URBAN RETROFIT BUILDING INTEGRATED PHOTOVOLTAICS [BIPV] IN SCOTLAND, WITH PARTICULAR REFERENCE TO DOUBLE SKIN FACADES

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ABSTRACT

The broad aim of this thesis was to investigate opportunities for retrofit with building-integrated photovoltaics [BIPV] in the Scottish urban environment. The Literature Review presents the relevant research work done in the area of integrating BIPV systems in new and retrofit buildings in the Northern European built environment context. The double skin façade with BIPV was identified as the least explored BIPV retrofit technique. This is where there was a significant gap in knowledge and it was therefore the main research focus in this thesis.

The specific hypothesis regarding the opportunities for retrofit building-integrated photovoltaics [BIPV] applied to a double skin façade construction is that

a) In peak summer conditions, (i) stack driven air movement within the double skin construction will keep the temperature behind the photovoltaic [PV] cells low enough to ensure that loss of PV cells' efficiency is not excessive; (ii) any overheating attributable to the outer skin can be tackled by means of a basic system of mechanical supply coupled with natural exhaust to the double skin;
b) In cold winter conditions, although the thermal input of the photovoltaics is insignificant, the PV electrical contribution is useful relative to the power for fans operating a mechanical warm air supply with significant passive ventilation pre-heat and heat recovery;
c) Although the addition of the double skin façade with BIPV component reduces daylight entering the interior, with careful room design, materials specification and positioning of PV cells, the reduction of daylight is not critical, and the distribution of daylight in rooms can be improved compared to the pre-refurbishment situation.

Having identified a gap in knowledge, the second objective was to select a case study site in a Scottish urban area as representative of typical 'workplace' building with many environmental problems, including opening windows on to a busy street. The third objective was to set up the energy improvement strategy; identify constraints with respect to BIPV; and develop architectural proposals where BIPV plays an integral part of the whole building design approach. The double skin façade with BIPV was then tested by means of an integrated thermal, electrical and daylight computer simulation appraisal. In response to the three research questions, the three hypotheses were proved and all research questions were satisfactorily answered. The last objective was to appraise and summarise all findings relative to the hypothesis and research questions.

Recommendations for future research work in this field were finally suggested. The thrust of such work could be a detailed CFD analysis of the air flow in offices and the proposed 'spoiler' at roof level of the 'solar chimney'.

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GLOSSARY

AMORPHOUS PHOTOVOLTAICS

PV modules manufactured by applying a thin film of amorphous silicon to a substrate. PV modules made from amorphous silicon have lower efficiencies than crystalline silicon and their performance degrades with time but, they can be manufactured more cheaply.

BUILDING INTEGRATED PHOTOVOLTAICS

Photovoltaic systems integrated with the building's electrical and ventilation systems as well as architecturally exploited as structurally integrated components of the building envelope.

BALANCE OF SYSTEM [B.O.S.]

Balance of System components is the name given to the electrical components other than the PV modules themselves, which make up the PV electrical system. [Prasad D. and Byrnes J., *Architectural Applications of Photovoltaics, Environment Design Guide,* p. 7, The Royal Australian Institute of Architects, 1999.

CRYSTALLINE SILICON

PV cells manufactured by growing and slicing silicon crystals. Majority of the PV cells are currently made from crystalline silicon and can be either mono-crystalline or poly-crystalline.

DAYLIGHT FACTOR

The daylight factor [DF] is the ratio of the interior illuminance evaluated at a point on a work plane to the global horizontal illuminance, under CIE standard overcast sky conditions [10,000Lux], as specified by the Commission Internationale de l'Eclairage (CIE), Goulding J.R., Lewis O.J., Steemers T.C., *Energy in Architecture, the European Passive Solar Handbook,* Batsford for the Commission of the European Communities, London, UK, 1992, p. 116.

HYBRID PV SYSTEMS

Building-integrated photovoltaic [BIPV] components when used to generate heat in addition to electrical power, are called hybrid PV system.

HEAT TO POWER RATIO

The potential heating power recovered from the back of the PV modules (based on the difference between inlet and outlet air temperature), divided by the electrical power production [Clarke J.A., Hand K.W., Janak M., Johnstone C., Strachan P.A. [d], *PV-Hybrid_PAS Development of Procedures for Overall Performance Evaluation of Hybrid Photovoltaic Building Components,* Annex Report: Modelling 6, Simulation Case Study: ELSA Building, Ispra, Italy, p.12, PASLINK EEIG, Brussels, 1998].

ILLUMINANCE LEVEL

The illuminance level is the daylight striking the work plane surface and measured in Lux.

INVERTER

A component that converts dc electricity into ac.

PHOTOVOLTAICS

Photovoltaics are devices that convert the energy of sunlight directly into electricity. The term originally comes from the Greek work 'photo', meaning "derived from the light", combined with the name of the Italian physicist, Alessandro Volta, who invented the first battery.

PHOTOVOLTAIC (PV) MODULE

A group of PV cells encapsulated between a back-plate (which can be opaque or transparent) and a front-plate (which must be transparent) and mounted in a frame in standard sizes that will vary between manufacturers. A PV module that does not have a frame may be referred to as a laminate or a frameless module.

U-VALUE

Thermal transmittance coefficient, measured in W/m^2K

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I address special thanks to everyone in the Architecture Department of the Mackintosh School of Architecture for broadening my architectural knowledge, financial assistance at difficult times and an opportunity to work in an international environment. My gratitude also goes to the Overseas Research Students Awards Scheme of the UK Universities and the Open Society Institute Network Scholarship Programs in Budapest, Hungary, for their financial assistance.

DECLARATION

I hereby state that this thesis is solely based upon original work carried out by myself and that any reference to past research have been appropriately acknowledged.

Irena Kondratenko

[redacted]

To my parents.

1 INTRODUCTION

CHAPTER 1 INTRODUCTION

1.1 BUILDING INTEGRATED PHOTOVOLTAICS [BIPV] IN THE URBAN ENVIRONMENT

There are a large number of 'workplace' buildings In Scottish cities built in the late 1950s and early 1960s which are over 40 years old and in need of a refurbishment. Their architecture is typical expression of the time when they were built, usually of concrete frame structure, concrete cladding panels and single glazed strips of windows. They were built at a time of different environmental consciousness in building design and energy, and with different building regulations and standards. In most cases they are under-insulated, over-glazed, have a rundown internal and external appearance, and inefficient ventilation and heating systems. All these factors lead to high-energy consumption and CO_2 emissions as well as uncomfortable spaces for building users.

The term building integrated photovoltaics [BIPV] in this research work is defined as photovoltaic systems integrated with the building's electrical and ventilation systems as well as architecturally exploited as structurally integrated components of the building envelope. Building integrated photovoltaics [BIPV] is a renewable energy generating system capable of mass application in urban areas that offers an opportunity to produce electricity and utilize heat as a by-product, from the sun in the urban environment. It also offers non-polluting energy production at the point of use, reducing the CO_2 emissions, and expressing through its visibility the environmental awareness of the building's owner.

Large buildings in urban areas offer large façade and roof surfaces suitable for BIPV integration. However, surrounding buildings affect each other by shadowing effects at different times of the day and at different seasons. A careful analysis of the site sunlight availability as well as array design and connection has to be taken into account when designing a BIPV system to avoid, or in some cases, minimize the PV efficiency losses by the shadow effect. BIPV systems can be integrated on buildings in need of refurbishment, for example on roofs or façades, replacing or enhancing conventional building materials, thereby offsetting some of the capital cost, and even achieving higher architectural quality. BIPV as a refurbishment option on urban buildings is particularly viable because building integrated components can simultaneously fulfil a number of functions: provision of clean electricity generation, pre-heating of air [from behind the panels], regulation of light and noise, provision of shading elements, improving weather tightness, and lifting the aesthetic appeal of the building. The cost savings through these combined functions can be substantial, especially in refurbishment cases when new components have to replace existing ones, and much of the cost is embedded in the building operation itself – plant, labour, etc.

PV technology is still expensive and the payback time for BIPV systems, without taking into consideration the broader environmental costs and impacts, is still very long in most cases, and a major barrier to widespread uptake of this technology in buildings. However, costs are likely to fall as the market grows, technology improves and new cheaper and more efficient products become available. Reinforcing the point made above, savings in replacing external materials, with multi-functional BIPV systems offsetting the capital costs, is seen as the best opportunity to reduce the payback time for investments during the coming period of market penetration. In any event, this is the strategic stance taken in this thesis, without any attempt to justify the use of BIPV on costs. The principle is that BIPV can become economical for both new-build and retrofit, provided that its performance is viable as part of a comprehensive environmental 'engine'. This will be tested against a potentially real situation in the latter category [retrofit] in Glasgow.

1.2 TOWARDS ENERGY EFFICIENT, SOLAR HEATED AND PV POWERED BUILDINGS

The strategy when considering integration of PV systems on a building should be to reduce the energy demand by introducing energy conservation and efficiency technologies first [improved insulation, better energy performing windows, heat recovery units for heating and ventilation systems]; passive solar technologies next [sunspaces, atria]; and active systems, such as PV technology, third and last [Hestnes, 2001]. The primary objective therefore is to design the building envelope as a climate modifier using the passive solar energy to make the building low energy demanding, and only then to introduce photovoltaics as hybrid or active solar energy components. The building's demand for electrical energy must be minimized in order to minimize the area of integrated PVs needed to match electrical loads and for the PVs to make a meaningful contribution to the overall energy performance. However, designing a building integrated photovoltaic system can sometimes conflict with the passive solar design intentions. For example, the opaque PV cells do not transmit light and therefore may reduce the direct solar radiation into a space that may be desired for thermal benefit. Also, PV cells produce heat by the solar conversion that might be desirable from the passive solar point of view [as long as it does not contribute to space overheating], but if the heat is not readily dissipated, it can raise module's temperature and therefore reduce PV efficiency.

For a successful integration of PV systems it is necessary to have a 'whole building approach'. This means that a multidisciplinary design team with a good understanding and knowledge of the building's energy performance and, especially, the integrated solar systems, should be involved in the building design process from its earliest stages. The approach should take the building as a whole rather than only integrating a particular solar system. It should start with minimizing the energy load, evaluating what types of renewable energy will be best suited for each particular case, and finally, in case of PVs, finding the most appropriate combination for integration with the building envelope and energy systems [Hestnes, 2001]. In case of a refurbishment, the 'whole building approach' to reduce or solve an existing building's environmental problems, should start with the traditional energy conservation and energy efficiency measures, followed by passive solar techniques, and then introducing building integrated photovoltaic systems. Ideally, the last should play an integral and strong part of the environmental and energy solution strategy, including the comfort and well-being of the users.

Early BIPV systems were either attached to the building too closely and aggressively or integrated on building roofs and façades in a way that the PV systems visually dominate relative to other conventional external materials. [Fig. 1.1 a-f].

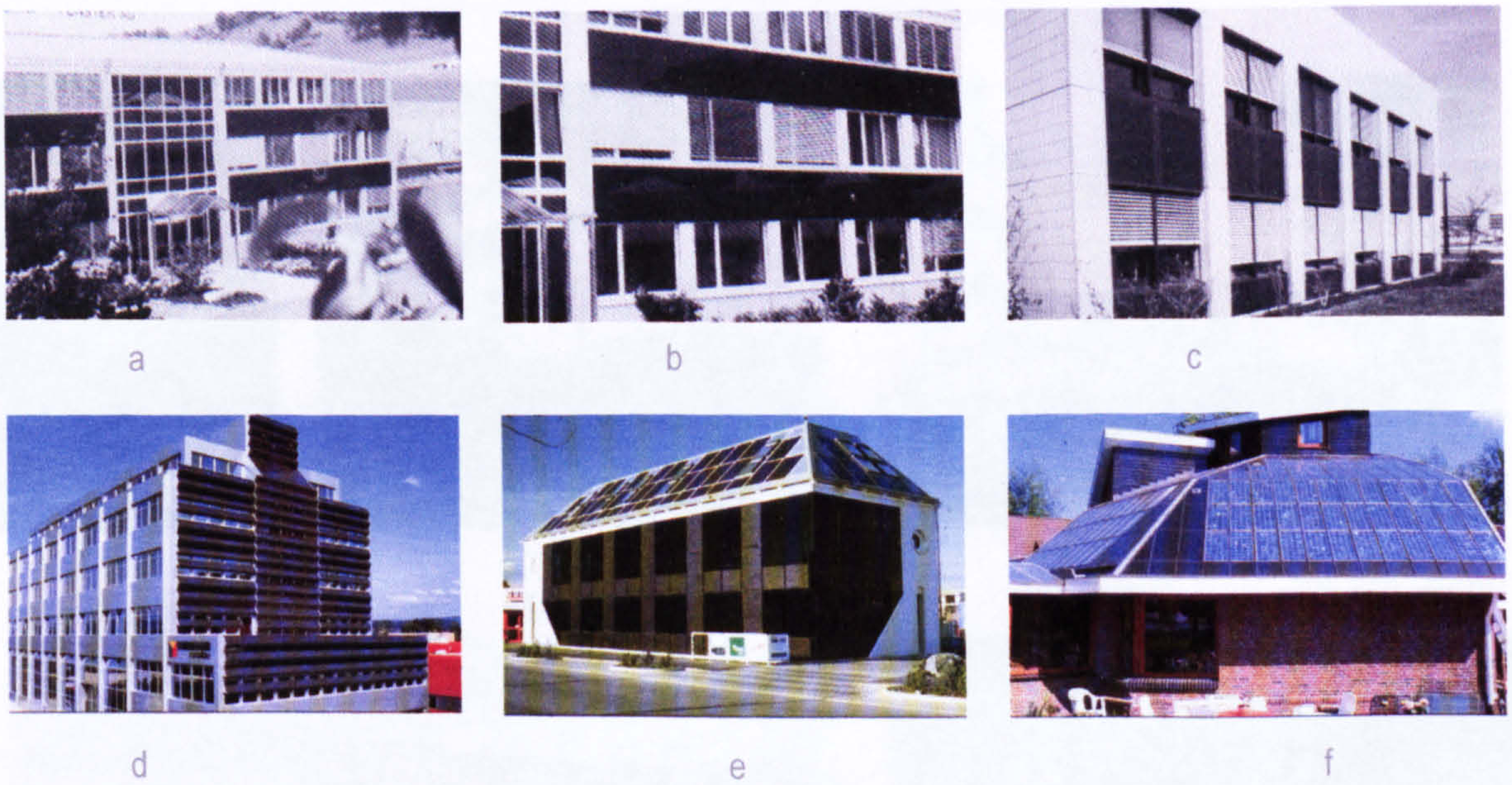

Fig. 1.1 [a-f] Early examples of photovoltaic systems integration on roofs and façades

In recent years, there is a tendency to a more subtle quality of BIPV systems, still with a clear expression of their integration as part of the building, but with enhanced aesthetic appeal and a desire to signal concern with the global environment through the more sensitive visibility of the PV [Fig. 1.2 a-e]. To a certain extent, this is due to development of PV cells technology and products offering a variety of types, formats, colours, textures, as well variety of module sizes and availability of integrating systems. Photovoltaic elements can be opaque modules, but also transparent [opaque mono or poly crystalline cells integrated in clear glass panels with varying cell spacing leading to different transparency level], and translucent [as thin film amorphous silicon panels with applied laser grooved technology in different patterns, resulting in different level of translucency]. Architects are increasingly finding photovoltaics a challenging material for aesthetic expression and in support of this contention is the fact that several internationally renowned architects such as Norman Foster and Tadao Ando have included photovoltaics as part of their design. [http://www.iea.org/venice/beneman.pdf] [http://www.task7.org/Public/IEA_Sydney_conference_papers/Paper_J_Jiro_Ohno.pdf].

a b c d e

Fig. 1.2 [a-e] Recent examples of photovoltaic systems integration on roofs and façades

1.3 MULTIFUNCTIONAL FAÇADES AND / OR ROOFS WITH BIPV

Large urban buildings have large areas of façade that have a potential for application of integrated solar energy components. The façades can, for example, collect electrical energy whilst diverting unwanted thermal energy. For that, southerly oriented façades offer best opportunity for façade integration due to largest irradiation level. However, other orientations [up to due east or west] can also give good energy generation. To confirm this, a study done by the Northumberland Photovoltaics Application Centre, at the University of Northumberland, Newcastle upon Tyne [Wilshaw, Crick and Pearsall, 2000, pp.1804-1807], investigated the impact of façade orientation in high latitudes [Newcastle upon Tyne, 55°]. It concluded that the annual irradiation on the south vertical plane is 85% of that on the horizontal, whilst the east vertical surface receives 64%, the west receives 53%, and the north vertical plane receives 32% of that on the horizontal plane. Such values may, of course be modified by optimising tilt, as at Northumberland is pioneering demonstration project [see literature review].

The building envelope with BIPV becomes an energy producer with multifunctional façades or roofs that generate electricity, optimise and control daylight, and utilize heat. The terms 'multifunctional' or 'intelligent' façade are used to describe building façades that

> "Incorporate variable devices whose adjustability and control adaptability is used to further enhance the façade's role as a climate moderator. This capacity gives the façade the ability to accept and reject free energy from the external environment and thus reduce the amount of energy required to achieve a comfortable internal environment " [Wigginton and Harris, 2002, p.174].

The multifunctional solar façades and roofs with integrated photovoltaics can produce electricity, generate or deflect heat, provide and control daylight, regulate noise, etc. Any building envelope is multi-functional in its character performing a number or tasks at the same time as a weather protector, a source of light and ventilation. When a photovoltaic system is integrated in the building envelope, it adds to such multi-functionality. In this way, the façade and/or roof elements work together in achieving a desired energy performance.

1.4 SCOPE OF WORK

The scope of work of this thesis is directed to retrofit with building-integrated photovoltaics [BIPV] in the Scottish urban environment. The Literature Review in Chapter 2, will present the relevant research work done in the area of integrating BIPV systems in new and retrofit buildings in the Northern European built environment context. The review will identify the double skin façade with BIPV as the least explored BIPV retrofit technique. This constitutes a significant gap in knowledge and represents the research focus in this thesis. However, the investigation will be set in a context of more comprehensive BIPV and environmental retrofit measures where, as the Literature Review will show, reasonable knowledge of performance already exists. In other words the detailed part of the investigation will be set within a 'whole-building' context where BIPV proposals align themselves with wider energy-efficient solutions for a set of known problems.

1.4.1 AIMS

The wider research question of this thesis was to investigate possibilities for retrofit BIPV to make a significant annual electrical contribution in Scottish 'work place' buildings. Issues here included the overall electrical performance of the

PVs, efficiency of the PV system, load matching, etc. The narrower research question looked at possibilities for retrofit BIPV to make a significant thermal contribution in addition to the electrical one. Issues here included previous modelling, where the specific thermal input from PV was not isolated from other heat gains.

Since the main research focus in this thesis is the double skin façade with BIPV, the following specific research questions were addressed:

a) Can retrofit building-integrated photovoltaics [BIPV] applied to a double skin façade make a significant annual electrical contribution?
b) Can this retrofit BIPV applied to a double skin facade make any useful thermal contribution over and above that implied by the secondary skin itself within the heating season; and can it avoid summer overheating, detrimental to both work spaces and the efficiency of the PV cells?
c) Can the whole system be configured in such a way that there is no daylight penalty to the work-place environment?

1.4.2 HYPOTHESIS

In response to those questions, the three specific hypotheses regarding the opportunities for retrofit building-integrated photovoltaics [BIPV] applied to a double skin façade construction are that:

a) In peak summer conditions, (i) stack driven air movement within the double skin construction will keep the temperature behind the photovoltaic [PV] cells low enough to ensure that loss of PV cells' efficiency is not excessive; (ii) any overheating attributable to the outer skin can be tackled by means of a basic system of mechanical supply coupled with natural exhaust to the double skin;
b) In cold winter conditions, although the thermal input of the photovoltaics is insignificant, the PV electrical contribution is useful relative to the power for fans operating a mechanical warm air supply with significant passive ventilation pre-heat and heat recovery;
c) Although the addition of the double skin façade with BIPV component reduces daylight entering the interior, with careful room design, materials specification and positioning of PV cells, the reduction of daylight is not critical, and the distribution of daylight in rooms can be improved compared to the pre-refurbishment situation.

1.4.3 OBJECTIVES

The first objective was to identify where case studies have significantly increased knowledge of BIPV performance and conversely, where knowledge remains uncertain or absent. The review was confined geographically to relevant research done in the area of integrating BIPV systems in new and renovated buildings in the Northern Europe built environment context. In total eleven building examples have been selected to represent the state of knowledge in building integration of photovoltaics from an architectural perspective in this climatic region. At the end of the literature review, an attribute analysis of the building examples summarizes the quality of PV systems building integration and performance, and their relevance to the main study of this thesis. Effectively this systemizes the objective of identifying a gap in knowledge that the double skin façade with building-integrated photovoltaics is the least explored BIPV technique in Northern Europe.

The second objective of this thesis was to select a case study site in a Scottish urban area as representative of typical 'workplace' building with many environmental problems, including traffic noise along the southern boundaries, i.e. where an opportunity existed to test a solution which involved filling the main gap in knowledge. The energy shortcomings and environmental problems of the case study building were identified; and site visit and interviews with building users were conducted.

The third objective was to set up the energy improvement strategy; identify constraints with respect to BIPV; and develop architectural proposals where BIPV plays an integral part of the whole building design approach. The BIPV proposals, where reasonable knowledge of performance exists, are deemed not to require modelling, leaving the focus on testing the south façade refurbishment solution of a double skin façade with BIPV by means of an integrated thermal, electrical and daylight computer simulation appraisal. Inevitably, this particular element represents archetypal tensions and dilemmas for environmental control – natural ventilation versus street noise; daylight and sunlight versus glare; heat gain versus heat loss; as well as opportunities for saving energy – ventilation pre-heat and heat recovery; electricity generation to power air handling; reduced thermal losses and reduced cooling loads.

In meeting the third objective with respect to the least explored BIPV technique in Northern Europe, the work was divided into three specific tasks:
a) The first task was to investigate the summer critical week energy performance of the case study building as existing non-refurbished; as refurbished but without the double skin façade component; and with the double skin façade with BIPV. For this, a detailed energy model was developed in ESP-r, a dynamic thermal modelling programme. Critical to the energy model development was achieving comfortable room temperatures during summer peak temperatures and keeping the temperature behind the photovoltaic [PV] cells low enough to ensure that loss of PV cells' efficiency is not excessive. Finally, the summer week electrical contribution of the BIPV system was calculated and compared with the total daily electrical load of all offices.

b) The second task was to analyse and summarize findings from the thermal and electrical modelling for winter critical week. Similarly to the summer critical week energy modelling, the case study building was investigated as existing non-refurbished; as refurbished but without the double skin façade component; and with the double skin façade with BIPV. Of particular interest here was to investigate the pre-heat contribution from the double skin façade, and the thermal contribution from the BIPV [heat generated from PV cells as they generate electricity], relative to the overall pre-heat contribution of the double skin façade. The BIPV winter week electrical contribution was also calculated and compared to the power needed for fans operating a mechanical warm air supply with passive ventilation pre-heat and heat recovery.

c) The third task was to investigate the effect of the double skin façade component on the daylight environment of offices. Specifically this involves determining whether the negative impact of the outer skin might be critical in terms of leading to increased use of lighting, and whether this issue could be simply tackled by internal layout and other design strategies.

The last objective was to appraise and summarize all findings relative to the hypothesis and research questions, and to suggest recommendations for future research work in this field.

1.4.4 RESEARCH METHODOLOGY

This research started with reviewing the research done in the area of BIPV systems, including those that utilize waste heat in addition to electrical power – the so-called hybrid PV systems. The review concentrated on the work done and demonstration projects built, representing the integration of multifunctional PV systems in the Northern European urban context. Research work related to BIPV systems in Scotland was also examined. There is a particular lack of built projects here but a gap in knowledge was identified for retrofit building-integrated photovoltaics applied to a double skin façade construction in Northern Europe. This research work then concentrated on the selected case study site in Glasgow, identifying the environmental problems of the case study building with the BIPV components as an integral part of the energy improvement strategy. One architectural proposal of a double skin façade with BIPV as a multifunctional façade solution was tested by means of detailed predictive computer modelling, based on an integrated thermal, electrical and daylight simulation. Two modelling programs were used, ESP-r, a dynamic thermal modelling program allowing an integrated appraisal of the thermal and electrical performance, and Radiance, a lighting visualization modelling program with ability to accurately simulate light behaviour in complicated environments. Iterative modelling findings were analysed and conclusions made regarding the opportunities for BIPV in the Scottish building environment with particular reference to double skin facades. The nature or number of the iterations varied in accordance with each hypothesis to be tested. Suffice to say, the method adopted in each case was shown to be competent in this regard. In turn, results enabled authoritative recommendations for future work in the field aimed at fine-tuning performance.

Throughout the research process, the author has engaged with the solar community, particularly in local, national and international meetings [e.g. Euro Sun 2002, International Solar Energy Society [ISES] Congress, Bologna, Italy, June 2002; North Sun 2001, Conference on Solar Energy in High Latitudes, Leiden, Holland, May 2001; Euro Sun 2000, International Solar Energy Society Congress, Copenhagen, Denmark, June 2000; 16th European Photovoltaic Solar Energy Conference, Glasgow, May 2000; Seminar in Understanding Building Integrated Photovoltaics, CIBSE, London, September 2000; European Commission S.A.V.E. [Energy] Program, Environmental Workshop, Glasgow, February 2000; Conference on Developing Scotland's Renewable Energy Strategy, Edinburgh, February 1999. The author presented her own papers at three of these events, and took in part in other activities such as national and international tours of solar projects through the Scottish Solar Energy Group [e.g. East Midlands Tour, April 2002; Sustainable Housing Refurbishment Visit, Paisley, Scotland, March 2002; Summer Rhineland Tour, Germany, July 1999]. These activities gave an opportunity to learn about research activities and follow other researchers work in the field of integration of photovoltaics in buildings.

The author has also attended training courses in computer modelling programs [e.g. training course in Radiance, Energy Systems Research Unit [ESRU], University of Strathclyde, Glasgow in March 2001, and a training course in ESP-r; Energy Systems Research Unit [ESRU], University of Strathclyde, Glasgow in November 2001.

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LITERATURE REVIEW 2

CHAPTER 2 LITERATURE REVIEW

2.1 INTRODUCTION

This chapter is a review of the relevant research work done in the area of integrating BIPV systems in new and retrofit buildings in the Northern European built environment context. All case study projects have been carefully selected to represent the state of knowledge in building integration of photovoltaics from an architectural perspective. Also, all case studies have been useful in terms of helping to direct the work undertaken in this research into a specific area of building integrated photovoltaics which is, as this literature review shows, relatively unexplored due to differences in the climate, the built context or the building typology.

This review of relevant BIPV projects starts with an overview of one of the main European research projects in PV hybrid [thermal and electrical] systems. The review continues with one built example in Scotland, then with projects showing the integration of photovoltaic systems as cladding and as a sun shading option. Several examples of BIPV in atria follow, including integration on atria roofs and atria façades. In all these projects, the multi-functionality of BIPV is clearly expressed, although their architectural quality and successful integration into the overall building energy strategy varies from one example to another. Finally, an example of a retrofit building with a double skin façade with BIPV is presented. The fact that only one example [located in Norway], that uses a double skin façade with BIPV as a retrofit technique has been identified, shows the lack of investigation into the energy performance of such a BIPV technique for the climatic context of Scotland. It is worth mentioning that an underlying theme connecting all building examples is the use of some predictive tool, i.e. computer energy modelling and testing of design options, as in the case of the retrofit exploration undertaken in this research work.

2.2 RESEARCH IN HYBRID PV [ELECTRICAL AND THERMAL] BUILDING INTEGRATED PHOTOVOLTAIC [BIPV] SYSTEMS

PV cells convert only part of the incoming solar irradiation into electricity. Commercially, PV cells have conversion efficiency between 5 up to 17% depending on various technologies [CIBSE TM25, 2000, p.1]. The rest is in the form of reflected light or sensible heat. About 85% of the energy generated in photo-electric conversion is produced as heat. It means that from 1,000 W/m^2 of solar irradiation, 850-940 W/m^2 is lost as sensible heat by radiation, conduction and convection [Basilian and Prasad, 2000]. The use of convective air behind the PV modules to utilise waste heat from photovoltaic modules has been researched as heat removed from roof mounted or façade integrated PV systems. The air flow is either driven by the stack effect or by extract fans and introduced to the ventilation system with heat recovery [Clarke *et al*, 1997, p.855-860].

One of the main researches done in this area is the PV-Hybrid-PAS project completed in 1998, funded by the European Commission as part of the JOULE Programme [PASLINK EEIG, 2000]. Its objective was to develop a performance assessment method for building-integrated photovoltaic [BIPV] components when used to generate heat in addition to electrical power, the so-called hybrid PV system. One of the case study buildings of this research was the Lighthouse viewing gallery, located in Glasgow, Scotland [latitude 56°N]. This research work was built on an earlier work on a prototype ventilated PV façade, based at the Building Research Establishment [BRE] in East Kilbride, Scotland, also part of the JOULE Programme [http://www.paslink.org/members/bre/pvfacade.htm, 1997]. The project had two main objectives: to reduce the operating temperature of the PV modules and hence improve their electrical efficiency; and to use the thermal energy generated within the façade to contribute to a natural ventilation system within the building [http://www.paslink.org/members/bre/pvfacade.htm, 1997].

2.2.1 THE LIGHTHOUSE VIEWING GALLERY

GLASGOW [56°N] SCOTLAND

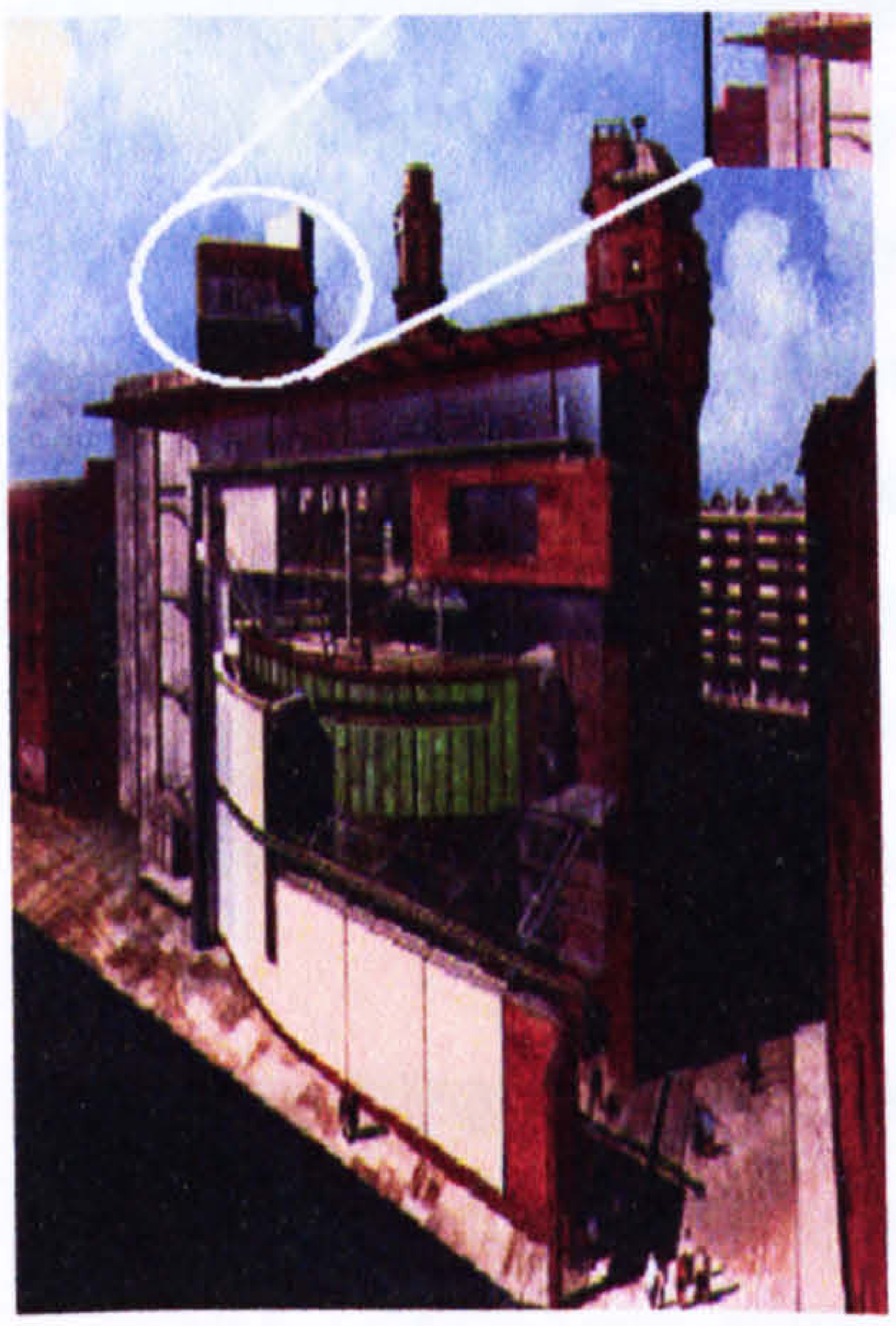


Fig. 2.1 Lighthouse viewing gallery

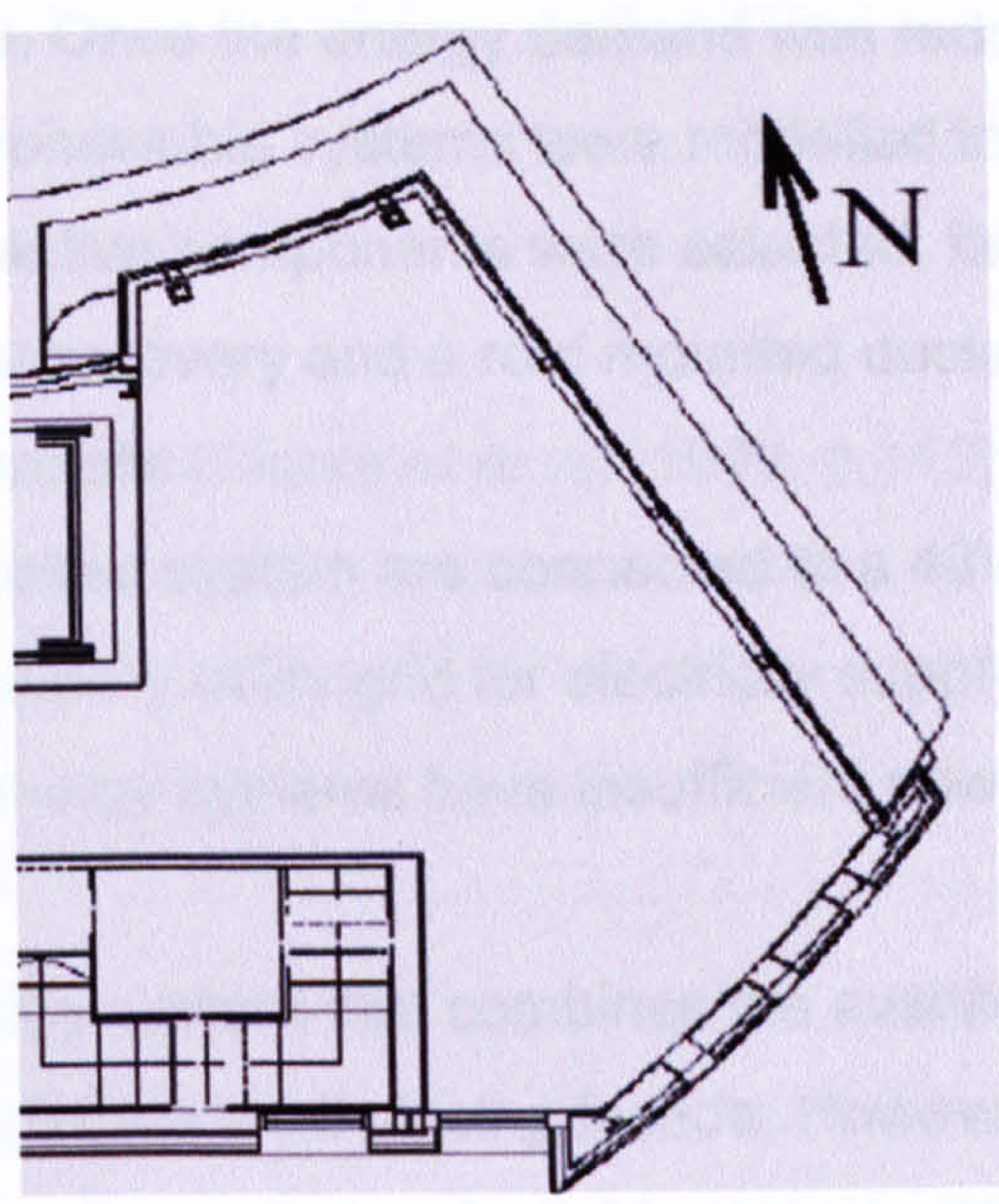


Fig. 2.2 Lighthouse viewing gallery plan

Source: Clarke J.A., Hand W., Janak M., Johnstone C.M., Macdonald I.A., Strachan P.A. *PV-Hybrid-PAS* "Development of Procedures for Overall Performance Evaluation of Hybrid Photovoltaic Building Components", Final Report; Annex Report: Modelling 8, Simulation Case Study: Lighthouse Viewing Gallery, Glasgow, Scotland. p. 4. 1998.

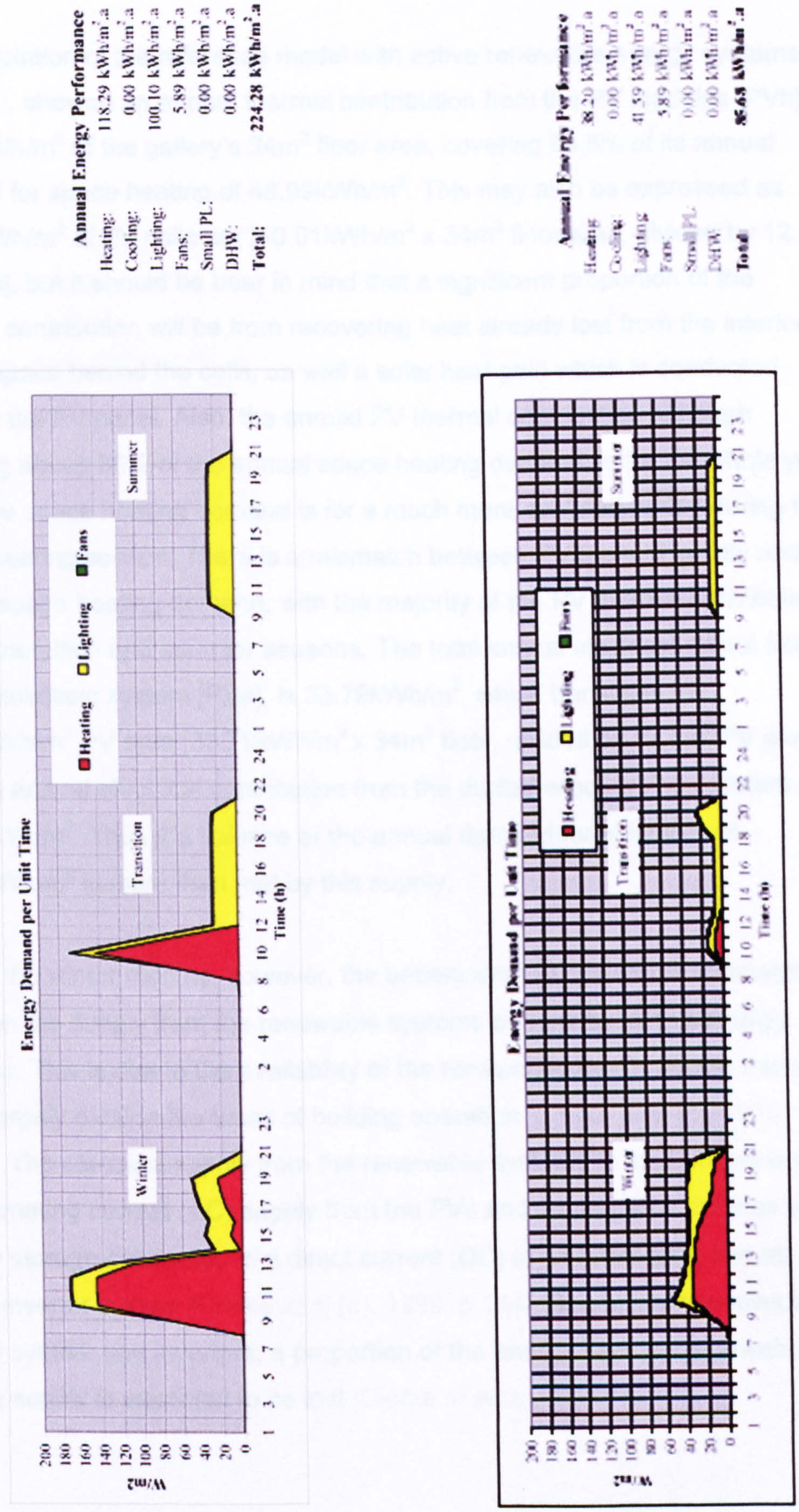
The refurbished Lighthouse building, originally designed by Charles Rennie Mackintosh, was the centrepiece of Glasgow as UK City of Architecture and Design 1999. The building is an A Category listed building of a major architectural importance, with a new viewing gallery as an extension above the building. The gallery has an area of 34m^2, and it is constructed of an insulated steel clad façade, an insulated lead sheet roof, double glazed east façade, internal concrete walls and a slate covered concrete floor slab. This small experimental project aimed to demonstrate the potential benefits of the integration of passive and active renewable energy technologies at the urban scale, taking into account the technical and planning restrictions associated with the city centre location and issues related to preserving the architectural heritage.

The ESP-r [Clarke, 1985] dynamic computer simulation program, which uses the control volume technique method, was used to determine the thermal and electrical [including hybrid PV] performance of a base case model [gallery as built], relative to several reference models. The aim of the simulation was to demonstrate the potential to reduce energy consumption in the gallery by modelling several energy-efficiency components in subsequent reference models, including the replacing of the double glazing with advanced triple glazing, illuminance based lighting control, and the integration of transparent insulation on part of the south façade. Once the energy demand was reduced by the passive components, the active renewable systems were modelled to meet the remaining energy demand. Two active components were selected, façade integrated photovoltaic cells with heat recovery and a roof mounted ducted wind turbines with integral photovoltaic aerofoils [Clarke *et al* (a), 1999, p.113]. The ducted wind turbines and the photovoltaic system are connected to a 48V battery unit, and also to the local electricity utility grid for electricity supply to cover periods when the renewable energy systems have insufficient power.

A building-integrated renewable energy system that combines the available wind and solar energy was found suitable for the south-facing façade. However, only a small façade area was available due to proximity of neighbouring buildings, and the conservation issues meant that the PVs and the ducted wind turbines were positioned at the back side of the building, away from the view of the public. The ducted wind turbines were suitable for the predominantly south-westerly wind direction in Glasgow and were positioned along the south and west roof edges. There are nine façade integrated mono-crystalline PV panels [total area of 7m^2] rated at 765Wp, and seven ducted wind turbines rated at 90Wp each. The integral PV aerofoils [total area 5.4 m^2 and installed on the ducted wind turbines at a 40° from the horizontal] are rated at 85Wp each. The total installed generation capacity of both wind and solar systems is 1990Wp [Clarke *et al* (b), 2000, p.1813-1814]. The two renewable technologies complement each other with the photovoltaics supplying the majority of the electricity in the summer when the solar irradiation is at its highest and the wind availability on the site at its lowest; and the wind turbines supplying the majority of the electricity in winter when the solar availability is at its lowest and the wind availability at its highest.

The base case ESP-r model was based on the viewing gallery design with an overall annual energy demand for heating, lighting and fans of 224.28kWh/m^2 [Fig. 2.3 (a)], [Clarke *et al* (b), 2000, p.1813]. The first reference model had the standard double-glazing on the east façade replaced with low-e coated, argon filled triple glazing [U-value of 0.8 W/m^{2}K]. The second reference model [Fig. 2.3 (b)], included a daylight responsive lighting control, and the third reference model included transparent insulation [TI] on the south-facing façade. All these reference models were aimed at minimizing the gallery's annual energy demand through the effectiveness of all energy-efficiency measures when compared to the base case model of the annual energy demand. This resulted in an overall annual energy demand reduction of 51%, i.e. a 45% reduction in the annual space heating energy demand and a 59% reduction in the annual lighting energy demand [Clarke *et al* (c), 1999, p.334].

The ESP-r modelling continued, aiming to further reduce gallery's energy demand by including a fast response, controlled convective heating system, including high efficiency luminaires. The reference models simulation results showed that in comparison with the base case model, the overall annual energy demand was reduced by 68%; of which a 58% reduction is in annual space heating demand and an 80% reduction in lighting energy demand [Clarke *et al* (c), 1999, p.334]. Once the overall annual energy demand of the building was significantly reduced to 68.96kWh/m^2 per year, the modelling continued, now including the hybrid PV and ducted wind turbine systems, to explore the potential of these systems to meet the remaining energy demand.



a) b)

Fig. 2. 3 Integrated performance view a) base case model (as built) b) Second reference model with a daylight responsive lighting control, and transparent insulation [TI] on the south-facing façade.

Source: Clarke J.A., Hand W., Janak M., Johnstone C.M., Macdonald I.A., Strachan P.A. *PV-Hybrid-PAS* "Development of Procedures for Overall Performance Evaluation of Hybrid Photovoltaic Building Components", Final Report; Annex Report: Modelling 8, Simulation Case Study: Lighthouse Viewing Gallery, Glasgow, Scotland. p. 12 and 14. 1998.

The simulation of the reference model with active renewable energy systems, [Fig. 2.4], showed an annual thermal contribution from the PV modules [PVh], of 40.91kWh/m^2 of the gallery's 34m^2 floor area, covering 83.5% of its annual demand for space heating of 48.99kWh/m^2. This may also be expressed as 112.2kWh/m^2 of PV collector [40.91kWh/m^2 x 34m^2 floor area, divided by 12.4m^2 PV area], but it should be bear in mind that a significant proportion of the thermal contribution will be from recovering heat already lost from the interior to the air space behind the cells, as well a solar heat gain which is conducted through the PV panel. Also, the annual PV thermal contribution although covering above 80% of the annual space heating demand, is for the whole year, while the space heating demand is for a much more confined period during the space heating season. There is a mismatch between PV thermal supply and gallery space heating demand, with the majority of the PV thermal contribution during transition and summer seasons. The total annual electrical output from the photovoltaic system [PVe], is 33.79kWh/m^2, which translates to 92.65kWh/m^2 PV area [33.79kWh/m^2 x 34m^2 floor, divided by 12.4m^2 PV area], and the annual electrical contribution from the ducted wind turbines system is 25.03kWh/m^2. Thus the balance of the annual demand for electricity of 19.96kWh/m^2 is more than met by this supply.

During the winter months, however, the battery system covers the mismatch between the supply from the renewable systems and the building's energy demand. This is due to the availability of the renewable energy supply mainly wind, largely outside the times of building operation [Clarke *et al* (c), 1999, p.335]. The electrical supply from the renewable systems to the building is with an alternating current (AC) supply from the PVs and ducted wind turbines via battery storage connected to a direct current (DC) to an alternating current (AC) power inverter system [Clarke *et al* (a), 1999, p.114]. Due to inefficiencies in the battery system and inverters, a proportion of the energy from the renewable energy supply is expected to be lost [Clarke *et al* (a), 1999, p.114].

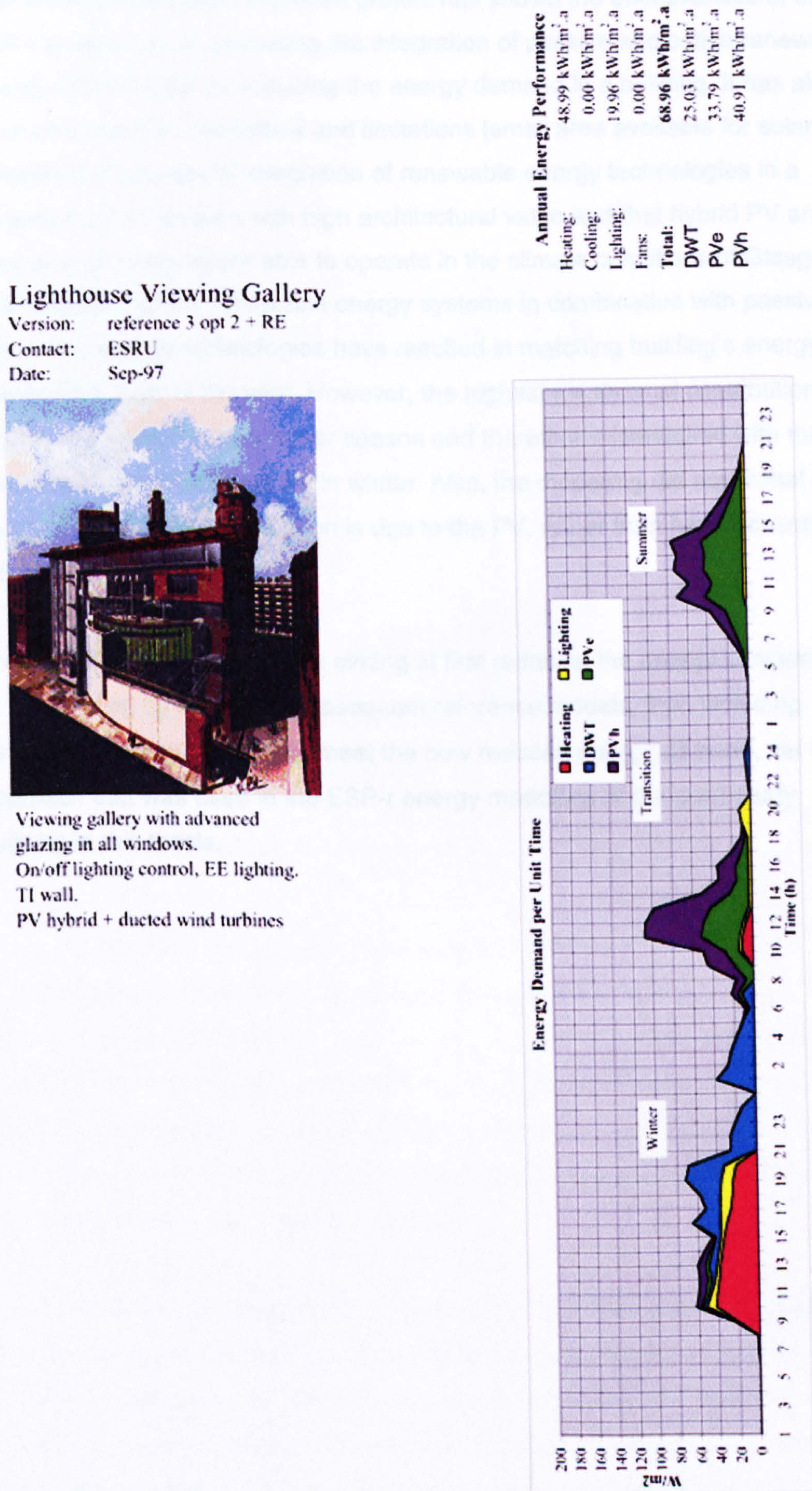


Fig. 2.4 Integrated performance view, model with passive and active renewable energy systems

Source: Clarke J.A., Hensen J.L.M., Johnstone C.M., MacDonald I. "On the use of Simulation in the Design of Embedded Energy Systems", Proceedings: 6th *International IBSA Conference Building Simulation 1999*, Kyoto, Japan. Vol.1. International Building Performance Simulation Association, p. 118. 1999.

This small Scottish demonstration project has shown the effectiveness of the ESP-r programme in assessing the integration of passive and active renewable energy technologies for reducing the energy demand in a building. It has also demonstrated the possibilities and limitations [small area available for solar collection] of successful integration of renewable energy technologies in a densely built urban area with high architectural value and that hybrid PV and wind energy systems are able to operate in the climate conditions of Glasgow. The modelling of the renewable energy systems in combination with passive renewable energy technologies have resulted in matching building's energy demand for most of the year. However, the highest PV thermal contribution is largely in transition and summer season and therefore mismatched with the space heating demand mostly in winter. Also, the modelling did not reveal how much of PV thermal contribution is due to the PV, rather than heat recovery from the gallery space.

The ESP-r modelling approach aiming at first reducing the energy consumption of the building by modelling subsequent reference models, then including renewable energy systems to meet the now reduced energy demand, set up an approach that was used in the ESP-r energy modelling of the case study building in this thesis.

2.3 RESEARCH IN BUILDING INTEGRATED PHOTOVOLTAIC SYSTEMS / BIPV AS CLADDING OPTION

2.3.1 THE EUROPEAN LABORATORY FOR STRUCTURAL ASSESSMENT [ELSA] BUILDING ISPRA [45°24'N] ITALY

Fig. 2.5 ELSA building, Ispra, Italy. South façade

Source: Clarke J.A., Hand W., Janak M., Johnstone C.M., Strachan P.A. *PV-Hybrid-PAS* "Development of Procedures for Overall Performance Evaluation of Hybrid Photovoltaic Building Components", Final Report; Annex Report: Modelling 6, Simulation Case Study: ELSA Building, Ispra, Italy. p. 4. 1998.

Another case study building from the PV-Hybrid-PAS project is the ELSA Building at the Commission of the European Community's Joint Research Centre, in Ispra [45°24'N], Italy [Clarke *et al* (d), 1998, p.3]. The research was done after the building was built and aimed to demonstrate the integrated electrical, thermal and ventilation modelling capabilities of the ESP-r simulation in predicting the PV electrical power output and heat recovered from air passing behind the building integrated PV modules.

The Joint Research Centre [JRC], located in Ispra, Northern Italy, is a central research facility of the European Commission. The European Laboratory for Structural Assessment [ELSA] is one research unit at the JRC that hosts a number of European earthquake engineering research projects. The building has a large volume, open plan space used as an earthquakes testing laboratory [area 1,236m^2], and a three-storey office wing in front of it. The south facing façade of the laboratory, above the office wing, has attached to it a non-ventilated photovoltaic façade, separated by narrow strips of glazing. The PV façade integrated system has 420 amorphous silicon PV panels [a-Si, efficiency 3.2%] with a total area of $512.8m^2$ and an electrical power output rating of 30kWp [Kelly and Clarke, 1997].

The focus of this study was initially the base case model of the laboratory space as it was constructed, i.e. with a non-ventilated amorphous PV south facing façade. The PV backing was assumed with a 4.0cm thick glass fibre insulation layer between two 0.2cm thick layers of steel panels resulting in U value of 0.43 W/Km^2. The strips of glazing were assumed as single, clear glass with U value of $5.5W/Km^2$. The ESP-r energy model consisted of eight zones, one for the factory building, three zones representing each floor of the office block and four PV layer zones [Fig. 2.6].

