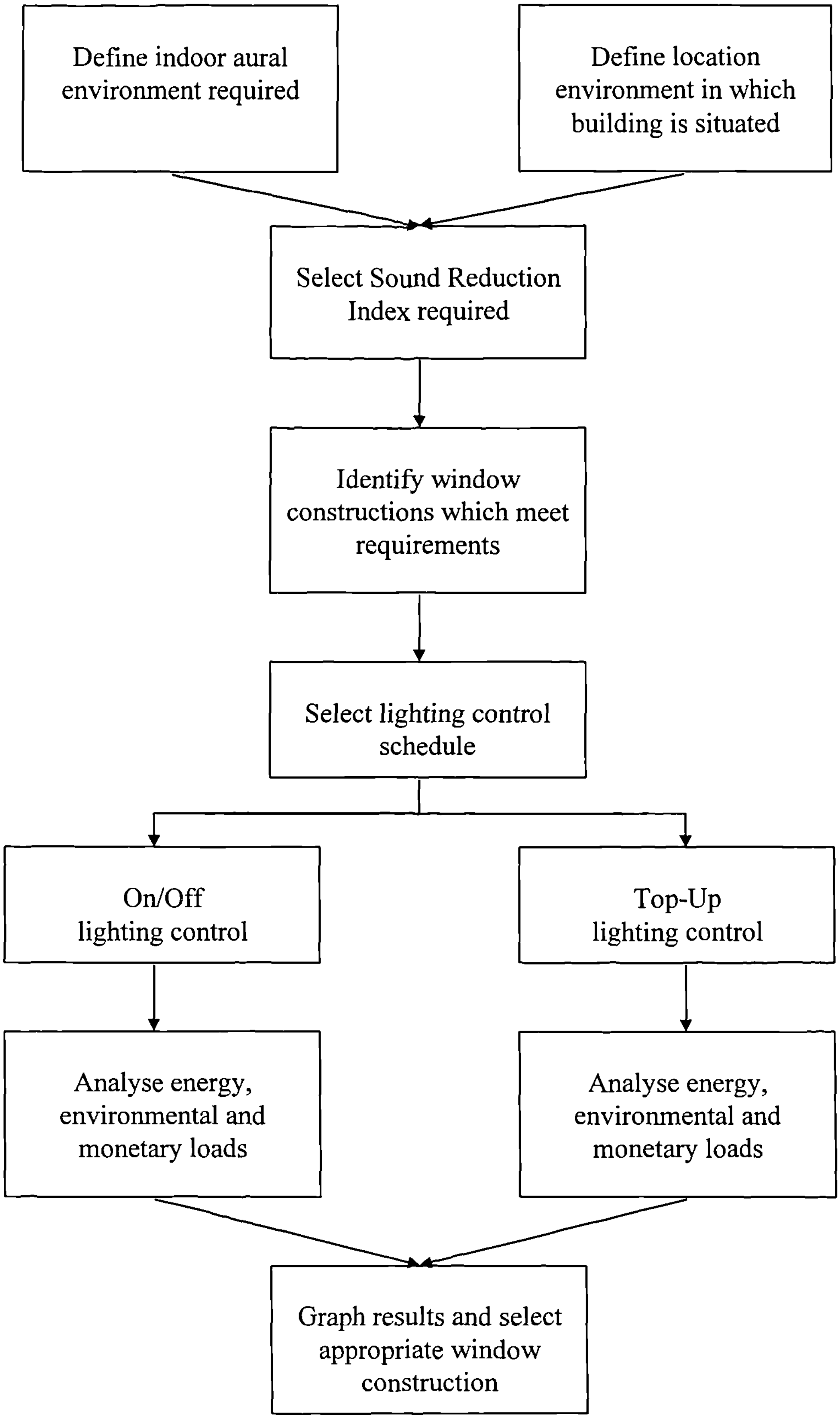


Figure 8.6 Optimisation flowchart

Note: The above flow diagram is linked to the discussion contained within section 8.5.

9. Improvement analysis

9.1 Introduction

The final stage in a recognised approach to LCA is to perform an improvement analysis, based on the information gained through detailed inventory analyses and impact assessments. This thesis, therefore, would be incomplete without inclusion of such an important stage. The work presented so far in this thesis may, however, be regarded as a pre-empting of the improvement analysis stage; the systematic development of all analysis models, and the final energy, global environment and comfort optimisation models are all focused on product improvement. It addresses a practical problem which stands in the way of sustainable building initiatives; that of providing a solid framework for selection of multi-glazed windows, which provide the standard of indoor environment expected by today's building user, whilst offering solutions which eliminate profligate use of energy and which impact excessively on the environment. The development of thermal and visual analysis models to assess energy requirements was necessary as part of a full inventory analysis. No inventory analysis is complete without due consideration to product use. The need for aural analysis was borne out of consideration to holistic design criteria in building component design and selection [Loe & Davidson, 1993]. With the provision of data pertaining to the energy requirement and resulting environmental impact of window life cycles, the optimisation models provide the designer with practical and workable tools. This is in agreement with requirements of the improvement analysis to define realistic and practical solutions.

Improvement analysis involves decision making to reduce environmental burdens. This requires taking an objective view of a product life cycle and assessing the impact which changes would make on the environment. The conclusion of any analytical study is borne out of underlying scope and goal definitions. The outcome of an LCA study is no different. The conditions fixed during the introductory stages of an assessment set the limits for possible improvements. The main objective set out in the introductory chapter of this thesis was to provide a method by which to compare window constructions, such that the high demands expected in building construction are adhered to, whilst profligate use of energy is eliminated and greenhouse gas emissions kept to a minimum. The resulting optimisation models developed through Chapters 4-8, and based upon the principles of Life Cycle Assessment, have met this objective.

Further improvements to the LCA results presented could, however, be achieved. The work which follows relies heavily on literature review of improvement techniques and sustainability criteria, but is included at this stage of the thesis for two reasons:

1. Life Cycle Assessments follow a structured approach of inventory analysis work, leading to impact assessment, and subsequent improvement analysis. To deviate from this documented approach would be misleading.

2. Improvement analysis would appear to be the final stage in an LCA. It must, however, be borne in mind that Life Cycle Assessments are iterative in nature. Pending improvements which are identified through the first iteration should be followed through, resulting in product, process or activity changes. These changes demand further inventory analyses, leading to extended impact assessments, and a continued identification of possible improvements. The optimisation models presented in this thesis provide the foundations on which to build subsequent investigations and test future improvement criteria.

Product design changes, raw material substitutions, manufacturing process changes, improved waste management facilities, or suggested consumer use changes, should be made as part of a long-term, pro-active and strategic response to necessary and sustainable environmental initiatives. Little room is allowed for defensive, pragmatic assertions, based solely on the consequences upon human interest in the short term. The most common definition of sustainable development stems initially from the Bruntland report, expressed as:

> *'an approach to progress which meets the needs of the present without compromising the ability of future generations to meet their own needs' [WCED, 1987].*

Improvement analyses which aim merely to improve environmental accountability with approaches which are not sustainable do not display sufficient initiative. To this end, the aims of the improvement analysis should focus on meeting the needs of the present without compromising the ability of future generations to meet their own needs. Environmental sustainability provides a benchmark on which to base criteria for life cycle improvement analysis; a purposeful and challenging goal which is more rewarding than abstract and ambiguous attempts to 'lessen environmental burdens'. An unrestrained improvement analysis leaves too much scope for individual interpretation and poor judgement values.