In order to explore different options, including a hybrid PV system, several reference models were developed. All models were simulated in ESP-r using the average monthly temperatures for the standard average European Test Reference Year [TRY] for Milan, Italy, and is with assumed occupancy of 20 people from 8.00am – 4.00pm during week days, resulting in casual gains of $1.5W/m^2$, and continuous artificial lighting during working hours with a heat load of $10W/m^2$. It was assumed that the factory was mechanically ventilated without a heat recovery system, and with relatively high ventilation rate of 7.0 l/s m^2 [fresh air supplied to remove contaminated air in the building]. The convective heating and cooling system set points were set up to 20°C for heating and 27°C for cooling during working hours [Clarke *et al* (d), 1998, p.6].

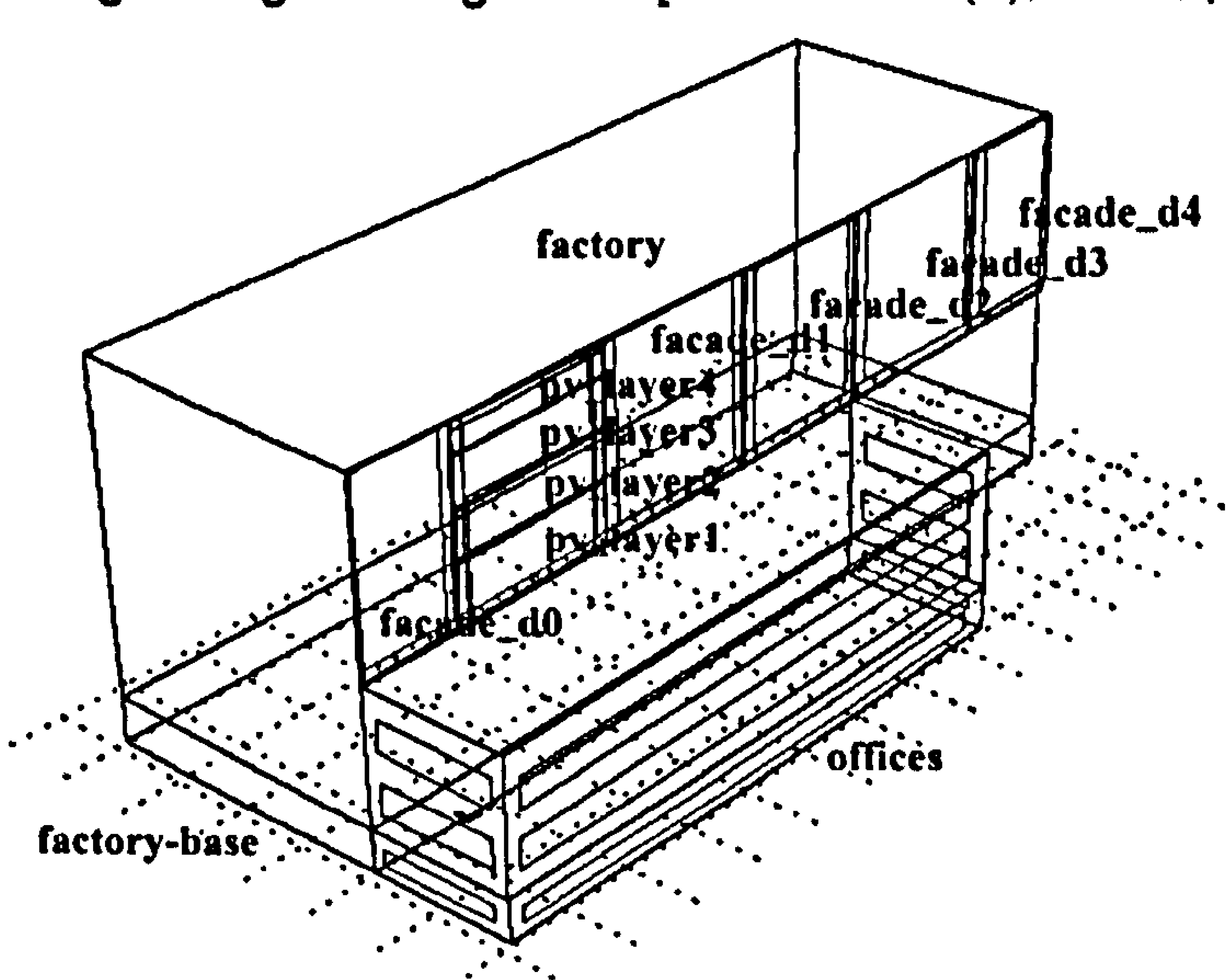


Fig. 2.6 ESP-r model of the ELSA building

Source: Clarke J.A., Hand W., Janak M., Johnstone C.M., Strachan P.A. *PV-Hybrid-PAS* "Development of Procedures for Overall Performance Evaluation of Hybrid Photovoltaic Building Components", Final Report; Annex Report: Modelling 6, Simulation Case Study: ELSA Building, Ispra, Italy. p. 5. 1998.

The first reference model looked at the potential for direct use of the heat recovered from behind the PV panels in the laboratory space. Mechanical ventilation of the air gap behind the PV panels was introduced with a plate heat exchanger between the PV façade extract flow and the laboratory ventilation supply flow.

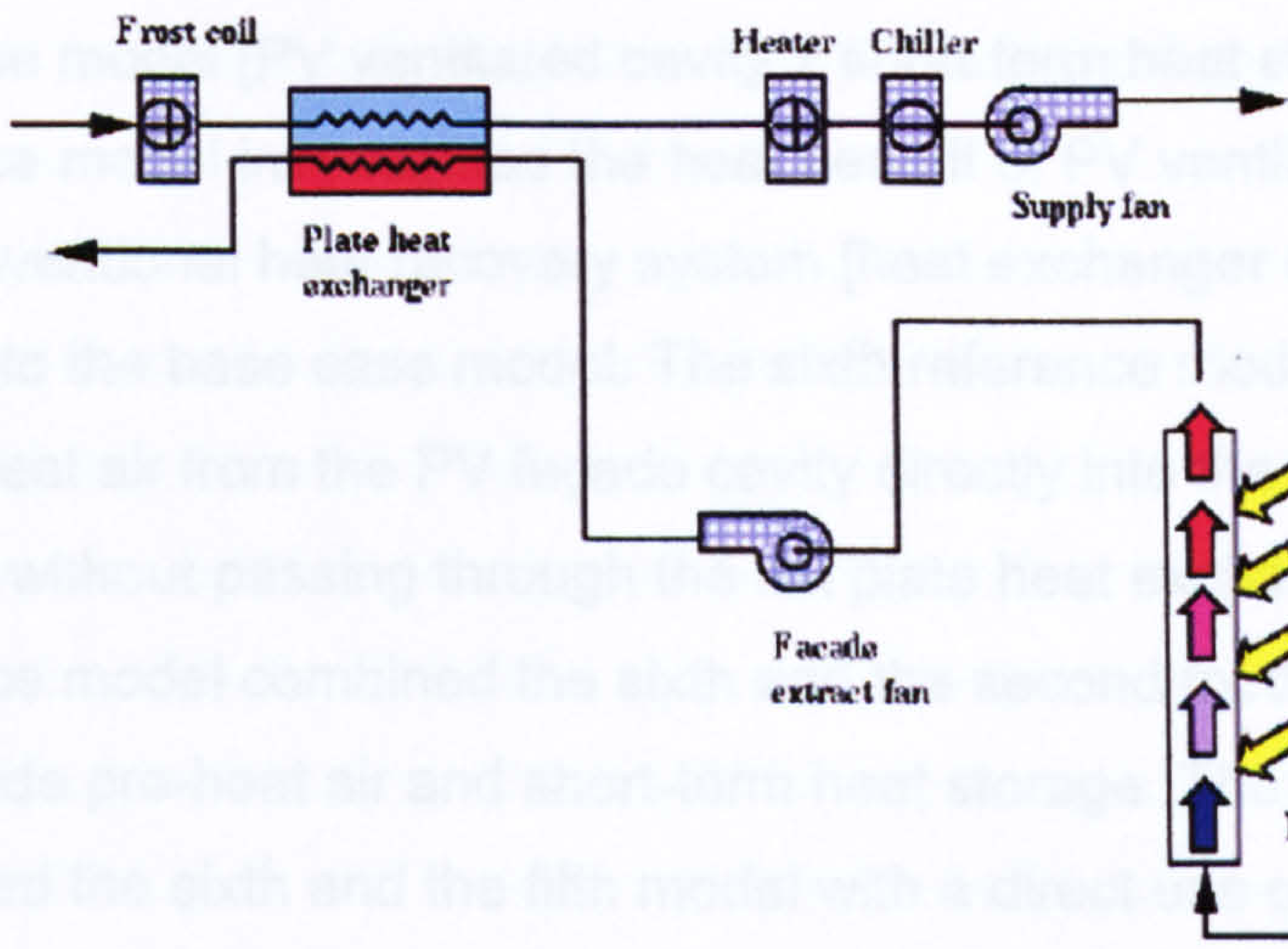


Fig. 2.7 Reference one model, ventilation system diagram

Source: Clarke J.A., Hand W., Janak M., Johnstone C.M., Strachan P.A. *PV-Hybrid-PAS* "Development of Procedures for Overall Performance Evaluation of Hybrid Photovoltaic Building Components", Final Report; Annex Report: Modelling 6, Simulation Case Study: ELSA Building, Ispra, Italy. p. 8. 1998.

The second reference model investigated the potential for short-term heat storage. The mechanical ventilation system connects the PV air cavity with the laboratory floor acting as a thermal store. The temperature difference between PV pre-heat air and short-term heat storage was set to 5°C. If the difference is larger than 5°C, the pre-heated air is directed to the short-term storage.

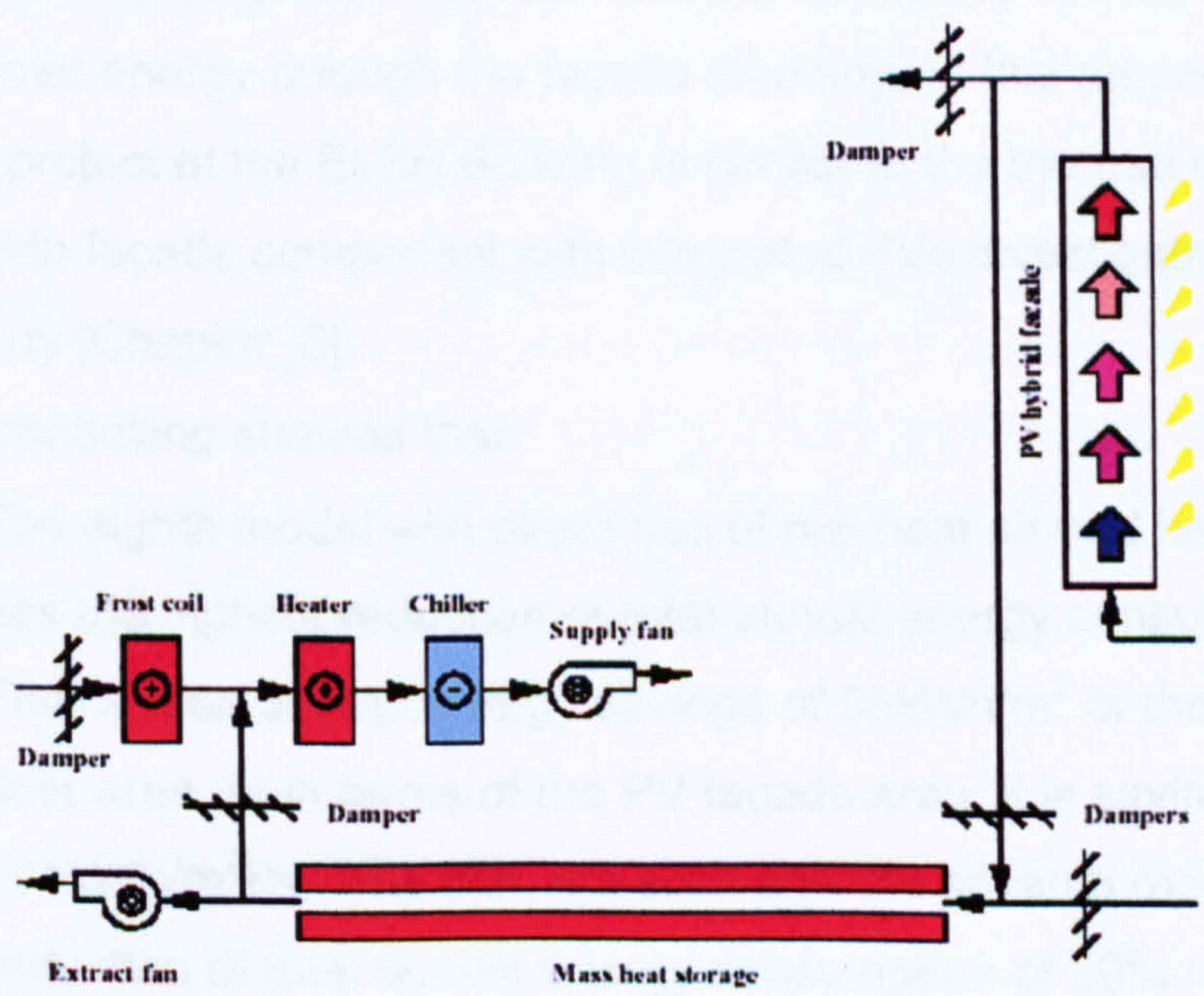


Fig. 2.8 Reference two model, ventilation system diagram

Source: Clarke J.A., Hand W., Janak M., Johnstone C.M., Strachan P.A. *PV-Hybrid-PAS* "Development of Procedures for Overall Performance Evaluation of Hybrid Photovoltaic Building Components", Final Report; Annex Report: Modelling 6, Simulation Case Study: ELSA Building, Ispra, Italy. p. 9. 1998.

The third reference model investigated the potential for natural ventilation, using the pre-heat air from the PV façade directly in the laboratory space by means of stack effect associated with the PV façade cavity. The fourth reference model investigated the effect of replacing the amorphous silicon modules with poly-crystalline PV modules [efficiency 12.9%], when applied on the second reference model [PV ventilated cavity + short term heat storage]. The fifth reference model investigates the heat benefit of PV ventilated façade compared to a conventional heat recovery system [heat exchanger efficiency 50%] when applied to the base case model. The sixth reference model investigated the use of pre-heat air from the PV façade cavity directly into the laboratory by means of fan, but without passing through the flat plate heat exchanger. The seventh reference model combined the sixth and the second model with a direct use of PV façade pre-heat air and short-term heat storage. The eighth reference model combined the sixth and the fifth model with a direct use of PV façade pre-heated air and a conventional heat recovery system. The fresh air is taken and pre-heated in a heat exchanger, then drawn through the cavity behind PV panels to further increase air temperature.

It is worth mentioning again, as with the Lighthouse modelling in Glasgow, that the pre-heat air collected from behind the PV panels in all reference models simulating the hybrid PV system takes into account the overall pre-heat contribution resulting from the PV cells when they convert the incoming solar irradiation into electricity; the heat lost from the laboratory space; and the conducted solar energy through the façade cladding. In this respect, the PV-Hybrid-PAS project at the ELSA Building is similar to the thermal contribution of the double skin façade component with integrated PVs investigated in this research study [Chapter_6].

The energy modelling showed that:

- The eighth model with direct use of pre-heat air and heat recovery has the highest reduction of total annual energy consumption of 25%. That is total annual energy savings of 68kWh/m^2 of the laboratory floor area, or in terms of the PV façade area, it is savings of 141kWh/m^{2}PV. The fifth, the sixth and the seventh model have a reduction of total annual energy consumption of 20% [Clarke *et al* (d), 1998, p.16].
- The fourth model with poly-crystalline PV modules increased the annual predicted electric power generation to 40.2kWh/m^2 floor area,

compared with amorphous silicon PV modules predicted electric generation of 14.1kWh/m^2. For the building floor area of 1,236m^2 and PV system total area of 512.8m^2, the annual predicted electrical contribution from the amorphous silicon is 33.98kWh/m^2 PV [note low cell efficiency of 3.2%], and significantly higher in the case of poly-crystalline PV modules with 96.89kWh/m^2 PV [cell efficiency 12.9%].

Of particular interest in this project is the replication study of the second reference model where the mechanical ventilation system connects the PV air cavity with the laboratory floor acting as a thermal store. This model was analysed with a UK climate [weather data for Kew 1967]. As shown on the Fig. 2.9, the climatic context of Milan and Kew are significantly different. Milan has cold but fairly sunny winters [winter insolation of 5,656kWh], while Kew is similar to Glasgow with less sunny and moderate winters, [winter insolation of 1,606kWh]. The table also shows differences in insolation levels in spring and summer, with Milan having higher insulation levels.

	UK, Kew 1967 Test Reference Year			Italy, Milan, standard European Test Reference Year		
	Winter	Spring	Summer	Winter	Spring	Summer
Insolation (kWh)	1,606	7,906	11,975	5,656	9,704	12,928
Electrical Energy (kWh)	157	837	1,241	586	1,026	1,340
Electrical Efficiency (%)	9.8	10.6	10.4	10.4	10.6	10.4
Useful Heat (kWh)	801	2,966	3,053	2,196	4,922	300
Heat : Power ratio	5.1:1	3.5:1	2.5:1	3.7:1	4.8:1	0.22:1
Combined Efficiency (%)	59.6	48.1	35.8	49.2	61.3	12.7

Fig. 2.9 Comparison of Italian and UK PV façade performance, replication study of the second reference model.

Source: Clarke J.A., Johnstone C., Kelly N., Strachan P.A. "The Simulation of Photovoltaic-Integrated Building Façades ". http://www.hvac.okstate.edu/pdfs/bs97/papers/P214.PDF. 1997.

The base case model [the laboratory space as constructed] and the second reference model [mechanical ventilation system connects the PV air cavity with the laboratory floor acting as a thermal store] were simulated for the climate data for Kew, UK, and climate of Milan. The potential for PV electrical energy in winter for Milan climate is over 3 times higher than in Kew [586kWh PV electrical energy in winter compares to 157kWh PV electrical energy in Kew]. Also, in spring, the PV electrical energy in Milan is higher for 189kWh than in Kew [1,026kWh – 837kWh]. In summer, the 1,241kWh PV electrical energy generated in Kew is close to 1,340kWh PV electrical energy generated in Milan, as the availability of solar radiation is similar to both location.

The replication model was also compared in terms of the heat potential for space heating of the building in winter and transition seasons. The thermal contribution in winter and in transition seasons in Milan is significantly higher [2,169kWh] compared to 801kWh in Kew. In spring, 4,922kWh useful heat in Milan compares to 2,966kWh in Kew. In summer, however, the useful heat results for Kew is ten-fold higher that the Milan. That may not be surprising as Milan has much higher summer temperatures compared to Kew and Kew has lower summer temperatures with longer heating season and more need for heat. However, one has to bear in mind that the modelling had specified a rather high heating internal temperature set point of 20°C, for which one might expect the workers to be relatively inactive. Also, with casual gains specified as 1.5W/m^2 factory floor area and poor insulation levels of the factory fabric, the substantial useful heat contribution in Kew in summer is relatively misleading.

The heat to power ratio, which represents the potential heating power recovered from the back of the PV modules divided by the electrical power production [Clarke *et al* (d), 1998, p.12], is highest for Kew during winter with 5.1:1 compared to 3.7:1 for Milan. The combined efficiency of PV electrical and PV thermal systems is also higher for Kew in winter [59.6%] compared to Milan [49.2%]. This would suggest that in winter months, the overall potential of a PV-hybrid [PV electrical and thermal] system is more suitable for Kew climate than in Milan. However, such relativity must be set against the very low absolute heating and electrical contribution predicted for Kew compared with Milan. During spring, the heat to power ratio for Milan is higher than in Kew with combined efficiency also higher for Milan. One also has to bear in mind that these results are theoretical predictions based on computer based energy simulation results and not on measured data and therefore are not validated.

The significance of this study to the main subject of this research is that it shows the capabilities for integrated electrical, thermal and ventilation modelling of the ESP-r simulation program in predicting the energy performance of a hybrid PV system integrated on an existing building. It also shows the capability of the program to test different design scenarios, explore various energy options, and to simulate the same building energy models for different climatic contexts. The study has also shown that the highest reduction in the building's total annual energy demand is when the pre-heat air from behind the PV panels is directly used in a ventilation system together with heat recovery. The replication study of the second reference model analysed with a UK climate and compared to a Milan climate has shown that the heat to power ratio in winter and in summer is greater in Kew than in Milan, while during transition seasons Milan has better heat to power ratio compared to Kew. This was useful for this thesis as it shows a high potential for utilisation of PV thermal in combination with PV electrical energy in a climate not significantly different from Glasgow. However, as with the Glasgow Lighthouse simulations, the greatest supply of heat from the PV cladding is out of phase with demand, and we do not know what proportion of this is attributable to the PV itself.

2.3.2 NORTHUMBERLAND BUILDING
NEWCASTLE UPON TYNE [55°N] ENGLAND

Fig. 2.10 Northumberland building south façade

Source: Northumberland Building; BP Solar www.bpsolar.com; Application, Building Integration. 1995.

The Northumberland Building is significant as the first UK demonstration project of a PV façade cladding system on an existing institutional building, in a high latitude urban environment. The building is situated on the campus of the University of Northumbria, in the city centre of Newcastle upon Tyne, [55°N], on the north-east coast of England. It is a five-storey building accommodating several academic departments, computer laboratories and University's central computer unit. The building is a typical 1960s office block with a façade of concrete cladding panels with mosaic finish and strips of window. The existing façade was in poor condition and in need for refurbishment due to deterioration of the concrete panels' fixing and the original mosaic cladding. Both north and south façades were refurbished, with a PV system installed on the south façade.

It should also be noted that since the building is situated in a campus park, traffic noise and pollution are not issues, allowing windows to be freely opened by the building users.

In the summer of 1994, the PV system was integrated into the aluminium rain-screen over cladding on the south façade of the building. The support structure for the PV panels was made of aluminium with a light-grey coated finish. This was chosen to be similar to the colour of the original mosaic cladding. The PV cladding units are inclined 60° to horizontal. That gives better solar collection, provides some shading to reduce solar gain in summer, allows back ventilation to assist cooling of the PV modules, and also provides space for the wiring and junction boxes to be located behind the units [Pearsall, Hynes and Hill, 1997, p.869]. The disadvantage of the tilt is that it may reduce daylight in offices in overcast sky conditions, and that could result in increased use of artificial light and thus lead to higher electricity demand.

The façade elements allow air to flow behind the modules through the perforated soffit panel that encloses the space created by the inclination of the façade and through a gap above the modules. The system does not utilise the waste heat from behind PV panels, i.e. it is a non-hybrid BIPV system. The PV installation comprises of 465 BP Solar Saturn '585 laminates with mono-crystalline with 14% efficiency cells, with a total PV array area of 285m^2. Each panel is rated at 85Wp, with a total PV array rating of 39.5kWp. The building has a high electricity load profile due to teaching activities during weekdays extending to the evening hours, and location of computer laboratories and the main administrative computer of the University.

The Northumberland Building has a significant amount of shading from surrounding buildings with similar height and from a boiler house chimney stack on the west side of the south elevation. The neighbouring buildings cause a diagonal shadow, most intensive in low sun angles, during morning periods and in winter months. The building in front of the south façade causes shading on the lower strips of cladding, especially under low winter sun angle. The boiler house chimney stack shades the cladding units behind it and the shading effect changes as the sun position changes at different time of the day and season. As the shading of the south façade was unavoidable, the stringing sequences for the units were chosen in order to minimise the effects of façade shading on PV electrical output.

The Northumberland Building PV system performance was extensively monitored throughout its continuous operation for five years after it's official opening in January 1995. The five-year monitoring status report gives information on PV façade long-term performance and reliability [Pearsall and Hynes, 2000, p.1806]. The electricity generated from the PV façade is lower than building's electrical load and the total amount of power generated by the PV system is used directly in the building. The system had generated over 100,000kWh from January 1995 until January 2000, with measured annual average PV electricity output of:

Year	PV electrical output
1995	21,836 kWh
1996	17,460 kWh
1997	21,435 kWh
1998	18,834 kWh
1999	20,730 kWh

The 5-year mean of measured PV electrical output is 20,059kWh per annum. Divided by the PV area of 285m^2 gives an annual electrical output for the total area of PV of 70.38kWh/m^2 PV. Compared to the equivalent value of the Lighthouse in Glasgow [92.65kWh/m^2 PV; N.B. theoretical results with no balance of system inefficiencies included], the Northumbria building has lower results. However, that might be explained by the fact that the PV system in Glasgow was not affected by shading and the Glasgow results given are predicted and not monitored measurements.

The average system efficiency of the PV system on the Northumberland building over the five-year monitoring period is 8.1%, before correction for the shading on the system of about 25% i.e. it would be approximately 10.5% without shading [Pearsall and Hynes, 2000, p.1806]. The shading was caused by surrounding buildings with similar height and from a boiler house chimney stack on the west side of the south elevation. If one assumes that 70.38kWh/m^2 PV on average is produced with 8.1% PV system efficiency, then the calculated incident solar radiation is 869kWh/m^2 [70.38kWh/m^2 PV x 100, divided by 8.1% = 869kWh/m^2]. The annual incident solar radiation for Newcastle upon Tyne, from the Climate in the United Kingdom atlas [Page and Lebens, 1986, p.170], taken as average over all weather conditions, south orientation and 60° tilted [to horizontal] surfaces, is 972kWh/m^2, then modified to 934kWh/m^2 for 65° tilt to horizontal. Compared to the above incident solar radiation of 869kWh/m^2, there is a difference of around 7%, which is acceptable, as the incident solar radiation will vary between years. Hence this comparison validates the atlas as a useful and rapid estimating tool for PV potential in UK locations, provided the system is established from existing projects such as Northumberland.

The differences in annual electricity outputs between monitored years are explained as an influence of shading and variations in external temperature and light level, due to variable weather conditions in different years. The five-year monitoring report of the PV system explains that the performance was particularly good during spring and autumn months due to the tilt angle of PV panels, which favours intermediate sun elevations, while it was significantly reduced in winter months due to shading received on the south façade.

A study in public reaction to building integrated photovoltaics [Blewett-Silcock, 2000, pp.1852-1854], in which the Northumberland Building was the case study, has revealed that the reflection into offices directly opposite the façade with PV cells causes problems, which were described as worse than before the refurbishment. The large windows before the refurbishment did cause some reflection in combination with a light coloured mosaic cladding. However, after the refurbishment, the PV panels are causing more glare problems to the opposite buildings due to highly reflective surface of the PV panels.

The 39.5kWp façade of the Northumberland Building has provided valuable experience and performance data for building integrated PV at northern latitudes. It has shown that, when designing a building integrated photovoltaic system in urban areas, the influence of the surrounding buildings must be taken into account as the shading can strongly affect the system's output efficiency. The project also showed that an integrated PV system as a refurbishment option on an existing office building at a northern latitude is a viable option. The photovoltaic system as designed, improves the energy-efficiency of the south façade compared to the pre-refurbished conditions. However, all PV generated electricity is used directly in the building without targeting a specific end-use load. Also, there was no monitoring of artificial lighting use before or after the refurbishment. Therefore, it is not known if lighting loads are now greater due to the presence of inclined PV cladding units on the south façade. Finally, the PV system does not utilise the waste heat from behind PV panels. If this energy had been used, for example for a part of the ventilation system of the building during the heating season, the system efficiency would have been higher.

2.4 RETROFIT WITH BIPV AS SUN SHADING OPTION

2.4.1 ECN BUILDING 31 PETTEN [52° 47N] THE NETHERLANDS

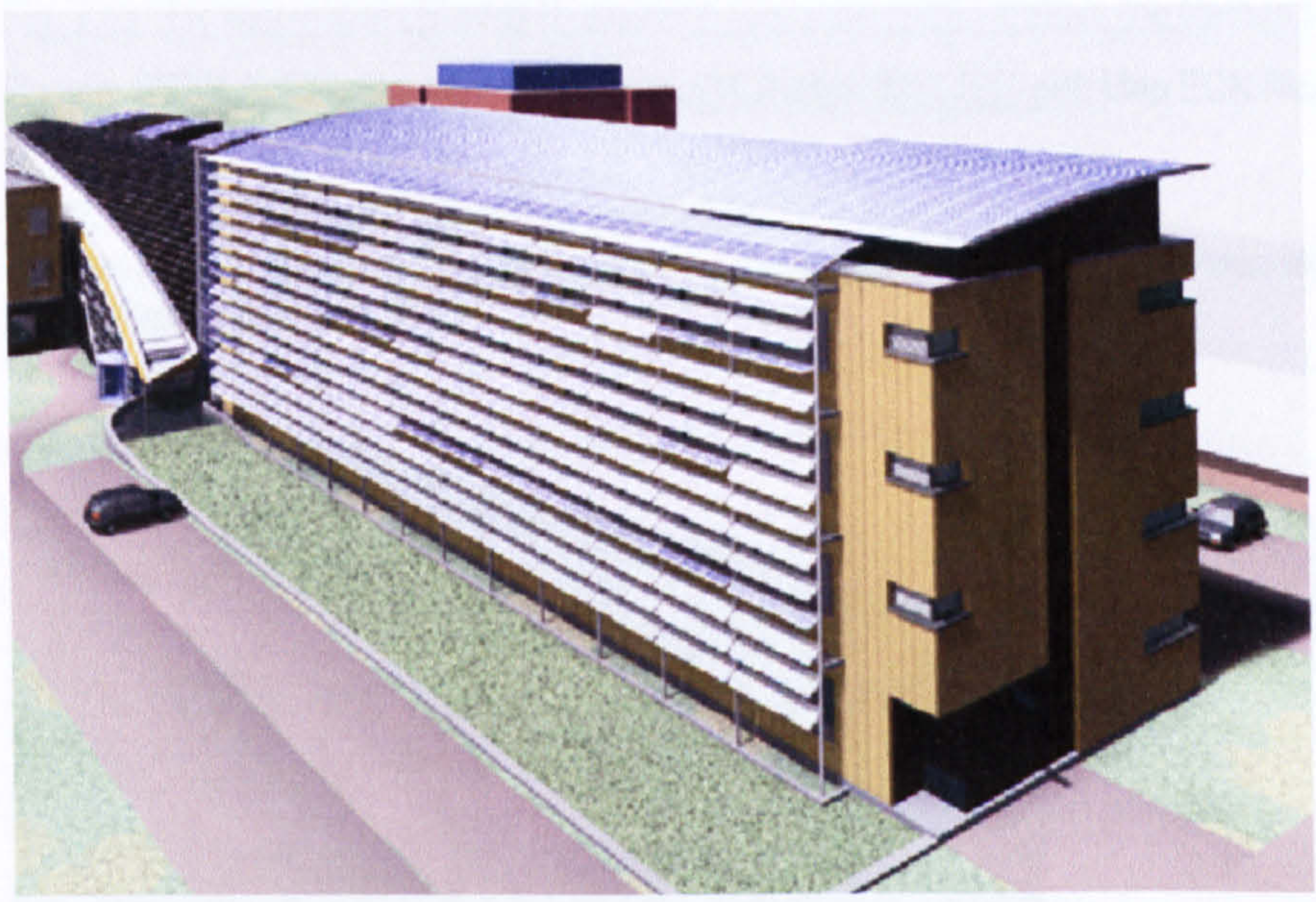


Fig. 2.11 ECN building 31, Petten, the Netherlands. Computer animation

Source: BEAR Achitecten: http://www.bear.nl/PDF/RetrofitECN31.pdf. Computer animation of the ECN Building 31 with PV-lamella system, canopy and curved roof PV integration; in the background: newly planned Building 42 with PV-atrium. p. 7. 2001.

The Netherlands Energy Research Foundation [ECN] is a leading institute for energy in the Netherlands. The ECN is actively involved in research activities concentrated in areas of renewable energy, energy efficiency, policy studies and renewable energy in the built environment. The complex of buildings belonging to the ECN is situated in North Holland, near the village of Petten [52° 47N]. The climate is described as a moderate, west-European sea climate, with January average temperature of –1.6°C and July average temperature of 22°C. The climatic context of Northern Holland is comparable to the climate of Scotland, only with somewhat colder winters and warmer summers, due to the continental influence. The ECN site includes extensive technical facilities built mainly during the 1960s. One of the research buildings is the General Laboratory, also named

ECN 31 building, built in 1963, a four storey building with a total floor area of $3530m^2$ [http://www.bear.nl/PDF/RetrofitECN31.pdf. 2001].

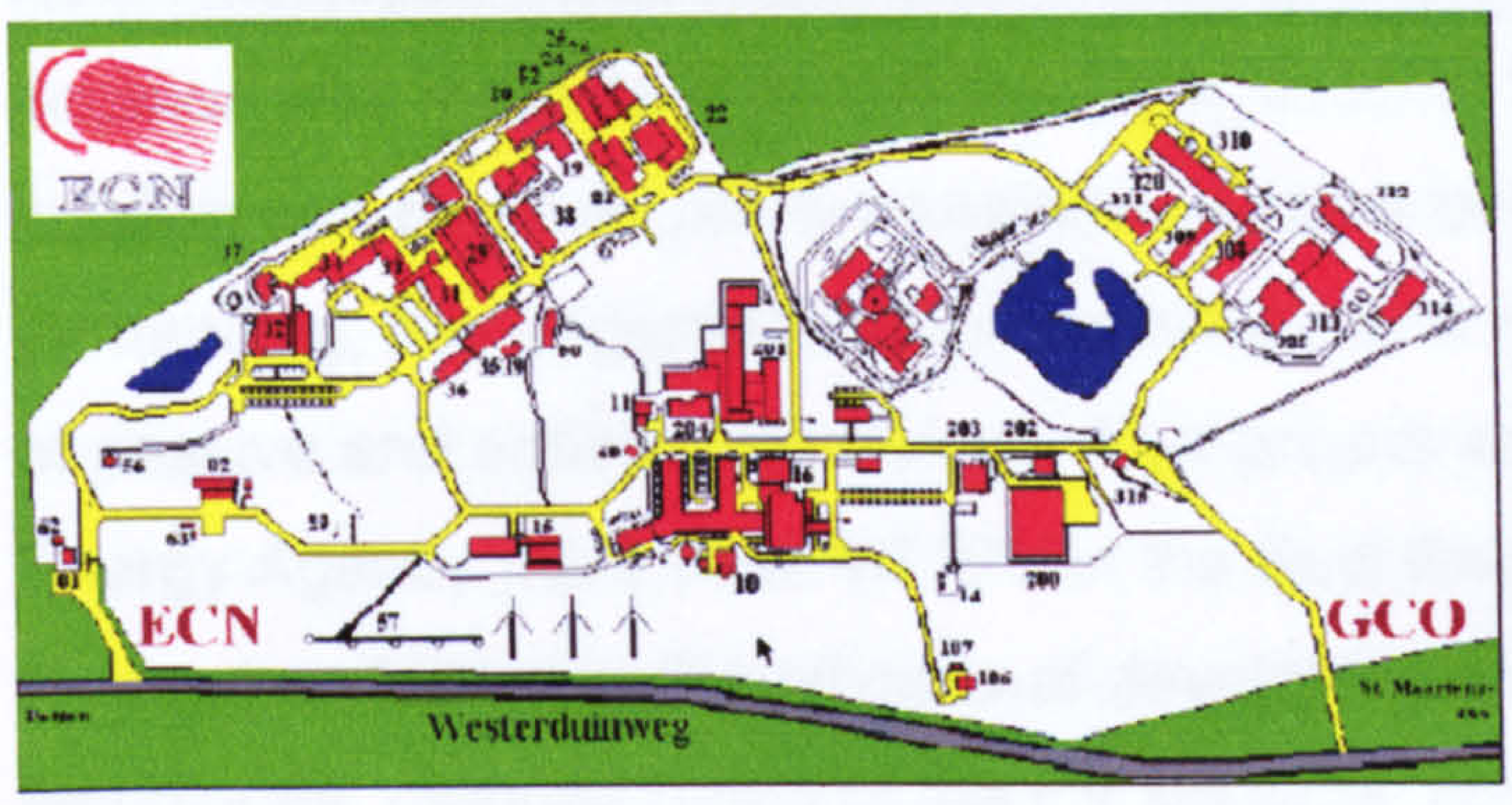


Fig. 2.12 The Netherlands Energy Research Foundation [ECN], Petten, the Netherlands. Site plan

Source: BEAR Achitecten: http://www.bear.nl/PDF/RetrofitECN31.pdf. Map ECN Research Area. p. 3. 2001.

Fig. 2.13 ECN 31 building site before renovation
Source: BEAR Achitecten: http://www.bear.nl/PDF/RetrofitECN31.pdf. Aerial view with ECN-31 Building before Renovation. p. 3. 2001.

Fig. 2.14 ECN 31 building before renovation. South façade

Source: BEAR Achitecten: http://www.bear.nl/PDF/RetrofitECN31.pdf. Building 31 before Renovation. p. 4. 2001.

In 1997 the ECN unit for Renewable Energy in the Built Environment made a study to evaluate the energy and environmental conditions of the building. The study revealed several technical and thermal problems including:

- insufficient building insulation
- many thermal bridges
- overheating in summer in rooms facing south,
- high heating and electricity demand,
- rundown façade,
- inefficient lighting, and

- inefficient ventilation system with high air rate supply and low comfort.

As an institution dedicated to promoting the use of renewable energies, the decision was made to renovate the ECN Building 31 and demonstrate how a building can be ecologically transformed into a building that is low energy demanding, has improved indoor conditions and comfort quality, and makes use of passive and active solar energy. This project was also part of the International Energy Agency [IEA] Task VII "PV in the Built Environment" programme, that focused on following the process of developing and designing PV integration techniques, manufacturing of the PV systems, construction of the building and engineering, and monitoring and evaluating of the building integrated PV systems [Kaan and Reijenga, 1998].

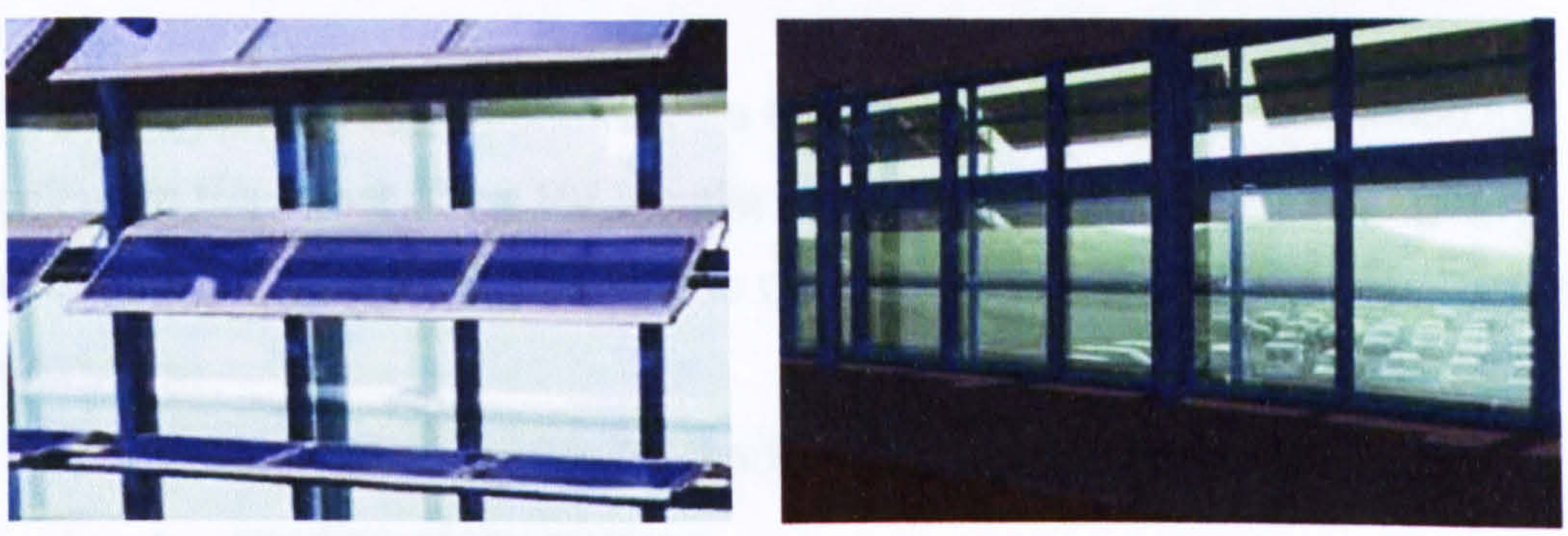
The renovation energy saving target was set at a reduction of approximately 75% of the total annual energy demand, compared to the building's pre-renovation overall energy consumption. The reduction of annual electricity load was set from 80kWh/m^2 before the renovation to 50kWh/m^2 after it, and reduction of the heating demand from 140kWh/m^2 before the renovation to 50kWh/m^2 after it [Reijenga and Kaan, 2000, p.1953]. The renovation strategy involved measures to directly tackle environmental problems defined as:

- renewal of the south and north façades with improved insulation,
- new heating system,
- energy efficient lighting system,
- mixed mode ventilation with heat recovery,
- night time ventilation for summer cooling, and
- PV roof integrated system and PV sun shading façade system [http://www.bear.nl/PDF/RetrofitECN31.pdf. 2001].

Behind the south façade, rooms are to be used as offices and laboratories. It was deemed necessary to have a mechanical ventilation system due to the nature of laboratory rooms requiring a high air exchange rate. To tackle the overheating problem associated with the south façade, a solution was adopted with a sun shading system of PV lamellas. The new sun shading system shades the façade, reducing the heat gain and avoiding the need for an expensive and energy consuming air-conditioning system. The PV lamella system design considered the architectural quality, effects on the daylight in rooms, solar energy benefits, and views from the interior to the exterior. The system also had to allow access and maintenance for PV panels and window cleaning, and simple construction and capability to integrate standard PV modules on shading lamellas.

The PV lamella system [Fig. 2.15 and 2.16] design solution consists of a separate metal structure placed 80cm from the existing façade, with maintenance platforms on each floor. After experimenting with a model in scale 1:10 and exploring the effect of several design options on the internal daylight level, a solution of four fixed lamellas on each floor was adopted. Each lamella is tilted 37° from the horizontal [optimum tilt for the Netherlands], with only the middle lamella possible to be moved by the occupants to provide a better outside view from offices. Each lamella is 84cm wide and 300cm long, containing three opaque poly-crystalline PV modules. The PV system integrated into the shading structure has 546 standard opaque PV modules [polycrystalline cells], with a total power output of 26.21kWp [http://www.bear.nl/PDF/RetrofitECN31.pdf. 2001].

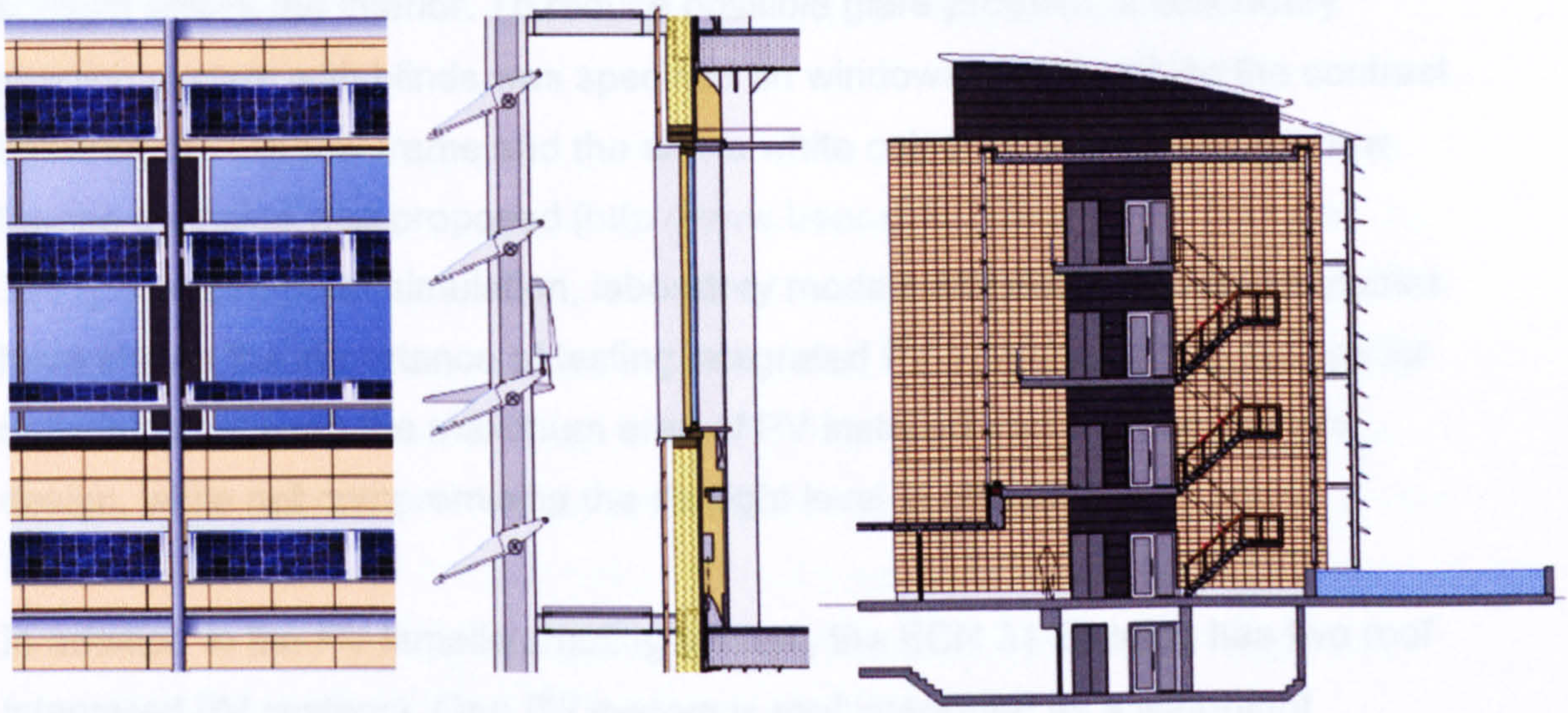
a



b

Fig. 2.15 [a-b] ECN building 31, Petten, the Netherlands, retrofit with BIPV as sun shading

Fig. 2.15 [a] Source: BEAR Achitecten: http://www.bear.nl/PDF/RetrofitECN31.pdf. Computer animation with PV-lamella system: view from office space to exterior with lamella on eye height in horizontal position. p. 8. 2001.
Fig. 2.15 [b] Source: BEAR Achitecten: http://www.bear.nl/PDF/RetrofitECN31.pdf. Building 31 during renovation with new façade. p. 5. 2001.



a b

Fig. 2.16 [a-b] ECN building 31, Petten, the Netherlands, retrofit with BIPV as sun shading. South elevation, section and west elevation

Fig. 2.16 [a] Source: BEAR Achitecten: http://www.bear.nl/PDF/RetrofitECN31.pdf. Lamella shading system of Building 31: south façade elevation and section. p. 12. 2001.
Fig. 2.16 [b] Source: BEAR Achitecten: http://www.bear.nl/PDF/RetrofitECN31.pdf. Building 31: West-facade. p. 13. 2001

The PV system design options were tested with a computer simulation to calculate the effect of the PV lamella shading structure on offices daylight environment. Computer simulations with the Radiance software were focused on:

- optimal solar gain for the PV lamella system,
- shading of the building,
- heat load of the building and passive solar gains in winter,
- views from the inside to the outside,
- self-shading of the PV lamella modules, and
- optimised daylight conditions in the interior [http://www.bear.nl/PDF/RetrofitECN31.pdf. 2001].

The modelling has shown that an option with all four movable lamellas increases the solar gain by only 10% compared to having three fixed and one movable lamella. It was therefore abandoned as non feasible.

The design of the PV lamellas was also tested as a full sized mock-up segment of the lamella system, placed in front of the existing façade. The monitoring addressed the possibility of noise produced by wind passing the metal structure, optimising the system construction and detailed design, and the effects of the lamella system on the daylight intensity in rooms. The monitoring showed that lamellas shade the building during summer with an efficiency of 85%, i.e. 15% of sunlight enters the interior. To reduce possible glare problem, a secondary shading system with blinds was specified on windows and to reduce the contrast between the window frame and the sky, a white coloured finish of the window frames on inside was proposed [http://www.bear.nl/PDF/RetrofitECN31.pdf. 2001]. The computer simulation, laboratory models and mock up system studies have shown the importance of testing integrated PV systems design options for optimising between the maximum area of PV installed and shading system design, while not compromising the daylight level in offices.

In addition to the PV lamella shading system, the ECN 31 Building has two roof integrated PV systems. One PV system is roof integrated as a watertight construction, consisting of 456 frameless standard PV modules [mono-crystalline cells] and total power output of 38.76kWp. The other PV system is integrated as a roof canopy directly above the south façade, consisting of 156 custom-made framed semi transparent glass PV modules with poly-crystalline cells, and total power output of 6.91kWp. The total area of the three PV systems installed on the ECN 31 building is 700m^2 with a total PV systems power output of 71.88kWp, predicted to cover approximately 30% of the building demand for electricity. All together, the prediction for the PV system annual generation of electricity is 56,440kWh [Reijenga, 2001, p.2466]. For the 700m^2 PV systems area that is 80.6kWh/m^2 PV area annually.

The monitoring programme conducted by the ECN in 2002 showed annual electricity generated of the PV roof systems of 29,721kWh per year and 22,276kWh per year for façade lamella and roof canopy PV systems [IEA PVPS TASK 7, 2002]. The total measured annual PV generated electricity is therefore 51,997kWh, which is lower than predicted annual generation of 56,440kWh [Reijenga, 2001, p.2466]. The reasons for lower PV total output, as explained in the report of the monitoring programme conducted by the ECN [IEA PVPS TASK 7, 2002], included: 31% of the total PV roof systems inverters failed once or more, 38% of the total PV façade system inverters failed once; the performance loss due to dirt on the PV roof systems estimated to 5% and 4% on the PV façade system; partial shading on the PV façade system due to shading by other lamellas; and the temperature rise of the PV modules of 35°C above ambient temperature at 1,000W/m^2 direct solar radiation for the façade lamella system, 23°C above ambient temperature at 1,000W/m^2 direct solar radiation for the roof integrated PV system, and 12°C above ambient temperature at 1,000W/m^2 direct solar radiation for the roof canopy system.

A recent visit of the Scottish Solar Energy Group to ECN in August 2003, and the author's personal contact with Dr. Colin Porteous who was the leader of the SSEG group, has revealed that although the building was completed in early 2002, it is still unoccupied. Measurements of the PV systems performance are permanently taken in the building. However, there is no monitoring other than the PV systems itself, i.e. no attempt is made to link the PV generated electricity to the use of electricity for a specific end-use load, and there are no plans to monitor environmental performance within the laboratories when occupied in order to compare with results from the mock-up.

The ECN 31 Building as a retrofit project has similarities to the retrofit exploration undertaken in this research work. The ECN 31 Building was built in the early 1960s and, with its architectural expression and environmental problems, has many commonalities with the main case study building in this research. In both cases a problem solving approach was used, with energy-efficiency, passive and active solar PV systems employed to reduce the energy demand, improve the indoor conditions and improve workspace comfort quality. Also, the climatic context of the site is not so different compared to the local climate of Glasgow. However, despite similarities, a different architectural solution was adopted for the south facing façade. The ECN 31 Building has a PV lamella shading system, while the proposal for the Glasgow case study building [Chapter_4] is a double skin construction with façade integrated semi transparent PV modules. The fact that the ECN 31 Building site is not subject to heavy traffic noise, and the requirement for a specific mechanical ventilation system for laboratories with sealed windows, provided the logic for a lamella solution, detached from the existing façade and without a need for an additional acoustic barrier.

Another similarity between the two buildings is the aspect of daylighting analysis. In both projects extensive computer modelling was used to assess the effect of added structures to the internal daylight environment and to assess tensions between competing environmental tactics. In particular for the PV lamella system, the possibility is that the PV array may reduce daylight to a level that will increase the electrical lighting load. Although respective design solutions are different [PV lamella shading system and double skin façade with BIPV], the common aspect is that both projects had to address extensive environmental problems and tackle complex issues related to south facing rooms.

2.5 BIPV IN NEW BUILDINGS

APPLICATION IN ATRIA

2.5.1 ECN BUILDING 42 PETTEN

[52°47N] THE NETHERLAND

Fig. 2.17 ECN 42 building, Petten, the Netherlands. View of the conservatory and ECN 31 building south façade
Source: BEAR Achitecten: http://www.bear.nl/PDF/OfficeECN42.pdf. Conservatory Roof of Building 42 with PV-Modules and connected to Building 31. p. 1. 2001.

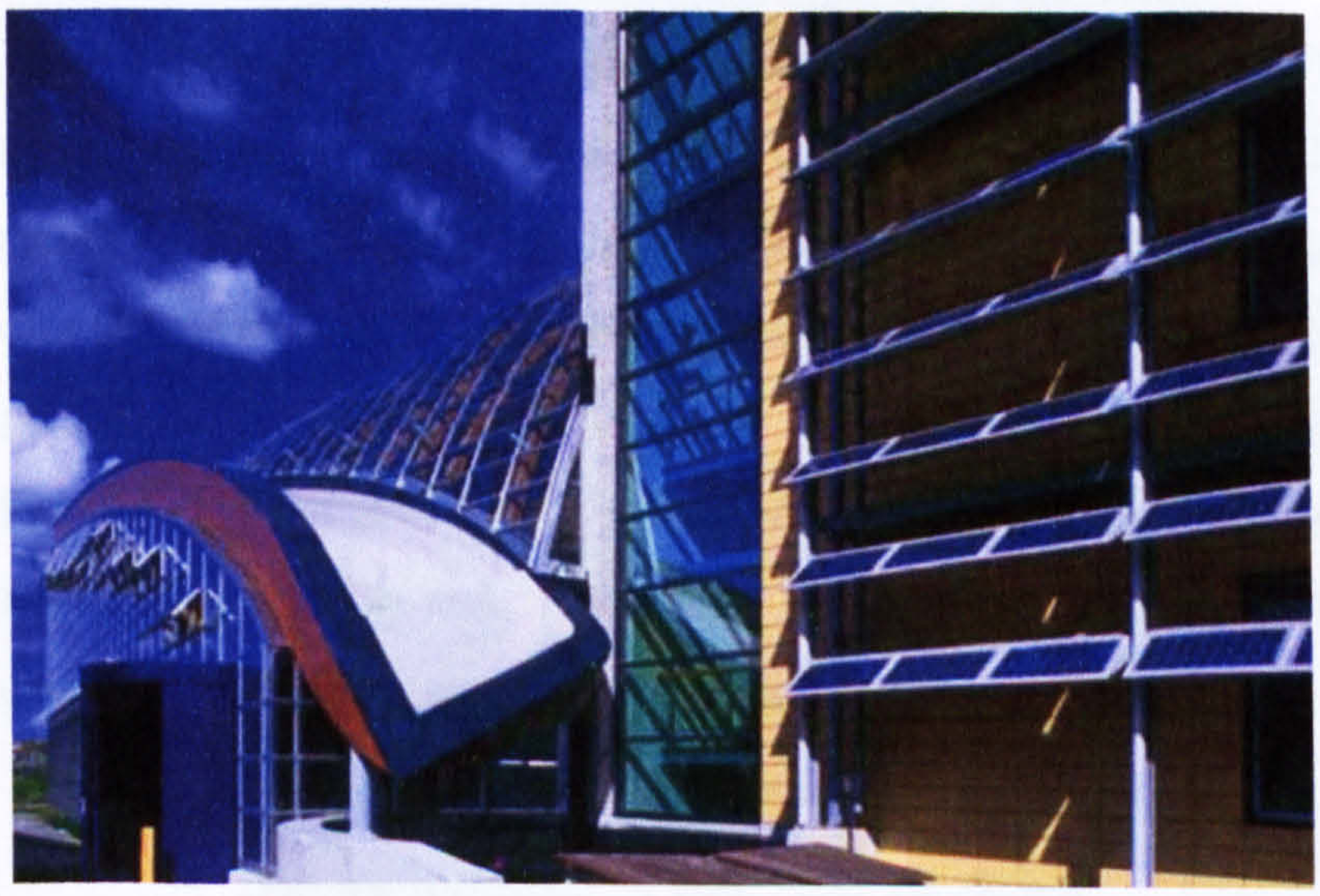


Fig. 2.18 ECN 42 building, Petten, the Netherlands. Main entrance

Source: BEAR Achitecten: http://www.bear.nl/PDF/OfficeECN42.pdf. Computer Animation: Entrance Area for Building 42 [left side] and Building 31 [right side]. Artistic impression by Mart van der Laan. p. 5. 2001.

The new ECN 42 Building is placed next to the renovated ECN 31 Building, built as a response to the growing demand for space in the Netherlands Energy

Research Foundation, and it is planned as an extension of the ECN 31 renovated building. The new ECN 42 Building is the first of three building blocks to be grouped around a glazed conservatory. [Fig. 2.19]. This conservatory has a south facing curved roof, connecting the new ECN 42 Building to the renovated building ECN 31 also serving as an entrance to both buildings.

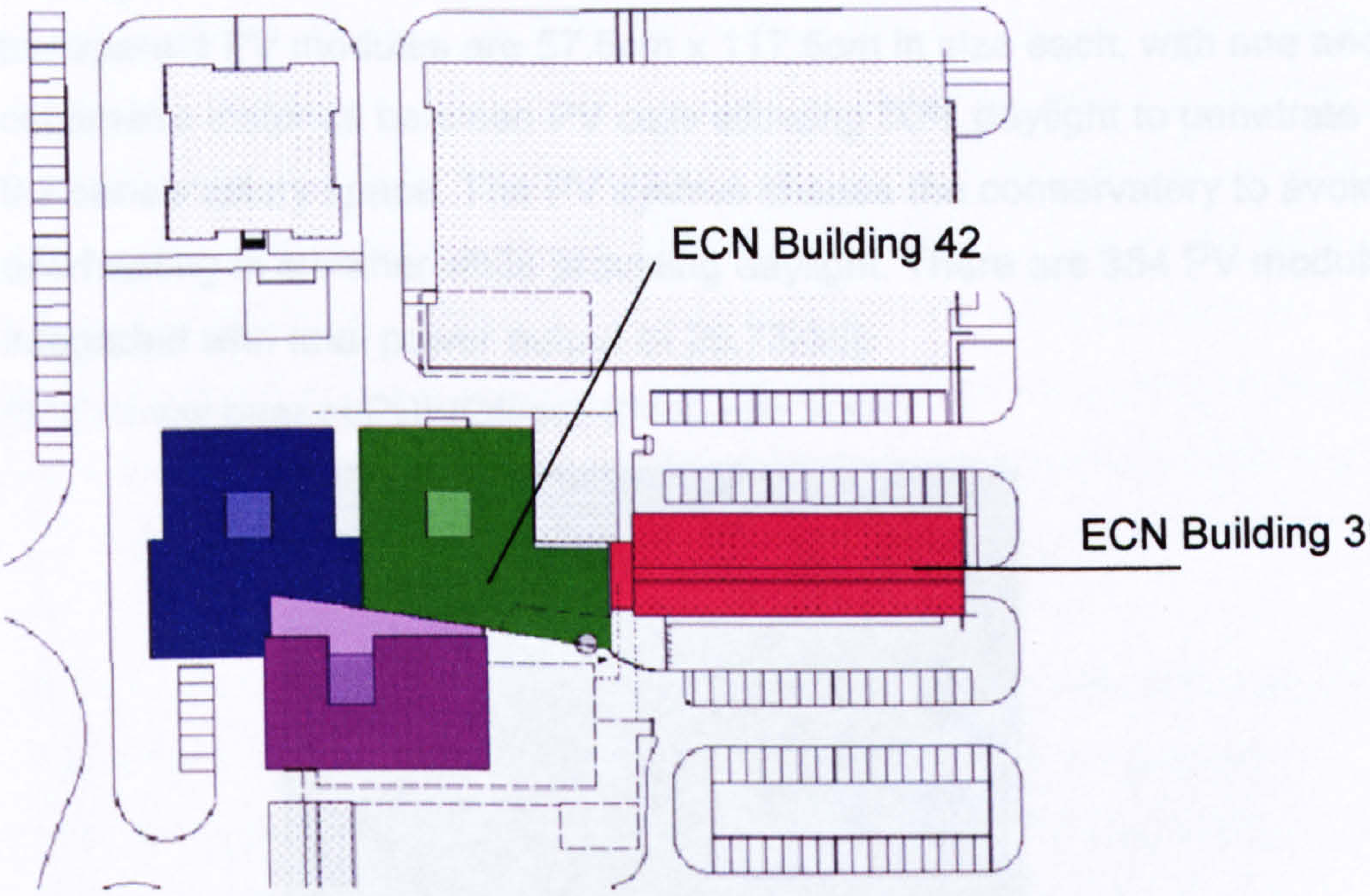


Fig. 2.19 ECN 42 building, Petten, the Netherlands. Site plan [western and southern blocks not yet built].

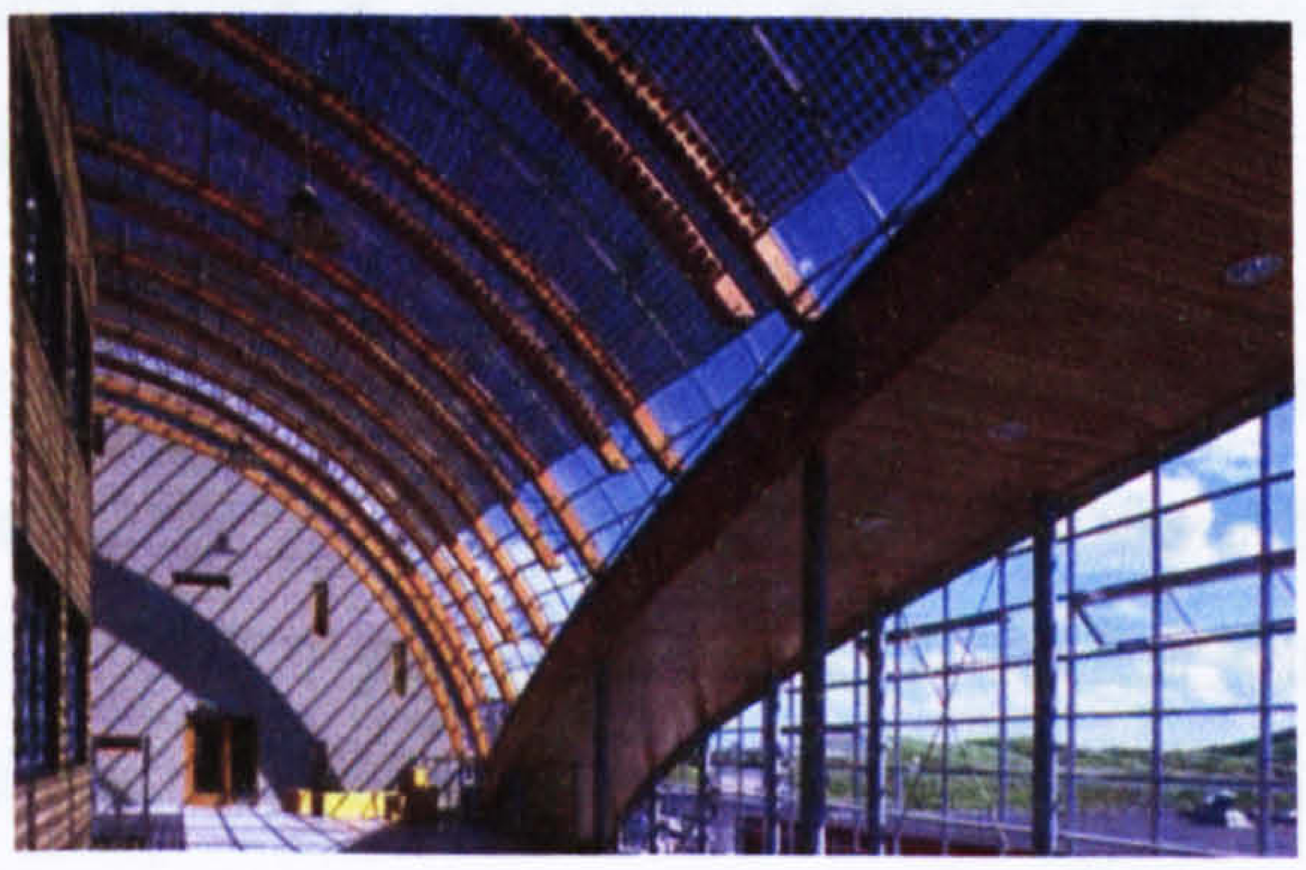
Source: BEAR Achitecten: http://www.bear.nl/PDF/OfficeECN42.pdf. Situation Plan of Buildings 42 and 31: red: 31, green 42 unit 1 – now realized, blue: 42 unit 2 – to be realized in 2002, violet 42 unit 3 to be realized in 2004. p. 7. 2001.

The new ECN 42 Building design concept was to continue with the design approach taken for the renovation of the ECN 31 building, by demonstrating a design of a low energy consumption and integration of solar energy in the built environment. The completed unit is three storeys high [basement level not shown on computer animations Fig. 2.20], serving as offices and laboratories. Providing mechanically supplied ventilation with heat recovery was unavoidable due to the specific requirement for increased air change rate in laboratories. The energy-efficient design also included:

- daylight controlled artificial lighting system
- ventilation system with heat recovery
- summer night ventilation through centrally openable windows
- windows and external wall with high insulation level
- compact building form
- unheated conservatory space as climatic buffer

[IEA PVPS TASK 7, 2002].

This conservatory is south oriented with a laminated wood roof construction. The glazing is single, enclosing an unheated space, acting as a climatic buffer for the rooms overlooking the conservatory. The 400m^2 of PV modules consists of glass-laminated panels with mono-crystalline PV cells, 125mm x 125mm each cell, and 16.5% efficiency. PV panels are integrated between thin metal profiles holding the conservatory glazing between laminated wood beams. The semi transparent PV modules are 57.5cm x 117.5cm in size each, with one and two centimetre distance between PV cells allowing 30% daylight to penetrate into the conservatory space. The PV system shades the conservatory to avoid overheating in summer while providing daylight. There are 354 PV modules integrated with total power output of 26.73kWp [http://www.bear.nl/PDF/OfficeECN42.pdf. 2001].



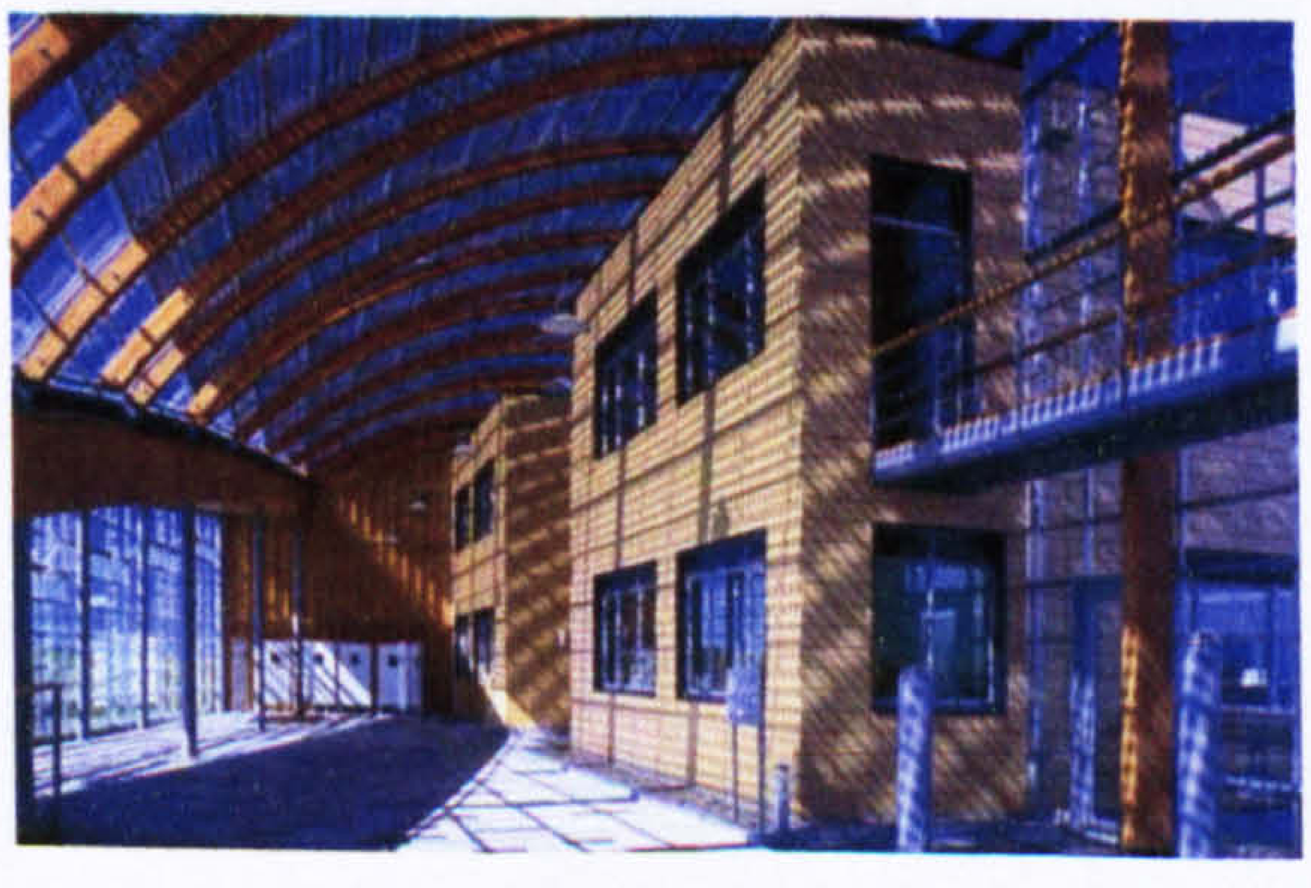


Fig. 2.20 ECN building 42, Petten, the Netherlands, BIPV in conservatory. Computer animations

Source: BEAR Achitecten: http://www.bear.nl. Computer Animations: views of the conservatory of the ECN building 42. Artistic impression by Mart van der Laan. pp. 9-10. 2001.

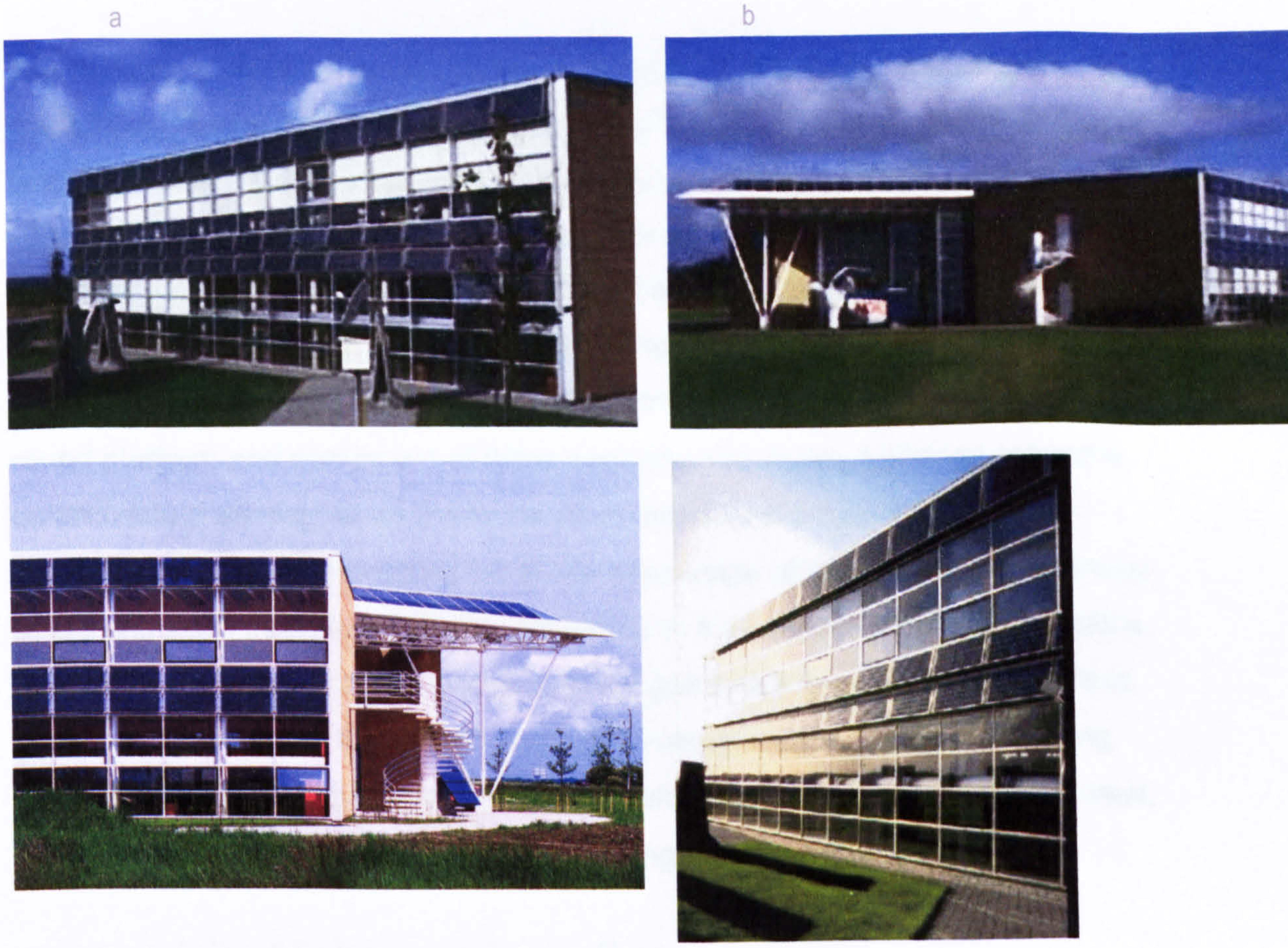
The ECN 42 building is an example of a glazed conservatory with roof integrated semi transparent PV modules, serving as a climatic buffer, providing shading, generating electricity and optimising daylight transmittance. The visit of the Scottish Solar Energy Group (SSEG), in August 2003, revealed that only the basement and ground floors are occupied while the first floor is still unoccupied. An observation made at the time of the visit was the very good daylight level on the first floor while the lower occupied floor had artificial lighting switched on. Although the daylight level may be expected to decrease from the first to lower floor levels, a question arises as to whether artificial lighting would have been used had the first floor been occupied. Similar to the ECN Building No. 31, measurements of the PV systems performance are permanently taken in the building, but with no link to occupancy influence over electrical loads such as artificial lighting.

Thus although the project will advance knowledge of the electrical performance of several specific BIPV applications, it would appear that the wider environmental aims, particularly with respect to the retrofit application, will not be evaluated. Also, although this project has relevance to the aims and objectives of this thesis investigation, its rural location contrasts starkly with the inland urban characteristics of Glasgow.

2.5.2 BRUNDTLAND CENTRE BUILDING

TOFTLUND [55°N] DENMARK

a b



c d

Fig. 2.21 [a-d] Brundtland Centre, Toftlund, Denmark. Views of the south façade

Fig. 2.21 [a-b] Source: IEA PVPS Task VII; European Commission: "The Brundtland Centre". http://www.eurec.be. September 2000.
Fig. 2.21 [c] Wigginton M., Harris J. "*Intelligent Skins*, Case study 11: The Brundtland Centre". Butterworth-Heinemann, Oxford, UK, p. 103, 2002.
Fig. 2.21 [d] Source: Clarke J.A., Hand W., Janak M., Johnstone C.M., Strachan P.A. *PV-Hybrid-PAS* "Development of Procedures for Overall Performance Evaluation of Hybrid Photovoltaic Building Components", Final Report; Annex Report: Modelling 5, Simulation Case Study:Brundtland Centre, Toftlund, Denmark. p. 1. 1998.

The Brundtland Centre is an office, conference and exhibition building, operating since 1995, located in Toftlund in the southern part of Denmark [latitude 55°N] and with a total floor area of 1,560m^2. The building project was a showcase of energy-efficiency, demonstrating innovative application of photovoltaics, daylighting systems, and utilisation of passive solar energy and ventilation. The aim of the project was to demonstrate that energy consumption in non-domestic buildings could be reduced to a half of the Danish Building Regulation Code BR95 for similar buildings in Denmark [http://www.caddet-re.org. 1998]. The main design principle was to maximise the utilisation of passive solar energy and natural ventilation, to minimise the amount of mechanical air treatment and duct-work in the building, and to avoid any need for a mechanical cooling [Madsen and Sorensen, 1994, p.230].

The building is situated on the southern outskirts of the town, on a site with no obstructions to solar access, away from noisy roads and surrounded with a park land. The local climate is northern coastal with minimum average temperature of -1.1°C in February and maximum average temperature of 16.7°C in July [Wigginton and Harris, 2002, p.104]. Compared to the climate of Glasgow, the Danish climate is similar, although, with stronger continental influence resulting in somewhat colder winters and warmer summers. The building is placed on a round platform and composed of three separate two-storey buildings around a central atrium serving as an entrance court and an exhibition space [Fig. 2.22]. The composition of the building takes the advantage of the passive solar energy by placing each individual building according to their function and internal gains. Therefore, the classrooms with high internal gains due to occupancy level face north-east orientation, the offices and exhibition space face south-east taking advantage of the passive solar gains, the multi-purpose space faces north-west, and the central atrium has a south-west facing entrance and a glazed roof.

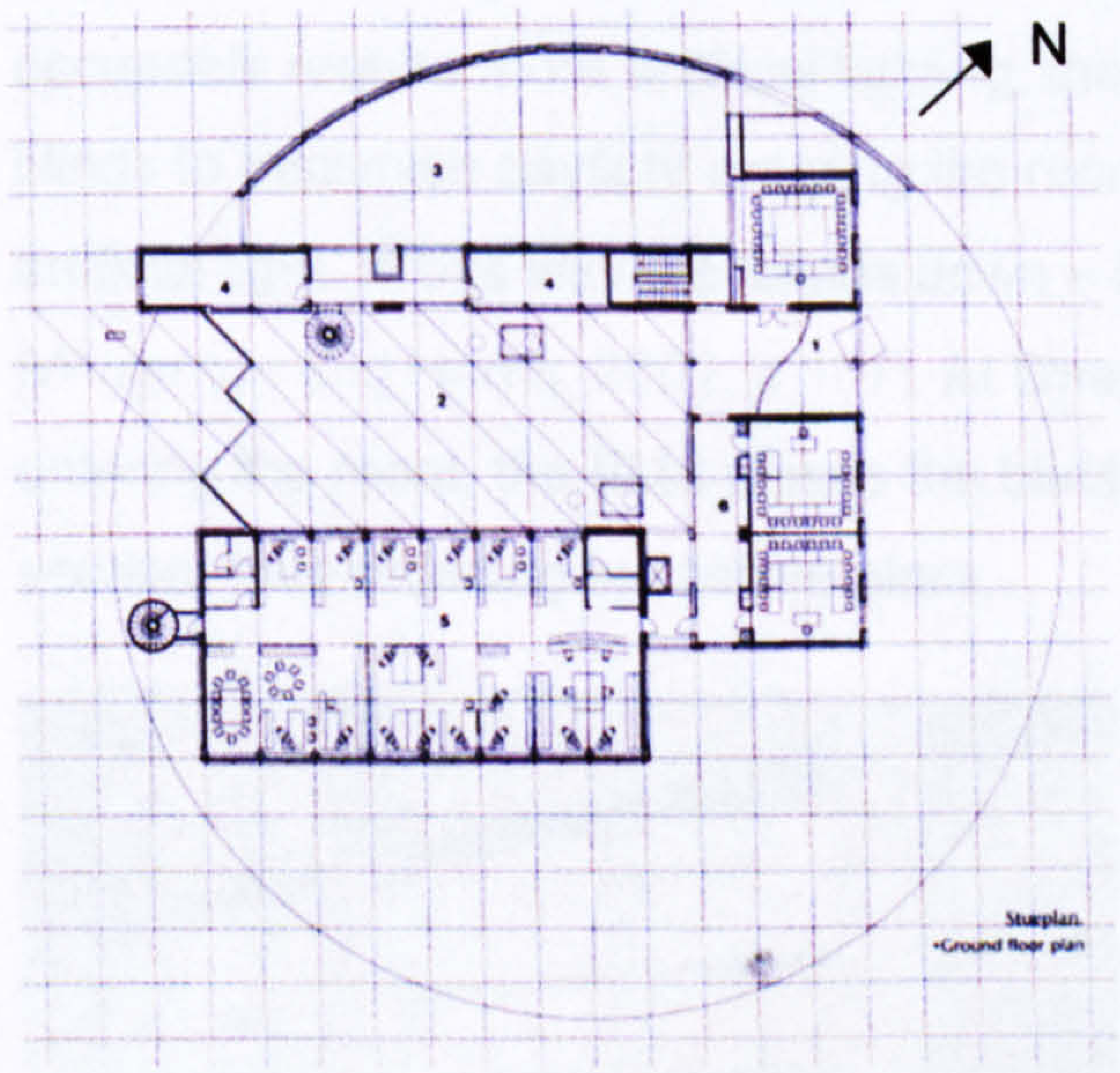


Fig. 2.22 Brundtland Centre, Toftlund, Denmark. Site plan

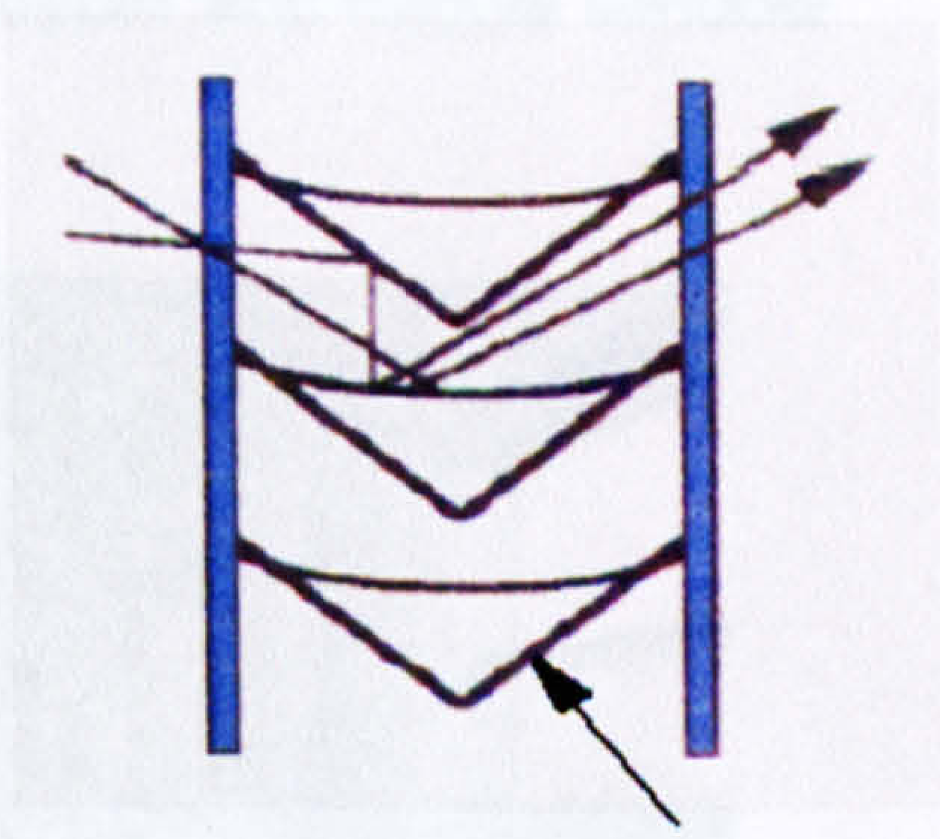


Fig. 2.23 'Fish blinds'

Fig. 2.22 Source: Wigginton M., Harris J. "*Intelligent Skins*, Case study 11: The Brundtland Centre". Butterworth-Heinemann, Oxford, UK, p. 103, 2002.
Fig. 2.23 Source: Clarke J.A., Hand W., Janak M., Johnstone C.M., Strachan P.A. *PV-Hybrid-PAS* "Development of Procedures for Overall Performance Evaluation of Hybrid Photovoltaic Building Components", Final Report; Annex Report: Modelling 5, Simulation Case Study: Brundtland Centre, Toftlund, Denmark. p. 6.1998.

The utilisation of daylight was an important design strategy due to its potential for energy savings. A special attention was given to good quality daylight in all rooms, the atrium, and especially in offices. The daylight design in offices included double glazed windows divided into horizontal sections. The top horizontal section located above occupants' vision level has reflecting blinds integrated into double glazed windows. These reflecting blinds reflect daylight towards a highly reflective ceiling, serving to redirect daylight deeper into the office. The middle window section has windows allowing views to outside and has curved blinds in the double glazed cavity, the so called 'fish blinds' [Fig. 2.23] to also reflect daylight deeper into the room via reflective ceiling [Wigginton and Harris, 2002, p.107]. The lower window section has windows that open to outside and can provide additional ventilation to offices [Fig. 2.24].

A special artificial lighting system was designed for offices consisting of up-lighting luminaires with fluorescent tubes, placed on the inside of the window façade and between the middle and lower window sections. The luminaires direct the artificial light upwards to the reflective ceiling that distributes the light over the working area. The occupants can adjust the intensity of light by a simple way of increasing or decreasing the amount of artificial lighting. The Building Management System [BMS] controls the blinds in the upper windows and adjusts the angle of the blinds in the middle window section. When the occupants require more artificial lighting, the BMS first adjusts the tilt of the blinds to maximise daylight entering the room before increasing the level of artificial light. In this way the 'blinds down – lights on' situation is avoided [Wigginton and Harris, 2002, p.107]. At times of a high level of direct sunlight entering the room, the BMS closes the blinds in the upper and middle window section, thus reducing excessive glare.

Fig. 2.24 Brundtland Centre, Toftlund, Denmark. Daylight control in offices

Source: Clarke J.A., Hand W., Janak M., Johnstone C.M., Strachan P.A. *PV-Hybrid-PAS* "Development of Procedures for Overall Performance Evaluation of Hybrid Photovoltaic Building Components", Final Report; Annex Report: Modelling 5, Simulation Case Study: Brundtland Centre, Toftlund, Denmark. p. 4.1998.

The building has a photovoltaic system integrated into the atrium roof, to generate electricity and provide shading to prevent atrium from overheating. The semi transparent PV modules, 245.1m² total atrium roof area, i.e. 242m² active PV cells area, [Clarke *et al* (e), 1998, p.10], with round shaped mono-crystalline cells, are placed between two layers of glass without an air cavity, allowing 20% of the daylight to enter the atrium. The atrium roof was constructed as a saw-tooth structure with vents for ventilation that run diagonally across the space to provide optimum orientation and tilt for the PV panels. Each length of the roof has two surfaces, one facing south and containing the semi transparent PV panels, and one facing north with clear glass for diffuse lighting [Fig. 2.25 a-b]. Because of winter shading, occurring at low sun angles, from one 'saw-tooth' to the next, the affected areas have dummy solar cells to avoid the effect of over shading reducing the electrical output of the active PV cells [http://www.caddet-re.org. 1998].

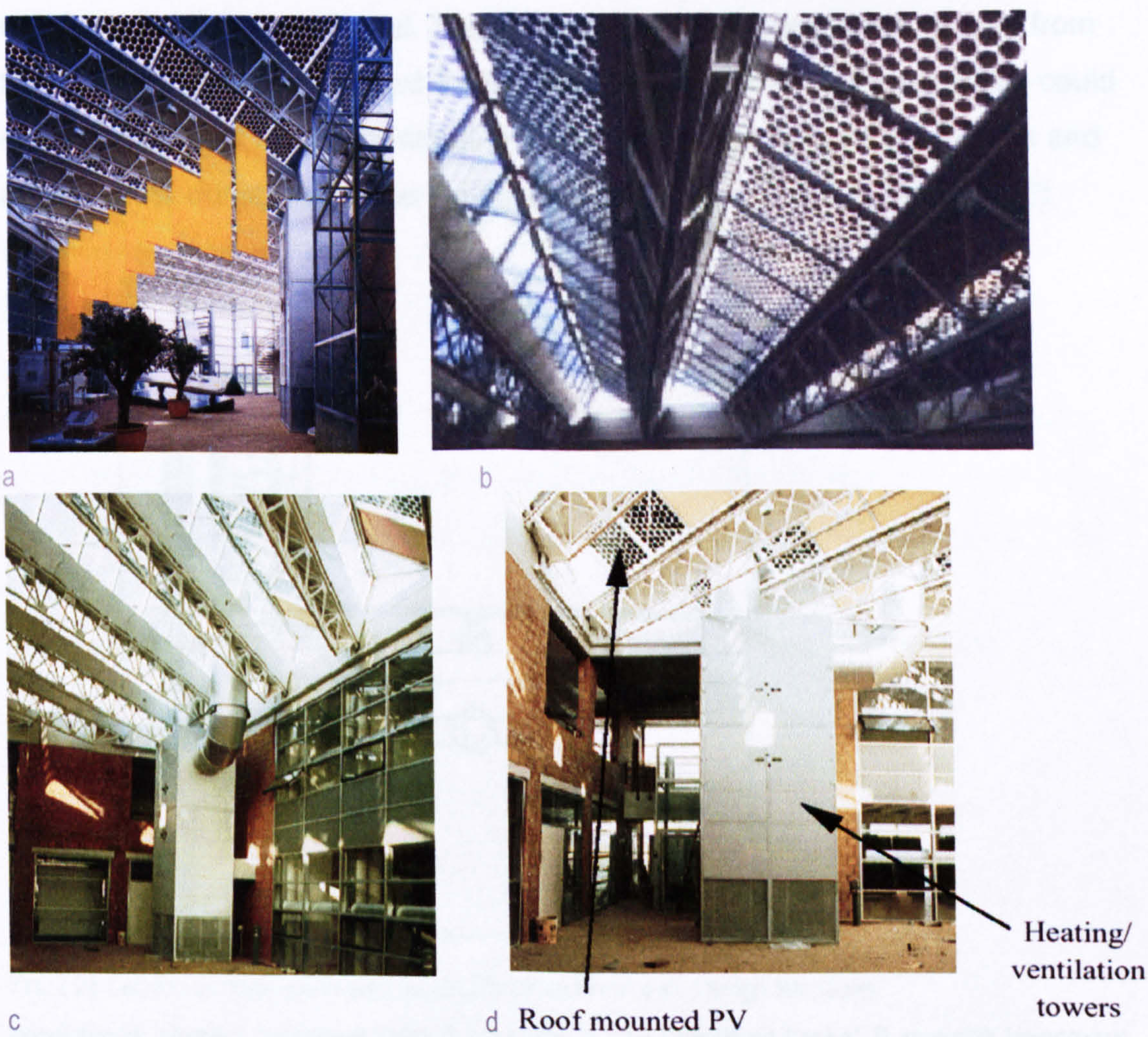


Fig. 2.25 [a-d] Brundtland Centre, Toftlund, Denmark. Views of the atrium

Fig. 2.25 [a] Wigginton M., Harris J. "Intelligent Skins, Case study 11: The Brundtland Centre". Butterworth-Heinemann, Oxford, UK, p. 106, 2002.

Fig. 2.25 [b] Source: IEA PVPS Task VII; European Commission: "The Brundtland Centre". http://www.eurec.be. September 2000.

Fig. 2.25 [c-d] Source: Clarke J.A., Hand W., Janak M., Johnstone C.M., Strachan P.A. *PV-Hybrid-PAS* "Development of Procedures for Overall Performance Evaluation of Hybrid Photovoltaic Building Components", Final Report; Annex Report: Modelling 5, Simulation Case Study: Brundtland Centre, Toftlund, Denmark. p. 4. 1998.

Another PV system was integrated on the offices façade facing south-east. The design intensions were to include opaque PV panels, total area 45m^2 [Clarke *et al* (e), 1998, p.10] on the lower section below windows in offices in a PV-hybrid [electrical and thermal] mode. The PV façade system would have an air intake at the bottom of the PV panels and an air exit at the top of the panels. When the air intake and the air exit are in the open position, the air will circulate in the cavity and cool the panels. When the air exit is in the closed position, pre-heated air behind the PV panels will be brought into offices at ceiling level [Fig. 2.26], with radiators in offices providing additional heating.

However, the hybrid PV panels were not implemented. Instead, openable windows were placed for additional ventilation on the ground floor, and two rows of PV panels detached from the façade, creating an open, naturally ventilated cavity, were installed on the first floor offices. A single row of similar PV panels was installed below roof level. The total predicted electrical power output from the roof and façade integrated PV systems is 13,500kWh per year, which could meet all electrical requirements of the building during the summer months and approx. 20% during the winter months [Wigginton and Harris, 2002, p.106].

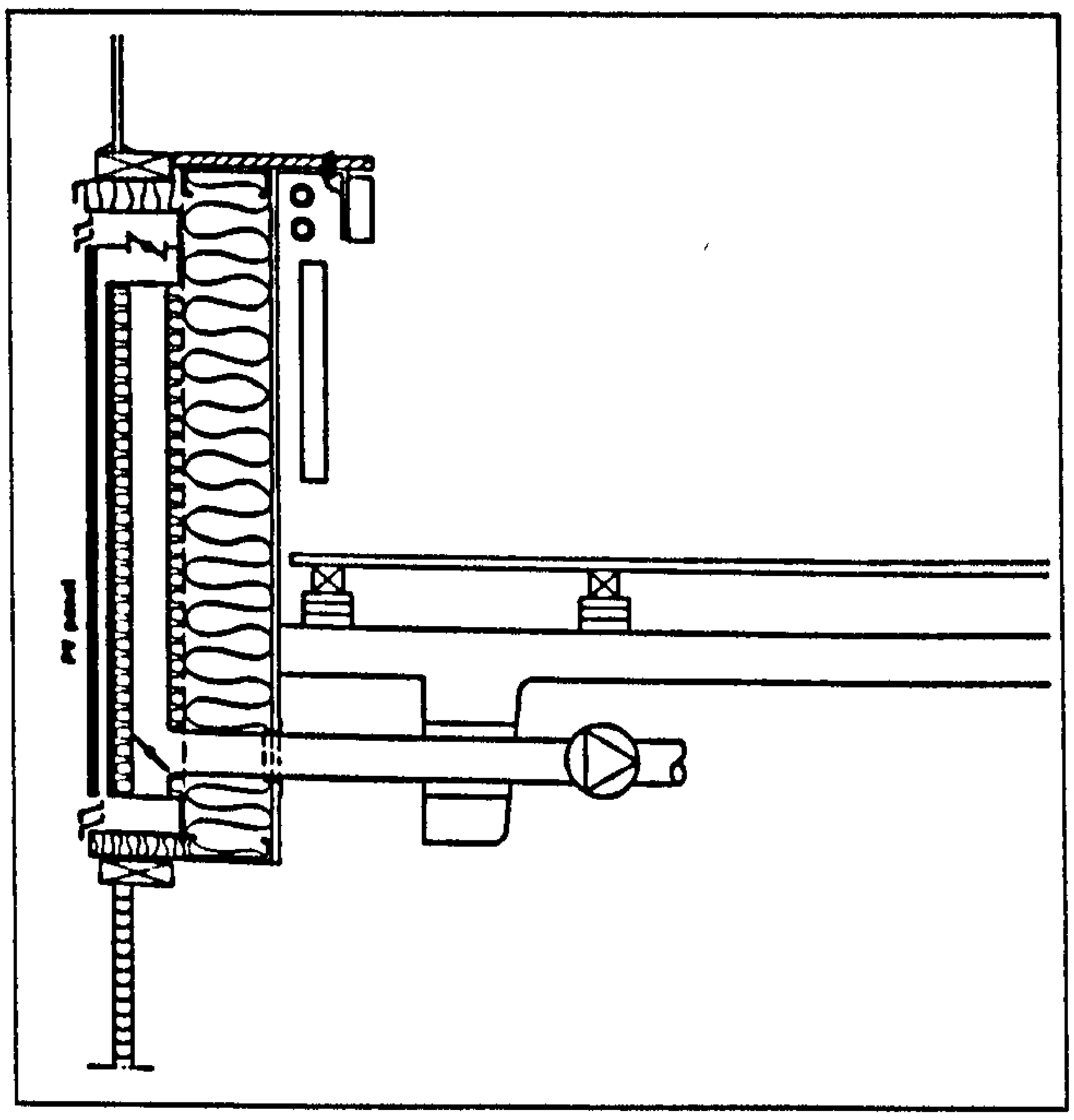


Fig. 2.26 Section through south-east facing offices external wall. Design intentions

Wigginton M., Harris J. "*Intelligent Skins*, Case study 11: The Brundtland Centre". Butterworth-Heinemann, Oxford, UK, p. 105, 2002.

Designing a non air-conditioned building with an energy-efficient ventilation system was another important strategy in reducing building's energy demand. The ventilation of the building [except for offices] is based on using the atrium as a buffer space for pre-heating the ambient air. The incoming air enters the building via two ventilation towers in the atrium and passes through heat exchangers before being delivered in the lower level of the atrium [Fig. 2.25 c-d]. The pre-heated air from the atrium is supplied to surrounding rooms by an extract air system, and the exhaust air from all rooms is ducted to the two ventilation towers in the atrium and passed through heat exchangers to pre-heat incoming fresh air [Wigginton and Harris, 2002, p.106]. The south-east offices are ventilated with decentralised units incorporating local fans and heat exchangers. The extract fans are controlled by movement detectors, ventilating only occupied offices and thus saving energy [Wigginton and Harris, 2002, p.106]. During the summer to avoid overheating, an atrium door and vents on atrium's roof can open for natural ventilation.

To evaluate and optimise the design solutions, various computer modelling and simulations were performed using ESP-r for thermal energy modelling and Radiance for lighting modelling. The building was also one of the case study buildings of the PV-Hybrid-PAS research [Clarke *et al* (e), 1998]. In this research, several energy models of the building were developed, starting from a base case model representing the building as built, and several reference models exploring PV hybrid [electrical and thermal] design options. The objective of this study was to compare the benefits of the PV hybrid system to those of only electrical, or the non-hybrid. The energy models were simulated with the average monthly temperatures for Standard European Test Reference Year [TRY] for Copenhagen, Denmark as closest available climate data to the location of Toftlund.

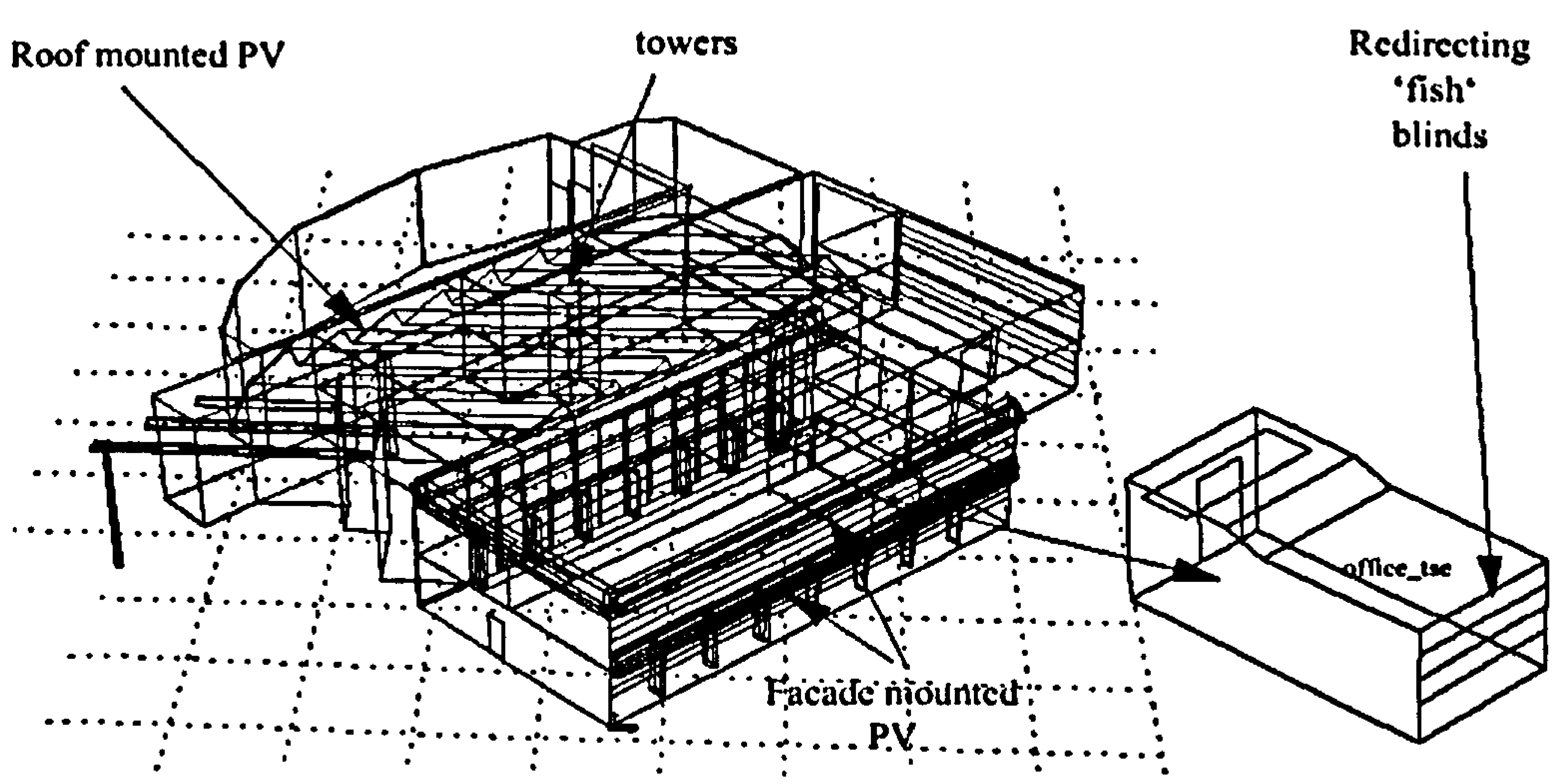


Fig. 2.27 ESP-r Model of the Brundtland Centre, Toftlund, Denmark

Source: Clarke J.A., Hand W., Janak M., Johnstone C.M., Strachan P.A. *PV-Hybrid-PAS* "Development of Procedures for Overall Performance Evaluation of Hybrid Photovoltaic Building Components", Final Report; Annex Report: Modelling 5, Simulation Case Study: Brundtland Centre, Toftlund, Denmark. p. 6. 1998.

The ESP-r model of the Brundtland Centre represents the atrium, rooms at the back of the atrium, and south-east facing offices. The base case model [building as built] has the non hybrid design of PV systems. It also has mechanical ventilation with two heat recovery towers in the atrium and separate heat recovery units for the offices. The base case modelling results [Fig. 2.27] have shown a total annual energy demand of 142.42kWh/m^2. The annual predicted electrical benefit from the PV systems is 9.54kWh/m^2, which nearly covers the annual demand for lighting of 10.0kWh/m^2. For the total building floor area of 1560m^2, a 242m^2 area of PV systems [both atrium roof and south-east façade wall], and an annual predicted electrical output from the PV systems of 9.54kWh/m^2, the annual predicted electrical contribution of the PV system is 61.5kWh/m^2 PV area. This result might be below expectations, and the author has reservations due to available information regarding the atrium PV system area, varying in different literature sources. In an attempt to confirm the area of the atrium roof PV system the author contacted the Esbensen Consultants, who have been involved with the Brundtland Centre with the energy strategy and integration of BIPV systems, but did not receive an answer.

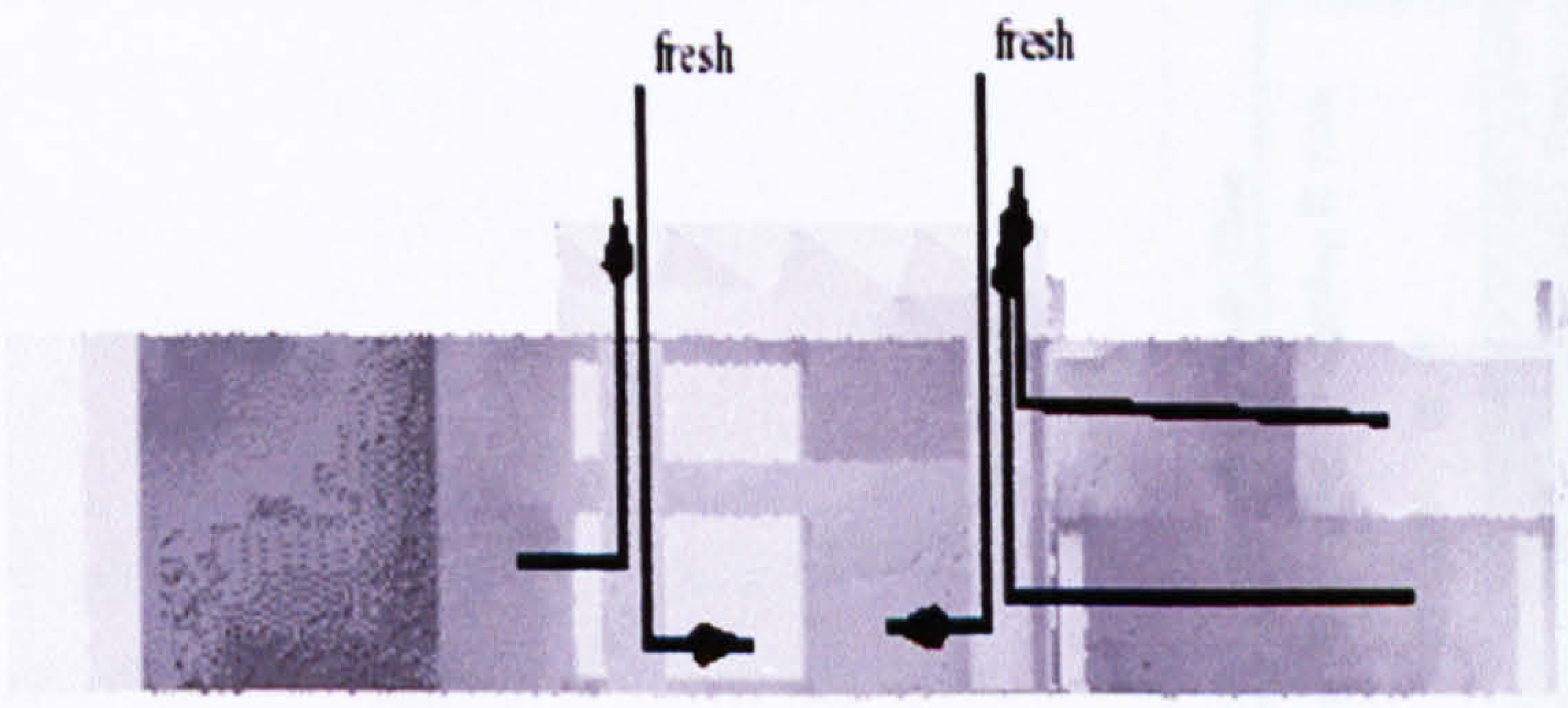


Fig. 2.28 Base case model

Source: Clarke J.A., Hand W., Janak M., Johnstone C.M., Strachan P.A. *PV-Hybrid-PAS* "Development of Procedures for Overall Performance Evaluation of Hybrid Photovoltaic Building Components", Final Report; Annex Report: Modelling 5, Simulation Case Study: Brundtland Centre, Toftlund, Denmark. p. 8. 1998.