Many LCA studies get little further than the inventory analysis stage, centred too much on quantifying energy and resource flows within a system. Progression to the impact assessment stage presents numerous challenges in agreed approach to the qualification of environmental impact. Further difficulties are experienced when improvement analysis demands realistic and practical solutions, providing strategic frameworks for action and continued commitment to provision of products, processes and activities which are environmentally benign.

The following analysis seeks to identify future improvements which may be practically and realistically implemented, highlighting problems which, as yet, remain unresolved. Much of the following discussion, rather than providing definitive solutions, poses questions to which the answers demand further research activity. No LCA, in its generic form, aims to answer all possible questions arising. LCA is a commitment to ongoing improvement, and in some instances merely furnishes the researcher with the 'right' questions to ask; questions which may be addressed in a second, third, or fourth iteration of research techniques.

9.2 BREEAM

With respect to assessment of buildings, the Building Research Establishment Environmental Assessment Method (BREEAM) [Birtles, 1997] identifies three main areas under which to group environmental issues, and which co-ordinate well with both LCA initiatives and the assessment of multi-glazed window design:

- Global issues and use of resources
- Local issues
- Indoor issues

Indoor issues of thermal, aural and visual working environments are well-documented in chapters 4-6. Global issues and use of resources have been discussed, in part, throughout chapters 7 and 8. A more detailed assessment and an outline of steps that can be taken to make the processes and activities involved more benign, are discussed herein.

9.3 LCA valuation

Volkwein and Klopffer [1996] laid out steps for LCA valuation, providing general principles on which to base improvement analysis. Their first point of reference with regard to sustainable development and the improvement of products, processes and activities is a very basic one. Article 3 of the Universal Declaration of Human Rights, December 10, 1948, states that each human being is guaranteed the 'right to life'. Human rights with a direct relationship to environmental issues are limited, but all human rights are an extension of the right to life. The right to attain the highest standard of physical and mental health, and the right to a healthy environment provide the basis of environmental initiatives and improvement criteria. Therefore, to be in accordance with these basic principles, requires environmental standards and precautionary goals. To meet goals of this nature requires decision making criteria and appropriate valuation methods. Table 9.1 shows possible product or process impacts by category, and lists the environmental aspects that demand attention if pollution is to be minimised. It is not intended to be an exhaustive list.

9.4 Improvement criteria and LCA

The Environmental Protection Agency [EPA, 1993] provide a comprehensive basis for design considerations within an LCA study. Seven key areas of focus are identified, as illustrated in Figure 9.1, setting a framework for improvement analysis. Each of these design criteria are discussed herein, and applied to the LCA of multi-glazed windows. Three key domains for reducing the impact of product life cycles are identified in Figure 9.1; products, materials, and management issues.

9.4.1 Products

Extending the useful life of a product means that fewer units are required over a given period of time to satisfy the same consumer need. The useful life of a product can be extended in a number of ways, all of which are dependent upon design criteria and quality of manufacture:

9.4.1.1 *Durability*

Durable items can withstand wear, stress and environmental degradation over long life cycles, but may demand material substitution, or increased use of material resources to achieve this. Optimisation of material use and performance is therefore required to analyse the cost-benefit analysis of use of resources. The term 'cost' is used with care, and should be interpreted as energy and environmental cost, rather than monetary cost to producer/consumer. Analysis should adopt a sensitive approach; design of products to perform beyond a realistic period of time is wasteful, whilst development of highly durable products which are subject to rapid technical change should be avoided. Materials should only be as durable as required.

Several initiatives are adopted in the production of multi-glazed windows. Impregnation of timber with water based preservatives limits timber deterioration due to weathering, fungi and insects, and minimises maintenance requirements in building-situ. Without this impregnating process the useful life of a window would be prematurely cut short. Likewise, the addition of aluminium cladding to the exterior of a window unit assists water run-off, preventing excess water damage, and reducing maintenance requirements. Aluminium is however an energy intensive resource to extract and manufacture. Further analysis is required to assess the benefit in terms of window unit longevity and the additional energy and material consumption associated with production of cladding.

9.4.1.2 Adaptability

Adaptable products make allowances for continual improvement and upgrading and/or may be used for more than one function. Designing for adaptability in products allows extended/alternative use of goods that would otherwise become obsolete before they are worn or degraded. Issues of adaptability are perhaps not most appropriate to window design. Windows serve to transmit daylight, permit ventilation, and provide a view to the outside, and whereas design of windows is competitive, it is not subject to rapid technological change. Principles of adaptability are of more concern within the process and manufacturing domain, than that of product design.

9.4.1.3 Reliability

Reliable products are able to meet performance criteria for a defined period of time, in an environment for which they were designed, without failing. This is often expressed as a probability, and is inextricably linked to issues of quality and manufacture. Reliability is something which is designed into products, not assessed as a statistical exercise prior to customer delivery.

In the current LCA, facilities are provided to test the reliability of window units produced. A sample number of windows are rigorously tested for mechanical performance, weather penetration and quality of finish. What is unknown, however, is the efficiency with which seals on glazing units withstand gas permeation. The assumption is made that the thermal, aural and visual properties possessed by a unit on leaving the factory gate, are maintained over the whole window life. Further investigation is required to ascertain the level of degradation of properties. If inert gas is lost from the glazing cavity very quickly, then the optimum window design in terms of thermal, aural and visual function, and in terms of energy consumption and greenhouse gas emissions will differ from the results presented in this thesis.

9.4.1.4 Maintenance

Products which are easily and practically maintained reduce the time required for repairs and preventative work. Labour requirements for products which are accessible and simply designed impose fewer demands on the owner/consumer, and raise the probability of products providing reliable performance for the duration of designed life. Maintenance requirements for windows were outlined in Chapter 7, but are generally outwith the control of the supplier. The frequency with which windows are treated over a life cycle is under the jurisdiction of the building manager, although manufacturers advise is of key importance. It is the responsibility of the manufacturer to ensure that standard components are adopted to ease replacement, and that access is simplified wherever possible.

9.4.1.5 Repairs

Products which allow the replacement of dysfunctional parts with ease, speed the return of systems to normal operating conditions, limiting down-time, and having little impact on operating efficiency. The age of the system and the probability of failure of other, or complimentary parts will define whether new or used parts are adopted in the repair. The same principles which apply to the maintenance of windows are applicable to the repair service also.

9.4.1.6 Reuse

Reuse of a product or part, once retired from a clearly defined duty, employs efficient use of resources but poses many questions about collection, transportation, processing and waste. Full analysis of the reusability of products demands an independent LCA study to assess the associated costs and benefits. Reuse of window units was demonstrated by the BRE in construction of an office building from demolition waste [Hobbs and Collins, 1997]. As the first demonstration of its kind in the UK, the exercise served to provide valuable information on technical and economic uncertainties, but also highlighted a number of research needs. In particular, the need for better and more reliable data on materials arising from construction and demolition waste, both nationally and regionally. Issues of quality control need to be addressed in order to promote further initiatives, and assure builders of material performance. At the heart of the issue there is a need to set up and maintain a management infrastructure to assist greater reuse and recycling.