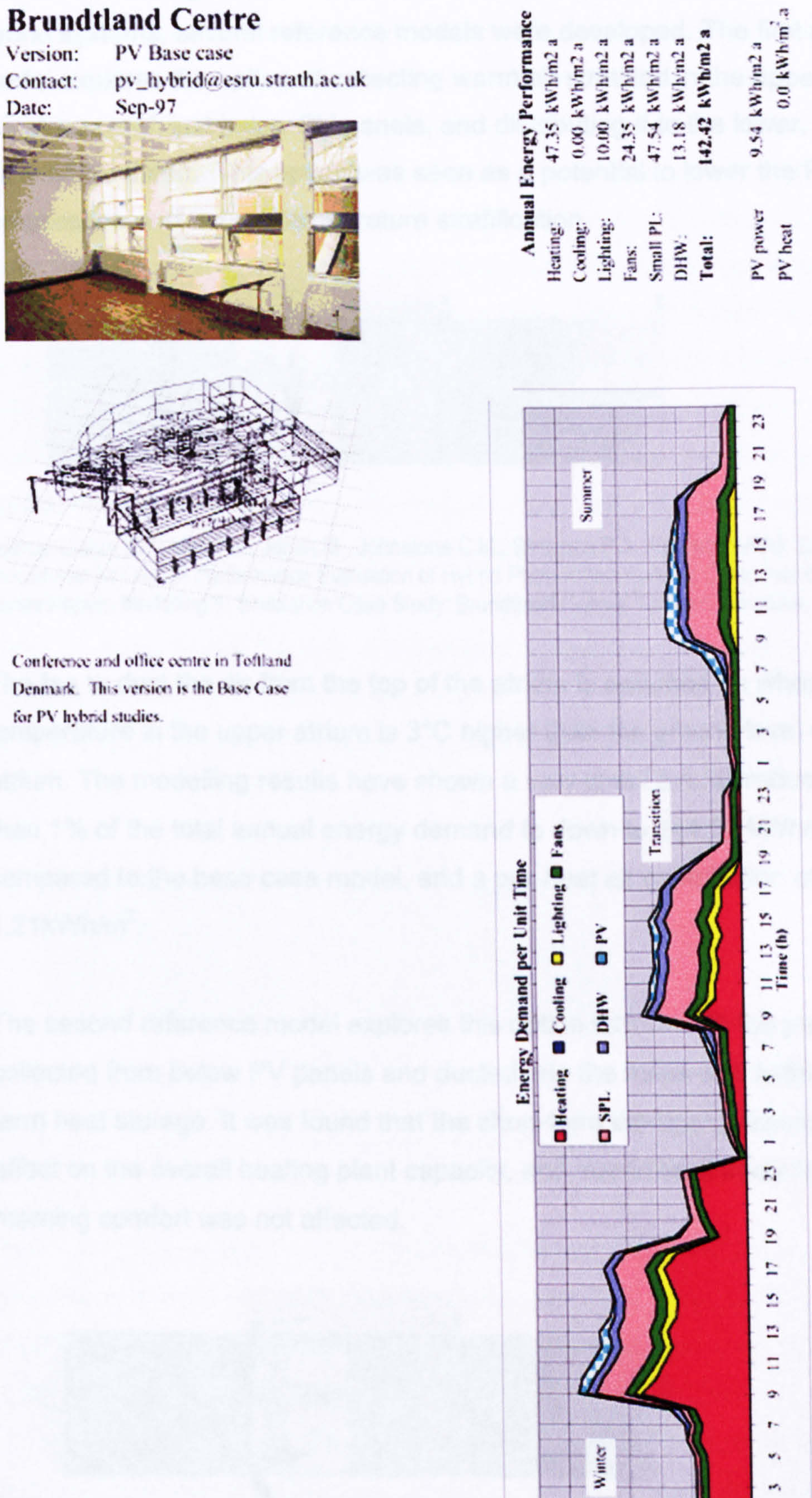


Fig. 2.29 Integrated performance view base case model

Source: Clarke J.A., Hand W., Janak M., Johnstone C.M., Strachan P.A. *PV-Hybrid-PAS* "Development of Procedures for Overall Performance Evaluation of Hybrid Photovoltaic Building Components", Final Report; Annex Report: Modelling 5, Simulation Case Study: Brundtland Centre, Toftlund, Denmark. p. 20. 1998.

In order to investigate possibilities for thermal and electrical contribution of PV-hybrid systems, several reference models were developed. The first reference model explores the option of collecting warm air stratified in the upper level of the atrium roof, just below PV panels, and distributing it to the lower, occupied parts of the atrium. This option was seen as a potential to lower the PV temperature and reduce temperature stratification.

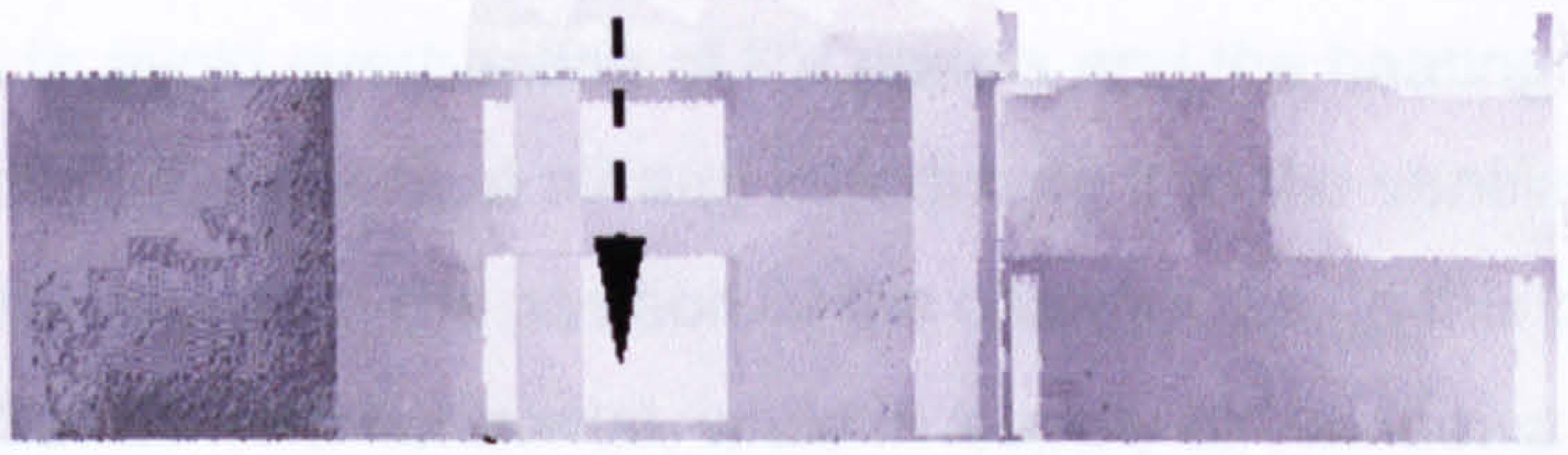


Fig. 2.30 Reference one model

Source: Clarke J.A., Hand W., Janak M., Johnstone C.M., Strachan P.A. *PV-Hybrid-PAS* "Development of Procedures for Overall Performance Evaluation of Hybrid Photovoltaic Building Components", Final Report; Annex Report: Modelling 5, Simulation Case Study: Brundtland Centre, Toftlund, Denmark. p. 9. 1998.

The fan to duct the air from the top of the atrium is switched on when the temperature in the upper atrium is 3°C higher than the ground level of the atrium. The modelling results have shown a very small overall reduction of less than 1% of the total annual energy demand to down to 141.21 kWh/m^2 compared to the base case model, and a pre-heat air contribution of 1.21kWh/m^2.

The second reference model explores this option further with the pre-heat air collected from below PV panels and ducted into the mass wall acting as a short-term heat storage. It was found that the short-term storage option has little or no effect on the overall heating plant capacity, and due to time delay the early morning comfort was not affected.

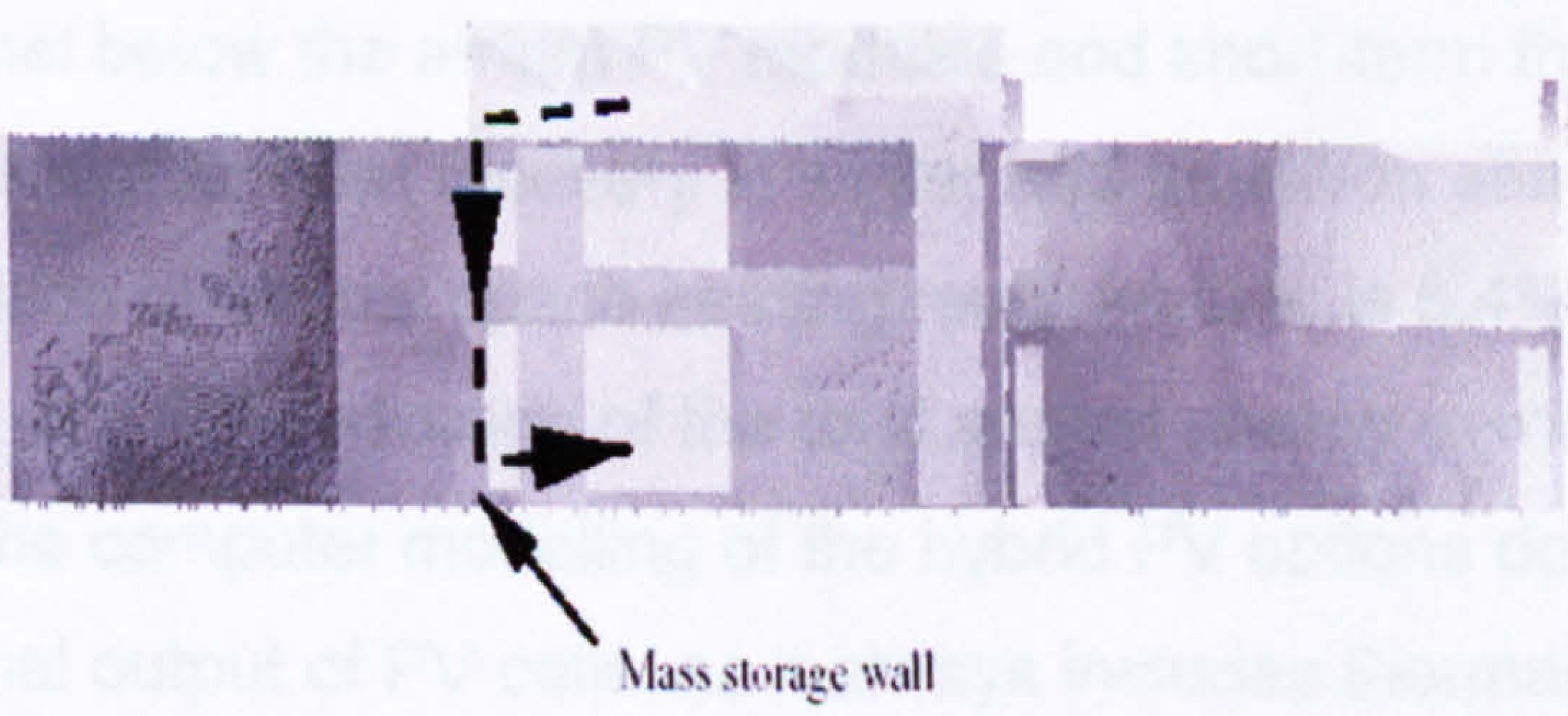


Fig. 2.31 Reference two model

Source: Clarke J.A., Hand W., Janak M., Johnstone C.M., Strachan P.A. *PV-Hybrid-PAS* "Development of Procedures for Overall Performance Evaluation of Hybrid Photovoltaic Building Components", Final Report; Annex Report: Modelling 5, Simulation Case Study: Brundtland Centre, Toftlund, Denmark. p. 9. 1998.

The third reference model explores the design proposal to create a transparent heat collector channel under the PV modules in order to increase the heat recovered. The warm air is collected from this few centimetres deep channel and ducted to the mass wall for short-term heat storage, as in the second reference model. The transparent heat collector channel under the PV modules is somewhat analogous with either 'supply air' windows or with a ventilated vertical double skin construction with integrated PVs, where ventilating the cavity helps to avoid overheating of PV panels and the heating demand is reduced by collecting the pre-heat air and introducing it to the ventilation system. The differences are in the position of the channel, i.e. in this roof system the channel is at 30° tilt from horizontal, while in 'supply air' windows or a double skin façade construction the cavity is normally vertical. Also, the roof transparent heat collector channel is limited to few centimetres, while in a double skin façade construction the cavity depth could vary from several centimetres to over a metre in cases where there are maintenance platforms. However, the main principle behind both cases is same, i.e. to collect and utilise the pre-heat air from the cavity to reduce building's heating load.

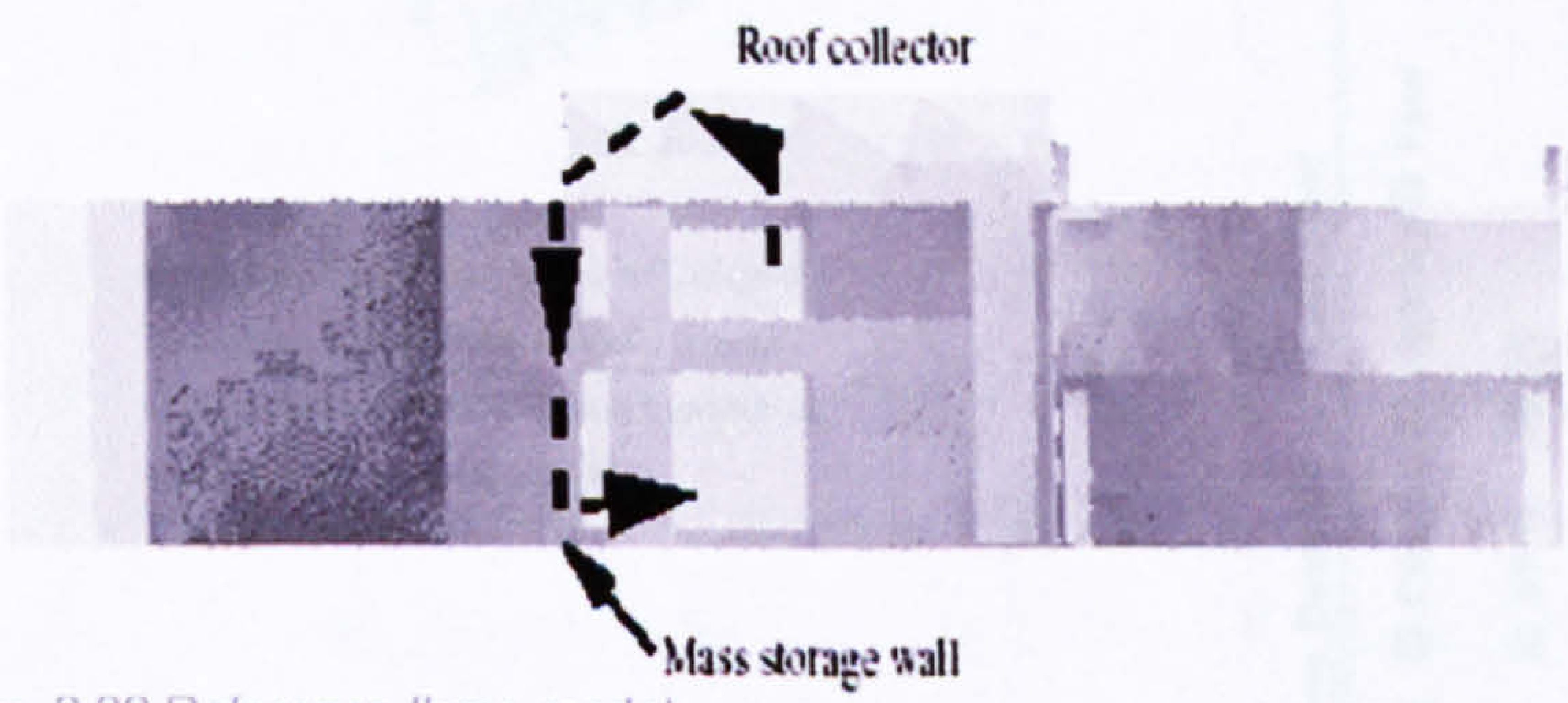


Fig. 2.32 Reference three model
Source: Clarke J.A., Hand W., Janak M., Johnstone C.M., Strachan P.A. *PV-Hybrid-PAS* "Development of Procedures for Overall Performance Evaluation of Hybrid Photovoltaic Building Components", Final Report; Annex Report: Modelling 5, Simulation Case Study: Brundtland Centre, Toftlund, Denmark. p. 10. 1998.

Results for this model [Fig. 2.33] have shown that the use of heat collector channel below the atrium PV modules and short-term thermal storage provides a potential for heat recovery in winter and transition seasons, and the overall reduction of annual space heating requirements is 5.4% [Clarke *et al* (e), 1998, p.16], or 1.8% reduction of the total annual energy demand. It should be noted that the computer modelling of the hybrid PV options does not reflect just the thermal output of PV cells, as it always includes thermal stratification effect in the atrium. Indeed one might reasonably expect the letter influence, recirculation of the warmest air, to be more dominant than waste heat from the cells during the period when heat is required.

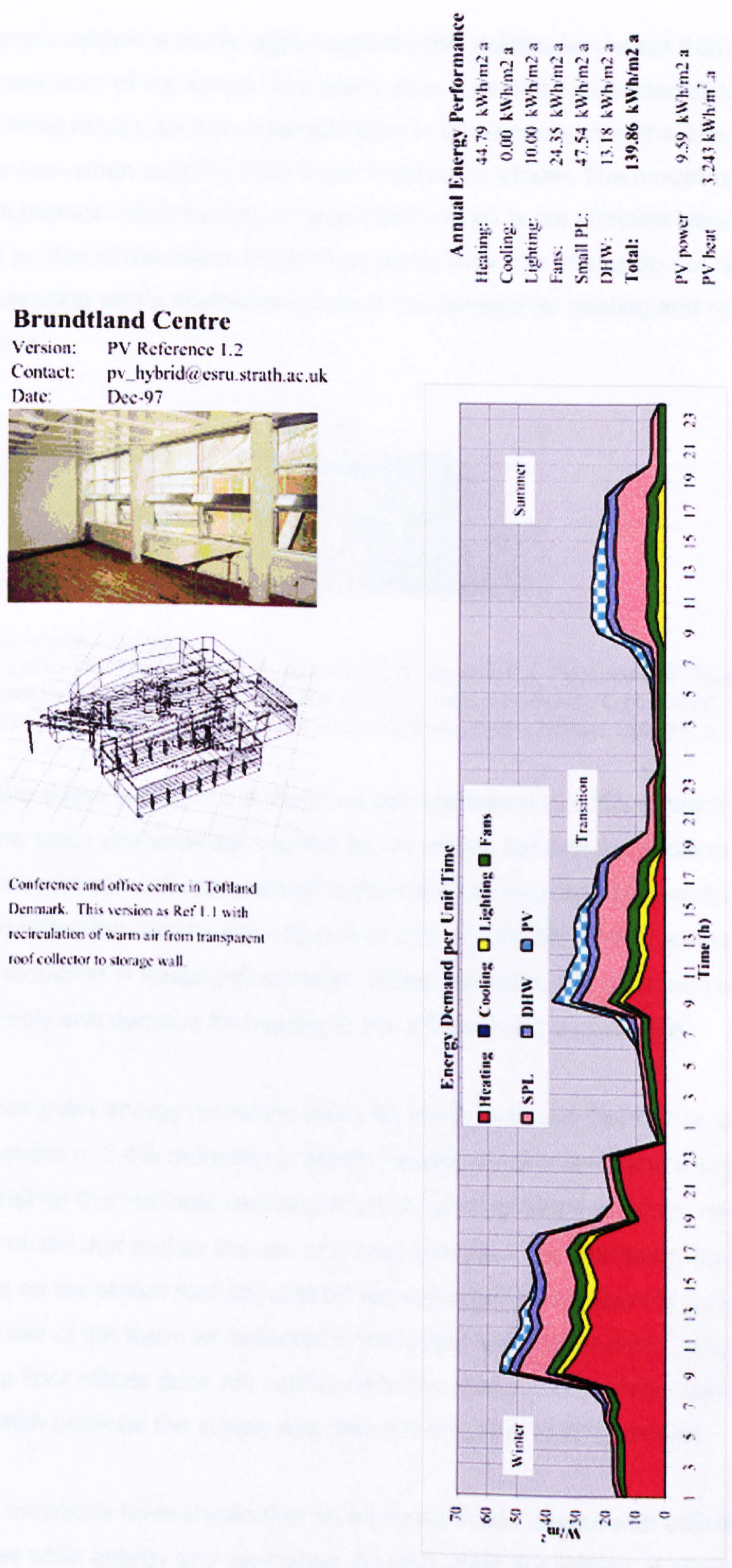


Fig. 2.33 Integrated performance view reference three model
Source: Clarke J.A., Hand W., Janak M., Johnstone C.M., Strachan P.A. *PV-Hybrid-PAS* "Development of Procedures for Overall Performance Evaluation of Hybrid Photovoltaic Building Components", Final Report; Annex Report: Modelling 5, Simulation Case Study: Brundtland Centre, Toftlund, Denmark. p. 23. 1998.

The fourth reference model again explores the stratification effect that occurs in the upper level of the atrium. The warm air is collected and ducted directly to upper level offices, as the air temperature in the upper level of the atrium is higher than when supplied from lower level of the atrium. The modelling has shown that the direct heating of upper floor offices is not effective because the upper portion of the atrium tends to be warm when the offices do not require heat resulting with a mismatch between the demand for heating and heat supply in offices.

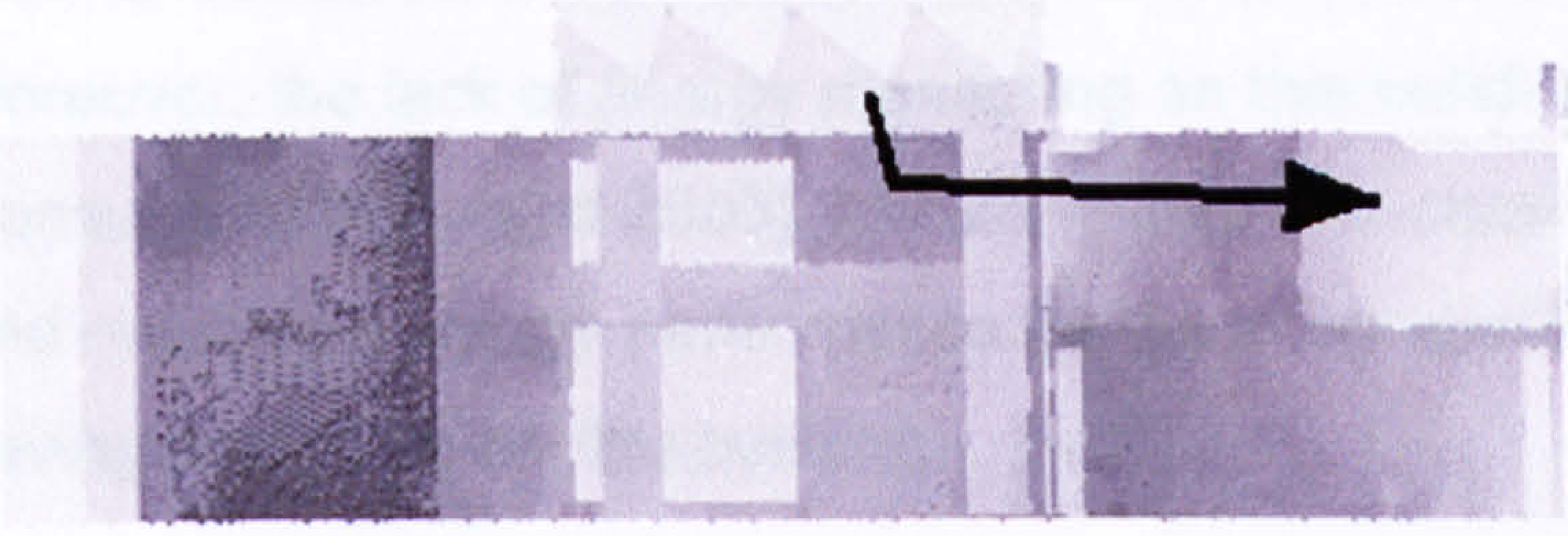


Fig. 2.34 Reference four model
Source: Clarke J.A., Hand W., Janak M., Johnstone C.M., Strachan P.A. *PV-Hybrid-PAS* "Development of Procedures for Overall Performance Evaluation of Hybrid Photovoltaic Building Components", Final Report; Annex Report: Modelling 5, Simulation Case Study: Brundtland Centre, Toftlund, Denmark. p. 10. 1998.

A further development of the fourth model was tested in a fifth reference model with the same characteristics as the fourth model, but with the addition of a transparent heat collector channel under the roof mounted PV modules, and ducted collection directly into upper floor offices. The fifth model results in a 3.6% reduction in heating demand in offices. However, the mismatch between the supply and demand for heating in the offices is still a downside.

This computer energy modelling study for the Brundtland Centre has shown that best results of 5.4% reduction in space heating requirements and a significant potential for thermal heat recovery in winter and transition seasons are achieved in the model that makes the use of a heat collection channel below the PV panels on the atrium roof and a short term storage. It has also shown that a direct use of the warm air collected in the upper atrium and ducted directly into the top floor offices does not contribute to the space heating reduction due to a mismatch between the supply and demand of space heating profiles.

The simulations have shown that an energy-efficient design with utilisation of passive solar energy and ventilation, an innovative application of photovoltaics and daylighting systems can significantly reduce the annual energy consumption for heating by about 60% and lighting by about 70% in non-domestic buildings, compared to the Danish Building Regulation Code BR95 for similar buildings in Denmark [Wigginton and Harris, 2002, p.108]. The extensive thermal, electrical and daylight computer modelling also served as another example for the integrated energy modelling approach taken in this research work at a similar latitude. Also, since opportunities for incorporating atria occur quite frequently in retrofit work (e.g. glazed courtyards), and can provide opportunities for efficient mixed mode ventilation, the modelling for the Brundtland Centre is at one level usefully informative. However, none of he scenarios attempted to isolate the thermal contribution from the PV itself. These remains here a gap in knowledge. Moreover, the lack of energy monitoring on this building [confirmed by Esbensen Consultants in August 2003], has prevented a comparison between predicted and measured energy performance for the integrated PV systems and energy saving measures on this building.

2.5.3 JUBILEE CAMPUS, NOTTINGHAM UNIVERSITY NOTTINGHAM [52° 58'N] ENGLAND

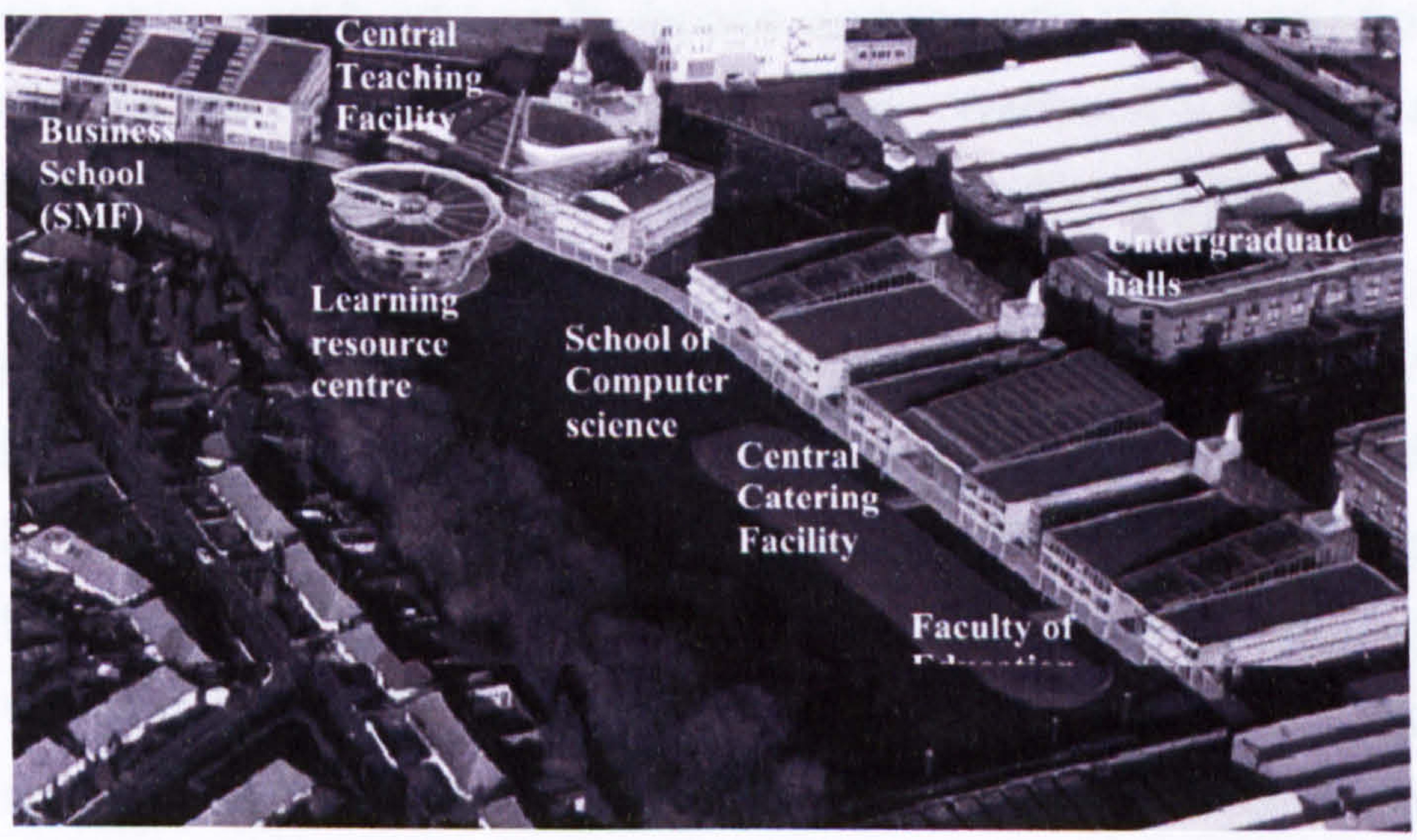


Fig. 2.35 Jubilee Campus Nottingham University, Nottingham, UK. Site aerial view

Source: Riffat S.B., Hicks W., Mustafa A., Berry J., Topp C. "The Jubilee Campus an Example of Building Integrated Renewable Energy". Conference Proceedings: *North Sun 2001, 6th-8th May 2001*, Leiden, the Netherlands. The Netherlands Conference Foundation, Leiden, the Netherlands, 2001.

The Jubilee Campus at the Nottingham University is a complex of environmentally designed buildings by the architects Michael Hopkins and Partners and the structural and service engineers Ove Arup and Partners. The campus was built one mile from the existing campus of the Nottingham University on a 7.5ha brown-field site of the former bicycle factory, set between an industrial zone and a housing area. The campus accommodates 2,500 students, 550 staff, and provides accommodation for 150 postgraduate and 600 undergraduate students in 41,000m^2 total buildings floor area. There are three faculty buildings, a central teaching building, learning resource centre, catering facilities, seminar rooms and offices. A central point to the campus layout is the 13,000m^2 lake, forming a buffer between the housing area edge and the new campus building. The lake creates amenity spaces, introduce wild life in the area and also has a cooling effect on the air entering buildings during warm days by the evaporation of its water. The site layout optimises the orientation and views of the landscape with situating buildings to exploit the prevailing south-westerly winds and to harness passive solar gains. The average winter temperature is 7°C and average summer temperature is 15°C.

The main faculty buildings consist of three wings of three storeys high building blocks connected with full height glazed atria and open courtyards acting as social spaces and environmental buffers. The buildings have several energy efficient, low embodied energy and renewable energy features. Those include: high thermal mass concrete construction; low embodied energy structural elements; moss/tundra roofs; façade cladding with cedar wood from sustainable sources and recycled shredded newspaper 'Warmcell' used for insulation; an efficient, low pressure mixed-mode ventilation with heat recovery; a PV system incorporated into the atrium roof glazing; and light shelves, wooden louvres, light pipes and daylight sensors to control lighting [Riffat *et al*, 2001]. The three faculty buildings have a concrete structure with 12m to18m deep floor plans, 2.7m ceilings height, and exposed concrete soffits and columns to provide thermal mass. The structural insulation of the building results in slightly lower U-values compared to UK building regulations at the time of building, [external walls 0.287W/m^{2}K; roof 0.22W/m^{2}K; ground floor 0.393W/m^{2}K; and windows 2.4W/m^{2}K] [Riffat *et al*, 2001].

The ventilation strategy of the building combines natural and mechanical ventilation systems, with transparent photovoltaic panels integrated into atrium roofs, generating electricity to run the ventilation fans for the heat recovery all year round. The new ventilation concept developed for this building uses fresh air inlet fans in the air handling units, located on the building roof, pushing the air through very large vertical duct shafts to reduce pressure losses, and then enter rooms through 35cm high floor voids via low pressure floor diffusers. The air then exits rooms through the corridor extract path and rises through the stairwell located at the back of the building. At the top of the stairwells the air returns to the handling units and passes through thermal wheels for heat recovery or evaporative cooling, depending on the incoming air's temperature requirements. Finally, the air exits the building through the distinctive metal cowls located at the top of the stairwells. As stated, the ventilation system was designed to keep the pressure drop low, in this case from 280Pa to 340Pa, compared to the typical mechanical ventilation system of 1200Pa to 1600Pa [Building Services Journal, August 1999, p.26], resulting in reduced requirement for fan power to move air through buildings.

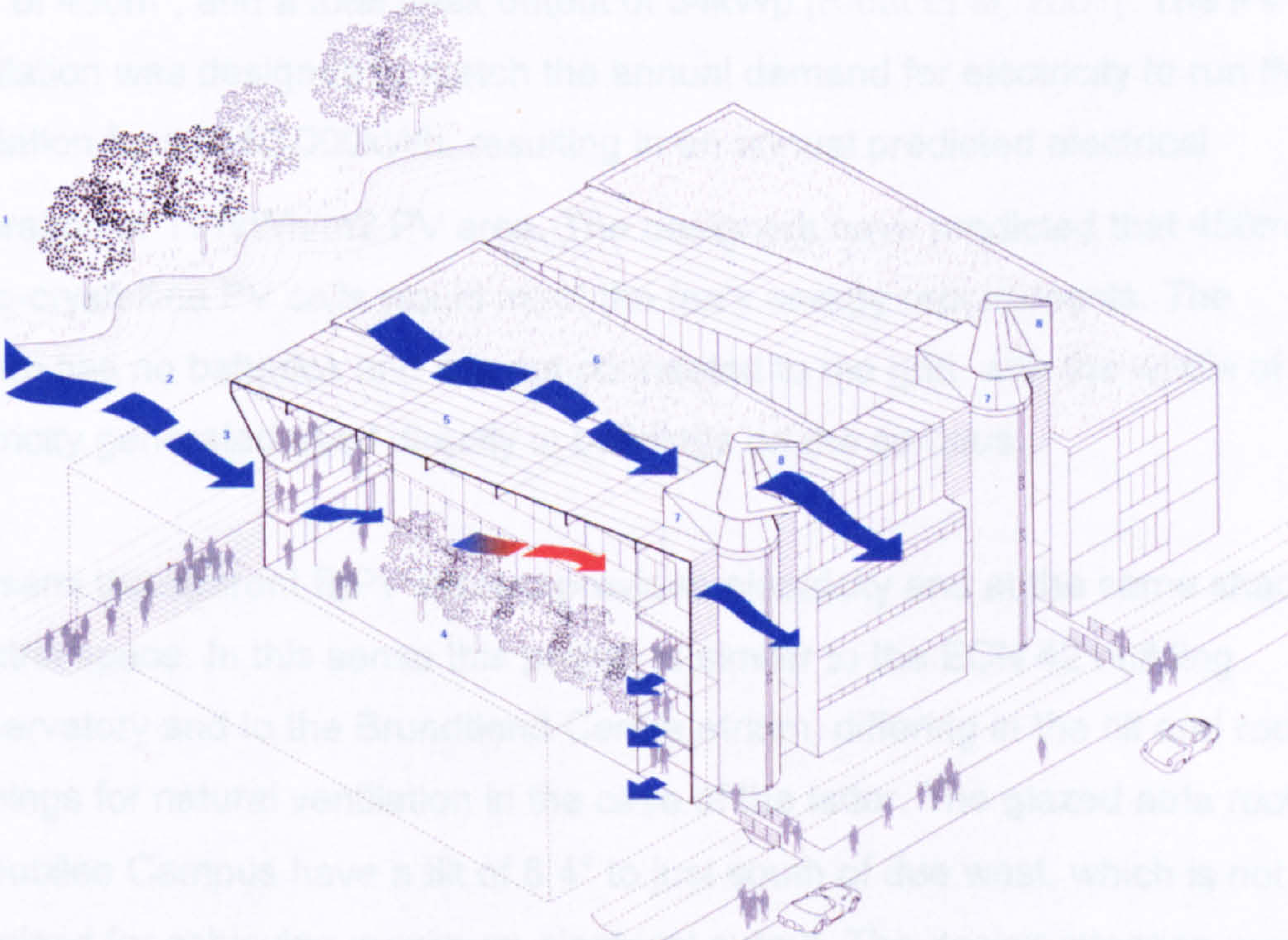


Fig. 2.36 Jubilee Campus building ventilation diagram
Source: Jenks C., Hodgkinson P. "*Hopkins 2, The work of Michael Hopkins and Partners*". 2001. Phaidon Press Limited, London, UK, p. 107. 2001.

The distinctive metal cowls, 3.5m high, are placed above the air handling units and rotate following the direction of the wind. They help maintaining the negative pressure at the top to suck the air outside. According to John Berry, from Ove Arup and Partners, the reality of wind suction mode provides only a very small force, e.g. the fan energy saved by using the cowls is less than 1% of the total fan power [Building Services Journal, August, 1999, p. 27]. The investment in the cowls on the faculty buildings is therefore not justified for the suction power. However, it was seen as an architectural statement and has values raising the awareness of energy issues.

The atria are naturally ventilated and unheated spaces. They rely on the internal gains of occupants, passive solar gain, high thermal mass, and warm air exiting through windows from offices overlooking the atria. Their construction consists of timber beams crossing the span of the atria, supporting galvanised steel frames with single glazed glass panels. The central area of each atrium roof is covered with semi transparent photovoltaic panels. One third of the glazing is covered with high efficient mono-crystalline PV cells [88 BP Saturn arranged into 8 x 11 grid of cells], integrated between two sheets of 6mm toughened glass. Each panel is 149.7cm x 117cm, with a total area of the PV system on all atria roofs of 450m^2, and a total peak output of 54kWp [Riffat *et al*, 2001]. The PV installation was designed to match the annual demand for electricity to run the ventilation fans of 50,000kWh, resulting in an annual predicted electrical generation of 111kWh/m2 PV area. The designers have predicted that 450m^{2}of mono-crystalline PV cells would meet the fan's energy requirements. The system has no batteries and it is not connected to the grid, with the whole of the electricity generated used directly in buildings on the campus.

The semi transparent BIPV system provides electricity and at the same shades the atria space. In this sense this project is similar to the ECN 42 building conservatory and to the Brundtland Centre atrium, differing in the tilt and roof openings for natural ventilation in the case of the latter. The glazed atria roofs of the Jubilee Campus have a tilt of 8.4° to just south of due west, which is not optimised for achieving maximum electrical output. The design intention was that the profile of the atrium would assists the wind reaching the cowls, thus ventilating the PV panels. However, the west facing soffit glazing is fixed and the PV panels integrated into atria roofs have no provision for efficient ventilation on the inside [Fig. 2.36].

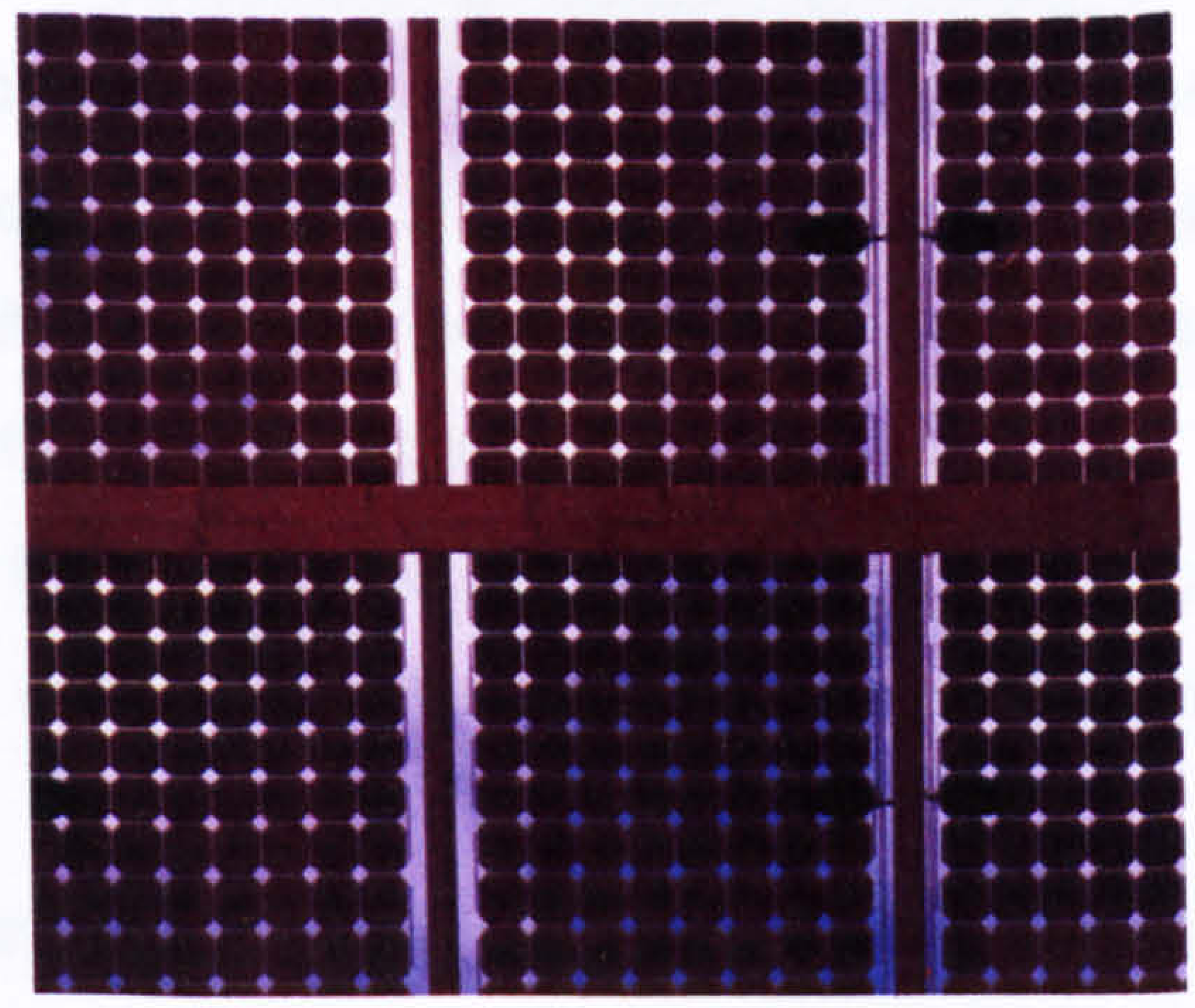



Fig. 2.37 [a-b] Jubilee Campus building – roof integrated transparent PV modules
Source: Jenks C., Hodgkinson P. "*Hopkins 2, The Work of Michael Hopkins and Partners*". 2001. Phaidon Press Limited, London, UK, pp. 105-106. 2001.

The daylighting aspect of the PV panels was taken into consideration as two thirds of each atrium roof is clear glass and the PV modules are concentrated in the middle area. The layer of clear glass at roof level will inevitably reduce the daylight penetration into atria compared with open courts. However, by placing the PV panels away from the building perimeter more daylight is allowed to penetrate the offices overlooking the atria. Also, there is a control system for electric lighting in offices with room occupancy sensors and luminaires along the perimeter of the glazed rooms with daylight sensors.

Monitoring of the energy performance, including the PV system performance, was carried out on the biggest of the three faculty buildings, the School of Management and Finance [floor area 4,350m^2 and total PV area installed of 196m^2]. The annual measured results have shown electrical output of 15,000 kWh [Riffat *et al*, 2001], or 76.5 kWh/m^2 PV area with a reported average PV system efficiency of 6.8% and 3.44kWh/m^2 floor area. The author enquired reasons for the rather low PV system efficiency through personal contact with Warren Hicks, a researcher at the School of the Built Environment at the Nottingham University at the time of building construction and monitoring, [e-mail correspondence with Warren Hicks, Halcrow Group, on 26/11/02], who pointed out several reasons including:

- Temperature losses

  [mono-crystalline cells are always quoted at the level of 1000W/m^2 solar irradiation and 25°C temperature, achieving 14-16% cells conversion efficiency. However, their cells efficiency drops significantly due to an increase in temperature]. In the case of the Jubilee campus atria PV system, the stratification of hot air at the roof level and dark colour of the cells lead to excessive temperatures. The recorded temperature of the PV panels was regularly around 75 to 80°C If there had been openings provided on the west facing soffit glazing, it would have been possible to cross ventilate atria and to ventilate the inside of PV panels.

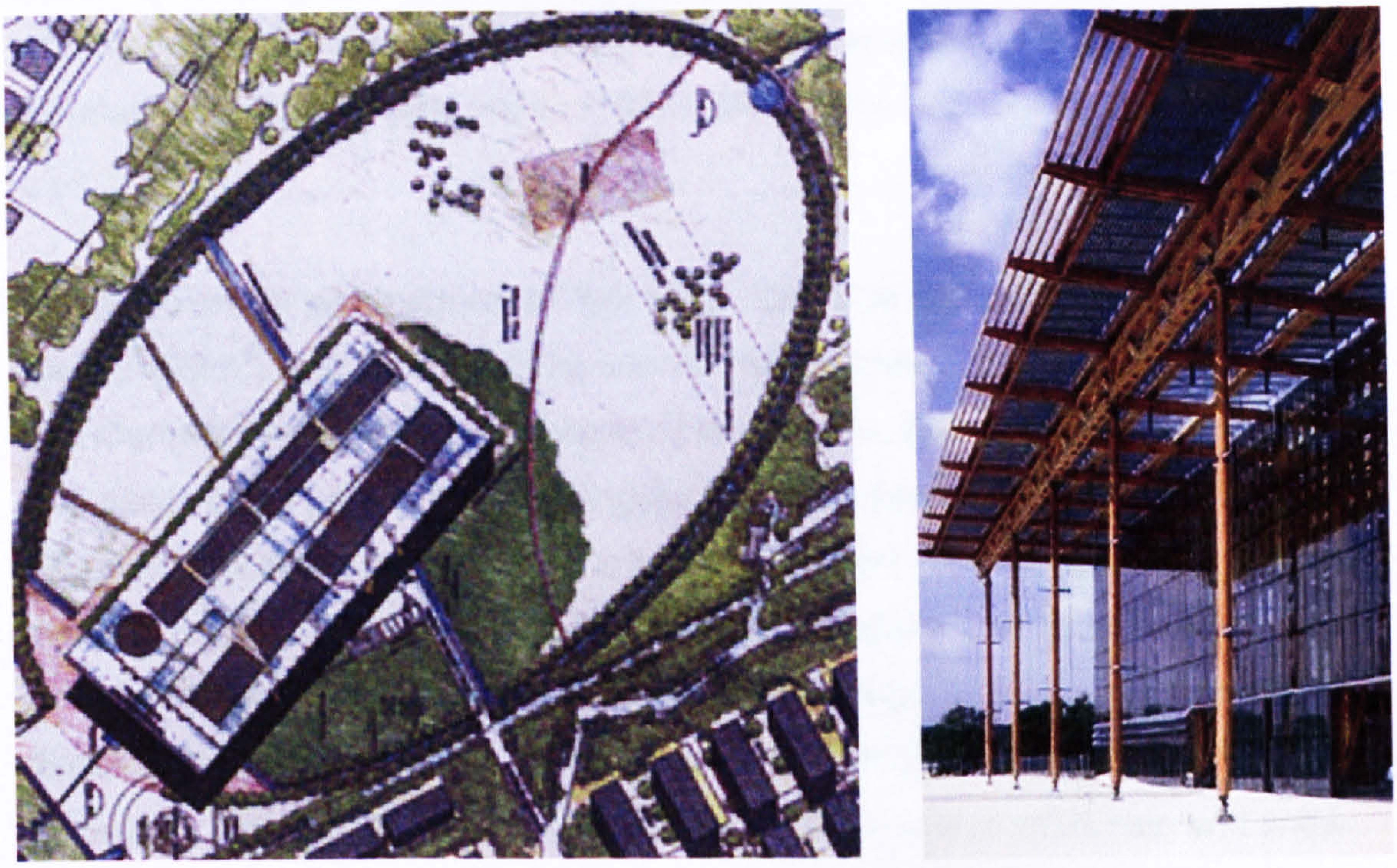
- Another reason contributing to the PV system efficiency level was the conversion losses in inverters, with an inverter efficiency of conversion of around 95%.

The measured photovoltaic system performance has shown a peak production in the summer months, with over 2,000kWh per month of electricity generated, and lowest levels in winter months, especially in December with only 220kWh produced [Riffat *et al,* 2001].

The Jubilee Campus is a recently built complex of environmentally designed and low-energy demanding buildings, with atria acting as environmental buffers and social spaces. The energy consumption of buildings is higher than the original design level, partly due to longer occupancy hours than initially anticipated. However, it still falls within the range of best practice for open plan naturally ventilated buildings [Riffat *et al,* 2001]. The PV system integrated on atria roofs supplies electricity for the low-pressure ventilation system fans, and the whole electricity generated is used directly on the site. Also, the reported stratification of warm air, as the main reason for increasing PV temperature and reducing efficiency, has provided an insight into the importance for providing effective ventilation on the inside of double skin façade with BIPV. However, again although there is heat generated by the PV cells within the skin of the building, this remains unquantified and unexplored, either as a thermal asset or deficit. The question remains – what is the relationship between direct solar gain blocked by the cells and indirect thermal gain from the cells?

2.5.4 MONT- CENIS ACADEMY

HERNE, SODINGEN [51° 32'N] GERMANY



a b

Fig. 2.38 [a-b] Mont-Cenis Academy, Herne, Sodingen, Germany, view of the south-east façade and site plan
Fig. 2.38 [a] Source: Optisol: http://www.flabeg.com.
Fig. 2.38 [b] Source: Downney C., Talarico W. "Giving Back to the Environment". Architectural, Record,December, p. 201. 1999.

The Mont-Cenis Academy near the towns of Herne and Sodingen in Germany, is a civil service training academy and community centre, located in the Ruhrgebiet, north of the river Ruhr in Germany, once Europe's largest industrial region. After the collapse of the coal and steel works industry during the 1980s, the region was economically and ecologically deprived. In 1989 a land development program was established, named as the International Architectural Exhibition " Internationale Bauausstellung Emscher Park [IBA]", aiming at the use of ecological approaches and new technology in building projects to transform major industrial sites into spaces for recreational and cultural activities [Downey and Talarico, 1999, p.199].

The Mont-Cenis Academy is built on a site that used to be a coal mining area, in a semi-urban context with the building situated as a large pavilion in a park, surrounded by relatively low-rise development. The climate is described as moderate humid, with winter average temperature of +4.8°C and summer average temperature of +14.35°C. The academy complex consists of a glass greenhouse structure that houses a library, a civic administration, a hotel accommodation, a community centre, a restaurant, leisure facilities, and an academy of further education. The project started in 1991 with a competition won by the French architects Jourda & Perraudin in collaboration with the German architects Hegger, Hegger and Schleif [Downey and Talarico, 1999, p.200].

The glass envelope structure is176m long, 72m wide and 15m high, [total floor area12,672m^2], with its longer elevations oriented west and east. The repetitive and modular system of the load-bearing structure is made of mature pine trees with single glass panes, creating a glass envelope around the inner buildings. The buildings inside are arranged in two non parallel rows along a central street, creating a sense of perspective. The pavement varies from concrete paths, gravel and water [also contributing to the heat storage capacity], and wooden decks outside buildings. The buildings are insulated to normal external standards, but they do not have to withstand the rigours of wind, rain and snow. In this way the construction costs for the individual buildings were reduced to partly offset the cost of their glazed enclosure.

The Mont-Cenis Academy uses a holistic approach to energy. The simplicity of the glasshouse form, structure and materials, is deceptive as it performs a series of energy roles. The large space it encloses is naturally ventilated and unheated. In the summer, fresh air can enter through a variety of adjustable openings [doors and windows at high and low level]. Additional ambient air, before entering the glass envelope, passes through 'earth ducts' below ground where the stable environment of constant below grade earth temperature naturally cools it. The warm air then exits through roof openings. This is helped by the stack effect created at the roof level also enhanced with roof internal shades that trap solar heat and induce airflow. All openings are monitored and automatically adjusted by a sophisticated computer system, responding to a number of factors including: internal and external temperature, wind direction, humidity, sun intensity, etc.

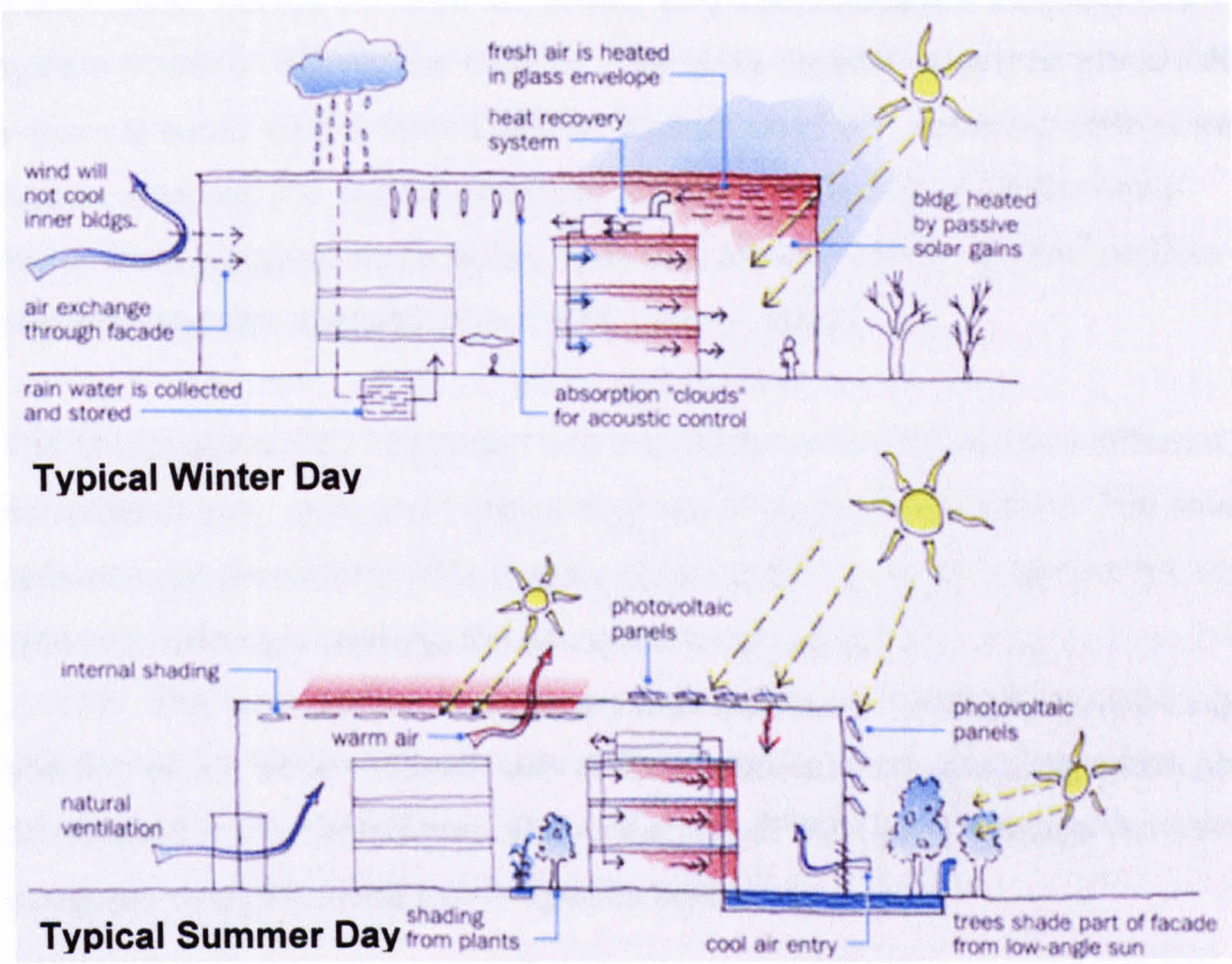


Fig. 2.39 Mont-Cenis Academy, Herne, Sodingen, Germany, energy diagrams
Source: Detail 3, *Solar Architecture*, "Academy of Further Education in Herne". January 1999. Institut for International Architecture, Munchen, Germany. January, p. 389. 1999.

In the winter, the interior space is partially heated by passive solar gains, with inevitable thermo-circulation and stratification within the 16m space height. The air is taken from the roof level of the glass envelope and drawn into the air-handling units with heat recovery systems, located at the top of buildings. Although solar pre-heat and heat recovery are in apparent competition, the lower temperature contrasts should be advantageous over a continental heating season. Adding to the holistic energy strategy solution is the photovoltaic installation integrated into the roof and the façade of the glass envelope, and the use of 'fire-damp' methane gas present in the old coal mines below the site. The latter is used as a fuel for a small co-generation plant to meet the balance of energy demand in the building [Porteous, 2002, p.161].

The roof integrated photovoltaic installation serves for electricity generation, sun shading of the interior for limiting overheating, and daylight control through varying light transmittance of the PV panels. The glass roof integrated photovoltaic panels are south-east oriented in a saw-tooth structure with an inclination of 5° of the horizontal. It consists of a 6mm upper, 8mm lower glass pane, and solar cells sandwiched in between [Benemann *et al*, 2000, p.1788]. The total area of roof modules is 9,744m^2, with an individual module area of

3.36m^2 (N.B. not the PV cells net area), and 2,900 modules installed with PV system power of 925Wp per module. The glass façade integrated photovoltaic system is south-west oriented with an inclination of 90°, covering 30% of the façade area and PV system power of 75kWp. It consists of similar semi-transparent photovoltaic modules, with total area of 789m^2, 2.78m^2 module size and 284 modules installed [IEA PVPS TASK7, 2002].

The photovoltaic cells integrated into the glass roof structure have different densities of solar cells and various degrees of glass transparency. The solar cells density varies from 86% directly above buildings to 58% above the 'street' between buildings, creating the so-called 'cloud effect' [Benemann *et al,* 2000, p.1788]. The most dense modules are located above buildings, maximising the shading effect, while modules with reduced cells density and clear glass panels are located in the central area above the 'street' between buildings providing adequate daylight conditions in spaces below.

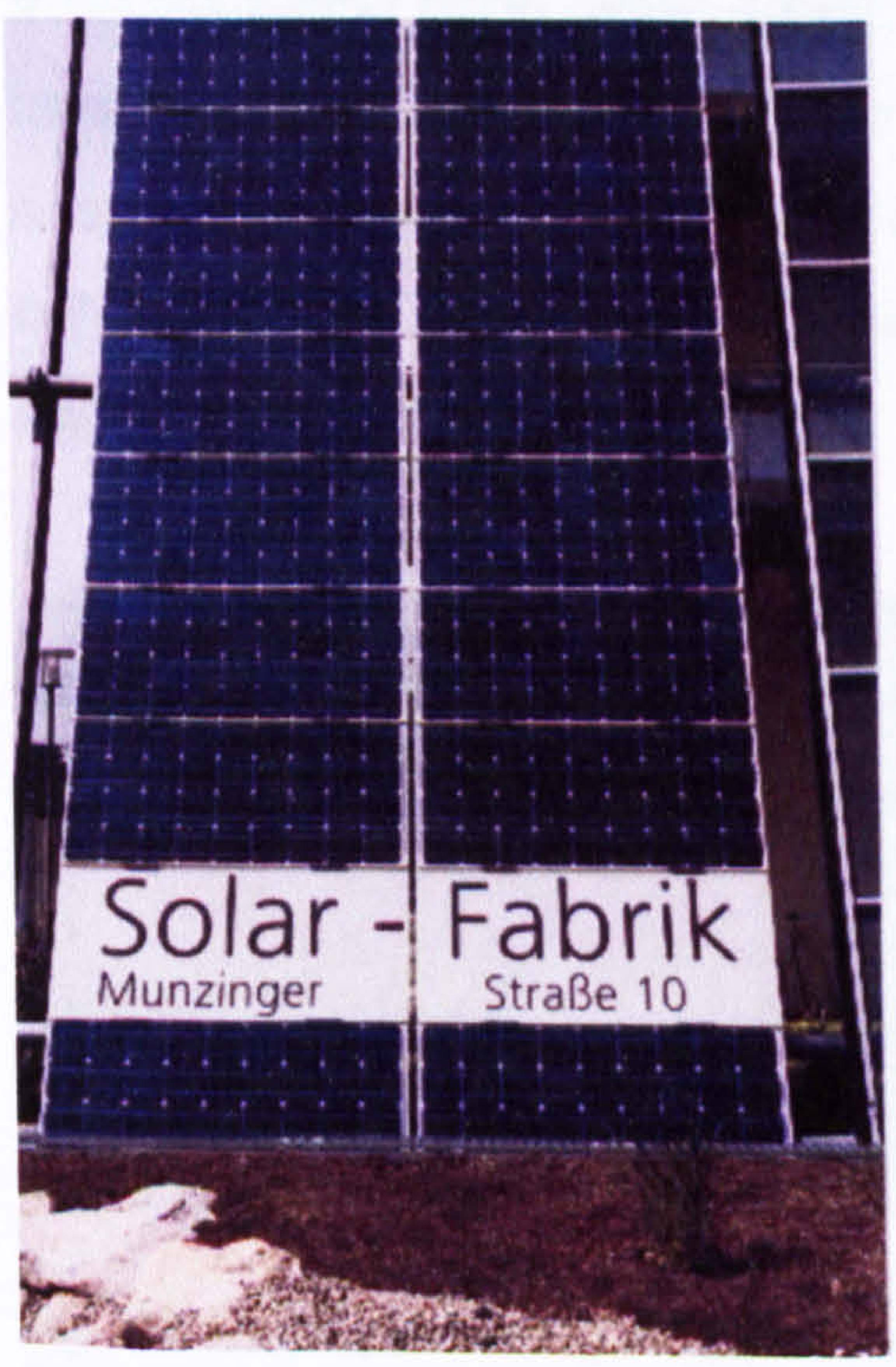
The total number of PV modules installed on the building is 3,184 with total PV system power of 1,000kWp. The annual power output of both PV integrated systems was estimated to be 700,000kWh, exceeding the energy demand of the complex, and was therefore connected to the public electricity grid providing electricity for the households in the area. The monitoring results of the PV system showed measured PV electrical output of 650,000kWh/year [IEA PVPS TASK 7, 2002]. It corresponds to almost 62kWh/m^2 of the total of 10,528m^2 PV area installed [9,744m^2 PV roof area and 784m^2 PV façade area] and 51.3kWh/m^2 of the building floor area. Although the predicted PV electrical generation was estimated to approximately 700,000kWh/year, it was recognised that the estimated figure was optimistic and did not take into account the non-optimised inclination of the PV roof structure [the roof arrays are only 5° from the horizontal] [IEA PVPS TASK 7, 2002].

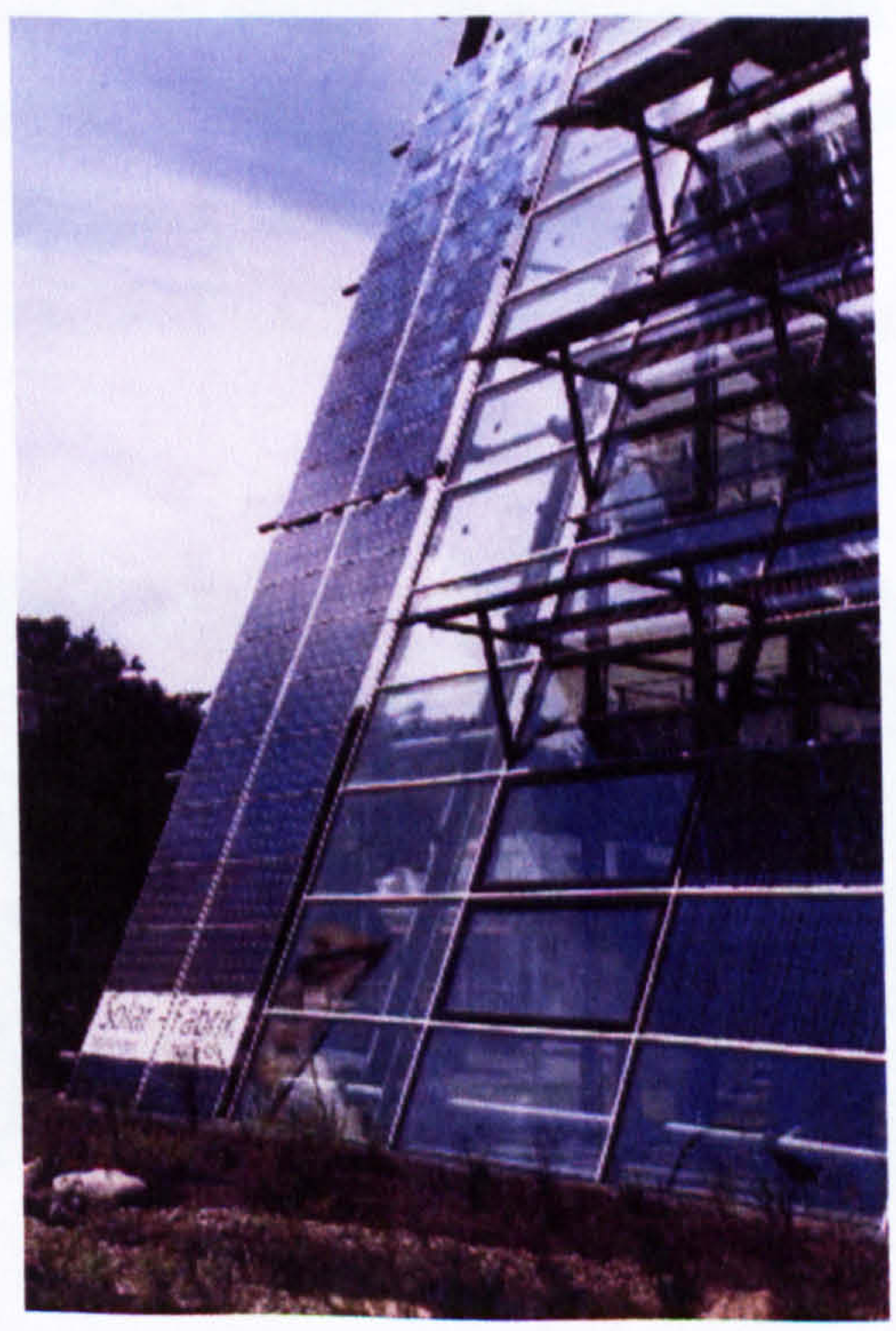
Since the building has been in operation, it was found that the air temperature below the roof integrated PV modules can reach high temperatures. The reason was the occasional failure of the natural ventilation system of the glass envelope, due to problems with the opening mechanisms of the automatically driven ventilation openings of the roof. Also, the saw-tooth roof structure and PV modules inclination [although only 5° from the horizontal], cause some shading of the PV modules under low sun angle, i.e. in early morning and evening hours and in winter [IEA PVPS TASK 7, 2002]. Both the effect of PV modules overheating and partial shading of the modules have resulted in lower total PV system electrical output than predicted.

The photovoltaic system installed in the Mont-Cenis Academy is an example of a PV system building integration, where semi transparent photovoltaic modules were used to perform multiple functions, including electricity generation, shading and daylight control. The big glass structure enclosure relative to its enclosed parts represents a radically different model compared with previous case studies, ECN Building 42 in Petten being the closest. The relevance of the case study for this thesis in the integration of semi-transparent roof and façade PV systems to perform multiple functions of electricity generation, shading and optimising daylight. It can be argued here that the relationship between thermal shading by the cells and the heat generated on the inside of the cells is of an interest. The enclosed volume is so large, and its capability for ventilation so great that heat from the PV is not exploitable. Nevertheless, the combined impact on daylighting within buildings, attributable to the outer skin and the substantial structure which support it, is likely to be considerable. But this aspect has not been evaluated.

2.5.5 SOLAR FABRIK BUILDING

FREIBURG [48° N] GERMANY





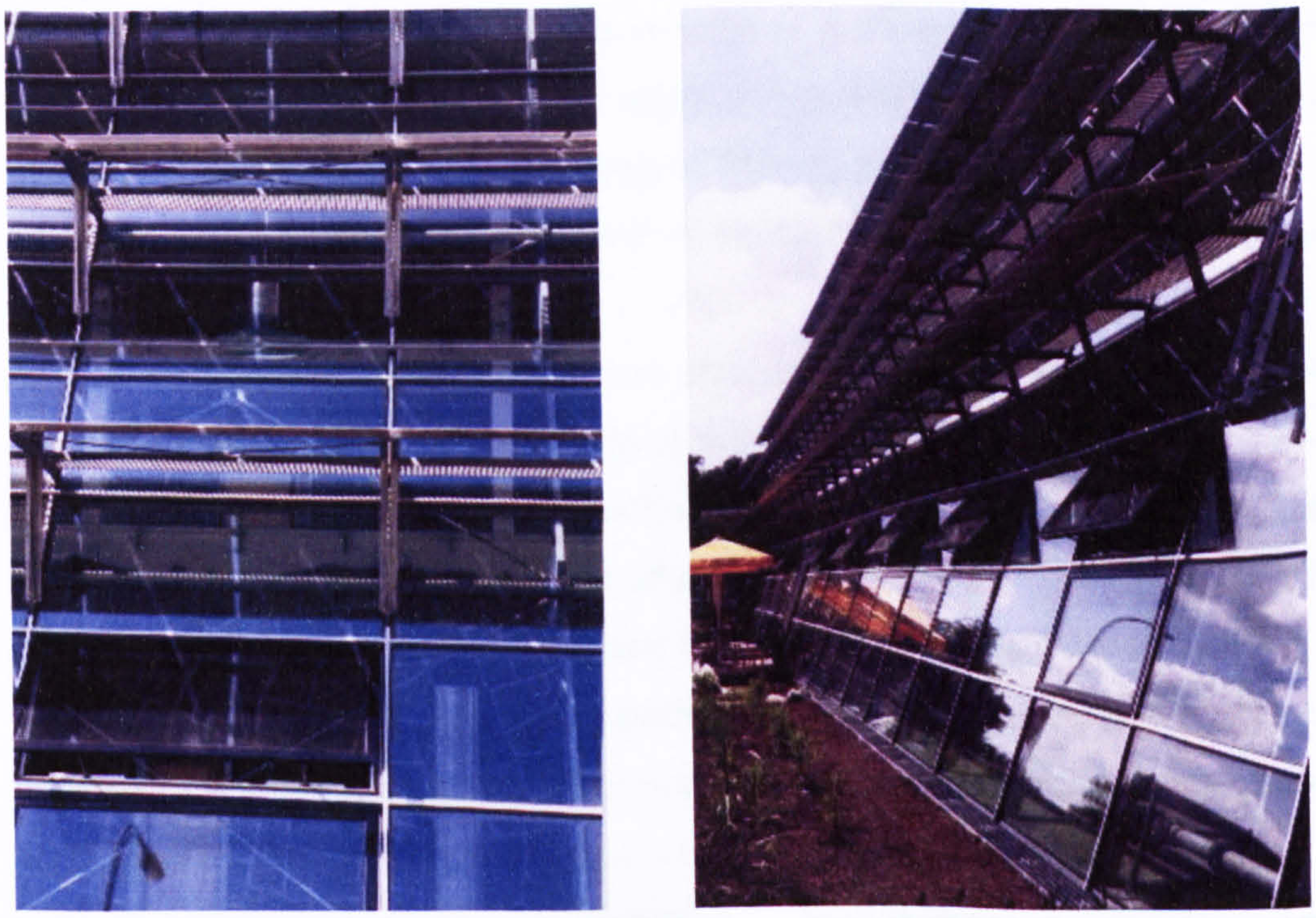


Fig. 2.40 Solar Fabrik building, Freiburg, Germany, south façade
Source: Photography, Kondratenko I. 2000.

The Solar Fabrik building is a PV cells production plant and an office building for the Solar Fabrik Company in Freiburg [48° N], Germany, designed by the architects Rolf and Hotz and energy consultant 'Buro fur Sonnenenergie' [Detail No. 3, 1999, p.407]. The production plant consists of one storey top lit hall linked to a four-storey office and apartment wing in front of it with a narrow glazed corridor. The three floors of offices are organized in a linear tract with openable windows facing north, while a pent-house floor of south facing apartments are accessed from the north. In front of the offices and extending over the entire south face of the building is a glazed hall serving as an access and communication space, venue for company events, and breakout space for the staff.

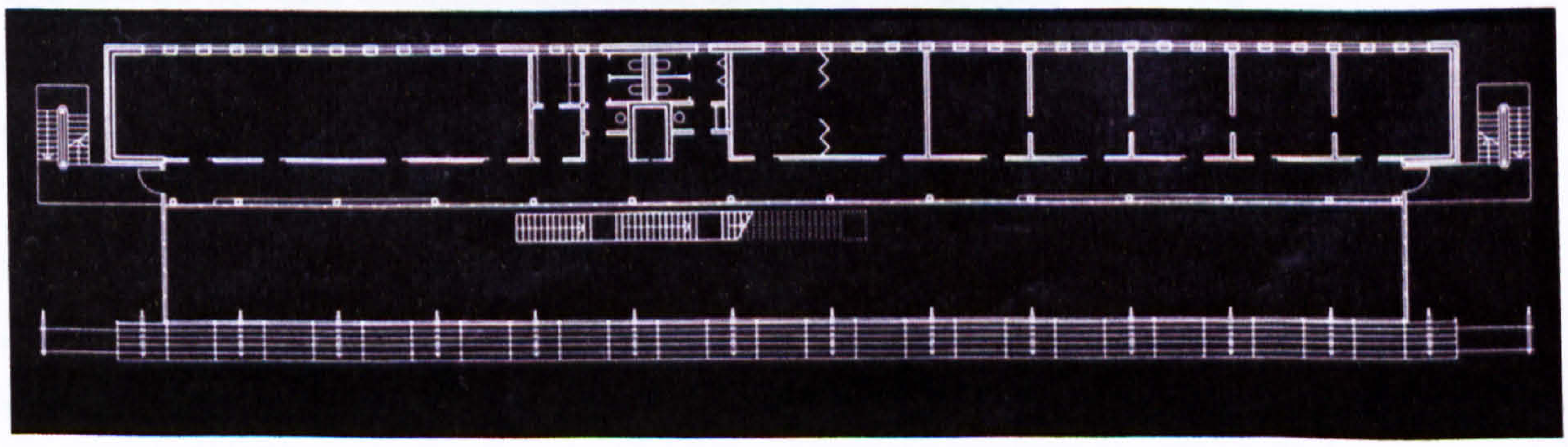


Fig. 2.41 Solar Fabrik building, Freiburg, Germany. First floor plan
Source: Detail 3, *Solar Architecture*, "Solar Factory in Freiburg ", January 1999. Institut for International Architecture, Munchen, Germany. January, p. 407. 1999.

The south 'solar' façade of the glazed hall has a steeply sloping glass structure at an angle of 17° from the vertical plane and two façade integrated photovoltaic systems. The first one, with total area of $210m^2$, includes a flat section of poly-crystalline PV panels at the west end of the façade, and a fixed shading device in a form of PV louvres [Detail No. 3, 1999, p.410]. The shading lamellas are spaced vertically to provide maximum shading of the atrium floor in summer and allow the low sun angle to penetrate in winter. Any reduction in daylight level from lamellas is not crucial to the activities in the hall or its general ambience, which is light and airy. The second photovoltaic system integrated into the canopy has a total area of $240m^2$ and consists of glass laminated semi-transparent PV panels. The entire photovoltaic installation on this building has an area of $450m^2$, with predicted annual electricity generation of approximately 40,000kWh [Detail No. 3, 1999, p.410], or 88.9 kWh/m^2 PV area installed.

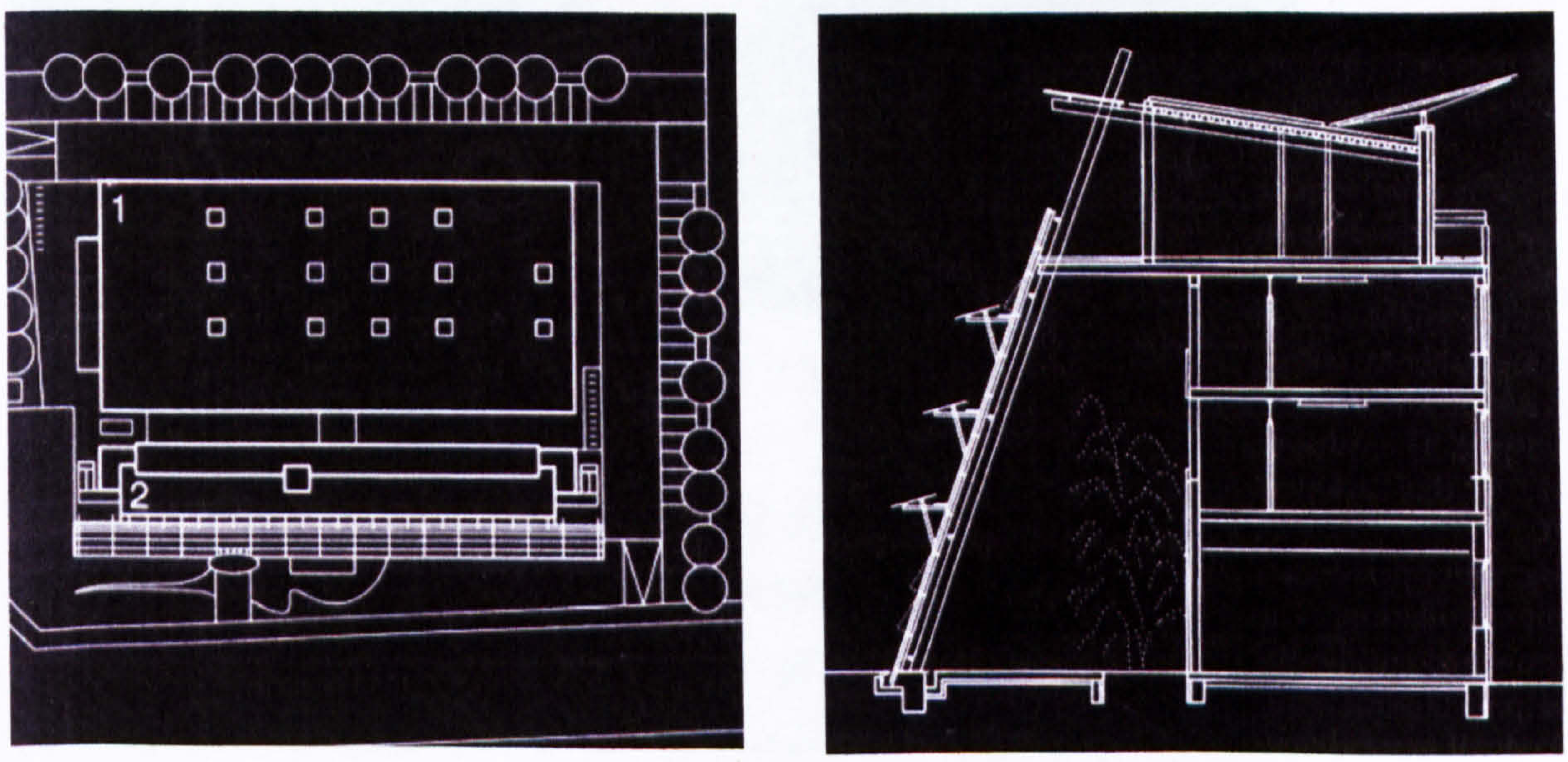


Fig. 2.42 Solar Fabrik building, Freiburg, Germany. Site plan and cross section

Source: Detail 3, *Solar Architecture*, "Solar Factory in Freiburg ", January 1999. Institut for International Architecture, Munchen, Germany. January. pp. 407-408, 1999.

The glazed hall and the adjoining office spaces are naturally ventilated, maintaining comfortable temperatures even on a hot sunny day by a combination of efficient natural ventilation, external shading and a thermal mass. The south glazed façade is naturally ventilated, with automatically controlled lower and upper window openings to boost the stack effect during warm summer days, also helped by windows in the north face of the offices permitting cross ventilation. For security reasons, during the night the cool air enters via two underground ducts rather than through the low level windows on the south façade, and exits through opening windows at the top [Porteous, 1999, p.158]. Each duct is 30m long with 1m diameter and gives an air supply of $7,200m^3/h$

[Detail No. 3, 1999, p.410]. The high thermal mass of the exposed concrete floor also helps tempering high temperatures, in combination with earth ducts for passive cooling and the small pond in front of the south facing façade, which humidifies and cools the incoming diurnal air.

Fig. 2.43 Solar Fabrik building, Freiburg, Germany. Atrium interior
Source: Photography, Kondratenko I. 2000.

The energy for heating and the balance of electrical power which is provided by another solar fuel - rape oil in a CHP [combined heat and power] plant, has an approximate annual rape oil consumption of 30,000 litres. The atrium space has a narrow strip of radiant panels at high level below the ceiling, along with small convector heaters below windows to tackle the downdraughts. Therefore, although the heating input is not substantial, the intention is to make the space habitable during winter.

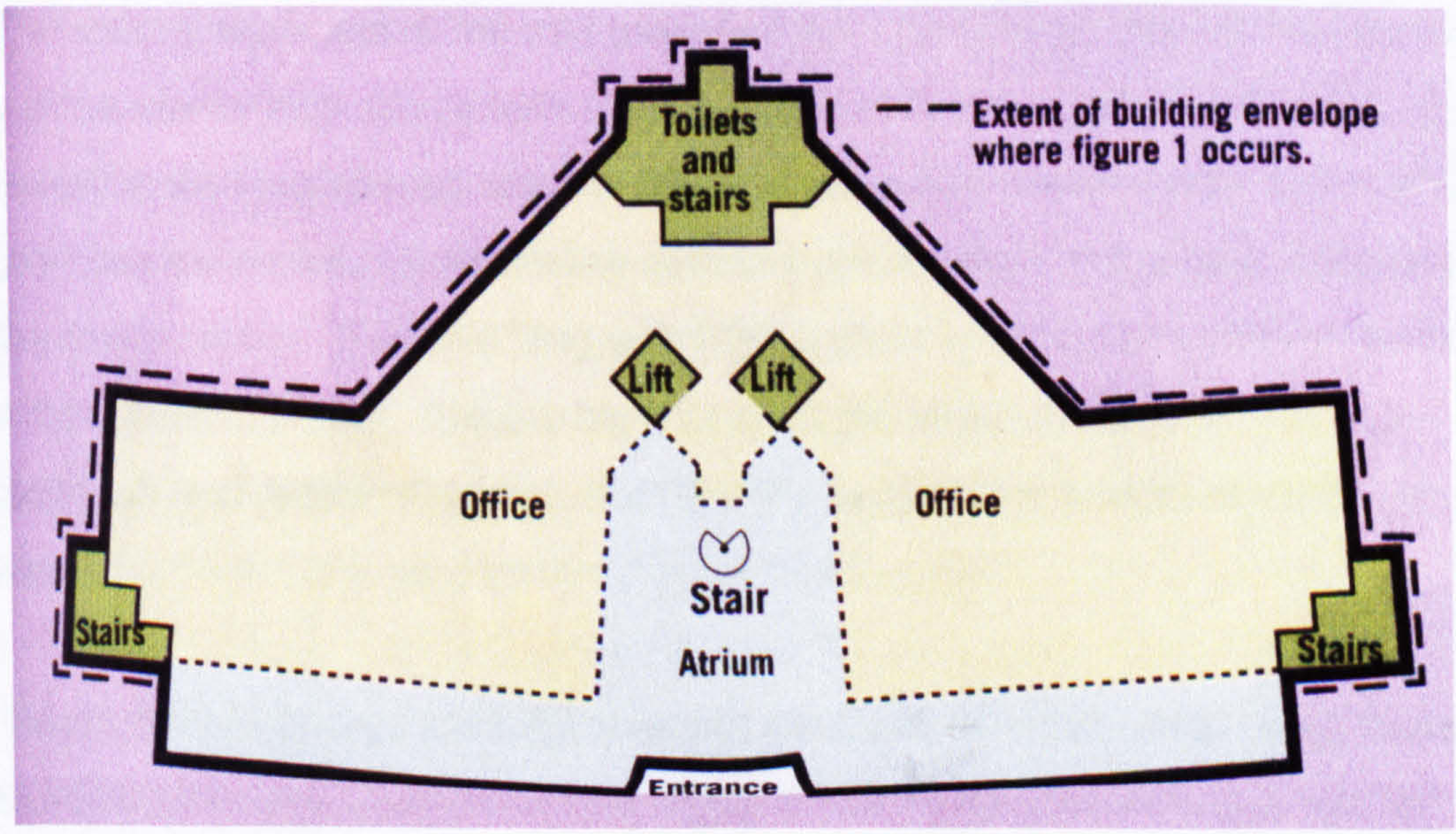
The Solar Fabrik building is an example of a building that uses techniques of passive and active solar energy and serves as a communication tool for the company of its products and business philosophy. The atrium space provides a useful breakout and venue space for the company, and it acts as a buffer zone between the access road to the building and the office environment, maintaining comfortable temperatures even on hot summer days. Unlike the Jubilee Campus building at the Nottingham University, the atria space of the Solar Fabrik building does not compromise light or air to the offices.

This building example is set in a climatic context different from that in Glasgow [Freiburg has a continental climate with much stronger winters and hotter summers compared to Glasgow], and since it is new, it is not directly comparable with the retrofit exploration undertaken in the following chapter. Also, although this thesis is specifically concerned with providing new insight into hybrid BIPV, it is of interest to review non-hybrid solutions, where the PV is by-functional, but where its efficiency is not compromised by overheating. Moreover, the Solar Factory building with its holistic environmental approach is in the vanguard of new Northern European BIPV buildings.

2.5.6 DOXFORD SOLAR OFFICE

SUNDERLAND [54° 9'N] ENGLAND

a



b

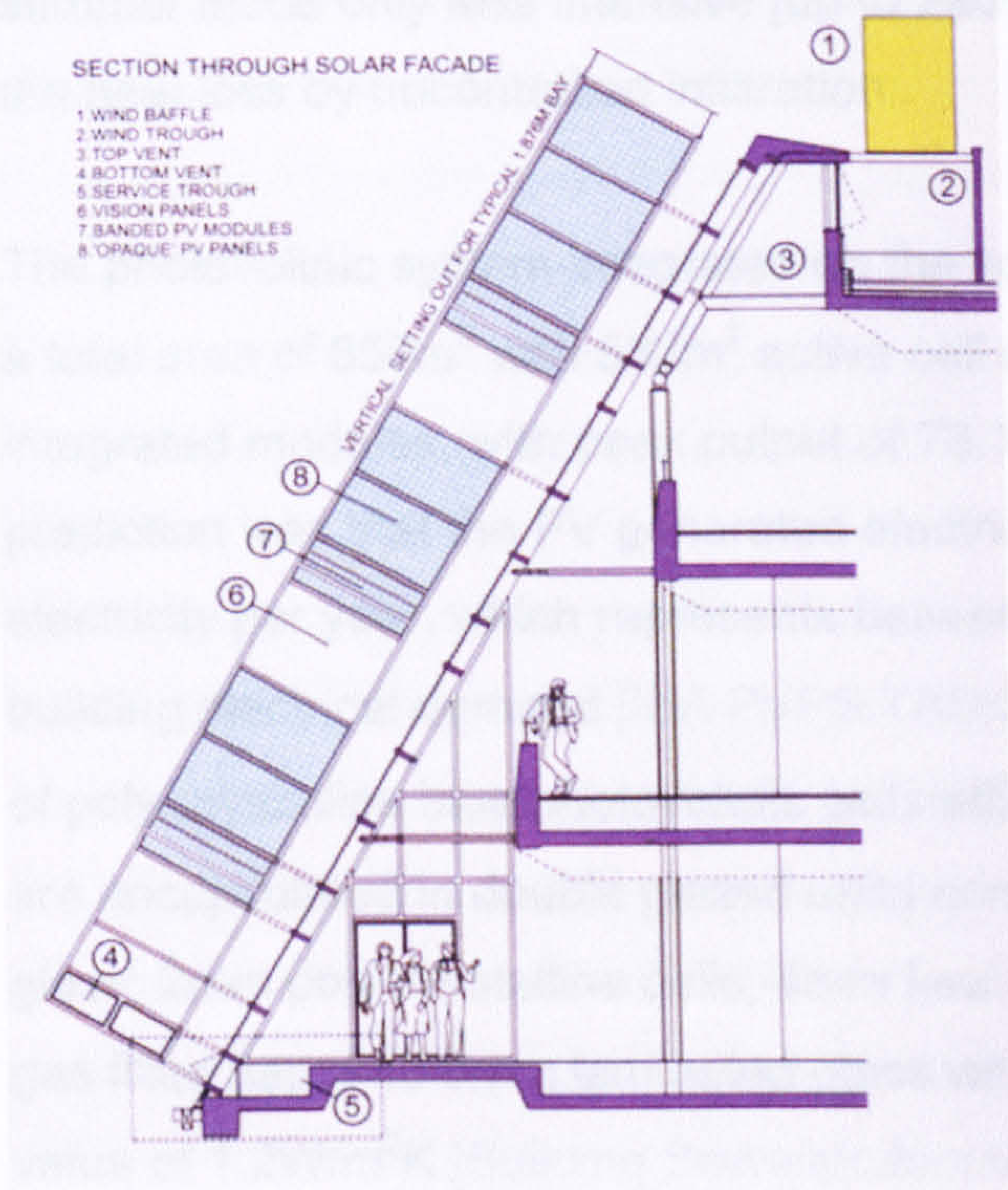
Fig. 2.44 [a-b] Doxford Solar Office, Sunderland, UK. South façade and plan diagram
Fig. 2.44 [a] Source: Studio E Architects, DTI New and Renewable Energy Programme, "*Photovoltaics in Buildings, BIPV Projects Report No ETSU S/P2/00328/REP*" Solar Office Doxford International, Department of Trade and Industry, London, UK. p. 22. 2000.
Fig. 2.44 [b] Source: Architectural Design "Green Architecture". Vol. 71 No 4, July 2001. John Wiley and Sons Ltd, 2001, London, UK.

The Doxford Solar Office is the first speculative office with building integrated photovoltaics in the UK. The building is designed by the Studio E Architects for Akeler Developments Ltd. and finished in 1998. The Doxford Solar Office is part of a 32Ha Doxford International Business Park, located close to the town of Sunderland, in the north-east of England.

The Solar Office building [total area 3,601m^2] is situated on a south-facing site with unobstructed solar access. There is an access road and a car park in front of the building causing little traffic noise. The building was designed to minimise the energy use, while its south facing façade with an integrated photovoltaic system was designed to generate electricity, meeting between one third and one quarter of building's yearly electrical power requirements [Jones (b), 2000, pp. 22-25]. The building exploits the energy from the sun and takes the advantage of the site's exposure to the wind. It has a broad based energy-efficiency approach with an integrated photovoltaic system playing an important part in the overall low energy strategy. The PV facade had to provide a balance between maximising solar irradiance, an internal environment without excessive solar gains, good internal daylight levels, views out, minimising glare, reasonable good thermal insulation [for an all-glass façade construction], and concealing the PV wiring and junction boxes [IEA PVPS TASK 7, 2002].

The main entrance is at the mid point of the south façade. Behind the façade is a three storey high atrium with a wing of offices facing it. The open planning between working spaces and the atrium means that it is markedly different from previous examples, necessitating careful consideration of the heat balance of the south façade. It is 66m long with high performance double-glazing, and has a total area of 950m^2. It leans back at an angle of 60° to optimise the solar radiation and reduce the glare from the PV cells on the drivers of the nearby road [Building Services Journal, August 1998, p.14].

The building's energy strategy is based on a well insulated and low air leakage building envelope; maximum floor depth of 15m and 3.2m ceiling height for cross ventilation; the use of the building concrete structure as a thermal mass; automatically controlled north facing windows with manual override; stack induced natural ventilation and automated top and bottom vents on the south façade; rooftop outlets in a sheltered trough; and parts of clear glazing on the south façade for daylight and automated roller blinds for glare control on windows. The provision of sufficient daylight into offices was taken into account to ensure a daylight factor of at least 2 over 80% of the office floor [Jones (a), 2000].



a

b

Fig. 2.45 [a-b] Doxford Solar Office, Sunderland, UK. South façade section and interior view
Fig. 2.45 [a] Source: Studio E Architects, DTI New and Renewable Energy Programme, *"Photovoltaics in Buildings, BIPV Projects Report No ETSU S/P2/00328/REP"* Solar Office Doxford International, Department of Trade and Industry, London, UK. p. 24. 2000.
Fig. 2.45 [b] Ibid. p. 23.

The building relies on natural ventilation for summer cooling, based on using the cross ventilation within the office space, the stack effect promoted by the PV façade, and the wind exposure at the roof of the building. The fresh air enters through north windows and through the office floors flows from the north to the south side of the building. Vents located at the top and bottom of the solar façade help air to rise up its surface and take up the heat behind PV glazed façade, also partly keeping the PV panels cooler. Finally, the air is expelled through the top vent at the roof level, where the rooftop outlets are in a sheltered trough, helping to maintain negative pressure needed to encourage the stack effect behind the south façade. Consideration was given to introducing openable windows in the PV façade but it was not feasible due to difficulties of achieving weather-tightness on a 60° from the horizontal inclined façade and the cost and complexity of window-opening mechanisms [IEA PVPS TASK 7, 2002].

The automated roller blinds on the inside of the PV façade are used to shade offices. It is possible that when the roller blinds are in use reducing the cooling load, the use of electricity for lighting is increased. On a winter day, the heat is largely generated from people and equipment in offices, supplemented by perimeter radiators. Cross ventilation through office space is similar to the summer mode only less intensive [up to 2ac/h], with an airtight envelope limiting the heat loss by uncontrolled infiltration.

The photovoltaic system integrated on the south facing inclined solar façade has a total area of 650m^2 with 532m^2 active cell area of 352 glass-on-glass façade integrated modules, with peak output of 73.1kWp [Jones (b), 2000, p.22]. The prediction was that the PV generated electricity would generate 55,100kWh electricity per year, which represents between one third and one quarter of the building electrical demand [IEA PVPS TASK 7, 2002]. The solar façade is made of poly-crystalline blue photovoltaic cells efficiency 14% at 25°C. The PV cells are encapsulated in double glazed units consisting of 5mm heat strengthened glass; 2mm poly-crystalline cells; 4mm heat strengthened glass; 12mm krypton gas filled gap; and 6mm laminated glass with low-e coating; resulting in an U-value of 1.2W/m^{2}K [Building Services Journal, August 1998, p.14]. The choice of double-glazed PV modules was based on better thermal properties for the large area of the south façade, at the cost of reduced PV cells efficiency due to their increased operating temperature in the double glazed unit. The design team considered an option of PV façade ventilated cavity that would improve PV efficiency, but it was not implemented, as no ready-made solutions and not enough development time were available.

The monitoring results of the Doxford Solar Office building for the 12 month period, between April 1998 and April 1999, have shown total electricity generated from the PV system of 47,894kWh from January to October 1999 [translates to 90kWh/m^2 PV area], suggesting an annual value somewhat below the expected electricity supply of 55,000kWh [or 103.38kWh/m^2 PV area], and an average measured PV system efficiency of 8% once inverters are included. The inverters were reported to be the main cause of operational problems causing intermittent output [IES PVPS TASK 7, 2002].

Compared to the monitored efficiency of 6.8% for the atrium PV system of the Jubilee Campus building at the Nottingham University, that for the Doxford Solar Office PV system is higher. Compared to the Northumberland building example with the PV system efficiency of 10.5% when unshaded, the Doxford Solar Office building has lower efficiency, but a greater output [90kWh/m^2 PV in

Doxford compared to 72.7kWh/m^2 PV in Northumberland in 1999]. The incident solar radiation for January - October 1999 at Doxford was 943kWh/m^2. This is 4% higher than January - October values for Newcastle upon Tyne, in the Climate in the United Kingdom atlas [Page and Lebens, 1986, p.170], averaged over all weather conditions, for south orientation and 60° tilted surfaces, at 906kWh/m^2. However, 1999 was 3.3% higher than the five-year monitored average at the Northumberland campus. Therefore, results again validate Page and Lebens, 1986, as a rapid estimation tool.

The Doxford Solar Office building is a new built office solution with a holistic combination of integrated renewable energy [photovoltaic system as an integral part of the south façade], harnessing both wind energy and stack effect to assist the ventilation of the building, and passive solar measures. The building is situated on a clear site, with no obstruction to the solar access from neighbouring buildings, and no issues related to traffic noise. In this sense the building differs from the retrofit exploration undertaken in this research work, which is situated in densely built urban area with overshadowing, noise and air pollution constraints. However, the climatic context is similar as the location of Sunderland [54° N] is not very far from Glasgow [56° N].

The photovoltaic system of the south façade of the Doxford building and the atrium space behind it, is different from all the previous examples of atria, since the façade is the external envelope of the primary working spaces. The clear glass integrated on each floor at occupants vision level is described as sufficient to provide daylight factor in offices of 2% and glare is tackled by automated roller blinds fixed on the inside of the façade. One potential problem associated with this solution is that when blinds are in use the daylight level is reduced leading to increased use of electricity for artificial lighting. Also, the double-glazing with integrated PVs used on the south façade must have some impact on the efficiency of the poly-crystalline PV. However it was a compromising decision between cells efficiency reduction on one side and less thermal loss from offices on the other.

In terms of hybrid BIPV, it is again not known how much, if any, of the thermal gain as a by-product of PV electrical generation is useful to the offices during winter, or how this would compare to the absence of the PV on the façade itself (as at Freiburg).

A similarity between the Doxford Solar Office, the Solar Fabrik in Freiburg, and the retrofit exploration undertaken in this research work is in the use of stack effect to draw air through the south façade, helped with vents at the top and bottom of the façade for summer cooling. In the case of the Doxford Office, its use of cross ventilation to draw air from the north to the south side, and use the prevailing winds with rooftop outlets in a sheltered trough is interesting. However, the tenants have an option to use displacement ventilation and air-conditioning, which again leads to increased use of energy. This inclusion of active systems indicates that the client and/or consultants lacked confidence in complete reliance on natural ventilation, unlike Solar Fabrik. Also, as the provision for energy-efficient lights and fittings is left to the tenants' decision, one may question their commitment to save energy.

2.6 RETROFIT WITH BIPV AS MULTIFUNCTIONAL FAÇADE

2.6.1 BP AMOCO SOLAR SKIN BUILDING

TRONDHEIM [63° N] NORWAY

a

b

c

Fig. 2.46 [a-c] BP Amoco Solar Skin, Trondheim, Norway. South façade
Fig. 2.46 [a] Source: Photography, Aschehoug O. 2002.
Fig. 2.46 [b-c] Source: http://www.bpsolar.com. "Solar Skin, Building Integration". 2001.

As a result of the collaboration between the BP Amoco Company in Norway, the solar energy research unit of the Norwegian University of Science and Technology [NTNU] in Trondheim [63°N], and SINTEF, a contract research foundation, a 1960s university office building of the Norwegian University of Science and Technology [NTNU] was refurbished using the technique of a double skin façade with façade integrated photovoltaics, as well suited for thermal upgrading and climate protection of an existing building [Aschehoug *et al*, 2003]. The context of the building is urban, a university campus, with a few trees in front of the south façade causing some shading and moderate road traffic surrounding the building. The new façade is oriented 25° east of south, it is four-storey high, 0.8m wide, with open grate steel maintenance platforms on each floor for monitoring, maintenance and cleaning purposes. The top and bottom façade openings are thermostatically controlled by the cavity temperature and automatically opened for cavity ventilation [Fig. 2.47]. In addition, the occupants can freely open office windows to the cavity.

The single glass façade panes are mounted on standard aluminium profiles carried by a load bearing steel structure bolted to the concrete floors of the existing façade. The clear glass panes are located in front of existing windows to provide unobstructed views out and allow maximum penetration of daylight. The high efficiency [about 16%] mono-crystalline solar cells laminated between two layers of glass [3m x 1m size of each PV module with 55% cells density] are located in front of the opaque parts of the existing façade. The total façade area is $455m^2$, with PV module area of $192\ m^2$ and total PV cells net area of $102m^2$. The PV cells generate low voltage direct current [with an estimated electrical peak output of 16W], connected to the building's electricity supply [Aschehoug *et al*, 2003]. The annual predicted PV electrical output has been quoted as 9,400kWh, which for the total PV cells net area of $102m^2$ gives $92.16kWh/m^2$ PV area [Aschehoug *et al*, 2003].

The new glass façade with southerly exposure acts in a similar way to a greenhouse or an atrium attached to the existing façade, for example that in Freiburg. The glazed cavity traps the solar radiation leading to increased temperatures in the buffer space. It provides extra thermal insulation to the existing façade, improved air tightness of the building and improved noise protection, and the energy captured can be used for pre-heating the supply ventilation air in the heating season [Aschehoug *et al*, 2003]. During the summer, to avoid overheating of the buffer space and PV panels, the cavity is ventilated to provide good ventilation at the back of the PV cells, thus keeping PV cells temperature down for better efficiency in generating electricity.

The pre-heat air from the cavity in the case of the BP Amoco Solar Skin Building could have been introduced to the mechanical ventilation system with heat recovery to pre-heat ventilation air. However, in this case, the cavity is used as a passive buffer without coupling to the ventilation system because the PV wall was installed just after major upgrade of the mechanical ventilation system in the building, and it was not feasible to incorporate the pre-heat air from the solar buffer space in the ventilation system [e-mail correspondence with Oyvind Aschehoug, Faculty of Architecture, Planning and Fine Arts, Norwegian University of Science and Technology [NTNU], on 30/10/02].

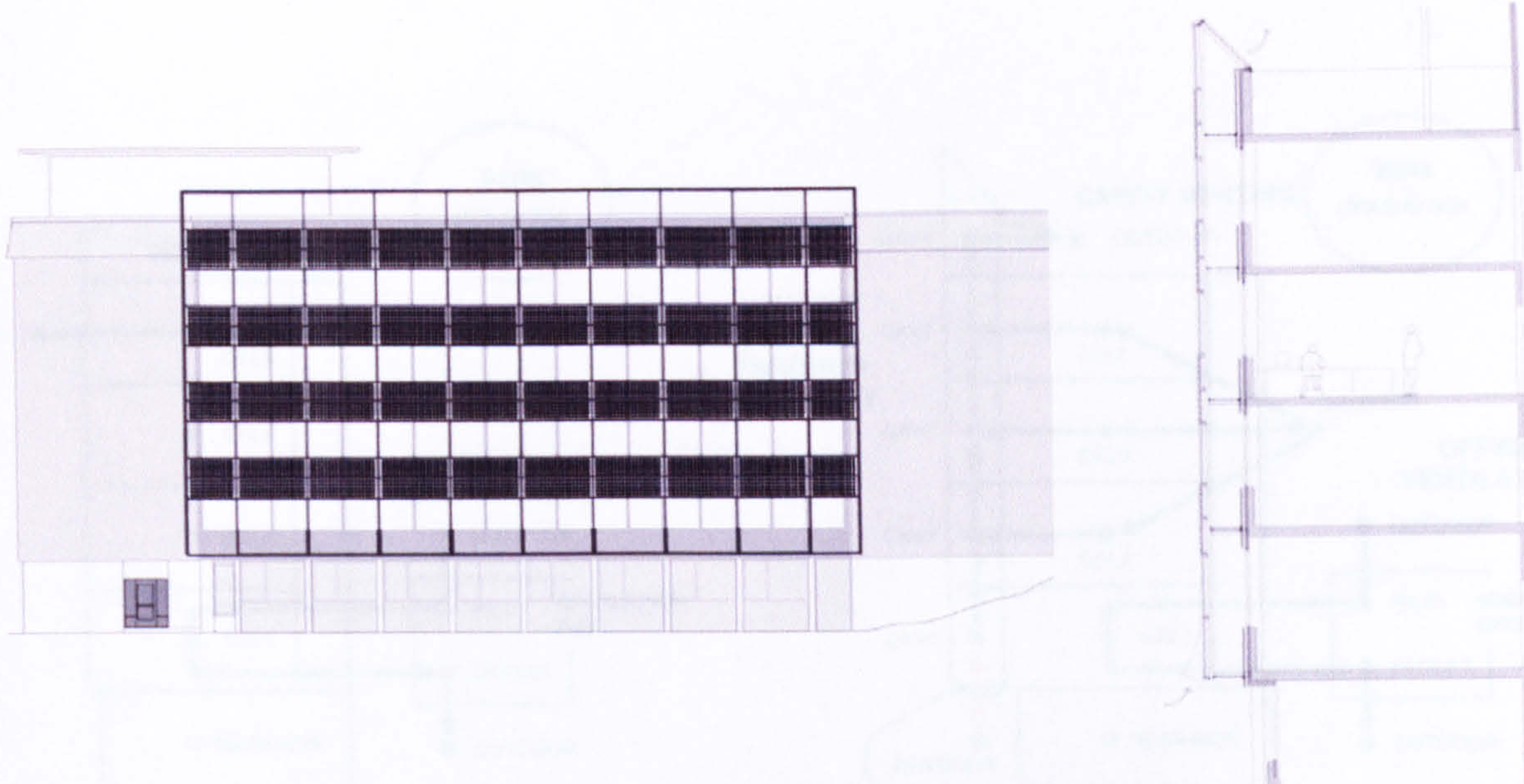


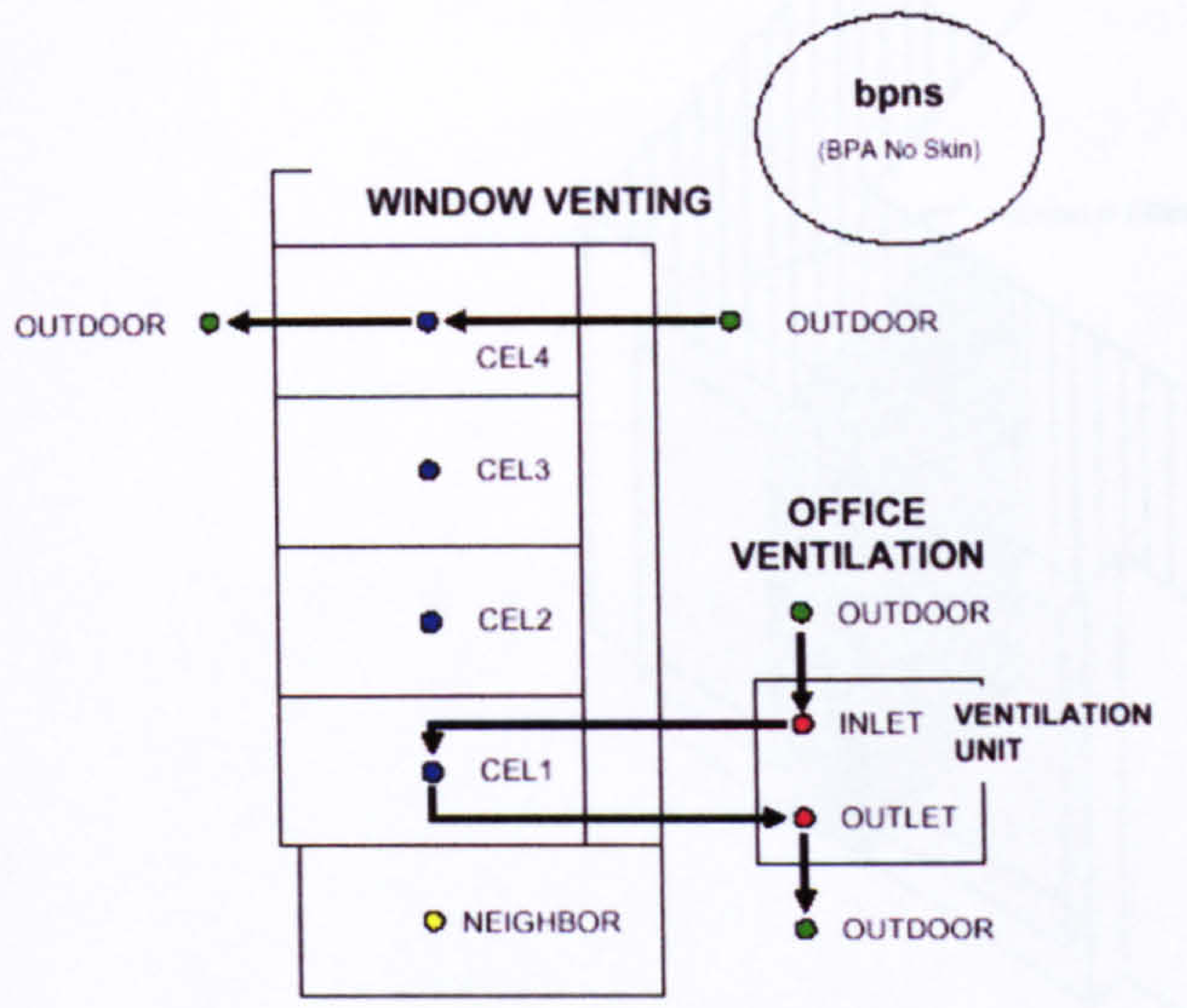
Fig. 2.47 BP Amoco Solar Skin, Trondheim, Norway, south elevation and cross section.

Source: Aschehoug O.A., Hestnes A.G., Matusiak B. "BP Amoco Solar Skin - a Double Facade with PV". *3rd ISES-Europe Solar Congress, EuroSun 2000*, 19th - 22nd June 2000, Copenhagen, Denmark. Danish Solar Energy Society.

Prior to the building refurbishment, a study of the thermal performance of the double skin façade was performed, focusing on the change in thermal comfort for the occupants. A thermal computer model was developed with the dynamic simulation program FRES [Flexible Room Climate and Energy Simulator [Fig. 2.50], a program developed at the Norwegian University of Science and Technology [NTNU]. The model represents only one segment of the building in the middle of the façade, to simplify the modelling problem [Aschehoug *et al,* 2000]. The thermal model consists of four 3m x 6m office rooms on four floors. A mechanical ventilation unit was defined for weekdays from 7.00am to 5.00pm during the heating season [November to April], with an air changes rate of 2.0 ac/h only during working hours, while in summer and autumn [May to October] there is no heating. The internal loads were defined as total of 365W per office for the occupants, lighting and equipment.