9.4.1.7 Remanufacture

Remanufacture of parts is an industrial process which restores worn units to like-new condition. Although no known facility exists for the remanufacture of window units, several component parts lend themselves appropriately to this process. Remanufacture of ironmongery incorporated in the window unit would reduce the need for virgin materials. The ability to provide this service is, however, a function of availability of old/used parts, existence of a trade network, collection and transportation facilities, and storage of both used and remanufactured components. The analysis involved in carrying out such an investigation merits the development of an independent LCA.

9.4.2 Materials

Extending the useful life of materials used to manufacture products and components can have a significant effect on the outcome of an LCA study. Energy embodied in material sourcing and processing, prior to manufacturing, is often the dominant source of environmental burdens in an LCA, either directly, or indirectly via fuel extraction and combustion to generate energy. There are several means by which the useful life of materials can be extended:

9.4.2.1 Substitution

Material substitution may be restricted by the need to use existing operating plant, but having capital equipment that may be adapted for a number of working materials enables a wider choice of markets to be sourced, and more informed decisions about the environmental impact of materials to be made. Additional capital expense may be required, but may be considered in the light of a full analysis of environmental costs and benefits. In all material substitution, shifting of an environmental burden from one stage of a life cycle to another must be avoided. There is little benefit to the overall life cycle of selecting materials which are easily produced and machined, and which are easily sourced in close proximity to the factory site, if they require constant maintenance and are irrecoverable at the end of a product's useful life. Any material substitution must be worked through the entire life cycle to assess total benefit/detriment to the environment. The optimisation models developed in this thesis provide a framework for these investigations.

In the current LCA the optimisation models developed highlight the need to avoid use of very heavy inert gases like Xenon. The benefits associated with improved U-value and reduced space heating requirements are not justified in terms of the energy and material resource requirements of manufacture. Use of the optimisation models to perform a comparative LCA study between the manufacture of UPVC, aluminium and timber framed windows, for example, would highlight the importance of material selection upon associated environmental burdens.

9.4.2.2 Recycling

Complete products or component parts may be regenerated in one of two ways. Closed loop recycling recovers materials that are suitable substitutes for virgin materials, and which are used to manufacture the same product or component again. Open loop recycling recovers materials a finite number of times before final disposal. Under ideal circumstances materials would be recovered numerous times until resources become too degraded to be of practical use. There are several design considerations associated with recycling. Components which are easily disassembled reduce processing and handling costs, while strategic and reliable material identification saves wasted time on analysis and testing. Knowledge of material compatibility is also an advantage, since material substitution can be allowed for, and production processes modified accordingly.

The components of a multi-glazed window unit lend themselves appropriately to recycling, since minimal handling would be required for disassembly. Both glass and aluminium are highly recyclable materials. In some applications the energy requirement to smelter recycled aluminium requires just 5% of the energy consumed in primary smelting, and the quality of the recycled aluminium is not inferior to the primary metal [UNEDO, 1989]. Broken window glass is used in the manufacture of fibreglass. Energy savings in producing insulation materials using waste window glass, compared to raw materials are significant [Buchanan & Honey, 1992]. Transportation, collection, processing, plant availability and management issues do, however, currently remain an obstacle to widespread recycling initiatives [Hobbs and Collins, 1997] [WRF, 1995].

9.4.2.3 Reduced material intensiveness

Conservation of material resources can result in less waste and reduced environmental impact. A material which is manufactured from smaller quantities of material is likely to be lighter in weight, and therefore requires less packaging and reduced transportation energy. The effect of varying the size of multi-glazed windows impacts on more than just material and energy consumption. Building performance is substantially influenced by window size. The impact of varying window size was investigated using the optimisation models developed in this thesis, although further consideration could be given to the transportation requirements of reduced material demand and lighter finished products.

9.4.3 Management issues

Product design factors and material selection issues are important to improvement analysis work. Additionally, management issues are central to environmental improvements. The planned use of materials and energy, and associated efficiency with which processes are carried out, impact heavily on LCA results.

9.4.3.1 Process substitution

Designers should be aware of the best available technology to perform a manufacturing requirement. Processes which create major environmental burdens should be replaced by more benign ones. Application of the best available technology limits material waste and inefficiencies in product and resource handling.

9.4.3.2 Process control

Control processes which suppress the influence of external disturbances and which ensure good performance stability should be adopted where practicable. Consideration should also be given to the layout of processes, such that output is consistent and efficient, and accident risks are reduced to a minimum.

9.4.3.4 Energy efficiency

Use of energy throughout the production process should be viewed holistically. Wherever possible heat losses from one system should be used to perform work in other processes. The provision of services should also be energy efficient, adopting the best available technology.

Combustion of fossil fuels remains the dominant source of greenhouse gas production throughout each stage of the current LCA, although minor manufacture processes generate small quantities of emissions independently. The focus of an improvement analysis is, however, upon reducing the most dominant environmental impacts. Appropriate use of energy resources in terms of energy conservation and selection of fuel sources is central to an improvement analysis. Priority is given towards renewable energy sources which minimise production of greenhouse gases and limit emissions which cause acidification of water bodies.

In the current LCA, generation of all electrical energy was based upon the UK mix of energy supply plant for ease of comparison. At the manufacture site of Nor-Dan in Moi, Norway, however, the supply of electricity comes from an energy structure which is 99.7% hydro-electric power. Table 9.2 lists the environmental burdens associated with *coal fuel cycles, while Table 9.3 lists those associated with hydro-electric power cycles.* Environmental damage associated with transmission of power is common to both generating plant types. Whereas the hydro-electric power cycle impacts upon ecology and human health, the coal fired generating cycle impacts additionally upon social, economic, global and other non-environmental factors. Hydro-electric power neither generates greenhouse gas emissions nor depletes fossil fuel resources. Sustainable and renewable energy resources and are beneficial to LCA results, highlighting the importance of manufacture location upon total global and regional effects. The principles associated with selection of responsible suppliers are reiterated here.

9.4.3.5 Inventory handling

Appropriately controlled resource and material handling whereby overstocking is eliminated limits waste due to spills and deterioration.

9.4.3.6 Facilities management

Flexible manufacturing principles can extend the useful life of facilities and equipment.

9.4.3.7 Packaging

The same principles of material substitution, recycling, reuse, product changes and use of reduced material intensiveness apply to packaging as well as finished products. Packaging and products should be designed to compliment each other, and wherever practically possible, the use of packaging should be eliminated.

9.4.3.8 Transportation

Where transportation of materials, finished products, waste or recycled resources is necessary, a number of considerations are offered. Reduced air pollution and emissions result directly from maximising vehicle capacity, and in back-hauling materials, eliminating empty journeys. Ensuring that products are properly contained reduces the risk of waste due to breakages on a journey, and consideration should be given as to the most appropriate route.

In the current LCA there are significant improvements which could be made in terms of transportation, particularly to the UK. The number of handling processes and different carriers required are numerous, and breakages are commonplace. Improved management whereby one carrier is responsible for delivery would limit risk of breakages.