Two options were tested. The first option is the building as existing, without the BP Amoco solar skin façade, and the second one with the BP Amoco solar skin added to the existing façade [Fig. 2.48 and Fig. 2.49]. These figures show how the simulation model is built up in two cases for lower and upper level offices:

> "The ventilation unit drawn in connection with CEL1 is also connected to all the other offices. There is a difference between CEL1 and the rest of the offices. This is due to the fact that there are no windows outside to corridor at the first floor it is therefore not possible to get airing through the corridor. "[Aschehoug *et al,* 2000].



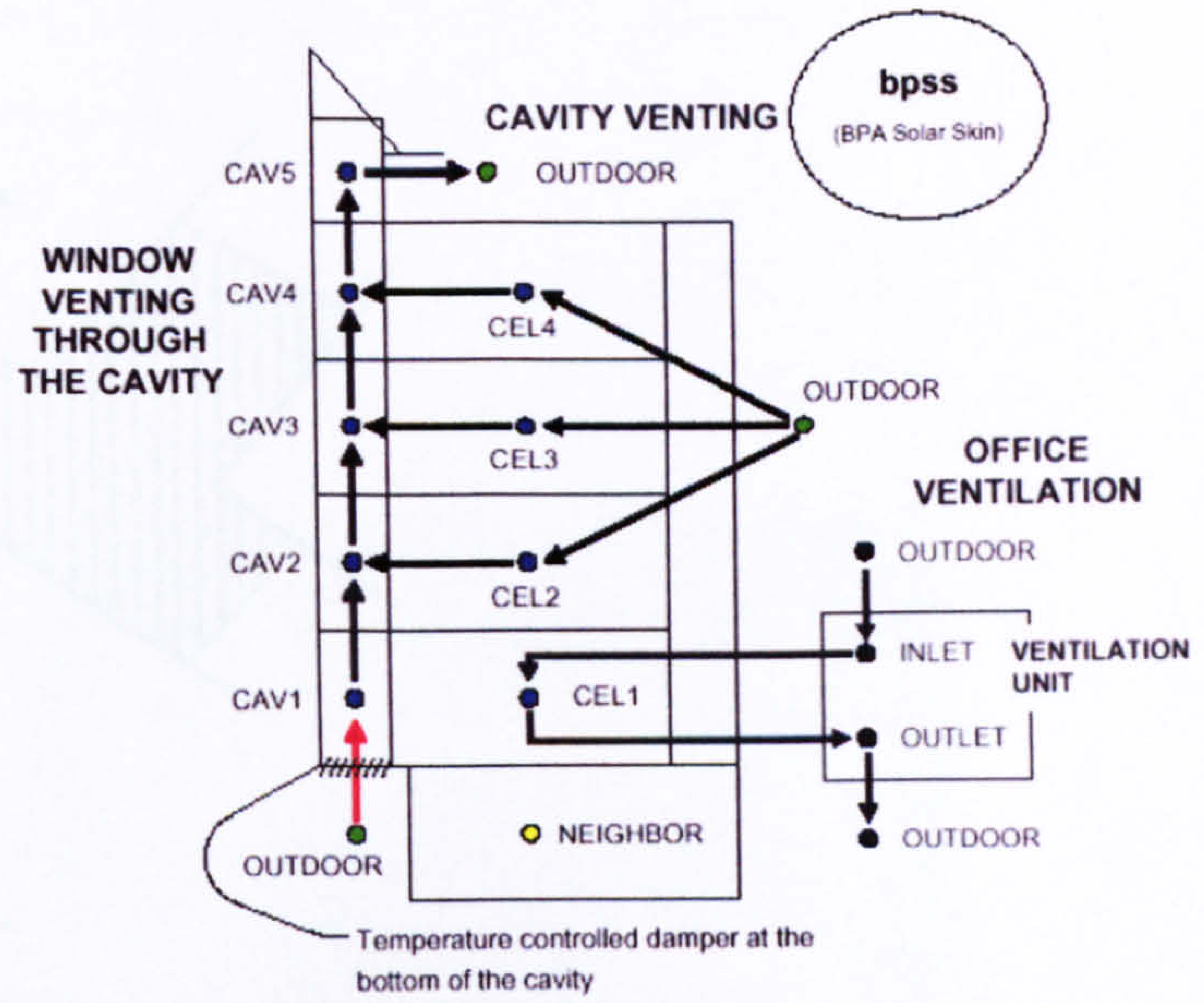


Fig. 2.48 Simulation model without BP Amoco solar skin

Fig. 2.49 Simulation model with BPAmoco solar skin

Source: Aschehoug O.A., Hestnes A.G., Matusiak B. "BP Amoco Solar Skin - a Double Facade with PV". *3rd ISES-Europe Solar Congress, EuroSun 2000*, 19th - 22nd June 2000, Copenhagen, Denmark. Danish Solar Energy Society.

Both options were simulated concentrating on the potential for overheating. It was acknowledged that optimal control of venting the cavity was of primary concern [Aschehoug *et al*, 2003]. The weather data for Trondheim [typical year 1971] was used with different outdoor climatic condition tested, including a day with a maximum temperature of 26.4°C. The cooling strategy adopted in the computer modelling was to keep office doors open to the north side corridor and draw cold air from the corridor windows, using the solar façade cavity as an exhaust stack [Aschehoug *et al*, 2003]. The simulation results have shown maximum office room temperature reaching 29.5°C in the model without the double skin and 29.8°C in the case with the double skin façade [assuming office windows opened to the cavity and double skin cavity open at the top and bottom]. Therefore, the rise in the office temperature on a hot summer day [above ambient air temperature] is similar in each case 3.1°C in the model without the double skin and 3.4°C in the model with the double skin façade. This means that sufficient air is provided through the cavity in order to ventilate the buffer space and PV panels mounted on the double skin.

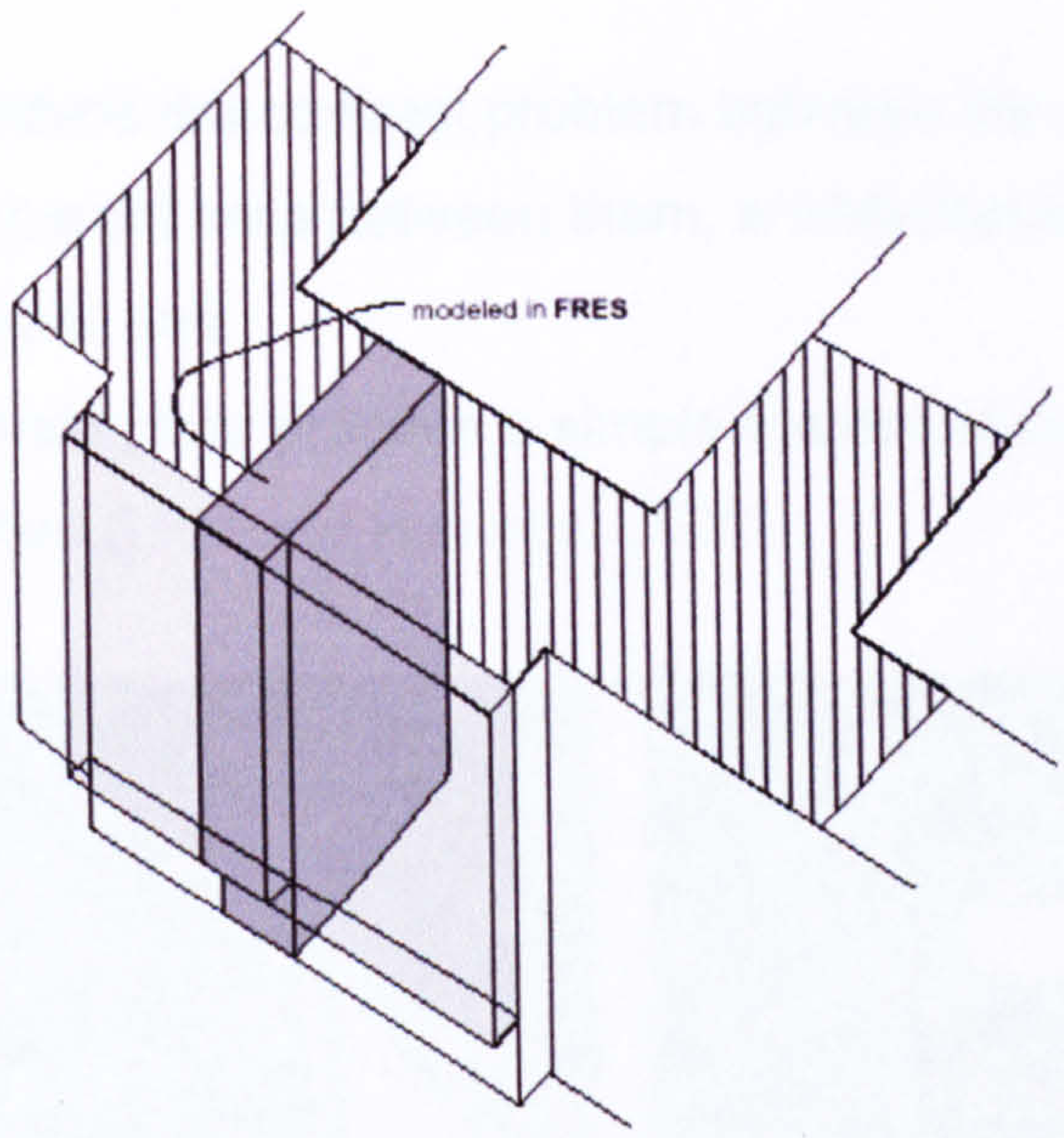


Fig. 2.50 FRES Flexible Room Climate and Energy Simulator thermal computer model
Source: Aschehoug O.A., Hestnes A.G., Matusiak B. "BP Amoco Solar Skin - a Double Facade with PV". *3rd ISES-Europe Solar Congress, EuroSun 2000,* 19th - 22nd June 2000, Copenhagen, Denmark. Danish Solar Energy Society.

The effect of the added façade on the energy consumption for office room heating was also investigated. On average, it was found that the annual energy consumption for office room heating in the case without the double skin is 63kWh/m^2 per year, and 56kWh/m^2 per year in the case with the BP Amoco solar skin, i.e. an annual reduction of the heating demand of 11% [Aschehoug *et al,* 2000]. The reduction of 6 kWh/m^2 per year may seem low. However one has to bear in mind that the solar façade is a passive buffer without the capacity of fans to drive the pre-heat air to the mechanical ventilation unit. The start value of 63kWh/m^2 is also already reasonably low, so that opportunities for further savings are quite limited.

Special attention in this project was given to the effect that the façade layer in front of the existing façade has on daylight level in offices. The transparency of the PV panels was studied in a visual study to achieve satisfactory visual comfort and daylight level [Lien and Hestnes, 2000]. Also, the influence on the visual amenity inside the rooms behind the façade was investigated. The visual comfort problems included: contrast, glare, view [focusing] and the daylight level in the room.

The visual study concluded that:

- The best way to reduce the confusing focus problem, occurring when looking through PV cells from inside room to outside, is to locate clear glass in the area where it is natural to look out, i.e. to use PV elements above or below window apertures.

- To reduce the contrast problem between the opaque cells and the transparent area between them, a white backing on the cells should be used, and
- To avoid glare problem a simple system of curtains or blinds should be used [Lien and Hestnes, 2000].

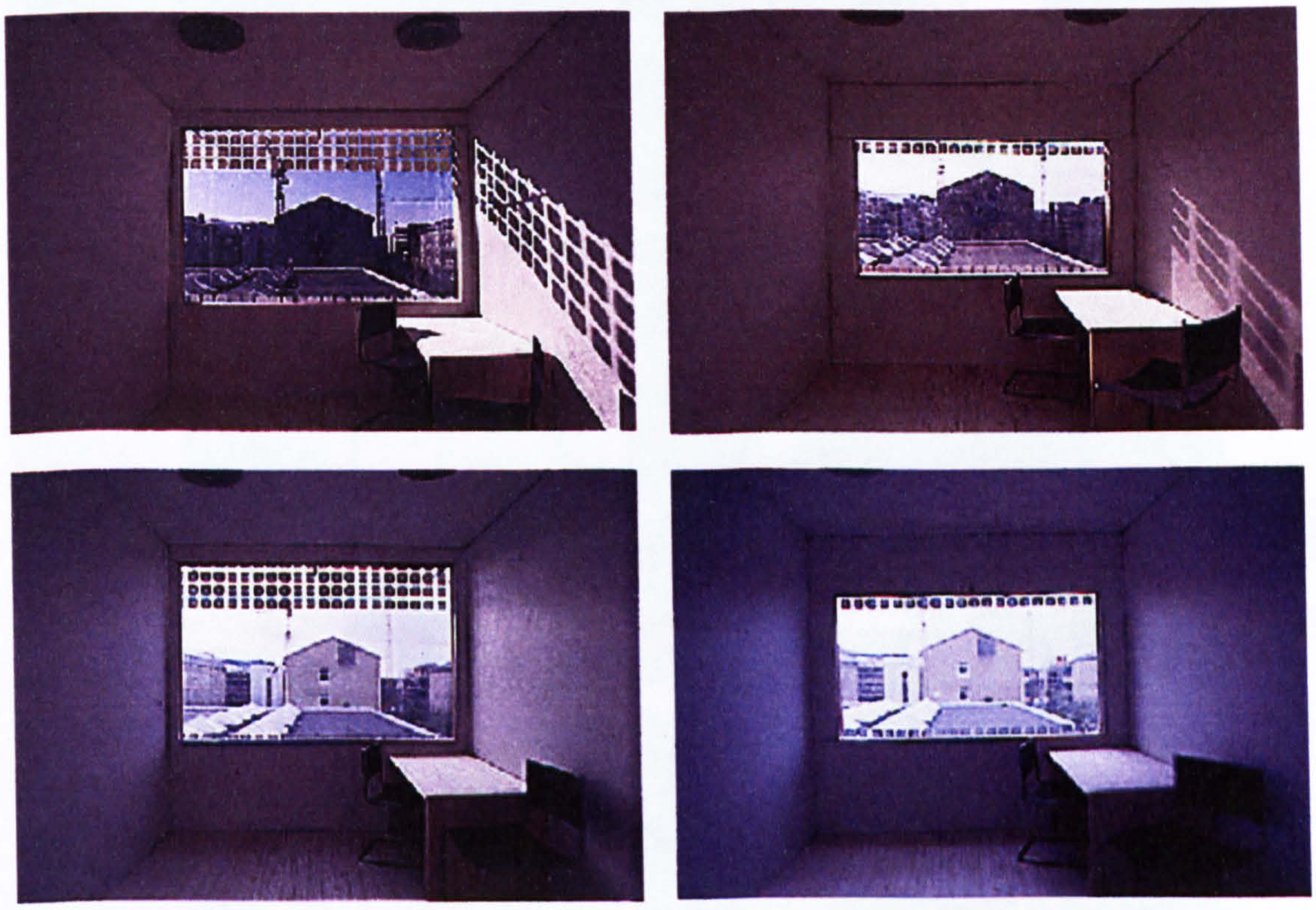


Fig. 2.51 Visual study of a double skin façade with glass integrated PV cells. Transparent appearance and aesthetic quality
Source: Aschehoug O.A., Hestnes A.G., Matusiak B. "BP Amoco Solar Skin - a Double Facade with PV". *3rd ISES-Europe Solar Congress, EuroSun 2000*, 19th - 22nd June 2000, Copenhagen, Denmark. Danish Solar Energy Society.

The daylight level in offices is inevitably reduced by adding the outer glass skin. It was acknowledged that the size and the location of windows, as well as the type of glazing, have an impact on the daylight level in offices. The daylight levels were calculated for a retrofit case of a double skin facade with 0.6m wide cavity distance from the existing building, [N.B. The 0.6m cavity width investigated differs from 0.8m cavity of the as built BP Amoco Solar Skin], with office window height of 1.0m and width of 1.5m [15% of the office floor area] with spacing between cells of 30mm in one modelling case and 15mm in another. The modelling results showed a daylight factor level in the middle of the room, 1.0m from one side wall and 0.8m above the office floor of 1.25% DF in case of spacing between cells of 30mm, and 1.20% DF in case of spacing between cells of 15mm. The Norwegian building code requires a daylight factor of 1% at 1.0m from one side wall and 0.8m above the office floor. Based on this, it was concluded that the daylight calculation results have shown that the double skin facade PV elements does not reduce the daylight level below the sufficient daylight level for in offices [Aschehoug *et al,* 2000].

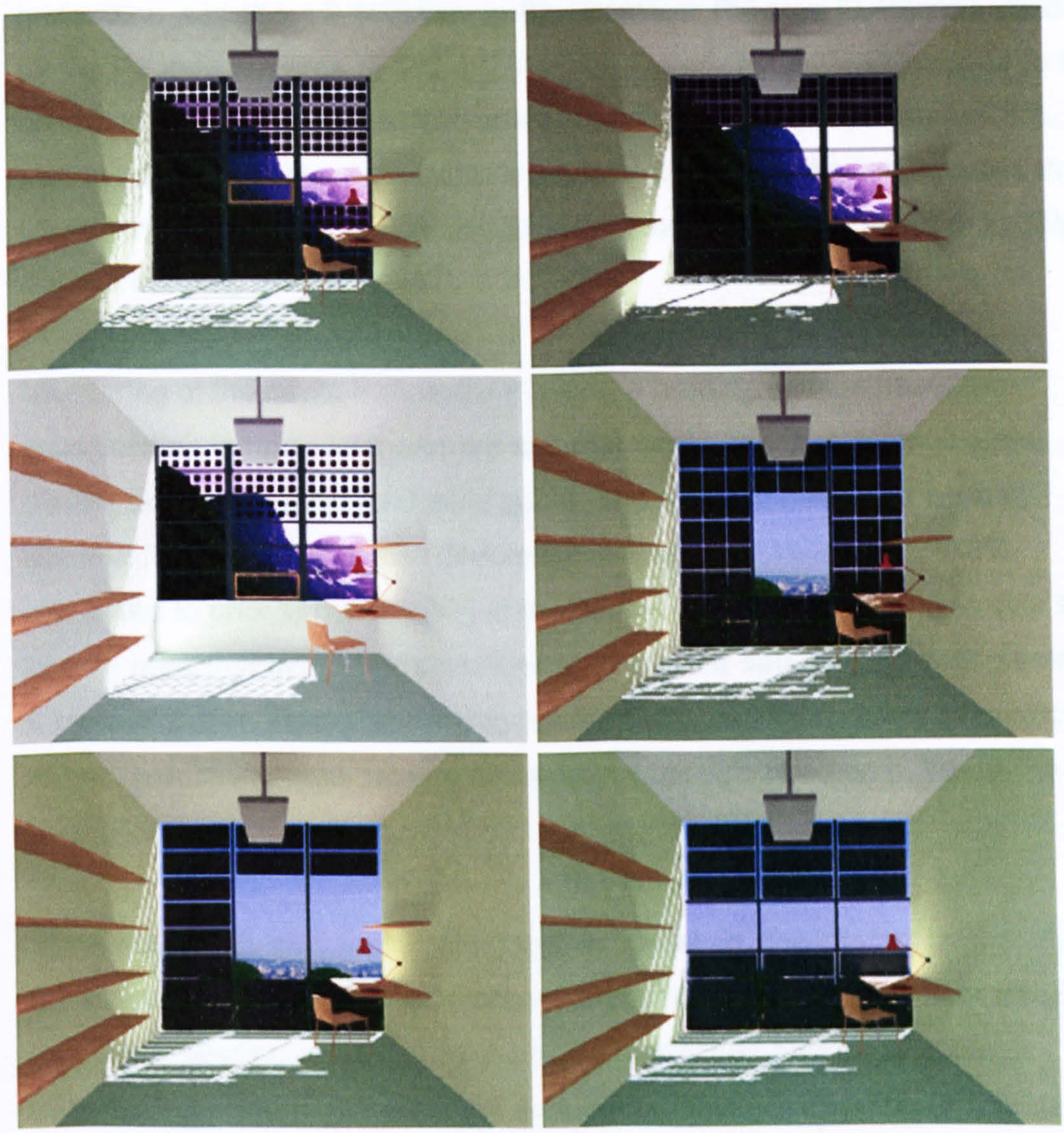


Fig. 2.52 Visual study of a double skin with glass integrated PV cells. Options of spacing between the cells
Source: Aschehoug O.A., Hestnes A.G., Matusiak B. "BP Amoco Solar Skin - a Double Facade with PV". *3rd ISES-Europe Solar Congress, EuroSun 2000*, 19th - 22nd June 2000, Copenhagen, Denmark. Danish Solar Energy Society.

The energy performance of the double skin façade was monitored for a one-year period, between May 2001 and May 2002 [Aschehoug *et al,* 2003]. The automated monitoring equipment measured the electricity generated from the PV panels and delivered to the building's grid, PV surface temperatures, air velocity, air temperature and position of the top and bottom vents on the cavity. It also monitored the effect that the new façade has on the space heating demand and indoor climate in offices facing the new façade. A weather station was also located on the roof of the building.

The monitoring results have shown that in one year the PV system delivered about 7,200kWh electricity. [Aschehoug *et al*, 2003]. For the total PV cells net area of $102m^2$, that is $70.58kWh/m^2$PV area. The theoretical predicted generation was about 9,400kWh, or $92.16kWh/m^2$ PV area [9,400kWh divided by the PV cells net area of 102 m^2] [Aschehoug *et al*, 2003]. Compared to the predicted results, the PV system overall monitored efficiency is about 75%. The loss in efficiency of the PV system is explained as a result of energy loss during short period of system malfunction [inverters failure] and the effect of shading at the site from the nearby trees.

Monitoring of the cavity temperature over the heating season has shown increased air temperature over the external temperature as a result of the double skin buffer effect and solar gains. The total annual space heating demand for offices facing the double skin façade was lowered for 7-8% compared to prior to the building of the double skin façade. However, one has to bear in mind that the savings are limited due to the solar façade acting solely as a passive buffer. These monitoring results compare slightly lower to predicted annual reduction of the heating demand of 11% described on p. 79 [Aschehoug *et al*, 2000].

Since the double skin façade has been in operation, the internal temperature in the monitored offices was satisfactory, except on the top, fourth floor offices. Some overheating problems have been experienced periods of summer overheating on summer days with an unfavourable combination of high solar radiation, high outdoor temperature and wind direction that creates a back-draft which counteracts the stack effect [e-mail correspondence with Oyvind Aschehoug, Faculty of Architecture, Planning and Fine Arts, Norwegian University of Science and Technology [NTNU], on 30/10/02]. This resulted in the air-flow in the cavity being reversed, with the top floor offices receiving hot cavity air through office windows. The current summer cooling strategy is to keep office doors open to the north side of corridor and draw cold air from the corridor windows, using the solar façade cavity as an exhaust stack [Aschehoug *et al*, 2003]. The building owners are now looking at implementing a revised ventilation strategy to overcome this problem and improve summer conditions in top floor offices.

It is possible that such a future refinement may involve some mechanical assistance and, that being the case, an opportunity could also occur for mechanically assisted ventilation preheat in winter. This would then raise the question of potential hybrid role for the PV in winter – its thermal contribution as a by-product of electrical generation, compared with the potential solar thermal gain that the presence of the PV blocks.

Thus this project, like most of those reviewed in this chapter, serves to highlight that particular aspect of BIPV. The isolation of its thermal contribution relative to others, such as heat lost from the building and direct solar gain, remains unexplored. Furthermore, the presence of a BIPV component, in this case the new outer skin, provided an unwelcome outcome due to the peak summer back-draught effect. This requires further exploration in the context of a whole-building solution. Finally, the daylight study at Trondheim raises a question as to whether minor adjustments within offices, or use of lightshelves, might compensate for the loss of light attributable to a second skin.

It is interesting that this project in Trondheim is the only example of a retrofit double skin BIPV solution to multiple environmental problems to be found in this review. This in itself points to a gap in knowledge, but the detailed appraisal also shows that at least one aspect of this lack is short with many case studies.

2.7 SUMMARY OF THE LITERATURE REVIEW

The examples of the case study buildings with integrated PV systems presented in this literature review served to identify the research work done in the area of the main European research projects in PV hybrid [thermal and electrical] systems, and integrating BIPV systems in new and retrofit buildings in the Northern European built environment context. The eleven building examples had a range of contexts and geographical locations and a range of BIPV techniques used.

The literature review has revealed that, for example, in the Scottish urban context, the size of the PV system applied was small and without the holistic approach taken in this research. In detailed terms the ESP-r computer modelling did not identify the proportion of the thermal contribution specifically from the PV cells in the hybrid [electrical and thermal] array.

The example of a factory building located in Ispra, Italy, with hybrid BIPV as a cladding option, again showed the capabilities for integrated electrical, thermal and ventilation modelling of the ESP-r simulation program in predicting the energy performance of a hybrid [electrical and thermal] PV system. It tested different design scenarios, explored various energy options, and simulated the same building energy models for different climatic contexts. But, notably, like the Lighthouse demonstration project in Glasgow, it did not isolate the thermal contribution of the PV in its hybrid scenarios for winter preheating.

Another building example of BIPV as cladding option, the Northumberland Building in Newcastle upon Tyne, England, has provided valuable experience and performance data for building integrated PV at northern latitudes. It has also shown that, when designing a building integrated photovoltaic system in urban areas, the influence of the surrounding buildings must be taken into account as the shading can strongly affect the system's output efficiency. The project confirmed that an integrated PV system as a refurbishment option on an existing office building at a northern latitude is a viable option. However, the PV generated electricity has been used directly in the building without targeting a specific end-use load, and the PV system does not attempt to utilise the waste heat from behind PV panels. Nor has there been any evaluation of the impact that the projecting arrays may have had on lighting use in offices.

The building example of retrofit with BIPV as sun shading option, the ECN 31 Building in Petten, The Netherlands, has similarities to the retrofit exploration to be undertaken in this research work. In both cases the underlining strategy is for energy-efficient measures, and passive and active solar PV systems to be employed to reduce the energy demand, improve the indoor conditions and improve workspace comfort quality. The use of extensive computer modelling and mock-ups to assess the effect of added structures to the internal daylight environment also applies to both projects. However, despite the apparent commonality of approach, there appear to be no plans at ECN to monitor the wider environmental aspects, including, again, the impact on lighting. Moreover, the quiet rural location of the ECN 31 Building site and the requirement for a specific mechanical ventilation system for laboratories, provided the logic for its lamella solution, but this would not be suitable for urban building with opening windows.

The BIPV technique with most building examples in this literature review is the BIPV application in atria. The first building example in this group, the ECN 42 building in Petten, The Netherlands, has relevance beyond rural new-built to many retrofit applications, including those sited within the dense urban morphology of cities such as Glasgow. In such cases the new glass roof acts as a climatic buffer, providing shading and generating electricity, but also affecting daylight transmittance to bounding spaces. This last aspect has not been fully explored in the case of the ECN 42 building.

The second building with BIPV in atria, the Brundtland Centre in Toftlund, Denmark, employed detailed energy modelling of the atrium where semi transparent photovoltaic panels have been integrated into atrium roof glazing. However, the lack of energy monitoring on this building has prevented a comparison between predicted and measured energy performance. In addition, the numerous theoretical modelling options did not isolate the specific thermal input attributable to the PV cells.

The third example of BIPV in atria, the Jubilee Campus at the Nottingham University, with the PV system integrated on atria roofs supplying electricity for the low-pressure ventilation system fans all year around, takes the technology to a similar climatic location to that used in this thesis. Furthermore, the reported stratification of warm air and lack of ventilation at atria roof level as the main reasons for increasing PV temperature and reducing efficiency, has provided an insight into the importance of effective ventilation of PV cells in relation to a double skin façade with BIPV.

The fourth example of BIPV in atria, Mont-Cenis Academy, Sodingen, Germany, with its big glass 'box' containing individual buildings, represents a radically different model compared with previous case studies of this technique. Nevertheless, the relevance of the case study for this thesis is in the integration of semi-transparent roof and façade PV systems to perform multiple functions of electricity generation, shading and optimising daylight. Again, however, aspects of overall performance have not been analysed – in particular the extra burden on artificial lighting that the extra skin may cause.

The fifth example of BIPV in atria, the Solar Fabrik in Freiburg, Germany, as a building example set in a climatic context different from that in Glasgow and a new building, is not directly comparable with the retrofit exploration undertaken in this thesis. In particular, as in the ECN 31 building, the heat generated from the PV systems cannot be harnessed, but neither can the cells overheat due to incorporation with the skin itself, rather than being attached to it. Thus the non-hybrid but multifunctional approach is relevant to this literature review even if only by virtue of pre-empting potential issues or problems that this thesis tackles.

The last example of buildings with BIPV in atria is the Doxford Solar Office in Sunderland, England. It is a new built office building with a holistic combination of integrated renewable energy and passive solar energy measures. The building is situated on a clear site, with no obstruction to the solar access from neighbouring buildings, and no issues related to traffic noise. In this sense the building differs from the retrofit exploration undertaken in this research work, which is situated in densely built urban area with overshadowing, noise and air pollution constraints. On the other hand, due to geographical and climatic similarity between Sutherland and Glasgow, the comparison of the computer predictions of PV performance and monitoring results of PV electricity measured data, has relevance to the case study building in this research. The photovoltaic system of the south façade of the Doxford building and the atrium space behind it, is also very different from all the previous examples of atria, since the façade is the external envelope of the primary working spaces. However, like other hybrid BIPV case studies, the heat attributable to the PV is not identified – whether useful in winter or problematic in summer.

The last building example in this literature review, the BP Amoco Solar Skin building in Trondheim, Norway is strategically the closest to the main exploration undertaken in this thesis. The building context is of a university campus, both retrofit projects on buildings of a similar age and using a double skin façade with building integrated photovoltaics as part of a holistic thermal and environmental improvement strategy. In the case of Trondheim, computer modelling investigated both the energy performance of buildings and the effect that the double skin façade has on internal daylight conditions within offices. However, the double skin cavity in the case of the Norwegian building, is only a passive buffer, so that the potential for hybrid BIPV, as part of a thermal ventilation preheat system in winter, is not tackled. In particular, we do not know whether the presence of the cells would benefit such a system. There is also a difference in the cooling strategy during summer period between the two buildings. The building in Norway relies on cross ventilation between a north oriented corridor and offices facing the double skin facade, by drawing fresh air through doors and corridor windows into offices. In case of the case study building in Glasgow, as yet not described, more typical central corridor prevents such a solution. Therefore, another tactics will be needed, assuming one-sided ventilation is not enough to avoid overheating. Finally, although a fairly detailed daylight study was undertaken at Trondheim in order to assess the effect of the double skin façade on the internal daylight level, this did not explore the potential to improve the quality of daylight distribution in offices by investigating various office design options.

Hence the gap in knowledge are clearly defined for the whole work:

a) New insights are needed for summer and winter performance of double skin facades;
b) For winter preheating, the thermal contribution of the double skin façade PV cells must be isolated from other heat gains;
c) For peak summer conditions, the impact on double skin façade cell efficiency must be identified and overheating of rooms solved;
d) Methods to positively counter the diminished daylight attributable to the double skin need to be explored. Therefore, this is where the analytical part of this thesis will focus.

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DOUBLE SKIN FAÇADE HISTORICAL OVERVIEW

3

3.1 DOUBLE SKIN FAÇADE

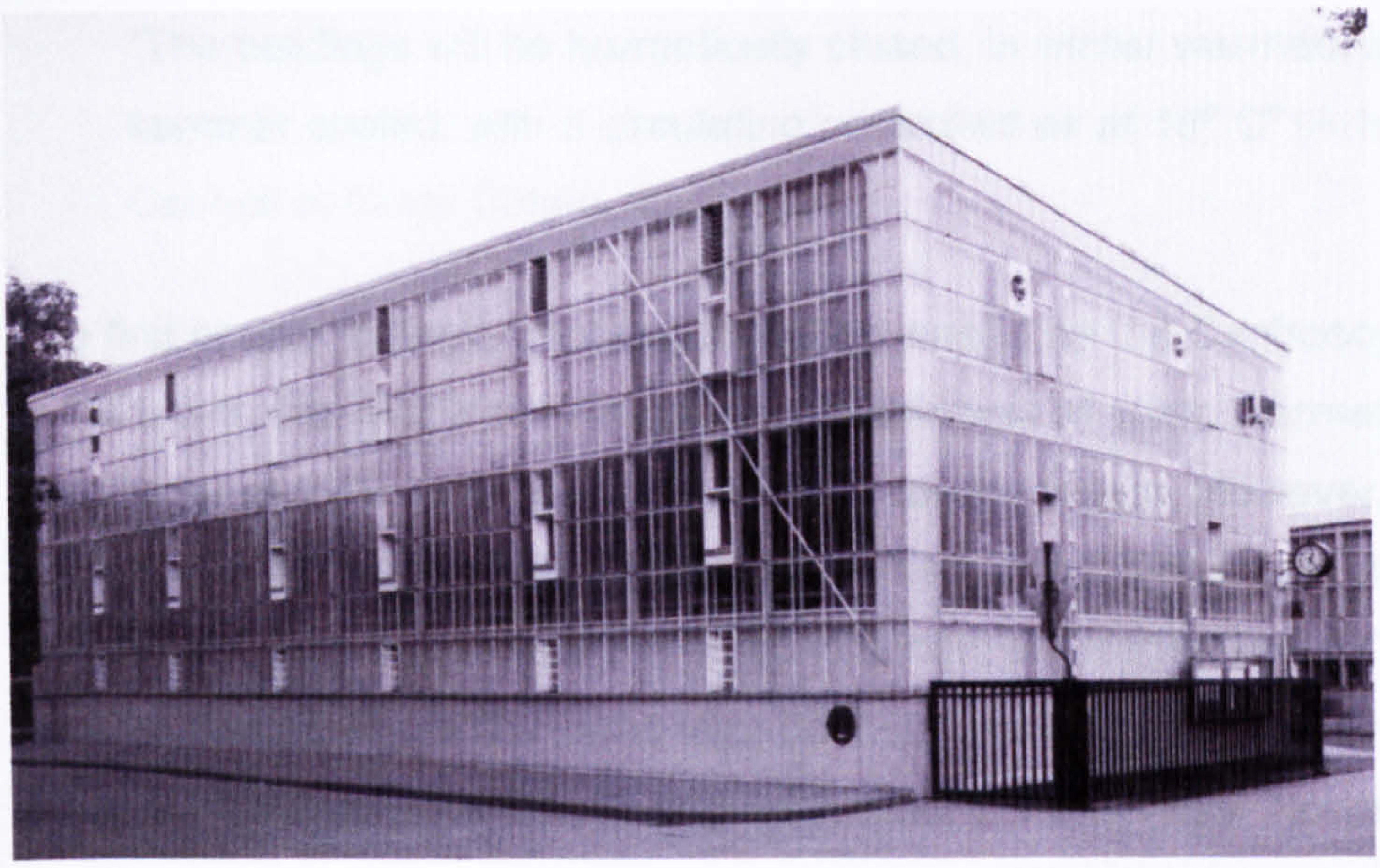


Fig. 3.1 Steiff Machine Hall, 1903, Germany

Source: Daniels K. "*The Technology of Ecological Building*". Birkhauser, Berlin, Germany. p. 158. 1997.

Since it has been declared that the most significant gap in knowledge with regard to BIPV lies with PV integrated double skin façades, with no work in a climatic context similar to that of Glasgow, and since this technique has to tackle archetypal architectural tensions, it seems appropriate to preface the next chapter by a brief summary of the technique as applied without PV.

The 20th century evolution of façade structures, arising from the more flexible transparent interface between inside and outside, in which the outer wall had no load bearing function but only of an enclosing skin, opened new possibilities for architects. In particular, double skin façades have been a fascination for a surprisingly long time, following developments in metal and glass based on 19th century greenhouse construction. The earliest known example of a double skin construction goes back to 1903 with the Steiff machine hall in Germany [Daniels, 1997, p.158], where it is reasonable to assume that the objective was maximising daylight, whilst keeping heat retention within acceptable limits.

Then the integration of a double skin and mechanical ventilation was promoted by Le Corbusier in 1929. He was attracted to the idea of binary air conditioning, one for the boundary layer between skins, and one for the interior. He saw this as an opportunity to design the same building, with the same equipment, for any climate in the world; one single building for all nations and all climates, the building with *'respiration exacte'.*

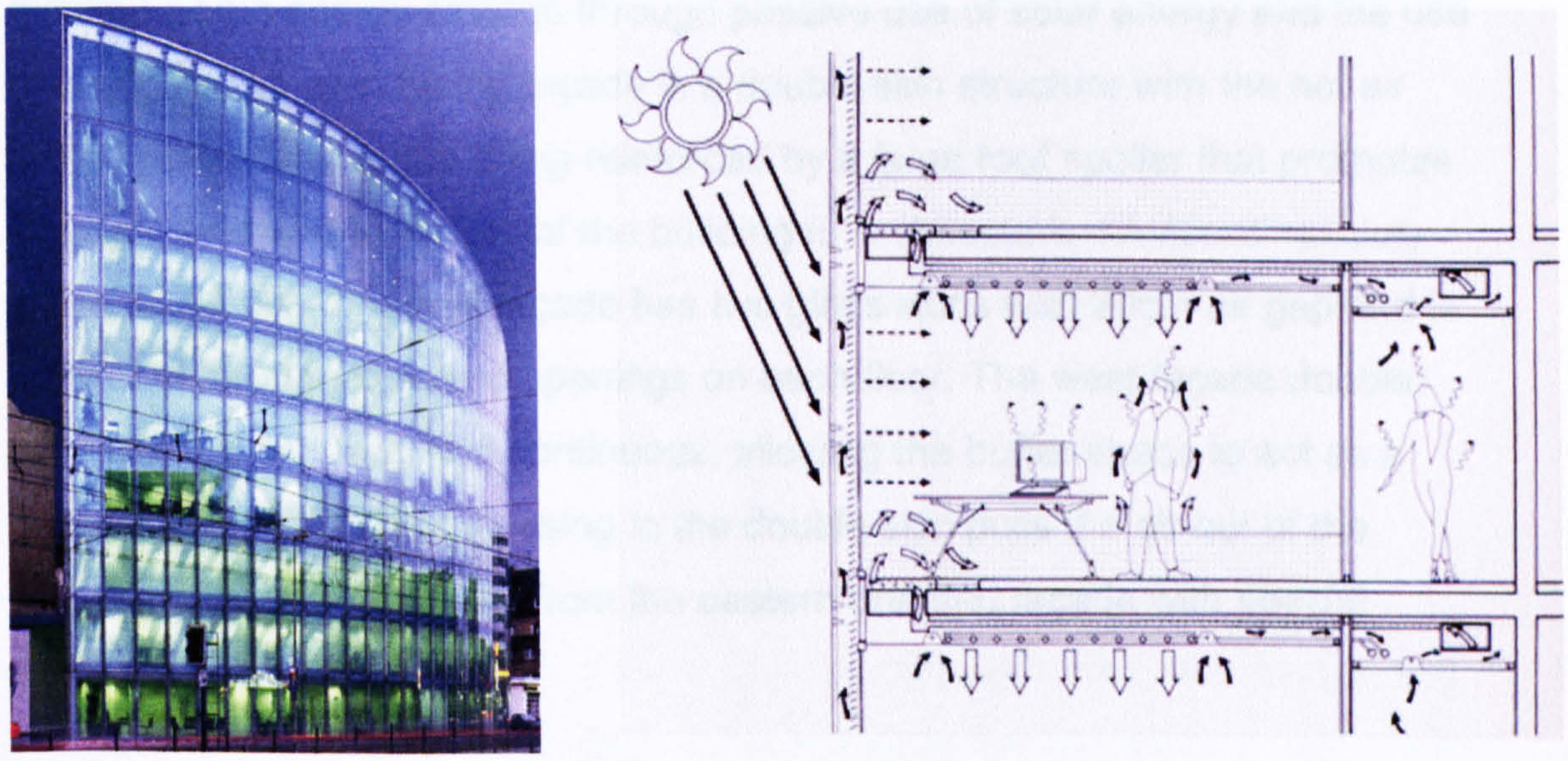
> "The buildings will be hermetically closed, in winter warmed, in summer cooled, with a circulating controlled air at 18° C" [Arts Council of Great Britain, 1987, p.169].

The first project to implement this invention was to be the Centrosoyus, Moscow, in 1929 with the 'Mur Neutralisant' double skin wall of glass, hermetically closed and the air at 18°C circulating between the façade layers. However, due to cost constraints, the idea was not fully implemented. The building with double skin was constructed, but without the air conditioning envisaged by Le Corbusier. Another project where the same idea [to install a system of total air-conditioning was proposed] was the Cite de Refuge project in Paris 1929. However, the double skin was rejected as economically impractical. As a result, the single south facing hermetic wall of glass proved disastrous in summer due to thermal gain and had to be adapted with opening windows and later with a concrete brise soleil [Arts Council of Great Britain, 1987, p.170]. Although the first experience of Le Corbusier's idea was unsuccessful, and rather illogical in terms of economic mechanical servicing, it is nevertheless now acknowledged as the beginning of the modern ventilated façade systems and of linking building mechanics with the external skin.

A significant passive example of the double wall principle in the UK was built in 1961. The St. George School Wallasey, designed by Emslie A. Morgan, incorporated a double skin wall, with the outer glass wall of clear glass 60cm apart from the inner wall of translucent panels. The aim was to meet the heating load by the passive solar gains and internal gains of lighting and pupils. However, an insufficient level of natural ventilation was produced by openings on the inner skin, while the outer skin remains closed, resulted in low rates of air changes in classrooms [Porteous, 2002, p.146].

In the 1980s, and especially in the1990s, the development of double skin façades in Northern Europe is significant. As early as 1981, Mike Davies from the Richard Rogers Partnership set up the vision for a polyvalent skin as a self regulating, multi-layered and multi-functional external skin structure. The polyvalent wall operates in order to heat, ventilate, light and cool a building with as little technological help and energy consumption as possible [Daniels, 1997, p.160].

Several well known architects designed buildings using the principle of double skins and a ventilated cavity as high performance and energy efficient cladding systems. For example, Norman Foster's Business Promotion Centre in Duisburg, Germany [1988-1993], is an eight-storey high office building where the double skin cavity allows accelerated ventilation, thereby cooling the inner skin in summer and pre-heating air in winter. The system also reduced the noise level, and with computer controlled perforated aluminium blinds allowed views out without glare. Comfort level in rooms is created under artificial conditions for heating and ventilation, with computer controlled light and temperature levels, and an option for individual controls [Behling and Behling, 1996, p.202]. The building originally intended to use PV cells, integrated into the roof structure, to generate electricity, and solar panels for warm water distributed through radiant panels beneath the concrete slabs. However, these systems were omitted, and although this building is pioneering an energy efficient system, its double skin does not allow natural ventilation between buffer space and offices, as the heating and ventilation systems are entirely mechanically controlled.



a b

Fig. 3.2 [a-b] Norman Foster's Business Promotion Centre, Duisburg, Germany 1988-1993. Façade view and energy diagram

Fig. 3.2 [a] Source: Pawley M.,"*Norman Foster, a Global Architecture*". Thames and Hudson, London, UK. p. 146. 1999. Fig. 3.2 [b] Ibid. p. 144.

In 1990 the architectural practice Future Systems, London, UK, designed a building with a double skin where the solar chimney is one continuous space, utilising the stack effect to pull the air out of the perimeter offices, while the fresh air is supplied from the atrium in the middle of the building [Pawley, 1993, pp.115-118]. Although the building was not built, its value remains as a theoretical research project for an energy efficient building.

a

b

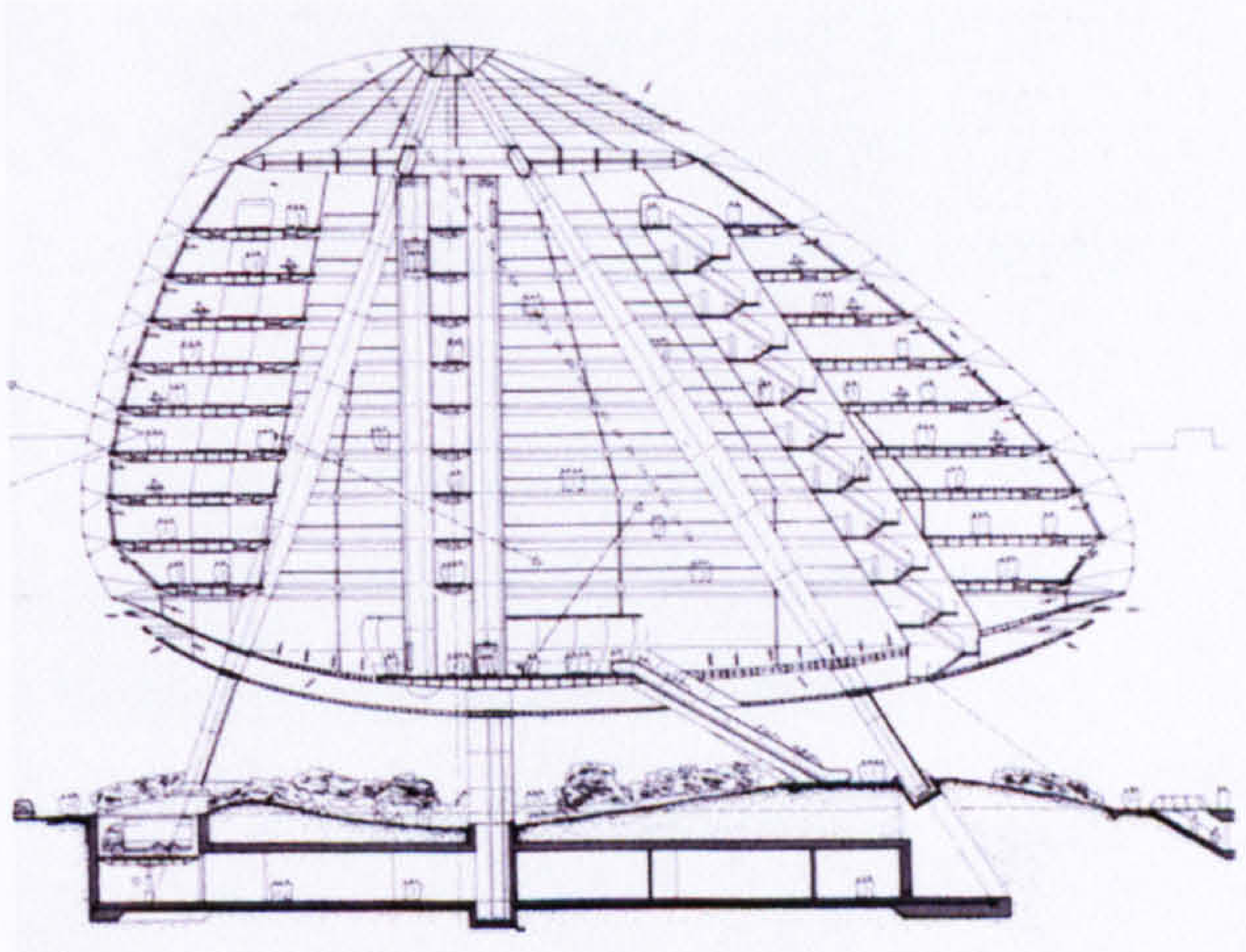


Fig. 3.3 [a-b] Future Systems, building with a double skin facade, 1990. Building model and section

Fig. 3.3 [a] Source: Pawley M.,"*Future Systems, The Story of Tomorrow*". Phaidon Press Ltd., London, UK. p. 115. 1993. Fig. 3.3 [b] Ibid. p. 118.

A more recent built example of a double skin façade as a continuous space is the GSW Building in Berlin by the architects Sauerbruch and Hutton. The system of an 11m deep floor width minimises the need for artificial lighting and allows natural ventilation. The idea behind using the double skin façade was to maximise both energy savings through passive use of solar energy and the use of daylight. The west facing façade is a double skin structure with the hot air rising in the cavity space being reinforced by a large roof spoiler that promotes negative pressure at the top of the building [L'Architecture d'Aujourd'hui, July 2000, pp.68-69]. The east façade has two glass skins with 20cm air gap and is ventilated through louvered openings on each floor. The west façade double skin cavity is 1m deep and continuous, allowing the buffer space to act as a 'solar chimney'. The hot air rising in the double skin pulls the air out of the offices while draws fresh air from the eastern oriented façade with special ventilation openings.

Fig. 3.4 GSW Building, Sauerbruch and Hutton Architects, Berlin, Germany
Source: Sauerbruch Hutton Architects.,"*GSW Headquarters, Berlin, Germany*". Lars Muller Publishers, Baden, Switzerland. p. 10. 2000.

Other architects, especially in Germany, have developed double skin façade systems where the air circulation is contained within each floor. One such example is the RWE Headquarters in Essen, Germany, by the architects Overdiek and Partner. The air inlet and air outlet are located at every slab floor and ceiling level in a 50cm deep double skin cavity space, where the outer skin is single glazed and the inner skin is double glazed with venetian blinds for glare control [Behling and Behling, 1996, p.205]. Although this building uses natural ventilation, it still have an air-conditioning system designed to be used only when the outside conditions do not permit reliance on natural ventilation.

An example of a double skin façade combined with user controlled natural and mechanical ventilation was designed as a model for the sustainable urban office building. The building is located in Hannover, Germany, and designed by the architect Thomas Herzog as part of the Expo 2000 exhibition. The new Deutsche Messe administration tower brief called for:

> "high quality workspaces and an innovative exploitation of environmentally friendly forms of energy" [Herzog, 2000, p.12].

The central transparent office tower volume of the building is wrapped in a double skin façade that forms a buffer space around the building. The 1.4m deep buffer space is divided into storey-high segments, creating large volume natural ventilation ducts. On the plan, these form two L-shaped spaces, which are linked by high level ducts at entry points so as to allow smooth positive and negative pressure effects from one side of the building to the other. Both the inner and outer façade layers are double glazed with sunshade blinds inside the outer façade layer. The outer skin of the façade has ventilation louvres at intervals that allow fresh air to enter in and out of the buffer space. The louvres are adjustable and controlled by a computer, responding to various real-time weather variables. The inner façade layer has user-controlled windows in the form of sliding doors, providing natural ventilation by opening into the intermediate space.

There are also circular air inlets housed in a skirting duct below the sliding door. These house the mechanical supply [linked to the inner ventilation shafts in the vicinity of the entry points at each floor], and can fine-tune the natural supply from the buffer space upwards or downwards in temperature, depending on season and specific daily weather conditions. The outer façade louvres can be automatically adjusted when office windows are opened. In this way, heat loss is reduced and the natural and mechanical forms of ventilation complement each other. The exhaust air is collected on each storey and drawn up through vertical shafts by natural stack effect to the top of the building where it exits. In winter, the air is passed through a 'thermal wheel' heat-exchanger that recovers 85% of the heat it is used to pre-heat the intake external air [Herzog, 2000, p.35].

Fig. 3.5 Deutsche Messe administration tower, Thomas Herzog, Hannover, Germany

Source: Herzog and Partner.,"*Sustainable Height, Deutsche Messe AG Hannover Administration Building*". Prestel Verlag., Munich, Germany. p. 7. 2000.

a b

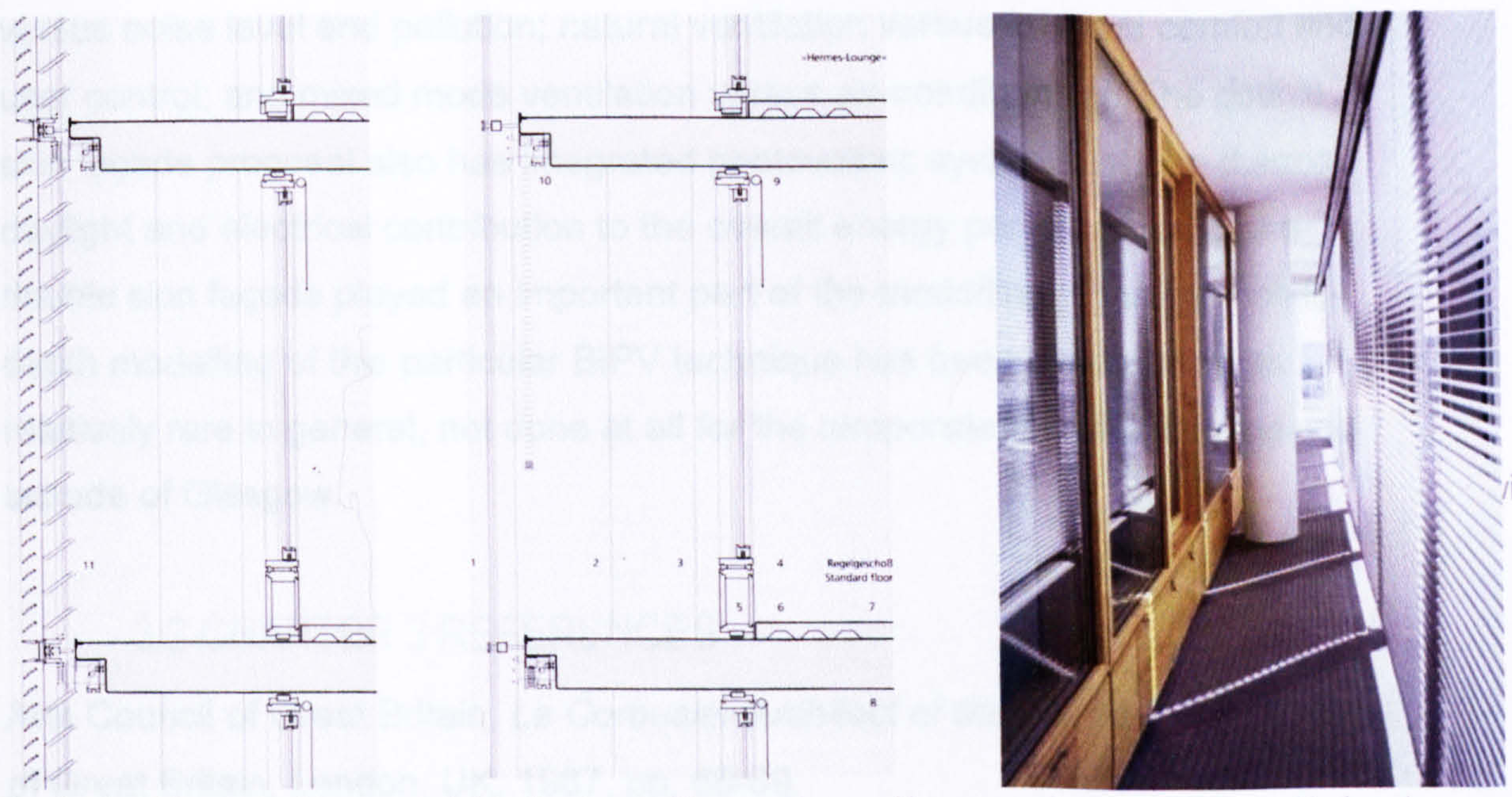


Fig. 3.6 [a-b] Deutsche Messe administration tower, Thomas Herzog, Hannover, Germany. Double skin façade section through external louvers and section through glazing on double skin façade

Source: Herzog and Partner.,"*Sustainable Height, Deutsche Messe AG Hannover Administration Building*". Prestel Verlag., Munich, Germany. p. 16. 2000.