Jorgensen et al [1996] investigated the importance of transportation in a range of LCA studies, drawing a number of conclusions. In none of the LCA's did transport contribute less than 5% of the energy related interventions or impacts, whereas contributions with more than 10% occurred regularly. The importance of transport is strongly influenced by product type. The authors emphasised that a contribution to energy consumption and CO_2 emissions cannot generally be used as indicators of the contribution of transport to environmental impacts, but that influences on CO, NO_x and hydrocarbon emissions are a better measure of importance. Transportation is of special interest when considering the impact categories of global warming. A strong requirement for further research is highlighted. Products which have more serious implications on the environment as a result of transportation needs possess different characteristics to those products which impose little impact. The importance of the disposal phase of a product, with particular reference to whether materials/products are recycled, continues to present the analyst with many unknowns. Research is in its infancy, but as LCA's gain widespread use, there is an increasing demand to investigate the detrimental effect on recycling initiatives due to transportation needs.

With respect to the current LCA, transportation energy requirements would appear to be relatively small compared to the extensive energy consumption on space heating and artificial lighting over a twenty year period. There is a danger in this that the environmental impact of transportation requirements is belittled and not given appropriate attention. If, however, the impact of space heating and artificial lighting is removed from the analysis, limiting assessment to material sourcing, manufacture and site delivery, transportation energy accounts for as much as 3% of total energy consumption. This value increases if appropriate consideration is given to disposal/recycling of materials upon window replacement. Making this comparison in terms of carbon dioxide production only reiterates the problem which Jorgensen et al [1996] highlights; that of ignoring the more serious impacts of nitrous oxides and hydro-carbon emissions. Focusing purely on nitrous oxides, transportation within the current LCA accounts for a minimum of 16% to a maximum of 66% of total NO_x production over window life. This is a significant contribution, demanding preventative action, and strategic improvement initiatives.

9.4.3.9 Selection of suppliers

Selection of environmentally responsible suppliers can significantly influence the environmental impact of a product's life cycle. Processes, activities and selection of materials further up the product development and component manufacturing tree can have a larger detrimental effect upon local and global environments than the final product itself. Significant impacts must be accounted for throughout all stages of the life cycle [WRF, 1995]. Where information was available, all major suppliers have been accounted for in the current LCA. Where lack of information prevailed, literature has been cited, and appropriate assumptions made. A balanced approach is required when sourcing materials. There is little benefit to be gained from selection of materials and components from responsible suppliers, if the transportation requirements necessary generate an imbalance in transport emissions.

9.4.3.10 Product labelling

Once a full LCA has been carried out, product labelling provides the consumer and retailer with information which allows them to make an informed choice. Labelling of products is a contentious issue however. All claims need to be backed up with scientific evidence, and require to be stated on a common basis. Eco-labelling initiatives provide a common basis on which to compare products, but as pointed out in Chapter 3, they do not go far enough to be considered a full Life Cycle Assessment. The provision for ranking products in order of environmental impact has been in place for some years. The decision to purchase electrical goods, like refrigerators, can now be made in terms of their electrical energy consumption over an annual period. Generally, more efficient refrigerators have a higher associated capital cost, but reduced running costs. No consideration is given, however, towards the energy and material consumption required to manufacture the product, and neither is information on reuse or recycling given at the point of sale. Windows would fall appropriately into the same kind of ranking system, but care must be taken to include consideration of each stage in the window life cycle, such that profligate use of energy during manufacture is accounted for, and weighted against the benefits available throughout window use. For example, a simple analysis would show that a triple glazed, Xenon filled window would be optimal in terms of thermal losses, but a full LCA study would highlight associated environmental costs in the light of such benefits.

Perhaps more efficient than the labelling of products would be the improved provision of education to building managers and domestic consumers to reduce the energy requirements of buildings. Lowering the prevailing temperature of a building interior by just 1°C can generate a 10% saving in energy consumption annually [Somervell & Talbot, 1991]. More frequent use of lighting control strategies would also limit profligate energy use on electric lighting and limit subsequent greenhouse gas emissions associated with the generation of electricity.

9.5 Summary

The above improvement analysis is not intended to be exhaustive, but addresses the main sources of environmental burden associated with the production of multi-glazed windows; those of energy requirements and efficiency, use of materials and transportation.

Possible initiatives to reduce the environmental burden of product life cycles are varied and numerous. The LCA of multi-glazed windows extends across a number of disciplines, incorporating a wide range of principles and offering unnumbered solutions to problems experienced currently. Research of all disciplines is not currently of sufficient stature to provide all the answers required, but adoption of the principles laid out in this thesis, and those outlined for future consideration above, will help reduce the environmental impacts imposed by today's operations and management, such that resources may be reserved for future generations.

Aggregating the above sustainable development criteria into the mind map developed in Chapter 2/ Figure 2.3 provides a complete and holistic view of the design parameters considered in this thesis. The final mind-map for Life Cycle Assessment of multi-glazed windows for sustainable buildings is illustrated in Figure 9.2. The complex nature of the analysis required in a comprehensive LCA can be seen. The need for several iterations of the analysis to reduce the number of unquantified/unqualified elements and the need for further research is highlighted. Organised environmental management systems which manage data acquisition and analysis efficiently is to be encouraged. Use of the optimisation models developed in this thesis will simplify ongoing research initiatives and provide both the foundations and the framework for ongoing investigations and further iterations of the current work.

9.6 References

1. Birtles, A., Environmental impact evaluation of buildings and cities for sustainability, Evaluation of the built environment for sustainability, Editors Brandon, P.S., Lombardi, P.L. and Bentivegna, V., Chapman & Hall, London (1997).
2. Buchanan, B.G. and Honey A.H., Environmental impacts of the New Zealand Building Industry, Department of Civil Engineering, University of Canterbury, New Zealand, Research report 92/2, June (1992).
3. EPA United States Environmental Protection Agency, Life cycle design guidance manual: environmental requirements and the product system, Office of Research and Development, Washington, January (1993).
4. Hobbs, G., and Collins, R., Demonstration of reuse and recycling of materials: BRE energy efficient office of the future, BRE Information Paper IP 3/97, (1997).
5. Jorgensen, A.M., Ywema, P.E., Frees, N., Exner, S. and Bracke, R., Transportation in LCA; a comparative evaluation of the importance of transport in four LCAs, International Journal of Life Cycle Assessment, 1 (4) 218-220, (1996).
6. Loe, D. and Davidson, P., A holistic approach to lighting design, Energy Management, Sep/Oct 16-18, (1996).
7. Pearce, D., Bann, C. and Georgiou, S., The social cost of fuel cycles, Centre for Social and Economic Research on the Global Environment, CSERGE, DTI, London, (1992).
8. Somervell, D. and Talbot, R., Educated Energy Management, University of Edinburgh, Chapman & Hall, (1991).
9. UNEDO, Industry and development - Global report 1989/90, United Nations Industrial Development Organisation, Vienna, (1990).
10. Volkwein, S. and Klopffer, W., The valuation step within LCA; Part I: General principles, International Journal of Life Cycle Assessment, 1 (1) 36-39, (1996).
11. WCED World Commission on Environment and Development, Our Common Future, Oxford Press, Suffolk, UK, (1987).
12. WRF World Resource Foundation, Information Paper: Life Cycle Analysis & Assessment, Warmer Bulletin, August (1995).