The Deutsche Messe administration building is a successful example of an office building with a double skin façade in an urban centre. However, some of the classic issues created with the double skin façade still remain. For example, is the thermal performance of the buffer space, divided as a storey-high segment, better or worse than a continuous intermediate space, as in the case of the GSW building in Berlin by Sauerbruch and Hutton? Does the 1.4 m deep intermediate space and two layers of double glazed windows on the outer and inner layer reduce the daylight level in offices to a level that results in increased use of artificial lighting in offices? What is the efficiency of this mixed mode ventilation system compared to similar systems used in other double skin façade buildings, and does it cope equally well with all four of the orientations [north-east or south-west]?

Having briefly touched on double skin precedents over the last century, and having already established the scope of work on BIPV double skins, the following part of this research focuses on testing one of the main architectural proposals, i.e. the double skin façade with a BIPV component as a refurbishment strategy for the south façade of the Graham Hills case study building. As previously stated, the double skin façade has been selected for detailed energy performance appraisal task because it embodies classic tensions between competing environmental aspects: reduced daylight due to double skin layer; daylight level versus overheating and glare; natural ventilation versus noise level and pollution; natural ventilation versus internal comfort and user control; and mixed mode ventilation versus air-conditioning. The double skin façade proposal also has integrated photovoltaic systems whose thermal, daylight and electrical contribution to the overall energy performance of the double skin façade played an important part of the modelling. Finally, such in-depth modelling of this particular BIPV technique has been established as relatively rare in general, not done at all for the temperate mild UK climate and latitude of Glasgow.

3.2 CHAPTER 3 REFERENCES

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4

DOUBLE SKIN FAÇADE WITH BIPV CASE STUDY BUILDING

CHAPTER 4 CASE STUDY BUILDING

4.1 THE SITE

The site of the case study buildings is situated in the city centre of Glasgow, to the east of the main city square, George Square. The case study buildings represent typical public buildings in a densely built urban area. They are part of the Strathclyde University Campus, situated on a steep south-sloping site with their long elevations facing slightly to the west of south orientation. The case study buildings are: Graham Hills Building; School of Architecture Building; and Colville Building. Although all three were known to have serious energy and environmental deficiencies, and all three had potential for BIPV, it was decided that the Graham Hills building, which is sited at the foot of the hill next to a busy street, merited detailed study, i.e. relative to the research questions and hypothesis, which address the gaps in knowledge identified in Chapter 2.

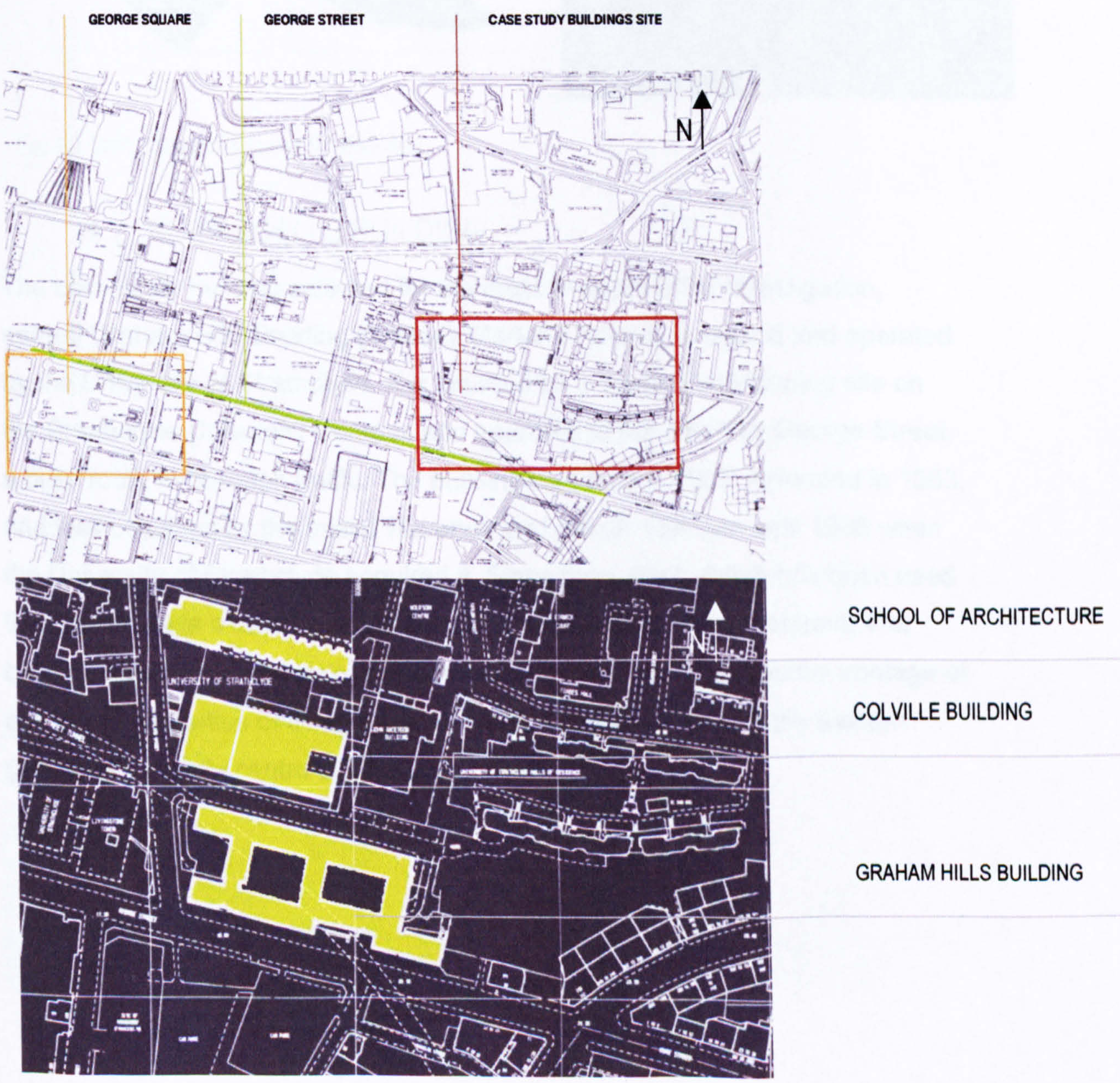

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Fig. 4.1 Case study building site

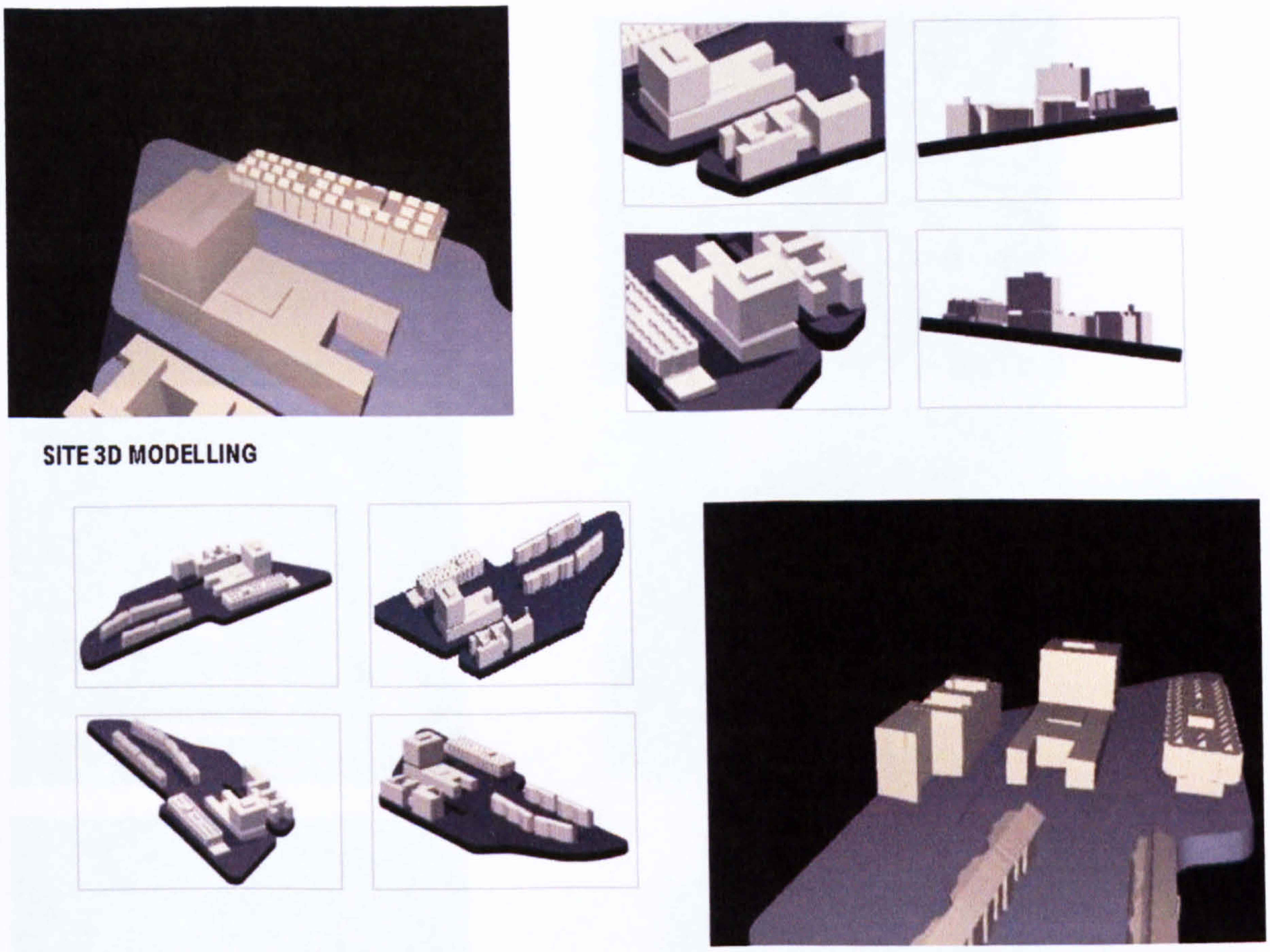


Fig. 4.2 Case study building site 3D Modelling

4.2 GRAHAM HILLS BUILDING

The case study building selected for the most in-depth BIPV investigation, named Graham Hills Building [formerly Marland House], is owned and operated by the University of Strathclyde. It is situated on a steep south-sloping site on the Strathclyde University Campus and bounded to the south by George Street, a busy route for through traffic. The building was built in 1957, extended in 1963, and was occupied by the Inland Revenue and British Telecom until 1988 when the University of Strathclyde acquired it. Since then, the building has been used to accommodate a mixture of teaching and administrative departments. The building has a very prominent position representing the largest public frontage of any of the properties of Strathclyde University and forms part of the eastern gateway to the city centre of Glasgow.

Fig. 4.3 Graham Hills building as existing

At present there is no obstruction to solar access - the site to the south of George St. is a car park. If, however, this were to be built up to a height of 27m [7 office floors], there would still be no shading of the south façade from the end of April to mid-August. From autumn through to spring there would be some shading, implying the need for careful design of PV strings in order to minimize shading losses.

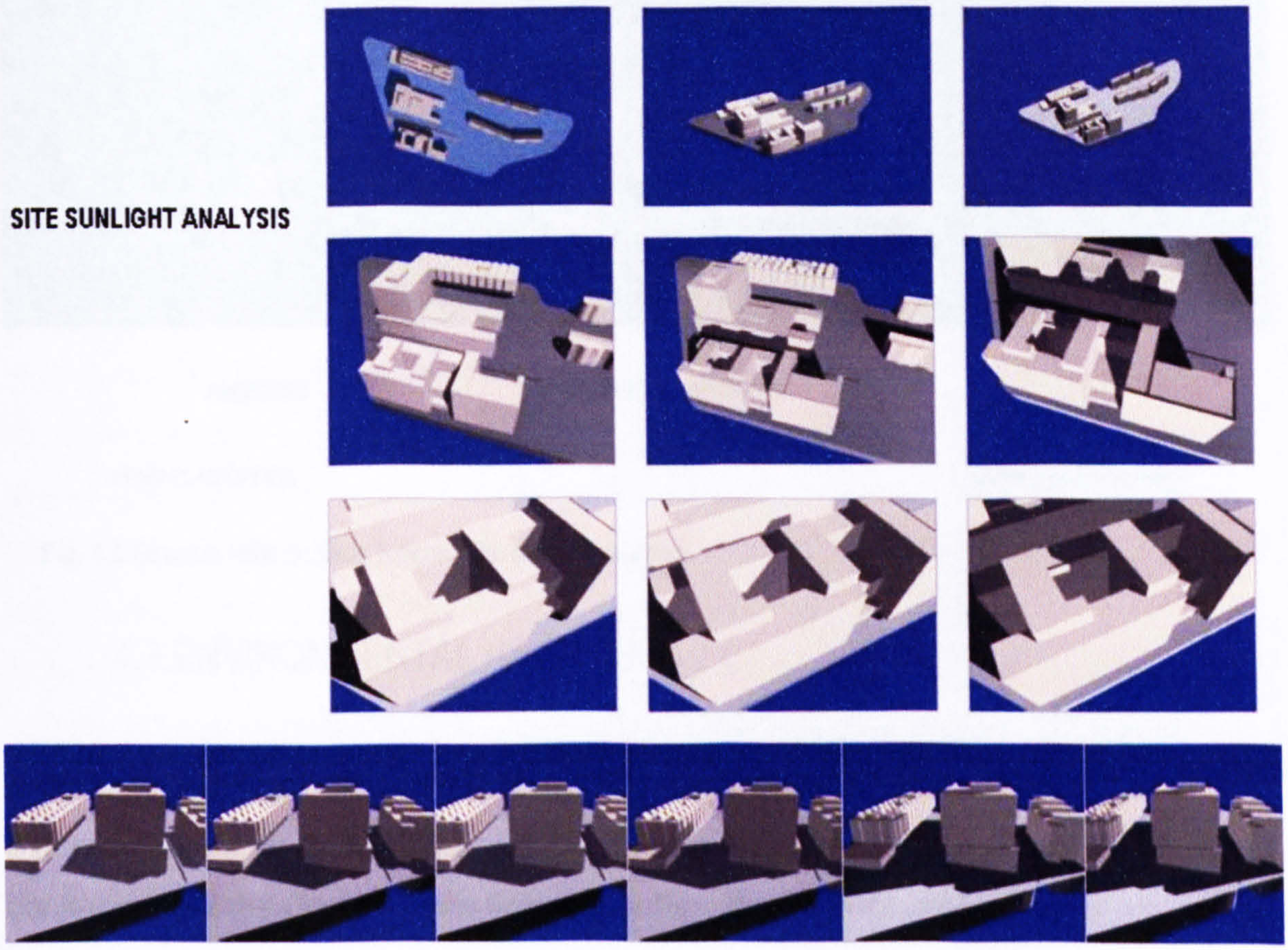


Fig. 4.4 Site sunlight analysis

The Graham Hills Building is a typical model of a 'form follows function' of its time, with cellular office accommodation and corridors, mixed with open plan offices or larger teaching areas. The plan uses three and four sided courtyards to achieve a relatively narrow footprint of approximately twelve meters from wall to wall in each wing of offices, with the only deep-plan sections occurring at the base of courtyards. The construction of the building is a typical expression of early 1960s architecture with in-situ concrete frame and pre-cast concrete cladding panels. It is eight stories high, under-insulated and over-fenestrated with single-glazed windows that are the sole means of ventilating offices. The main entrance is from George Street linking the two phases, and the building has car-park levels on the first and second floor accessed by ramps from the rear.

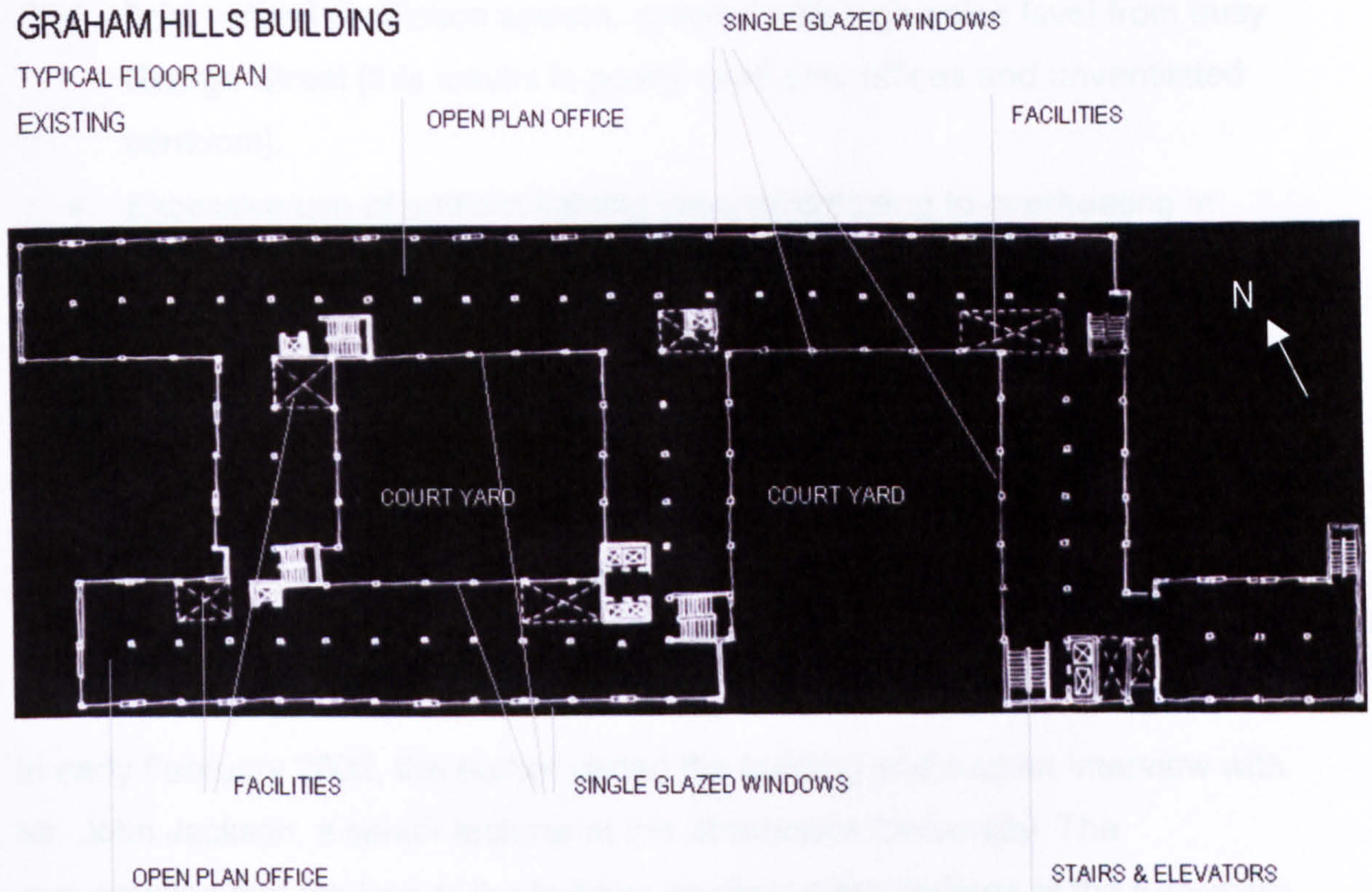


Fig. 4.5 Graham Hills building typical floor plan as existing

4.3 ENVIRONMENTAL PROBLEMS

A feasibility study produced in 1993 by the University of Strathclyde Energy Systems Research Unit, ESRU, [GA Group, University of Strathclyde, 1993], confirmed that the Graham Hills Building suffers from a wide range of environmental problems including:

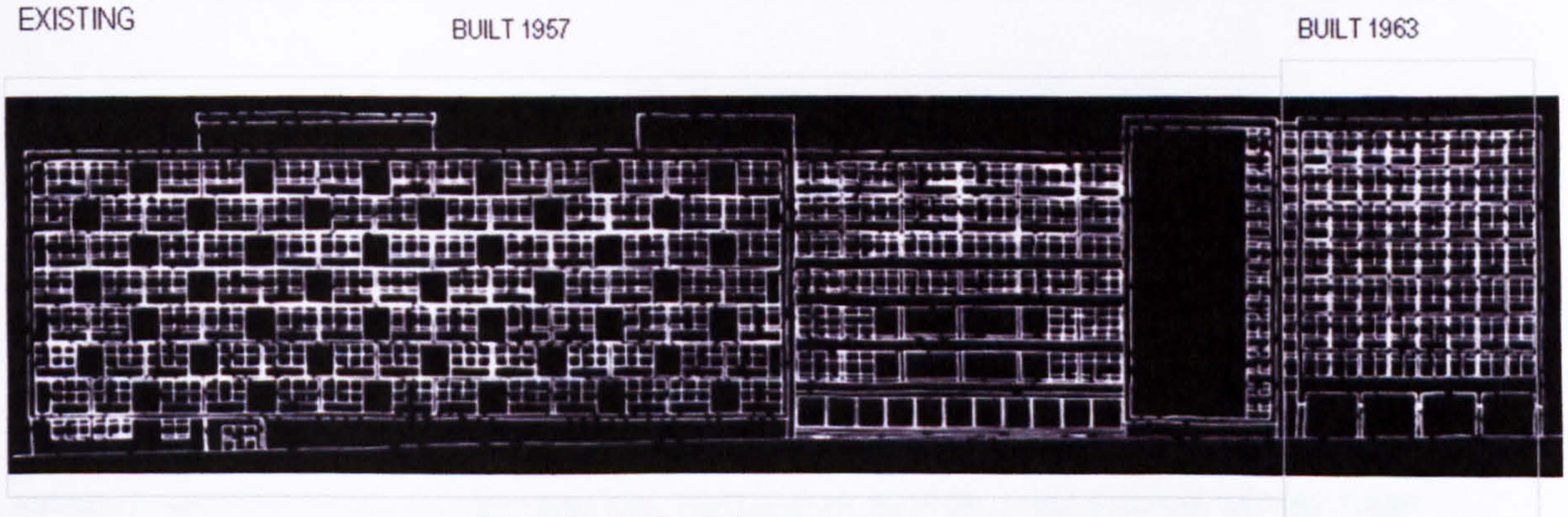
- Excessive heat loss in winter, especially on north elevation, due to poor insulation, cold-bridging and large single glazed areas.
- Severe cold-bridging on floor and sill junctions.
- Excessive window infiltration.
- Poor general thermal performance of the opaque external envelope [U-value approximately 1.4 W/Km^2].
- Poor heating controls [lack of zoning/temperature control, and badly positioned thermostats].
- Excessive heat gain and poor glare control – in spring, summer and autumn, especially on south elevation due large single-glazed metal windows [seldom opened], and an inefficient sun protection system of internal vertically slatted blinds.

- Poor natural ventilation system, coupled with high noise level from busy George Street [this results in poorly ventilated offices and unventilated corridors].
- Excessive use of artificial lighting [also contributing to overheating in summer].
- Rundown internal and external appearance [existing cladding panels have problems with water penetration, deterioration of render finishes and poor thermal performance].
- Lack of servicing facilities and amenities for both staff and students.
- High annual energy consumption for space heating, 126kWh/m^2 [GA Group, University of Strathclyde, 1993, p.26]

In early February 2002, the author visited the building and had an interview with Mr. John Jackson, a senior lecturer at the Strathclyde University. The conversation and the tour of the building confirmed the findings of the Feasibility Study [GA Group, University of Strathclyde, 1993] and the wide scope of environmental problems. The external observations were a general rundown appearance including deteriorated finishes of concrete cladding panels and their unsafe fixing arrangements and large glazed surfaces on all façades disregard their orientation. Internally, the building lacked ventilation in stairwells and corridors, zoning and control of the heating system [no thermostats on hot-water radiators] in offices, and there were visible marks of water penetration in places. In addition to the poor internal environment was the furniture arrangement in offices with computers placed below single glazed metal frame windows, often difficult to operate, with inefficient internal vertical blinds used during daytime to avoid glare and strong daylight, but then resulting in excessive use of electrical lighting. Furthermore, windows in offices subject to traffic noise were generally underused on all floors in terms of natural ventilation.

GRAHAM HILLS BUILDING

SOUTH ELEVATION
EXISTING



- Excessive heat gain in summer
- Large area of single-glazed windows
- Poor natural ventilation
- Heat loss in winter
- Cold bridging
- Poor glare control
- Rundown external appearance
- High external noise level

Fig. 4.6 Graham Hills building south elevation as existing

REFURBISHMENT PROPOSAL

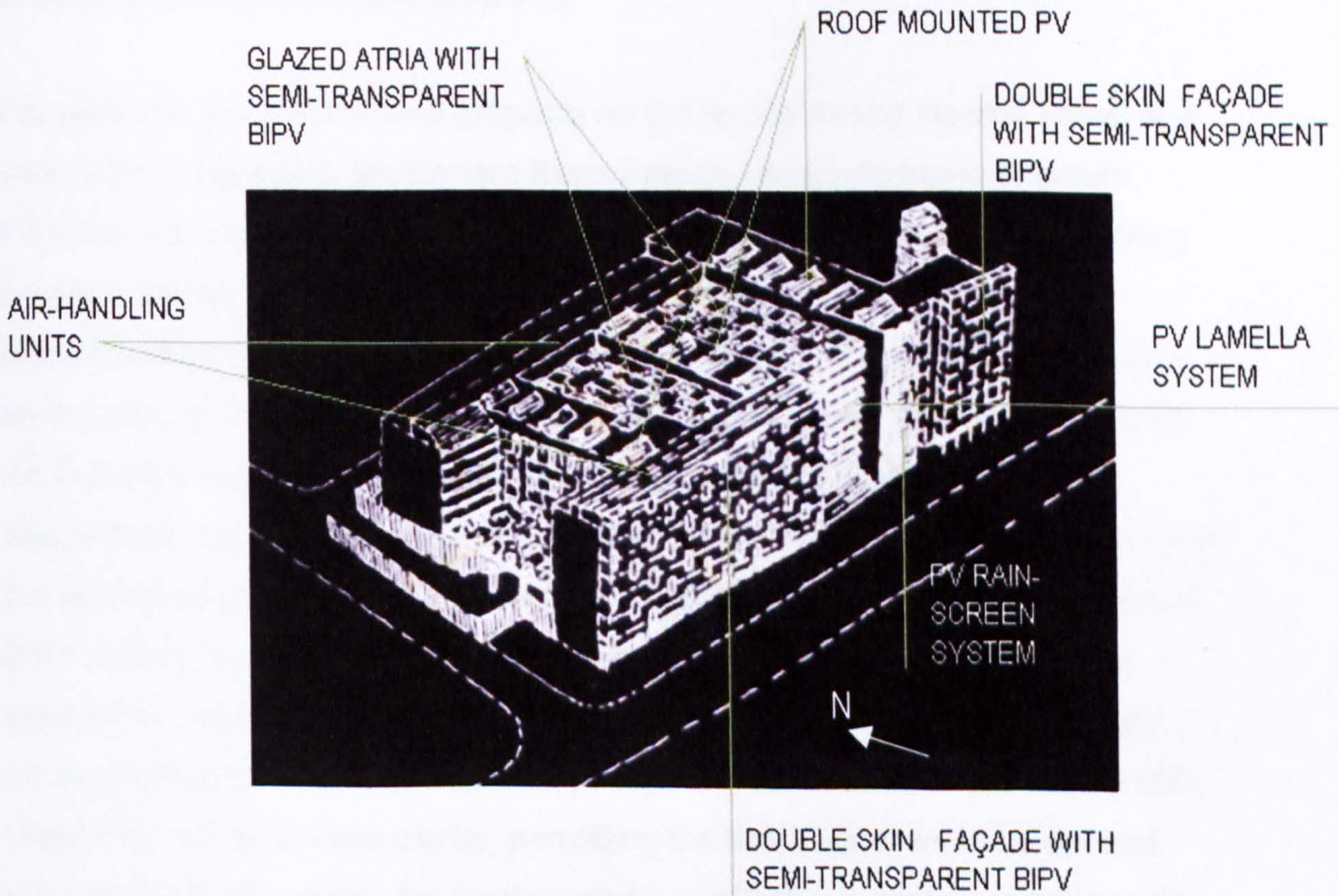


Fig. 4.7 Graham Hills building proposal

4.4 ENERGY IMPROVEMENT STRATEGY
POTENTIAL FOR BIPV AS ENVIRONMENTAL PROBLEM SOLVER

4.4.1 SOUTH ELEVATION [BUILT 1957]
DOUBLE SKIN CONSTRUCTION

The Graham Hills Building has its long front elevation south oriented overlooking a noisy street. Environmental problems, as stated above, include excessive summer overheating, a poor natural ventilation system, excessive winter heat loss [due to window infiltration, cold bridging and poor external wall U value], and high noise level. The architectural ideas and energy strategies, based partly on knowledge gained from the literature review [Chapter_2] and partly on the author's experience as an architect, involve a range of passive solar and BIPV applications aimed at reducing, or where possible, solving the problems cited above. Moreover, the proposed solution has an aesthetic dimension that acknowledges this building's role and prominent position. The concept employed was to exploit possibilities of BIPV and related passive solar techniques to provide targeted solutions to problems.

For example, the architectural proposal for the façade facing George Street is a secondary glazed skin, set forward 60cm from the concrete frame structure, from the first floor upwards. The distance of 60cm was chosen to allow walking on maintenance platforms on each floor and therefore access to window cleaning and maintenance of the PV panels. There is no double skin structure on the ground floor due to only few window openings compared to upper floors. An important aesthetic feature of the existing external envelope is pre-cast concrete panels positioned in a chessboard order. This has been 'translated' into the second-skin design as a combination of glass and vertical semi transparent BIPV panels in a chessboard formation set in front of concrete panels. This solution for placing the PV arrays conforms to the findings of the visual study undertaken at Trondheim [Chapter 2, p. 80]. The buffer zone of the double skin façade will act as a noise barrier, permitting the office windows to be opened towards the buffer space, pre-heating air for ventilation in winter, assisting with glare-free day-lighting, simplifying maintenance etc. Together with new inner double-glazed windows and insulated over-cladding to solid parts of the façade, the outer skin and solar enhanced air gap will also contribute to lowered U-values.

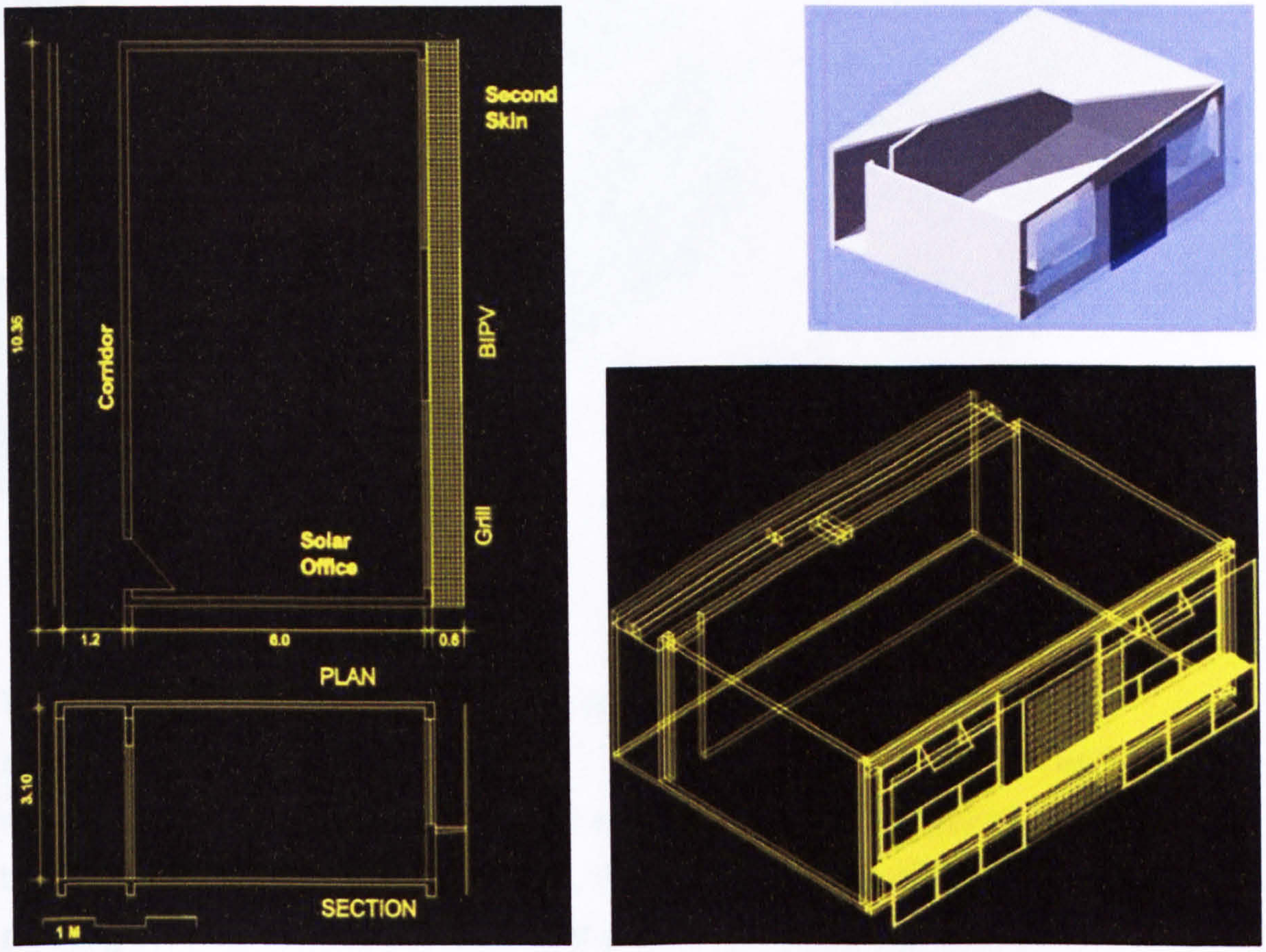


Fig. 4.8 Graham Hills building proposal for south facing offices, a double skin façade with BIPV

Two other options for positioning the BIPV panels were investigated. The first one, [Fig. 4.9], had the semi transparent PV panels in front of office's existing windows, leaving a clear glass panel of the double skin façade in front of the concrete panel. Although thermally this option would perform slightly better with the concrete panel exposed to direct sunlight, the position of the semi transparent BIPV panels in front of existing windows would reduce the daylight entering offices, and was therefore not accepted. As stated above, it also aligns itself with the visual study at Trondheim.

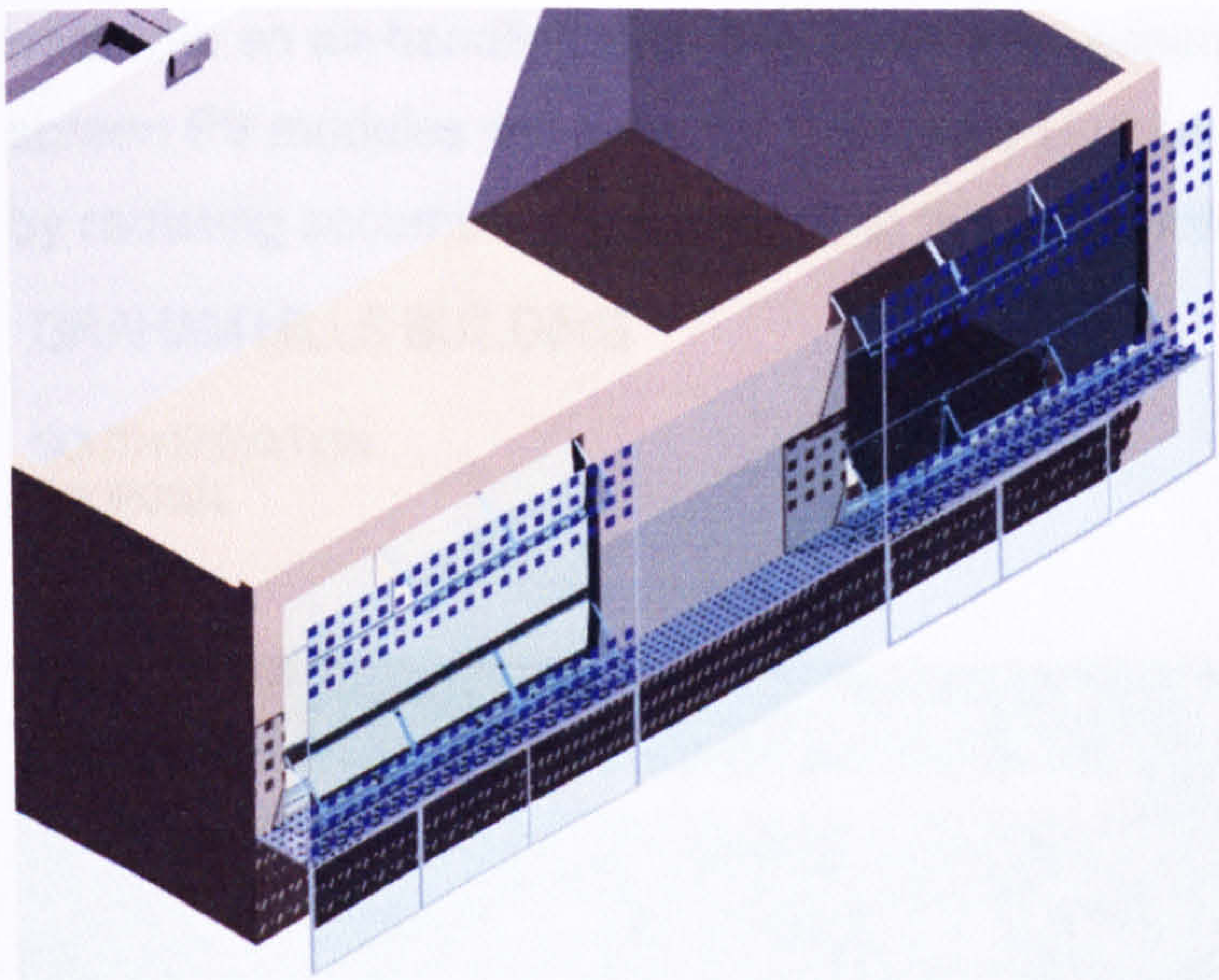


Fig. 4.9 First option for placing BIPV

The second option had the semi transparent BIPV panels placed in front of spandrel panels of the existing façade [Fig. 4.10]. Although this design option would leave most of the concrete panel exposed to direct sunlight and would not block the daylight from entering offices, the horizontal strips of BIPV would be in a strong contrast with the character of the existing façade, e.g. chess board formation of concrete panels, and was therefore also not regarded as an appropriate aesthetic solution.

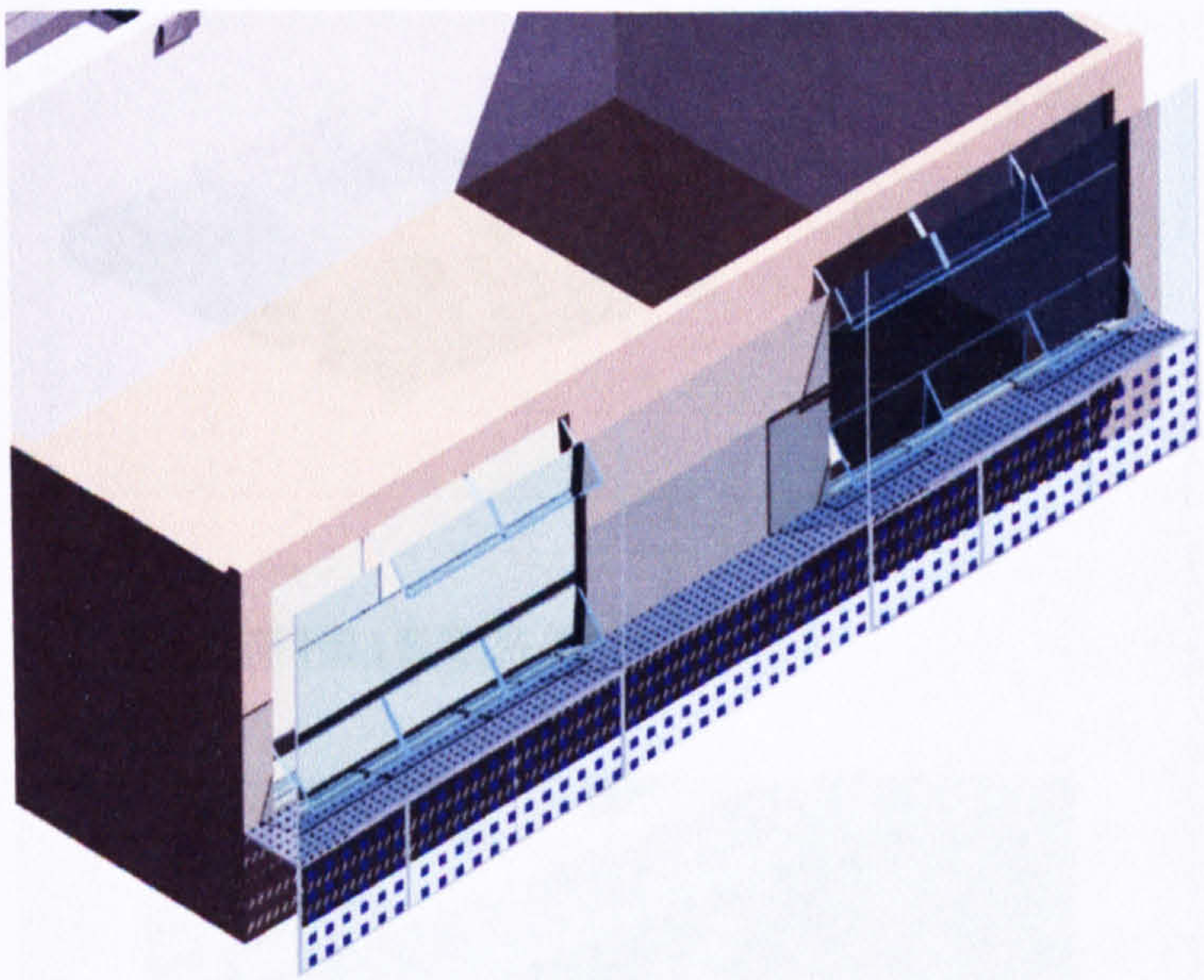


Fig. 4.10 Second option for placing BIPV

Another architectural proposal for the Graham Hills south facing façade includes integration of opaque, mono-crystalline PV modules as a ventilated rain-screen over-cladding system on a solid south wall, to the east of the main entrance to the building. The rain-screen PV system will have a ventilated cavity behind to eliminate potential for summer overheating. Here the application is not for PV hybrid [electrical-thermal] modules because of problems of linking generated heat with an air-handling unit. But, apart from generating electricity, the rain-screen PV modules will enhance the winter U-value level on the installation wall by radiating accumulated heat back to the wall behind.

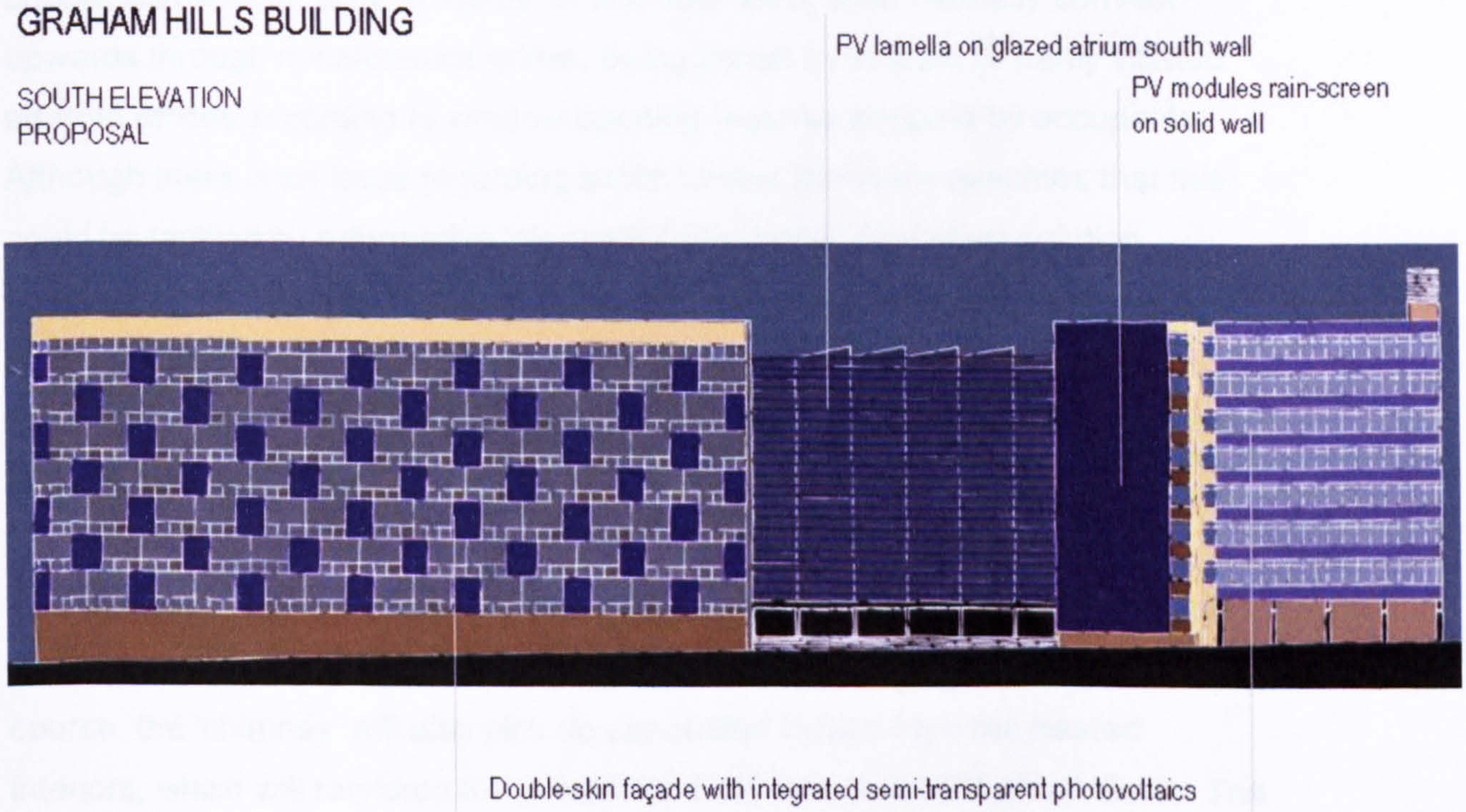


Fig. 4.11 Graham Hills building south elevation proposal

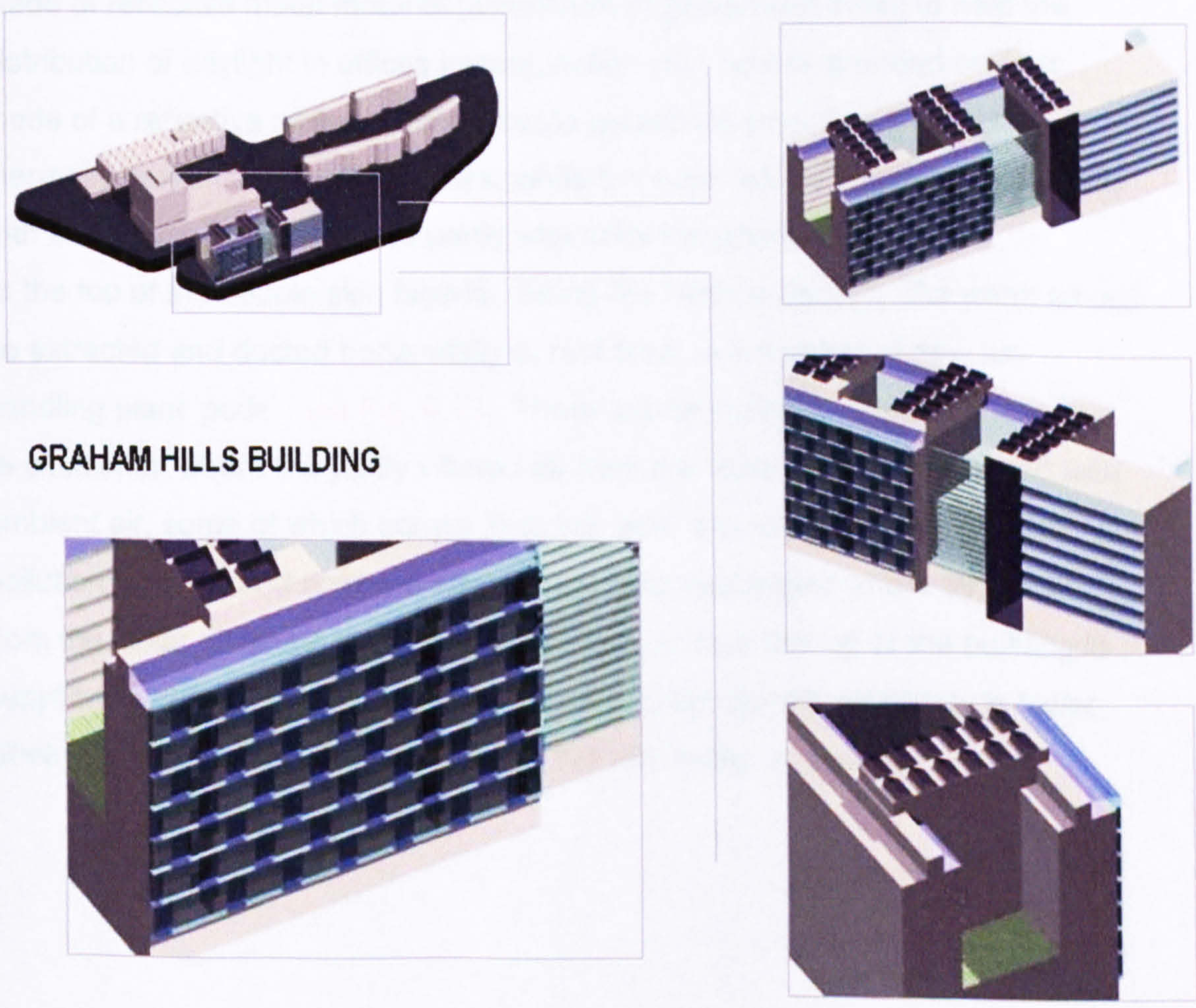


Fig. 4.12 Graham Hills building double skin façade 3D modelling [BIPV panels in front of existing concrete panels]

DOUBLE SKIN CONSTRUCTION WINTER MODE

The incoming cold ambient air will enter through partially open base of the double skin void or 'solar chimney' at first floor level, then naturally convect upwards through maintenance grilles, being joined by vitiated or partly vitiated air from offices according to window opening regimes adopted by occupants. Although there is an issue regarding traffic fumes, the study assumes that this could be tackled by reformative 'air quality' regulation. Any other solution architecturally, which conforms to the concept of maximising natural ventilation, would be impractical. However, it will be seen that the mixed mode solution adopted in both summer and winter simulation s prioritises air flow from offices into the 'solar chimney'.

The opaque parts of the façade, now well insulated externally, will act as solar absorbers and air will be further pre-heated as it passes behind PV panels. Of course, the 'chimney' will also pick up conducted losses from the heated interiors, which will reinforce the convected heat recovery through windows. The grilled walkways at each floor level will be initially modelled at sill level and be made of reflective metal material [aluminium or galvanized steel] to help the distribution of daylight in offices in conjunction with new suspended ceilings made of a reflective material. New double-glazed inner windows will have thermally-broken, slim metal frames; while the outer skin is single-glazed, partly with solar absorbing glass and partly with semi transparent PV panels.
At the top of the double skin façade, during the heating season, the warm air will be extracted and ducted horizontally at roof level to a number of new air-handling plant 'pods' [see Fig. 4.13]. There are two options: the first one is the re-circulation where the partly vitiated air from the 'solar chimney' is mixed with ambient air, some of which comes in at low level and will be prone to traffic pollution. The second option is an air-to-air heat exchanger where all the air from the 'solar chimney' is dumped and fresh air from the top of the building is supplied to offices. The first option is more efficient but the air quality is lower, while the second option is less efficient but with better air quality.

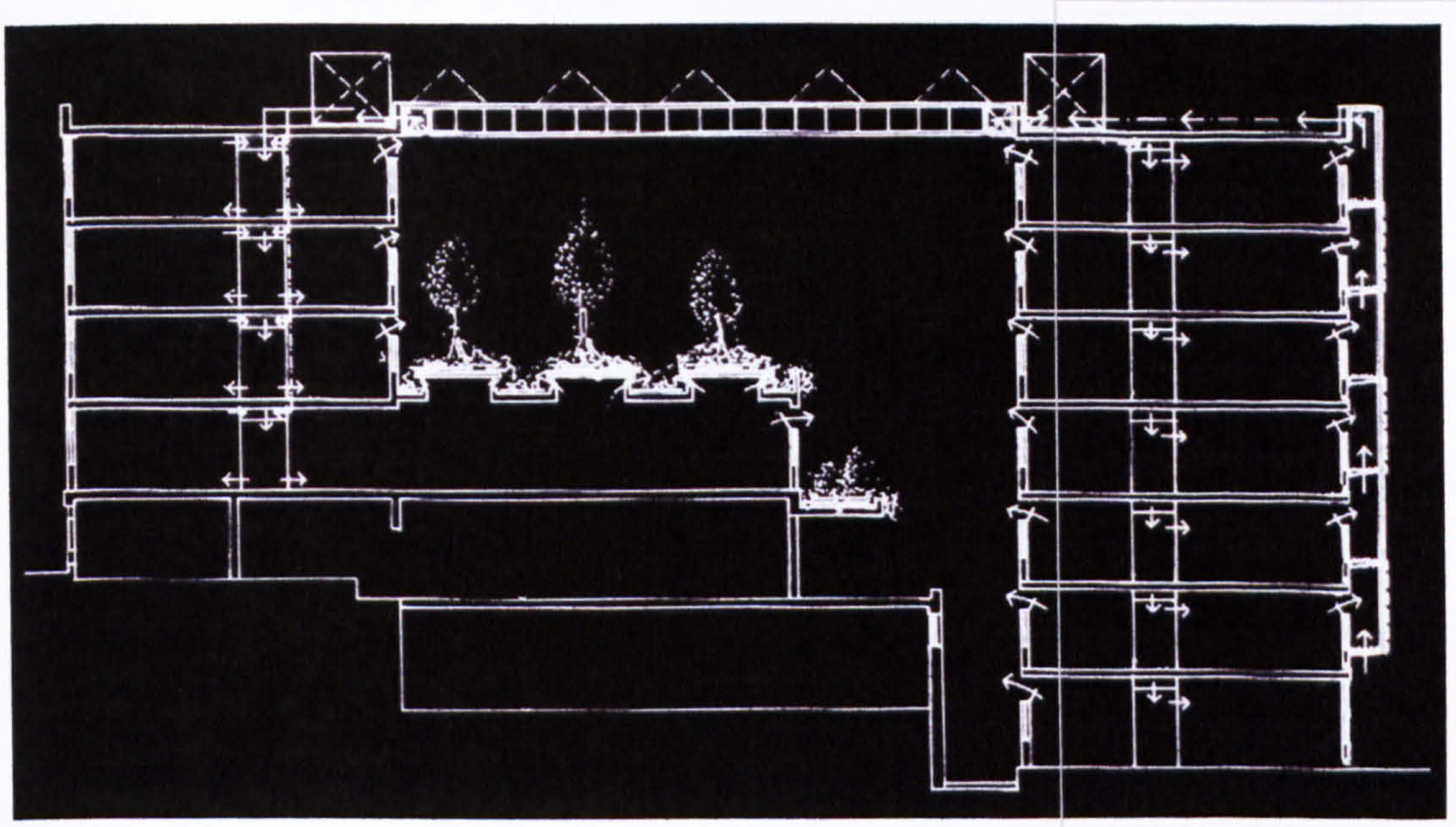


Fig.4.13 Graham Hills building winter energy diagram

Offices with the double skin façade

In the air-handling unit the pre-heated air will be passed through hot water coils and heated to 23°C [to test maximum, rather than minimum space heating needs]. New vertical shafts will transport the warm supply air down to horizontal ducts over corridors [i.e. above existing suspended ceilings]. This air, entering the corridor zone is then distributed to the office spaces on either side of the corridor and then back into the solar chimney through office windows [in the case of the south façade to George St]. There are two options for the air supply to offices. The first option [Fig. 4.14] is to supply air through a grill opening below ceiling level with a separate supply to corridor. The second option [Fig. 4.15] is to first supply air to corridor, in which case the corridor becomes a pressurised plenum, and then supplies air to offices through a grill opening below ceiling level. It is a design decision, the implications of which are most likely to be economic and acoustic – option two is cheaper and perhaps noisier for occupants in offices.