Table 9.1 Environmental impacts by category and improvement criteria [Volkwein and Klopffer, 1996]

Environmental impact	Focus of improvement criteria
resource depletion	**prioritise renewable resources** **develop appropriate management systems** **combat land degradation** **ensure clean drinking water**
water resources	**sewage treatment facilities** **avoidance of harmful pesticides** **eradication of water-borne diseases**
land use	**planning of land use**
global warming	**stabilisation of greenhouse gas concentrations**
Ozone depletion	**reduction in chlorine loading within the atmosphere**
acidification	**reduction of emissions causing acidification of water bodies**
waste	**prioritise avoidance of waste at source** **prioritise on recycling initiatives**
toxicity	**phase out use of toxic chemicals**
nuisances (noise, odour)	**no specific environmental goals**
safety and hygiene at work	**Health & Safety guidelines** **preventative management strategies**
energy	**prioritise use of renewable energy sources**

Table 9.2 Global, regional and local impacts of the coal fuel cycle [Pearce, et al, 1992].

CYCLE STAGE	EMISSIONS/BURDENS	IMPACT	IMPACT TYPE
MINING	dust noise/vibration methane emissions subsidence erosion water consumption siting sedimentation chemical pollutants trace metals risk of accidents	mortality morbidity	Human Health
BENEFICATION	liquid/solid waste air emissions dust leachates	crops forests commercial fishing recreation biodiversity	Ecological
STORAGE	siting risk of spontaneous combustion visual impact surface water runoff leachates	building materials land water visual amenity noise nuisance public services quality of life effects	Social Economic
TRANSPORTATION	noise risk of accidents road wear	noise nuisance quality of life effects	Social Economic
POWER STATION	air emissions siting water disturbance thermal pollution fly ash solid waste	energy security liability limits R&D subsidies non-fossil fuel obligation occupational health & safety infrastructure costs admin. costs global warming	Non- environmental Global
TRANSMISSION	electromagnetic effects visual intrusion siting	nuisance possible health effects	Social Economic Human Health

Table 9.3 Global, regional and local impacts of the hydro-electric power cycle [Pearce, et al, 1992].

CYCLE STAGE	EMISSIONS/BURDENS	IMPACT	IMPACT TYPE
DAM & POWER STATION	land irreversibly flooded siltation thermal stratification micro-climate changes impacts on natural habitats risk of dam rupture seismic activities landslides visual impacts	mortality morbidity biodiversity crops forestry commercial fishing recreation land water visual amenity quality of life effects	Human Health Ecological Social Economic
TRANSMISSION	electromagnetic effects visual intrusion siting	nuisance possible health effects	Social Economic Human Health

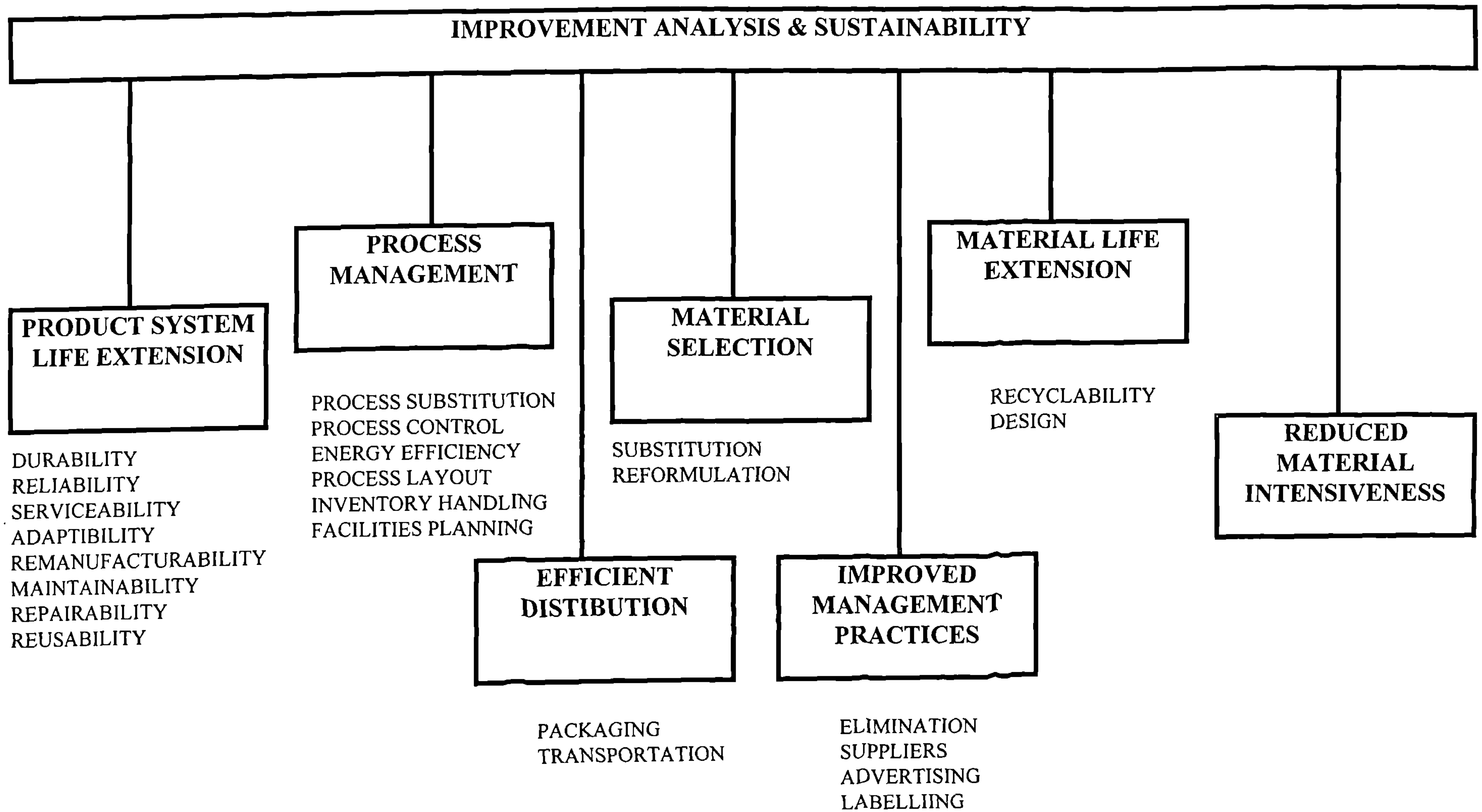


Figure 9.1 Improvement analysis and sustainability design criteria

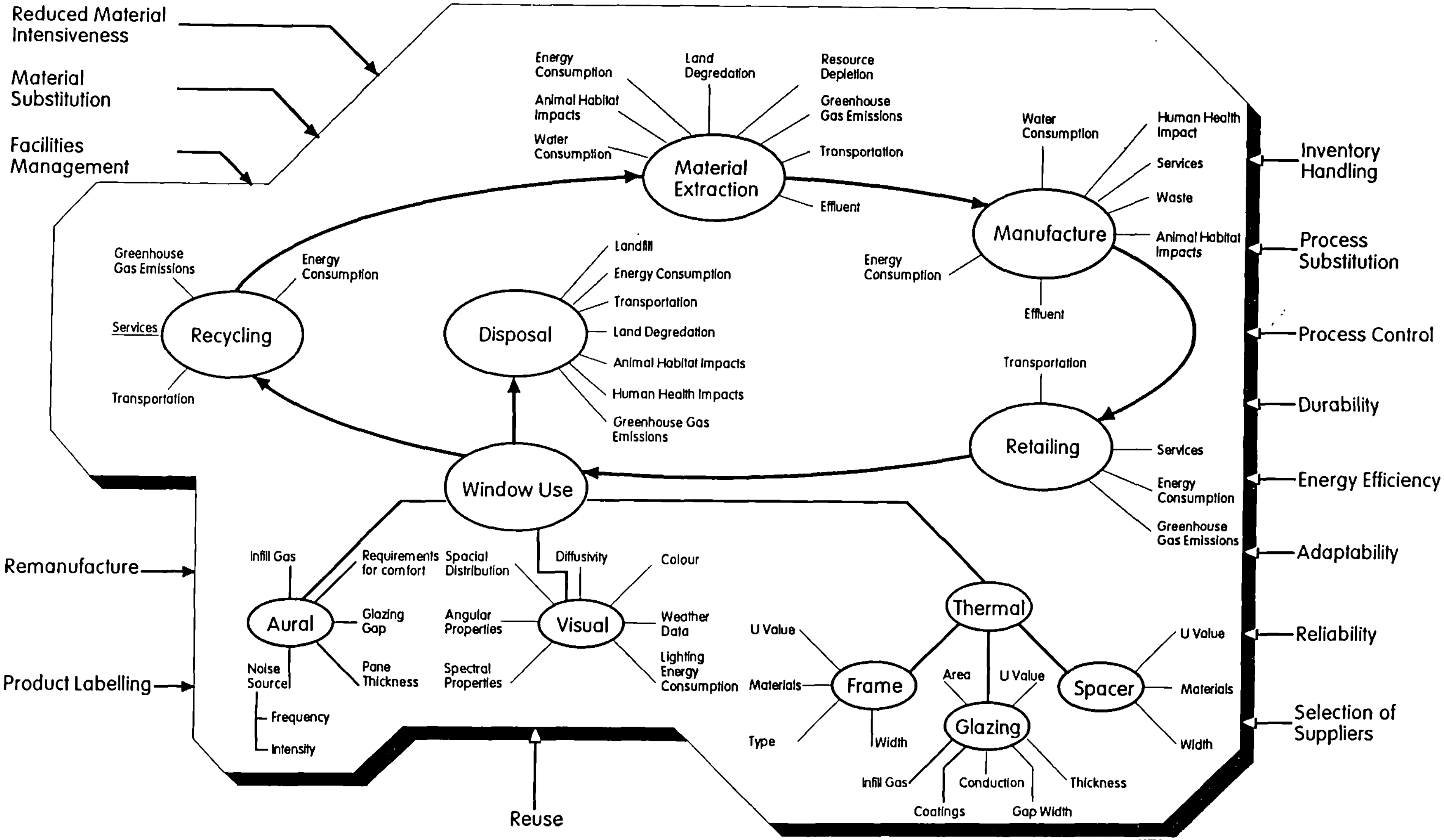


Figure 9.2 Mind map for LCA of multi-glazed windows for sustainable buildings

10. Conclusions

This research set out to achieve a number of specific objectives. The principal objective was to develop a methodology for LCA of multi-glazed windows for use in sustainable buildings. To do this, a multi-disciplinary procedure by which windows are designed and selected, such that energy and material consumption are optimised, and global environmental impact is minimised, was demanded. A number of tools were developed to simplify the analysis, and provide a standard methodology for window evaluation.

The main conclusions include:-

10.1 Definition of a multi-disciplinary methodology

Using LCA techniques, a multi-disciplinary methodology has been developed to aid architects, building services engineers and environmentalists in the design and selection of multi-glazed windows. Discussion of the major influencing factors affecting building occupant comfort in terms of the thermal, aural and visual environment, is also presented to provide a comprehensive understanding of the complex design criteria necessary in creating productive working environments. A summary of a thorough review of current literature relating to the thermal, aural and visual environment is presented in each case. This, together with the comprehensive range of models presented in this thesis may be applied to any window type, size or construction, and may be used to select windows for any building location, orientation or use.

10.2 Development of working models to aid analysis

Three working models are presented to assess the performance of multi-glazed windows. Models may be adapted to include any number of window constructions with known physical properties.

10.2.1 Thermal performance

For a window of any given U-value, dimensions, or proportion of building facade, the space heating input required to maintain the occupied building at any given environmental temperature may be calculated on an annual basis using MET office temperature data.

10.2.2 Aural performance

For a window of known construction, frequency dependent values of airborne sound insulation may be calculated and converted into a single number characterising the acoustical performance of the window. Models may be used to identify window constructions which provide a required level of sound insulation, or to select a single window construction which offers the best achievable sound insulation from a selection of available window options.

10.2.3 Visual performance

For any known window construction the electrical energy consumption of lighting demand associated with on-off and top-up lighting control strategies, over an annual period, may be calculated. Light transmission properties for twelve common window constructions are offered in this thesis, in both tabular and graphical format, which were not previously available in published form.

10.3 Acquisition of inventory analysis data

This research work involved detailed measurement and audit work at the sites of Pilkington Glass UK and Nor-Dan Window and Doors, and has provided inventory analysis and impact assessment data which was not previously available. Analysis of raw material depletion, and energy consumption for sourcing, preparing, manufacturing and transporting materials and finished products, is presented.

10.4 Development of optimisation techniques

A valuation procedure is offered which ensures that the thermal, aural and visual comfort of occupants is exploited to a maximum, without profligate use of energy or emission of excessive greenhouse gas quantities. Three optimisation models are presented, which may be used in three ways:

- to aid designers in the identification of a selection of windows which meet a given design criteria
- to select one window which provides the best performance from a number of alternatives
- to provide data on a selected window design for building/component rating purposes

10.4.1 Optimisation of energy consumption over window life

The embodied energy associated with extraction and preparation of raw materials, manufacture of finished window units, transportation at all stages, and all administration demands, is summed with the energy consumption required to heat and light a given building to a comfortable standard, over window life. The energy consumption optimisation model relies on data from the inventory analysis, thermal analysis and visual analysis models.

10.4.2 Optimisation of environmental impact over window life

Optimisation of environmental impact is based upon energy consumption over window life, and provides the designer with a means of calculating the total greenhouse gas emissions emitted over window life, as a direct result of fossil fuel combustion for both electrical energy demand and natural gas space heating, and emissions resulting from transportation.

10.4.3 Comfort, energy and environmental impact optimisation

In the form of a flow diagram, this optimisation allows the designer to specify the aural, thermal and visual conditions required within a building, and to evaluate the energy consumption and greenhouse gas emissions resulting from the selection of a particular window design, or range of designs.

The above mentioned optimisation models were not previously available. Calculations involved in performing an analysis of this nature are necessarily complex, and time consuming. Data acquisition is also difficult and time consuming. Therefore, the supply of data and computer models to architects, designers and engineers provides vital information which can ensure that more sustainable building initiatives are established and maintained. Information generated by the models, integrated with designer knowledge, will permit sound judgment with regard to design and selection of windows. Although further work is required to refine the quality of data input to the optimisation models, a comprehensive framework on which to build future improvements has been provided.

10.5 Optimisation results

For the range of single, double and triple glazed window options offered in this work, and for the example building described in Chapter 4, where the window area is 60% of the south facing facade, and the window life is assumed to be 20 years, the optimal window construction, in terms of energy consumption and greenhouse gas emissions was found to be:

4e-12Ar-4-12Ar-e4	triple glazed window with two 12mm glazing gaps, filled with Argon gas, and two low-emissivity glazing coatings.

It is highlighted, however, that the models should not be used in isolation of sound engineering judgment. Account should be made of less quantifiable effects, including perceived comfort and satisfaction with the indoor environment, as presented in this thesis throughout Chapters 4-6.

The impact on total energy consumption over window life of applying low emissivity glazing coatings was assessed using the energy optimisation model developed in Chapter 8. It was found that an 18% saving (54.5 GJ) in total energy consumption was achievable with the application of low-e coatings to both panes of a double glazed window unit having a 16mm Argon filled cavity (based on a glazed proportion of 60% of the example office layout). The additional energy requirement for materials and manufacture of the low-e coatings is just 91MJ, or 2.79% of the embodied energy of materials, manufacturing and transportation. These benefits are reflected in the global environmental optimisation model also; reduction in energy consumption at any stage of a product life cycle has knock on benefits for the global environment in terms of greenhouse gas production and conservation of finite resources.

A general trend was found throughout the energy consumption and global environment optimisation models, relating to material selection and window design. Windows which possess poor thermal insulating properties are characterised by a predominant energy requirement for space heating over window life. Windows which provide superior thermal insulating properties by use of highly energy intensive materials in construction are characterised by a predominant energy requirement in material sourcing and manufacture.

Design life was also found to be critical to window selection. Windows designed for longevity should possess good thermal insulating and daylight transmission properties, as the impact of using materials with higher energy contents is off-set by reduced requirement for space heating and artificial lighting energy consumption.

Window size is also important in design selection. For larger glazed areas, the benefit of using heavy inert gases like Xenon are outweighed by the environmental cost of energy embodied in materials.

10.6 Future work requirements

Numerous recommendations for future research activities were highlighted in Chapter 9, resulting from an in-depth analysis of improvement requirements and sustainable development criteria. Recommendations are made with respect to product durability, reliability and reuse, material substitution, recycling and intensiveness, transportation requirements, and data availability. The recommendations made as a result of this research work are summarised as follows:

10.6.1 Product longevity

Designing products which are durable increases longevity and reduces maintenance requirements. The benefit/detriment to the environment of producing aluminium cladding for exterior use on multi-glazed windows requires to be investigated using the *optimisation* models developed in this thesis.

10.6.2 Product reliability

Similarly, the efficiency with which glazing unit seals withstand gas permeation impacts upon product reliability. Further investigation is required to assess the level of degradation of materials and their properties.

10.6.3 Product reuse

A number of technical and economic difficulties are encountered in product reuse initiatives, highlighting several research needs:

- better and more reliable data on materials arising from construction and demolition waste is required
- quality control issues need addressing to reduce skepticism and assure builders of material quality and performance
- a management infrastructure to assist in greater reuse and recycling initiatives is demanded

10.6.4 Materials substitution

Extensive use of the optimisation models developed in this thesis would provide missing information and data relating to the feasibility for material substitutions. In particular, there is a need to compare the total environmental burden resulting from the life cycles of aluminium, timber and UPVC framed window designs. This would address the distinct lack of data, information and knowledge in this field.

10.6.5 Transportation

Transportation, collection, processing, plant availability, and management issues remain an obstacle to widespread recycling initiatives. Numerous unknowns cause widespread cynicism, and detract from the benefits of recycling. A particular requirement for data on transportation requirements within the recycling industry, and other stages of product cycles is expressed.

10.6.6 General availability of information

The greatest barrier to ongoing research in Life Cycle Assessment of any product, process or activity is the availability of reliable data of high quality. As the number of LCA's being carried out grow in number, and the technique gains general recognition as an objective assessment tool, capable of providing dependable information for decision making, the global database of available information will expand, and industry will benefit from increased confidence and improved efficiency. This research work not only serves to provide information and data that was not previously available, but provides a dependable methodology for the evaluation of multi-glazed windows, which may be adapted for numerous applications; it provides the foundation for new research initiatives and investigations.

Bibliography

1. Adams, M.S. and McManus, F., Noise and Noise Law: A practical approach, Wiley Chancery Law, London, (1994).
2. Aronoff, S. and Kaplan, A., Total workplace performance: rethinking the office environment, WDL Publication, Ottawa, Canada, (1995).
3. Buchanan, A. and Honey, B., Energy and carbon dioxide implicatins of building construction, Energy and Buildings, (20), 205-217, (1994).
4. Button, D. & Pye, B. (editors), Glass in Buildings, Butterworth Architecture, Pilkington Glass Ltd., (1993).
5. Cawthorne, D., Buildings, lighting and the *biological clock*, *The Martin* Centre for Architectural and Urban Studies, University of Cambridge (1991).
6. CIBSE Code for Interior Lighting, Yale Press Ltd, London (1984).
7. Environmental impact evaluation of buildings and cities for sustainability, International workshop proceedings, University of Florence, 13-15 September (1995).
8. EPA United States Environmental Protection Agency, Life cycle design guidance manual: environmental requirements and the product system, Office of Research and Development, Washington, January (1993).
9. Fanger, P.O., Thermal comfort: analysis and applications in environmental engineering, McGraw-Hill Book Company, London, (1970).
10. Field, F.R. III, J.A. Isaacs, and J.P.Clark, Life-Cycle Analysis of automobiles: a critical review of methodologies, Journal of Minerals, Metals and Materials Society, 46 (4), (1994), pp 12-16.
11. Glass and noise control, Pilkington Glass Products, CI/SfB (31), July (1995).
12. Loe, D. and Davidson, P., A holistic approach to lighting design, Energy Management, Sep/Oct pp16-18 (1996).
13. Parsons, K.C., Human thermal environments, Taylor and Francis, London, Chapter 10: Interference with activities, performance and productivity, 119-217, (1993)
14. Pearce, D., Bann, C. and Georgiou, S., The social cost of fuel cycles, Centre for Social and Economic Research on the Global Environment, CSERGE, DTI, London, (1992).
15. Society of Environmental Toxicology and Chemistry (SETAC), Life-cycle assessment: workshop report, Brussels, (1992).
16. UETP-EEE: The Finnish Association of Graduate Engineers, Environmental assessment of products: a course on life cycle assessment, ed B. Pedersen, (1995).
17. Wackernagel, M and Rees, W., Our ecological footprint: reducing human impact on the earth, The news catalyst bioregional series, New Society Publishers, Philadelphia, (1996).

Appendix A: Fanger's thermal comfort equation

Fanger's thermal comfort model is based upon the metabolic rate, efficiency and area of the human body, the air temperatures, air humidity and mean radiant temperature of the indoor environment, and the area of the body covered with clothing, and the heat transfer coefficient and temperature of the clothing worn. These variables combine to give the following relationship, on which Fanger's thermal comfort theory is based:

$$\frac{M}{A_{Du}}(1-\eta) - 0.35\left[43 - 0.061\frac{M}{A_{Du}}(1-\eta) - p_a\right] - 0.42\left[\frac{M}{A_{Du}}(1-\eta) - 50\right]$$

$$- 0.0023\frac{M}{A_{Du}}(44 - p_a) - 0.0014\frac{M}{A_{Du}}(34 - t_a)$$

$$= 3.4 \times 10\text{-}8\, f_{cl}\left[(t_{cl} + 273)^4 - (t_{mrt} + 273)^4\right] + f_{cl}\, h_c(t_{cl} - t_a)]$$

where **Activity variables**

M	metabolic rate
η	mechanical efficiency (mechanical power / metabolic rate)
A_{Du}	DuBois area

Environmental variables

p_a	air humidity
t_a	air temperature
t_{mrt}	mean radiant temperature

Clothing variables

f_{cl}	ratio of clothed body area to unclothed body area
t_{cl}	clothing temperature
h_c	convective heat transfer coefficient

Using the comfort equation, Fanger developed comfort diagrams to remove the laborious element of calculating multiple variables from the equation parameters. Comfort diagrams are for practical function and ease of use in evaluating variables at sedentary, medium and high levels of activity, varying from no clothing, through light and medium clothing, to heavy clothing levels.

Appendix B: Fanger's draught assessment equation

Fanger's draught model is based upon the mean air velocity of the indoor environment, prevailing air temperature, turbulence intensity of the air, and the percentage of room occupants who are dissatisfied due to the experience of draught sensations. These variables combine to give the following relationship, on which Fanger's draught theory is based:

$$PD = 3.143\,(34 - t_a)(v - 0.05)^{0.6223} + 0.36996\,v\,T_u\,(34 - t_a)\,(v - 0.05)^{0.6223}$$

where	PD	percentage dissatisfied
	v	mean velocity
	t_a	air temperature
	T_u	turbulence intensity

for $v < 0.05$ m/s insert $v = 0.05$ m/s

for PD > 100% use PD = 100%

Appendix C: Percentage People Dissatisfied (PPD) and Predicted Mean Vote (PMV)

Fanger's thermal comfort model was extended to calculate a "satisfaction" rating with the prevailing environmental temperature in an building interior. Predicted mean vote is a measure of how warm or cool a particular environment will feel, expressed as an index. The mean value of votes for a large group of people exposed to the same environment is evaluated on the following thermal sensation scale:

+3	hot
+2	warm
+1	slightly warm
0	neutral
-1	slightly cool
-2	cool
-3	cold

The PMV can be expressed mathematically via computer calculation, or in tabular from via ISO 7730. People differ in their perception of thermal comfort, and individual votes are scattered around the mean value. It is therefore useful to know the percentage of people in a group likely to feel uncomfortably warm or cool. This is established using the percentage people dissatisfied (PPD) index. There is a direct relationship between PMV and PPD, as shown in Figure C.1 below. ISO 7730 recommends that the PPD be less than 10%, corresponding to -0.5 < PMV < + 0.5.

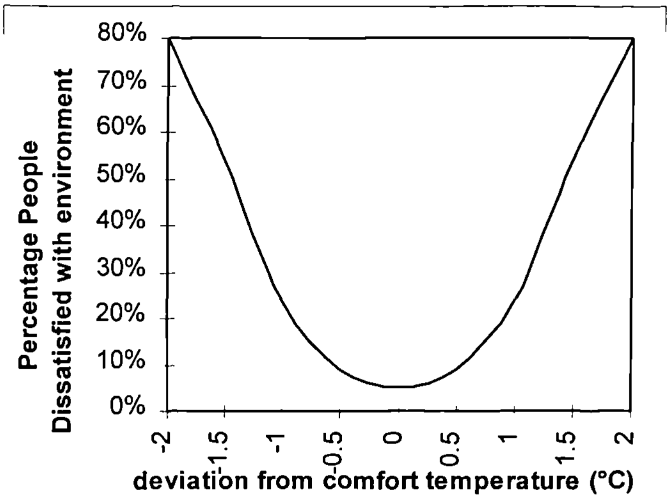


Figure C.1 Percentage People Dissatisfied versus deviation from comfort temperature

Appendix D: Daylight Factor

There are three components to Daylight Factor (DF) :

(a) the component that comes directly from the sky

(b) the component which comes from external reflective surfaces

(c) and the component which comes from interior reflections.

DF is dependent upon time of day, season, orientation of the building, orientation of the room within the building, and the prevailing sky conditions. It is defined as the illuminance at a point on a plane in an interior due to light received directly or indirectly from a sky of known luminance distribution, expressed as a percentage of the illuminance on a horizontal plane due to an unobstructed hemisphere of the same sky. The average DF on a horizontal plane in an empty interior is given by:

$$\text{Average Daylight Factor} = \frac{TW\text{Ø}}{A(1-R^2)} \quad (\%) \qquad \text{D.1}$$

Where

Where	T	Transmittance of glazing material, expressed as a decimal
	W	net area of glazing (m^2)
	Ø	angle (degrees) in vertical plane, subtended by the sky visible from the centre of a window or rooflight
	A	total area of indoor surfaces: ceilings + floor + walls, including windows or rooflights (m^2)
	R	area weighted average reflectance of all indoor surfaces, including windows or rooflights

Example Calculation

for the example office below:

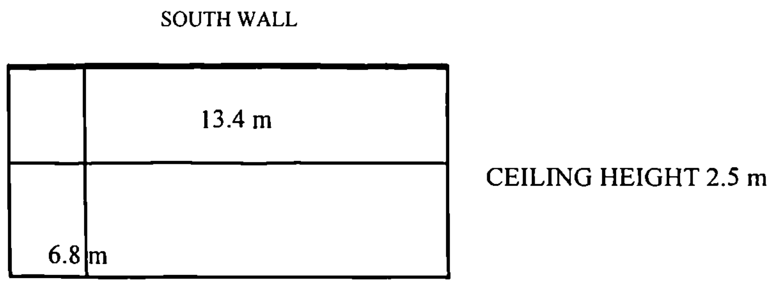


Figure D.1 Office dimensions and layout

Window type	Double Glazed window with Krypton gas-filled cavity (4-12Kr-4)

Transmittance	T	=	0.68
Window Area	W	=	60% of facade area
		=	0.6 * 33.5
		=	20.1 m^2
Angle in vertical plane	$Ø$	=	45°
Total area of surfaces	A	=	6.8*13.4*2 + 6.8*2.5*2 + 2.5*13.4*2
		=	283.24 m^2
Average reflectance	R	=	0.4

Using these typical values,

$$\text{Daylight Factor} \quad DF = \frac{TWØ}{A(1-R^2)}$$

$$= \frac{0.68 * 20.1 * 45}{283.24 * (1-0.4^2)}$$

$$= \underline{\underline{2.59}}\ \%$$

This is a reasonably high value for Daylight Factor within an office space, but is attributed to the large window area (60%) used. A smaller window area (25%), with poorer transmission properties (triple glazed with low-emissivity coating, T= 0.51) would produce a Daylight Factor of 0.81 % for the same office space. A single glazed window with high transmission properties (T=0.82), and the same glazing area (60%) would produce a high Daylight Factor of 3.12%.

Appendix E: Published work

1. Weir, G. and Muneer, T., Energy and environmental impact analysis of double-glazed windows, Proceedings of Green Building Materials '96, Gainesville, Florida, USA, 18-20 June (1996).
2. Weir, G. and Muneer, T., Low-emissivity coatings in high-performance double-glazed windows: Energy, monetary and environmental costs, Building Services Engineering Research and Technology, 18 (2), 125-127, (1997).
3. Weir, G. and Muneer, T., Energy and environmental impact analysis of double-glazed windows, Energy Conversion and Management 39 (3/4) 243-256, (1998).
4. Weir, G., Muneer, T. and Mackenzie, R., Life Cycle Assessment of multi-glazed windows for sustainable buildings, accepted for CIBSE National Conference '98, Harnessing technology for sustainable development, Bournemouth, 18-20 October, (1998).