Suspended ceiling of textile material

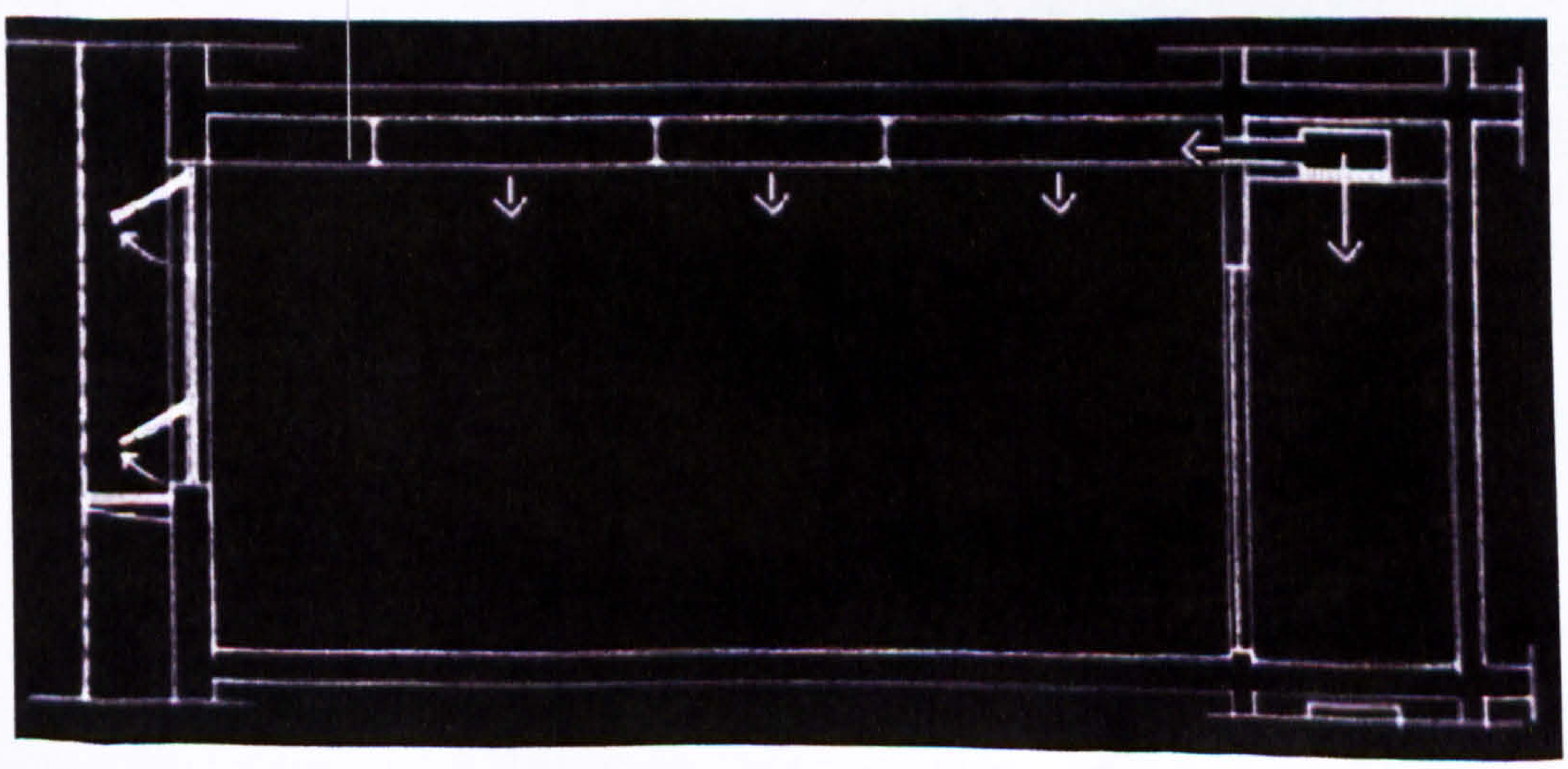


Fig. 4.14 Air supplied to offices from corridor side, first option

Suspended ceiling of textile material

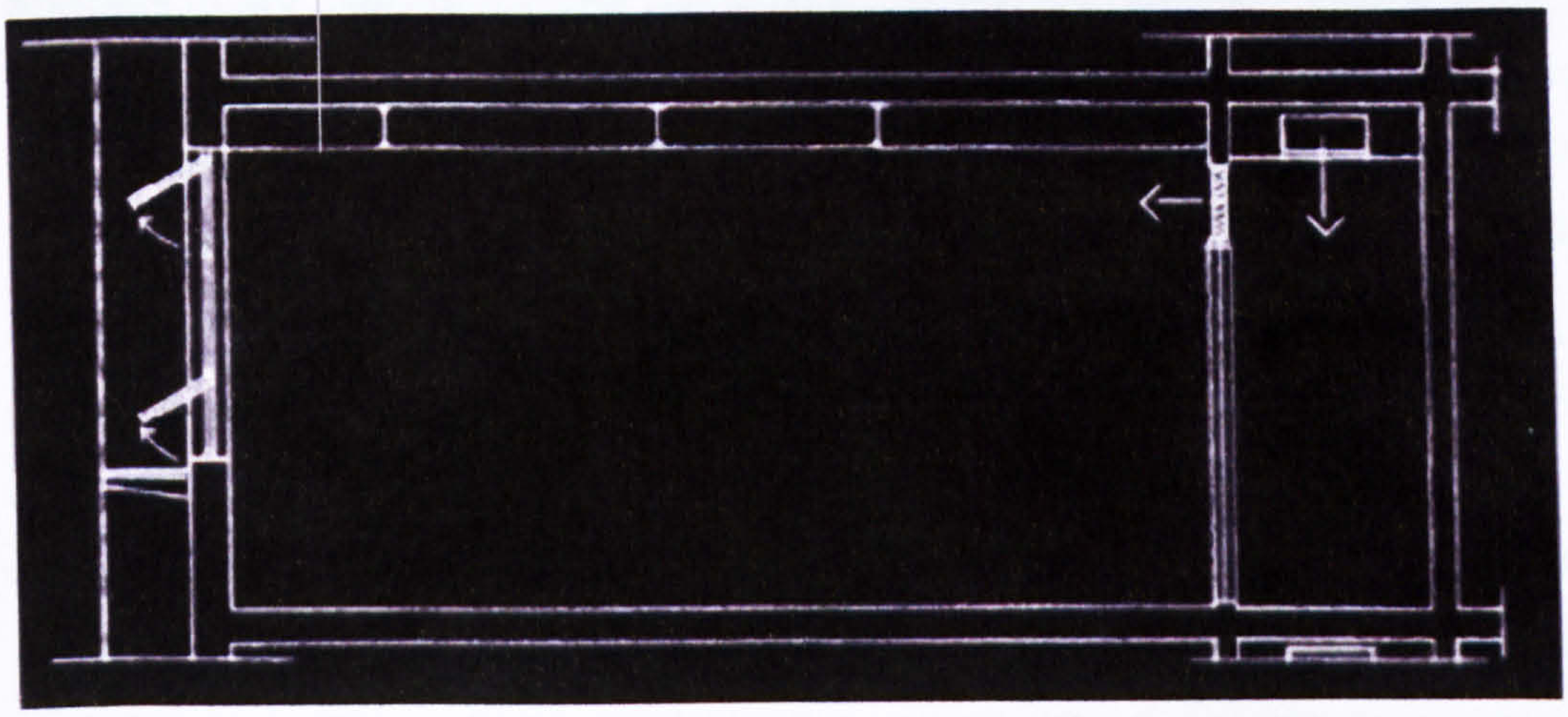
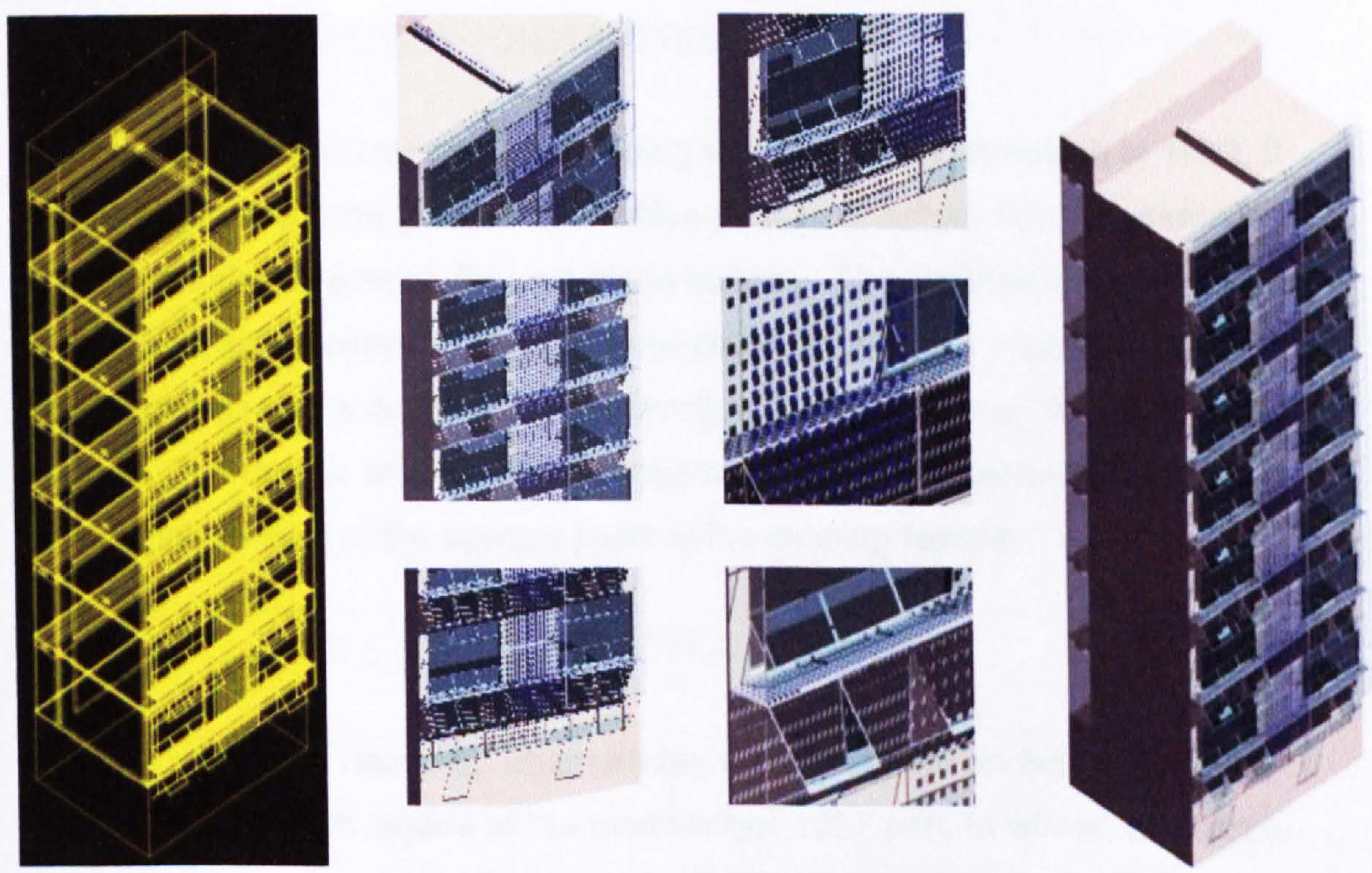


Fig. 4.15 Air supplied to offices from corridor side, second option

The semi transparent PV panels are modelled as frameless PV glass-glass laminates consisting of a front side 3mm clear hardened glass, PV cells, and backside 4mm glass. The cells are BP Solar Saturn mono-crystalline cells, 12.5cm x 12.5cm each, with an efficiency of 16.5%, and distance between cells 5cm. The total area of the semi transparent PV panels in front of each office is 280cm x 310cm. The electricity produced by the BIPV panels will be used to run fans distributing pre-heated-air, and any exceeding electricity for artificial lighting, and office computers.

The added glass façade in front of the existing façade will inevitably reduce the daylight level in the offices. The risk of compromising daylight is met partly by the glazing specification, partly by the new suspended reflective ceilings, and partly by new luminaires and switching, with better fine-tuning in term of control - e.g. modern venetian blinds within double glazing as proposed at Trondheim [Chapter 2, p. 81]. To avoid problems of contrast between the opaque cells and the transparent area between them, the backing of cells is white, and window frames are also white on the inside. Although there is much more 'active' sophistication in terms of heating, ventilation and lighting control, the user is also left with greater 'adaptive opportunity' [Baker and Standeven, 1995], to open and close office windows, manual light switching and regulation of brightness of lights.

The placement of furniture, especially computers, will have an effect on the energy use in offices. Encouraging computers being placed away from windows, in turn, discourages the over-zealous use of blinds, with compensatory over-use of luminaires. Daylight responsive lighting can also help in this regard. However, the computer energy simulation [presented in Chapters 5 and 6] cannot hope to address every user-influenced possibility. In general, 'adaptive opportunity' is seen to be essential to well-being of building users, but perverse application of such control can seriously compromise energy performance. Therefore, the position adopted in this research is to pragmatically accept the value of some occupancy interaction in the context of pragmatic design strategies. The purpose of later daylight modelling is to establish whether the obstruction of the outer skin can be addressed by means of surface geometry, colour and so forth to provide daylight distribution which is at least as good, if not better than the existing situation. Thus the modelling is restricted to a uniformly overcast sky and does not attempt to predict 'adaptive opportunity' scenarios, such as use of blinds.



DOUBLE SKIN SOLAR FAÇADE 3D MODELLING

Fig. 4.16 Graham Hills building double skin façade with semi-transparent BIPV, 3D modelling

DOUBLE SKIN CONSTRUCTION SUMMER MODE

In summer the upward flow of ambient air entering through bottom of the south façade grill opening will help to cool vertical PV modules [limiting reduction in their efficiency due to module high temperature] as well as the inner façade, before being exhausted at the top through openings, facilitating the increased flow rate compared with that in winter pre-heating mode. The air in each office will be warmed by internal gains [people, computers, and lighting], irrespective of variable solar heat. As warmed, the air will exit rooms through upper office window openings into the accelerated solar chimney. In the event that single sided ventilation into the solar chimney cannot avoid overheating in hot summer conditions, the option exists to use the mechanical air supply, described above for winter, to provide semi-active cooling. Offices can have a fresh supply of air from the corridor side through ambient air being sucked into the air-handling unit, passed over cool-water coils and distributed as in winter via ducts in corridor ceilings. Sun shading in the form of reflective blinds on the outside of the double glazed windows cavity [access from maintenance platforms], will serve to screen off unwanted solar gains and glare.

4.4.2 SOUTH ELEVATION [EXTENSION BUILT 1963]
DOUBLE SKIN CONSTRUCTION

The east wing of the Graham Hills Building was built as an extension in 1963. It has the same structural grid, an open office plan, and suffers from the same environmental problems as the rest of the building. The architectural proposal to tackle the existing problems includes over-cladding spandrel modules placed below windows and a double skin construction in front of former single glazed windows. The double skin construction will have parts with semi transparent BIPV panels in front of the opaque parts of the existing façade.

DOUBLE SKIN CONSTRUCTION WINTER MODE

This is in a sense a 'dead-leg' which invites a slight variant on the approach adopted for the south façade of the much larger 1957 part. In winter, the supply of air will now be directly pre-heated behind the second-skin glass. It will enter offices through high level opening windows, and due to stack-enhanced cross ventilation will enter the stair tower on the north side of the open plan office. The existing tower is at present partially enclosed and the proposal is that it be enclosed on all sides and its height extended creating a negative pressure at the top of the tower enhancing the vertical air movement.

DOUBLE SKIN CONSTRUCTION SUMMER MODE

In summer, the natural ventilation system will shift from south to north, and it is based on a cross ventilation of open plan offices, as more effective than single-sided ventilation. The ambient north-side air will enter through window openings on the stair tower [controlled by the Building Management System] and will cross-ventilate to the south side of the offices. When reaching the solar chimney, it will exit through upper windows and move upwards via stack-effect and again exit through glazed rooftop openings. The natural ventilation system proposed here is similar to the summer ventilation strategy of the BP Amoco building in Trondheim, Norway, where office doors are kept open to the north side of corridor and draw cold air from the corridor windows, using the solar façade cavity as an exhaust stack. However, since this building has been in operation, some overheating problems of the top floor offices have been experienced periods of summer overheating. When relying on the natural ventilation strategy, the expectation is that similar problems might be experienced within this part of the Graham Hills building. Therefore, a mixed mode ventilation strategy is suggested to overcome this problem and improve summer conditions in top floor offices.

The BP Amoco Solar Skin Building has other similarities with the case study building subject of this research. The building context is of a university campus, both retrofit projects on buildings of a similar age and using a double skin façade with building integrated photovoltaics as part of a holistic thermal and environmental improvement strategy. Also, both required a computer based thermal energy modelling to investigate the energy performance of buildings, especially the effect of the double skin façade on the space heating demand during the heating season, and the indoor thermal comfort in offices facing the double skin façade during the summer season. In both cases the double skin façade begins from the first floor upwards and is naturally ventilated with top and bottom openings. The effect that the double skin façade has on offices internal daylight conditions was also investigated in both buildings with modelling and analysis of the daylight factors.

Despite similarities, there are also differences between the two buildings. The first one is the different climatic characteristics of Trondheim and Glasgow. Trondheim has a further north geographic location from Glasgow and colder winters. A design difference is that the double skin in the Norwegian building is four stories high with 0.8m wide, while the case building in this research is seven stories high with 0.6m wide cavity. Another difference is the double skin cavity which, in case of the Norwegian building, is only a passive buffer, while the double skin façade investigated in this research has its passive heat recovery integrated with a mechanical ventilation system. There is also a difference in the cooling strategy during summer period between the two buildings. The building in Norway rely on cross ventilation between north oriented corridor and offices facing the double skin facade, by drawing fresh air through doors and corridor windows into offices. In case of the case study building in Glasgow, the summer cooling strategy rely on a mechanical supply of fresh air into offices from the corridor side, as the only solution as the corridor faces another row of offices on the north side. Finally, there is a different development of the daylight study from a similar starting point [to assess the effect of the double skin façade on the internal daylight level]. The daylight analysis undertaken in this research work goes further in assessing the daylight level to improve the quality of daylight distribution in offices by investigating various office design options.

The extensive energy performance modelling of the south façade refurbishment solution of a double skin façade with BIPV proposed on the Graham Hills building is presented in the following Chapter 5 and Chapter 6. Other architectural proposals for BIPV on Graham Hills building, such as BIPV in atria, façade over cladding, sun shading, etc. are presented in Appendix_A of this thesis. These proposals are based on building examples / findings of the literature review, and therefore there is no need for them to be subject to detailed analysis.

4.5 CHAPTER 4 REFERENCES

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GA Group, University of Strathclyde, *The Graham Hills Building Feasibility Study*, Glasgow, UK, University of Strathclyde, 1993.

5

TESTING THE DOUBLE SKIN FAÇADE SUMMER MODELLING

CHAPTER 5

TESTING THE DOUBLE SKIN FAÇADE SUMMER CRITICAL WEEK MODELLING

5.1 ENERGY MODELLING OF THE DOUBLE SKIN FAÇADE COMPONENT

The energy performance of the double skin façade component was tested with a detailed energy model developed in ESP-r, Environmental Systems Performance for research, [University of Strathclyde, 2000, p.2], a dynamic thermal modelling programme, and Radiance, a lighting and visualisation modelling programme. The thermal [including PV] and electrical, PV-electrical performance of the double skin solar façade were modelled in an integrated modelling approach, due to ability of the ESP-r to quantify the PV electrical power and the heat recovered by air flowing behind the modules as a function of the prevailing conditions [Kelly and Strachan, 2000, pp.2025-2027].

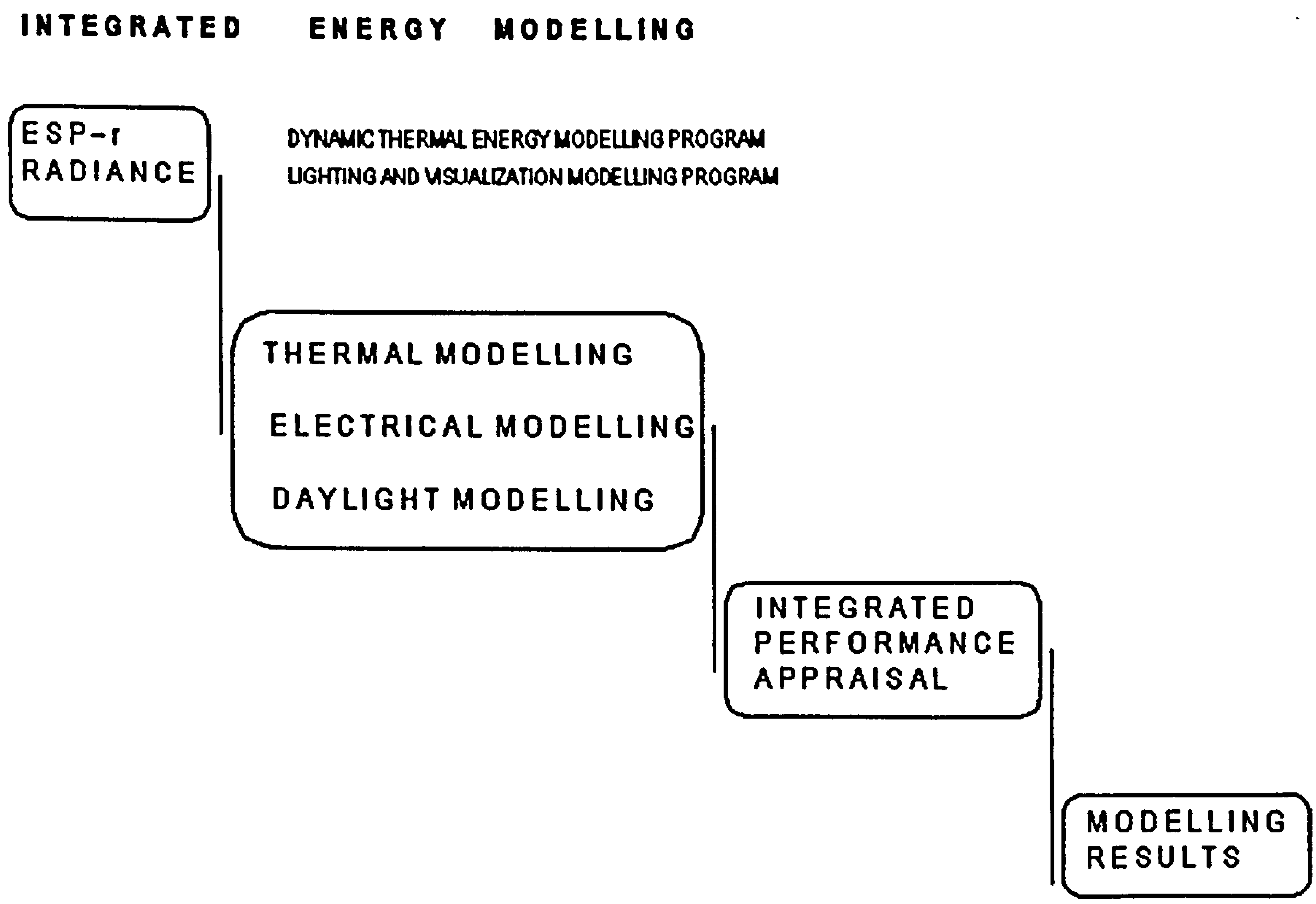

Fig. 5.1 Diagram of integrated energy modelling

The development of the [ESP-r] Environmental Systems Performance for research started as a prototype simulation tool in 1974 within the ABACUS unit at Strathclyde University and since has evolved to its present form through research programmes and contributions of various authors. Its growth is a result of the development over the years, supported by the Energy Simulation Research Unit [ESRU], formed in 1987 as part of the Strathclyde University, and through funded projects by the UK Science and Research Council and the European Commission DGXII Program [University of Strathclyde, 2000]. The programme is designed to run under UNIX operating system such as Linux and Solaris, and in this research the ESP-r was run under Linux version 6.2.

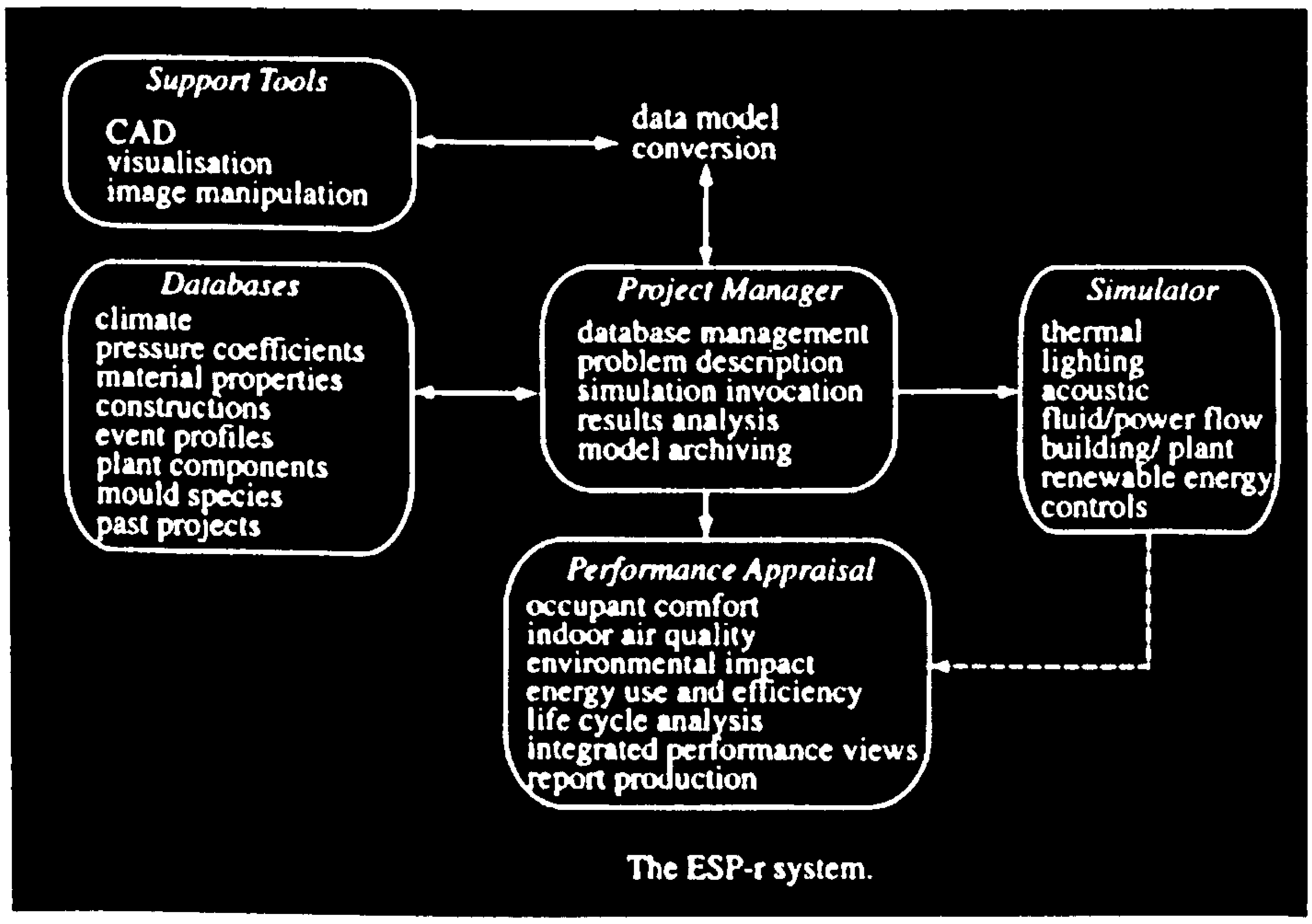

Fig. 5.2 The ESP-r system diagram

Source: Clarke J.A., *'Energy Simulation in Building Design'*. Butterworth-Heinemann, Oxford, UK. p. 355. 2001.

The ESP-r is a simulation system capable of modelling energy and fluid flows, combined with building and plant systems, constrained with various control systems. It also contains databases for climate, material properties, constructions, event profiles, and plant components. These help to reduce the information input load of the energy model and to some extent simplify the process of defining the model. An energy model in ESP-r consists of one or several zones defined with their geometry, construction, materials, and usage profiles. It also contains an air leakage distribution within the zones, defined as an air-flow network and a defined plant network connected to a specific control system.

The Project Manager plays an important part of the ESP-r program. It contains the energy model description with all zones, air-flow networks, plant networks and control systems, and also invoke simulation. The Simulator is part of the ESP-r that predicts building and plant energy/fluid flows by a rigorous mathematical model [University of Strathclyde, 2000]. The Simulator locates the simulation results in a database accessed by the Results Analyser, allowing a number of output options: graphs and tables, statistical analysis, etc. The three main modules, the Project Manager, the Simulator and the Results Analysis were used to investigate the energy performance of the energy model developed in this thesis.

5.1.1 CLIMATE DATA

The climate data selected for the model corresponds to the case study building's geographical location in Glasgow, and it is taken from the ESP-r climate database. It is based on a typical year climate data for Kew 1967, but modified for Glasgow with a longitude difference –4.10 and latitude 56.0. The climate data was analysed and a summer critical week was selected from 11th to 17th July with highest mid day temperature on 17th July of 27.7°C, [Fig. 5.3].

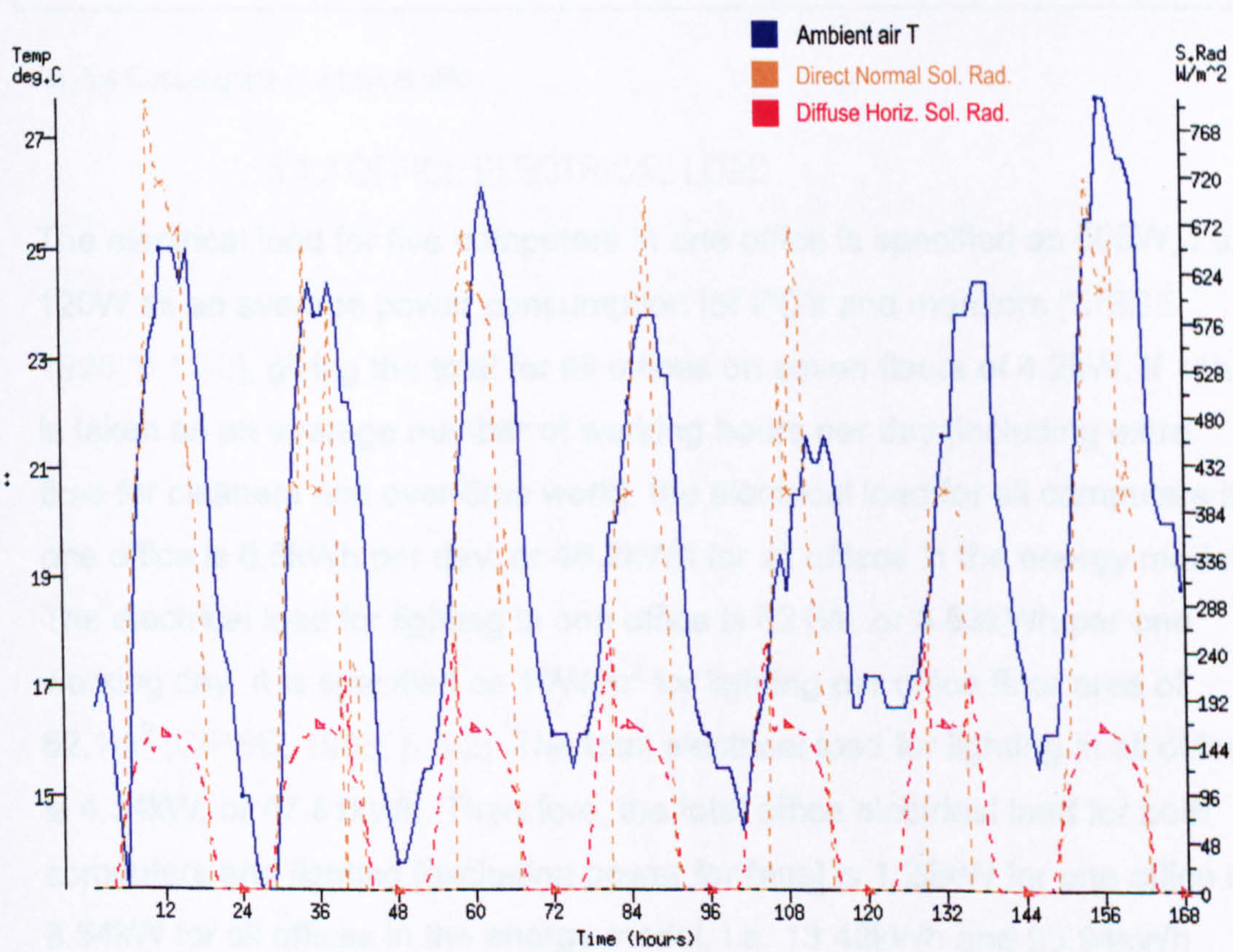

Fig. 5.3 Summer critical week [11th – 17th July] ambient air temperature, direct normal and diffuse horizontal solar radiation

Source: ESP-r climate database.

5.1.2 CASUAL GAINS

The typical office occupancy profile was set with weekdays Monday to Friday 9.00am to 6.00pm, and weekends Saturday and Sunday, without offices being used. There are five occupants in a 62.10m^2 office area, i.e. 12.4m^2 per occupant, four fluorescent lights, and five computers. The casual gains have been calculated for the level of occupancy and the simulation results have shown approximately 1.75kW of casual gains load per office during weekdays working hours and zero during weekdays, when the office is not occupied [assuming the lights and computers will be switched 'off' during weekends]. It may be noticed that the scenario for casual gains is consciously extreme in order to test for a 'worst case'. In reality, especially during sunny days in summer, it would be reasonable to expect the lighting load to be minimised if not zero.

	Period	Sensible Heat	Latent Heat	Radiant Convective [fraction]
Equipment [W]	9.00-18.00	625	0.0	0.3 / 0.7
Lights [W/m^2]	9.00-18.00	10.00	0.0	0.5 / 0.5
Occupants	9.00-18.00	500	200	0.5 / 0.5

Fig. 5.4 Casual gains in a typical office

5.1.3 OFFICE ELECTRICAL LOAD

The electrical load for five computers in one office is specified as 600W, i.e. 120W as an average power consumption for PC's and monitors [CIBSE, 1998, p.11-2], giving the total for all offices on seven floors of 4.2kW. If 11h is taken as an average number of working hours per day [including extra time for cleaners and over-time work], the electrical load for all computers in one office is 6.6kWh per day, or 46.2kWh for all offices in the energy model. The electrical load for lighting in one office is 621W, or 6.83kWh per one working day. It is specified as 10W/m^2 for lighting per office floor area of 62.1m^2 [CIBSE, 1998, p.8-2]. The total electrical load for lighting in all offices is 4.34kW, or 47.81kWh. Therefore, the total office electrical load for both computers and lighting [excluding power for fans] is 1.22kW for one office or 8.54kW for all offices in the energy model, i.e. 13.42kWh and 93.94kWh respectively. Again, in bright summer conditions and new energy-efficient efficient lighting systems, one would hope that the electrical load would fall well below this value.

5.1.4 AIR-FLOW NETWORKS

Elaborated air-flow networks were developed to represent various options of the air movement between all zones in the energy model. An air-flow network in ESP-r describes the air infiltration level through all openings and cracks between the exterior and the interior, and ventilation level between zones in the interior. The ESP-r air-flow network is composed of three basic constituents: nodes, connecting components and inter-nodal connections. Nodes are points in the network where the pressure is calculated. They are connected together by the components to form the flow network. Connecting components describe the flow characteristics between flow nodes. Those used in the air-flow network are: window openings and cracks on the double skin, window openings and cracks on office wall, maintenance grill openings and cracks allowing air to convect upwards between double skin zones, door openings between corridor and offices, and ducts for supply air to air-handling unit and ducts from corridor side to offices. Inter nodal connections are defined in terms of linking one node to another via a specific component. The height of the connection inlet and outlet relative to the nodes it connects is required for the calculation of stack effect on network flow. In the air-flow of the energy model the height of the connections between nodes in the double skin zone on different floors has been taken into account to represent the stack effect in the seven storey high double skin.

The summer critical week thermal performance of the Graham Hills building was tested with seven air-flow network models representing various model options, as shown in [Fig. 5.5].

MODELS	Office low wdws	Office upper wdws	Skin top/down	Skin wdws	Casual Gains	AH_unit to Corridor_Air	Corrid_air_supply to Offices	Controls
M1 'As existing' no double skin Option A	closed	closed	n/a	n/a	yes	no	no	no
M1 'As existing' no double skin Option B	closed	open	n/a	n/a	yes	no	no	no
M1 'As existing' no double skin Option C	open	open	n/a	n/a	yes	no	no	no
M2 'Improved' no double skin Option A	closed	closed	n/a	n/a	yes	no	no	no
M2 'Improved' no double skin Option B	closed	open	n/a	n/a	yes	no	no	no
M2 'Improved' no double skin Option C	open	open	n/a	n/a	yes	no	no	no
M3 with double skin	closed	closed	closed	closed	yes	no	no	no
M4 Option A with double skin	closed	closed	open	1 and 7 open	yes	no	no	no
M4 Option B with double skin	closed	closed	open	all open	yes	no	no	no
M5 with double skin	closed	open	closed	closed	yes	no	no	no
M6 with double skin	open	open	open	closed	yes	no	no	no
M7 with double skin	closed	open	open	1 and 7 open	yes	yes @ 20C	yes	yes

Fig. 5.5 Summer critical week air flow network model options

5.1.5 SURFACES IN ZONES

The energy model developed in ESP-r represents a segment of the Graham Hills case study building in the middle of the south facing façade. The energy model consists of zones representing offices on each floor, the double skin façade with BIPV, the pre-heat zone [the zone at the top of the double skin façade], the air handling unit zone, and the corridor air supply ducts to offices zone [Fig. 5.6].

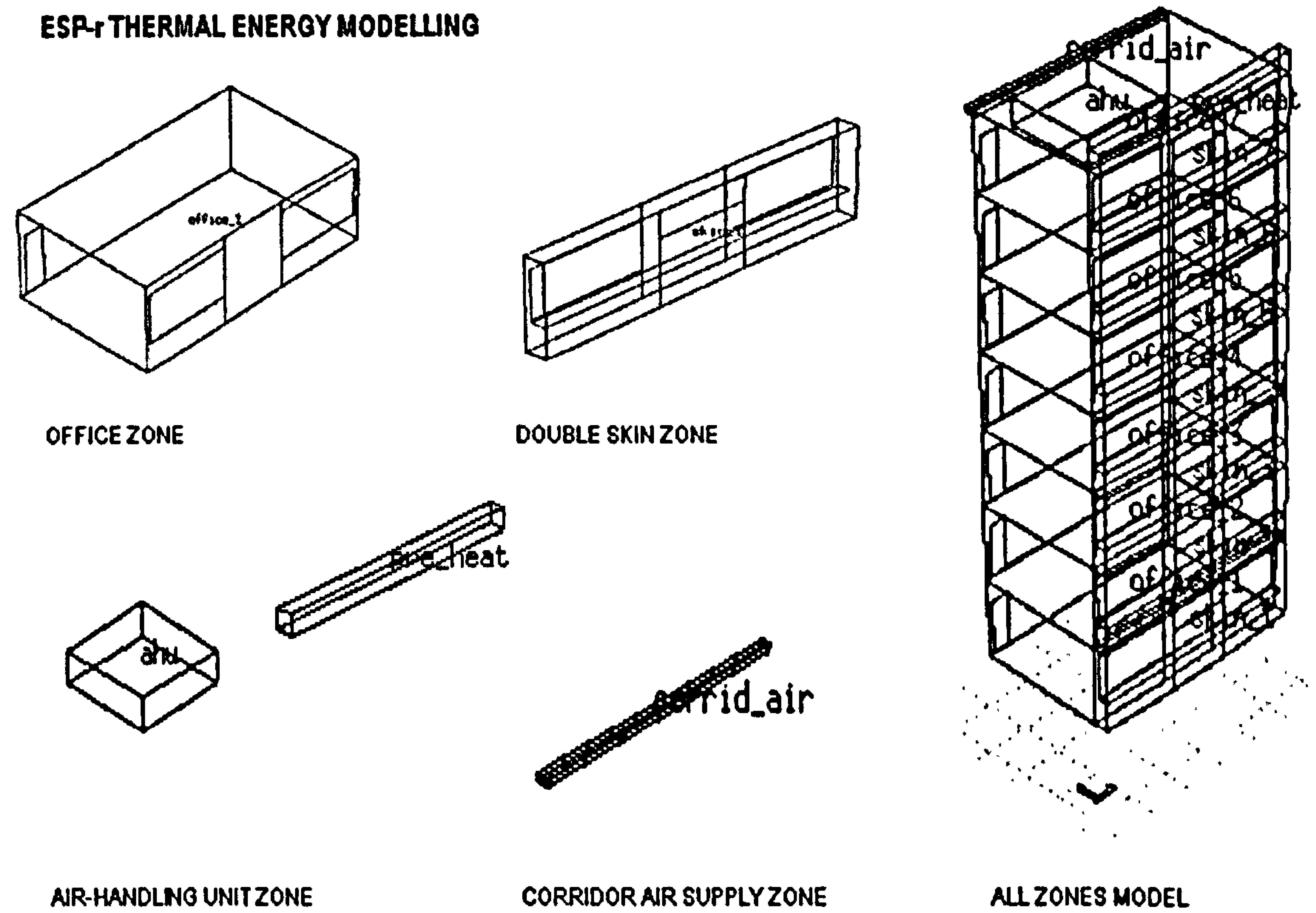

Fig. 5.6 M3 to M7 models zones

SOLAR OFFICE ZONE

The office zone of the ESP-r model represents the typical office of the Graham Hills Building. The zone model was developed in several stages. The first stage was to create the office geometry, 10.35m wide, 6.0m deep and 3.1m high. The external south-facing office wall has two windows, each 3.6m wide and 1.9m high with lower and higher level openings 0.4m high. Below windows are two spandrel panels, 1.0m high and 3.77m wide each, and between the windows is a concrete panel, 3.1m high and 2.8m wide.

The second stage was to create surfaces and assign surface materials for internal partition walls, ceiling, floor, spandrels, door, windows and concrete panel. The multi-layered constructions were created from selected materials within ESP-r construction composites and construction materials databases. The thermal and optical properties of the materials were taken from the materials and optical properties database within the ESP-r. They are representing the non-refurbished option with poor thermal properties [Model M1] of the typical office, and refurbished option with improved insulation and higher energy performance windows of the typical office [Models M2 to M7]. The following is the description of surface attributes for each surface in corresponding models.

SURFACES IN MODEL
M1 'AS EXISTING' [non refurbished]
WITHOUT DOUBLE SKIN FACADE

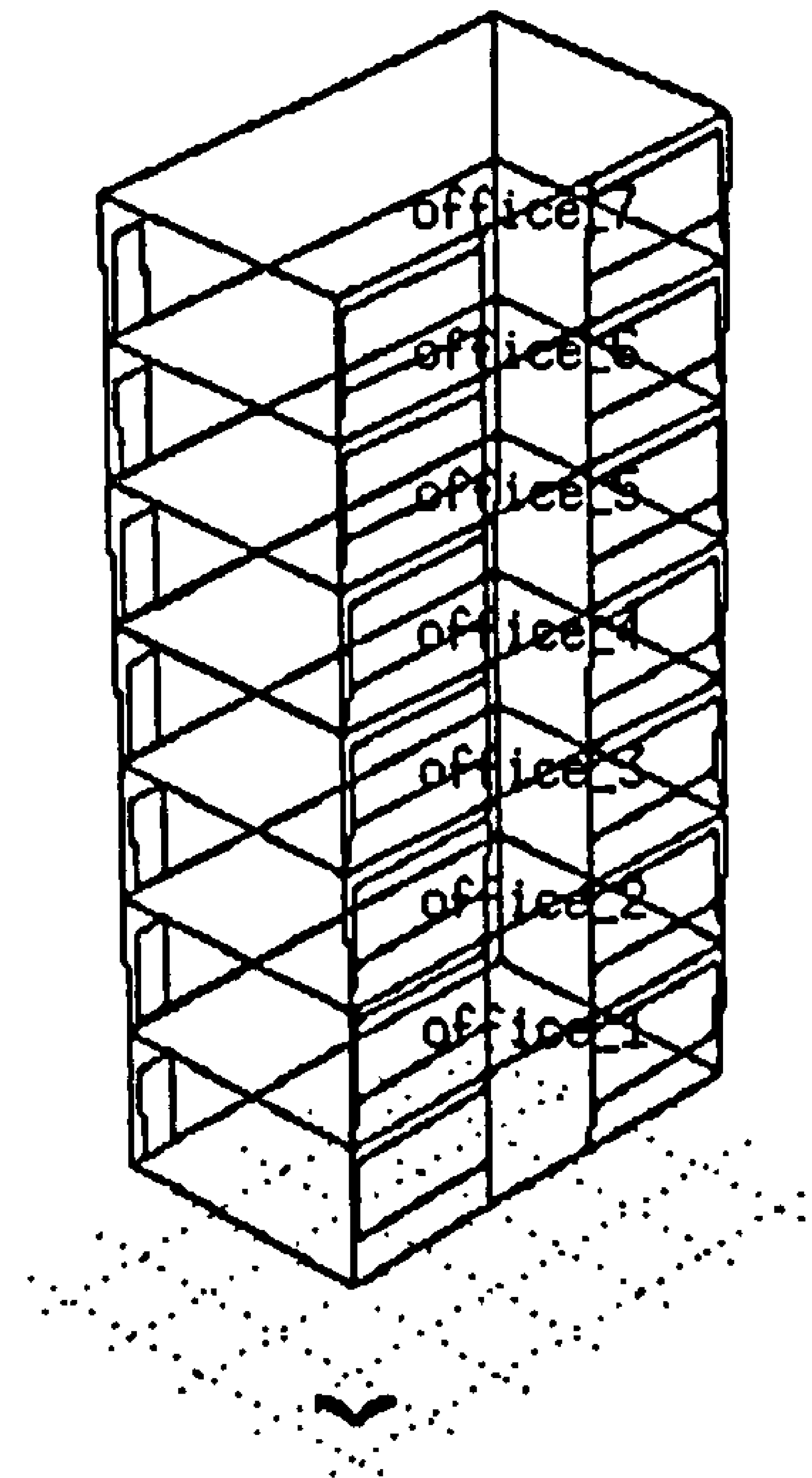

Fig. 5.7 ESP-r model
without double skin facade

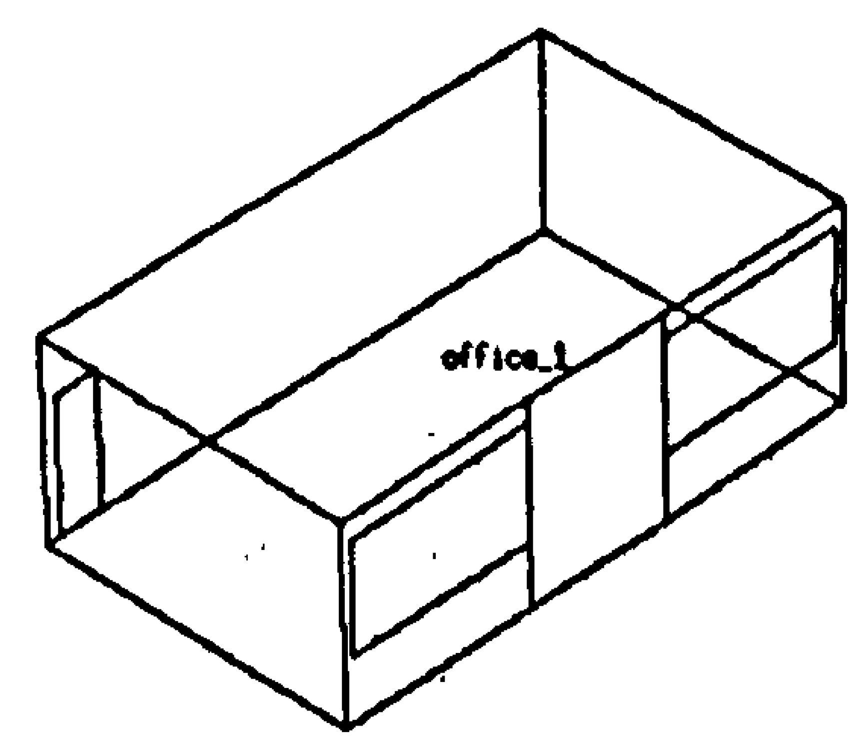

Fig. 5.8 The office zone

1. Spandrel panels [two]

Area: 5.40m^2 each

U-value = 1.48W/Km^2

Environment: external

2. Concrete panel

Area: 8.68m^2

U-value = 1.48W/Km^2

Environment: external

3. Office windows [two]

Area: 6.30m^2 each

Construction: single-glazed windows

U-value: 5.44W/Km^2

Environment: external

4. Corridor partition wall

Area: 30.40m^2

U-value: 0.77W/Km^2

Environment: Constant temperature of 18°C [static boundary conditions]

5. Partition wall [west and east]

Area: 18.60m^2

U-value: 0.77W/Km^2

Environment: identical on other side – office [similar boundary conditions]

6. Floor

Area: 62.10m^2

U-value = 0.75W/Km^2

Environment: ceiling in zone below

7. Corridor door

Area: 1.68m^2

U-value: 1.78W/Km^2

Environment: Constant temperature of 18°C [static boundary conditions]

8. Roof

Area: 62.10m^2

U-value: 1.48W/Km^2

Environment: exterior

SURFACES IN MODEL
M2 'IMPROVED' [refurbished option]
WITHOUT DOUBLE SKIN FACADE

1. Spandrel panels [two]

Area: 5.40m^2 each

U-value = 0.33W/Km^2

Environment: double skin zone

2. Concrete panel

Area: 8.68m^2

U-value = 0.33W/Km^2

Environment: double skin zone

3. Office windows [two]

Area: 6.30m^2 each

Construction: double-glazed windows

U-value: 2.78W/Km^2

Environment: double skin zone

4. Corridor partition wall

Area: 30.40m^2

U-value: 0.77W/Km^2

Environment: Constant temperature of 18°C [static boundary conditions]

5. Partition wall [west and east]

Area: 18.60m^2

U-value: 0.77W/Km^2

Environment: identical on other side – office [similar boundary conditions]

6. Floor

Area: 62.10m^2

U-value = 0.75W/Km^2

Environment: ceiling in zone below

7. Corridor door

Area: 1.68m^2

U-value: 1.78W/Km^2

Environment: Constant temperature of 18°C [static boundary conditions]

8. Roof

Area: 62.10m^2

U-value: 0.33W/Km^2

Environment: exterior

SURFACES IN MODELS
M3 to M7
WITH DOUBLE SKIN FACADE

1. Spandrel panels [two]

Area: 5.40m^2 each

U-value = 0.33W/Km^2

Environment: double skin zone

2. Concrete panel

Area: 8.68m^2

U-value = 0.33W/Km^2

Environment: double skin zone

3. Office windows [two]

Area: 6.30m^2 each

Construction: double-glazed windows

U-value: 2.78W/Km^2

Environment: double skin zone

4. Corridor partition wall

Area: 30.40m^2

U-value: 0.77W/Km^2

Environment: Constant temperature of 18°C [static boundary conditions]

5. Partition wall [west and east]

Area: 18.60m^2

U-value: 0.77W/Km^2

Environment: identical on other side – office [similar boundary conditions]

6. Floor

Area: 62.10m^2

U-value = 0.75W/Km^2

Environment: ceiling in zone below

7. Corridor door

Area: 1.68m^2

U-value: 1.78W/Km^2

Environment: Constant temperature of 18°C [static boundary conditions]

8. Roof

Area: 62.10m^2

U-value: 0.33W/Km^2

Environment: exterior

One should have in mind that the Graham Hills building as a University building would be likely to keep refurbishment costs as low as possible.

Therefore, the U-values of 0.33W/Km^2 for external walls and 2.78W/Km^2 for office windows are modest. However, when the dynamic enhancement of the outer skin is allowed, the performance is expected to be significantly better then these U-values would indicate.

The double skin zone model was developed following a similar procedure as for the typical office zone. The double skin zone consists of surface materials with thermal and optical properties representing the single glazed vertical glass panels, the semi transparent PV panels embedded in the middle part of the façade, set forward 0.6m from the existing façade concrete frame structure, and the grill walkway of reflective aluminium placed 0.9m above floor level.

DOUBLE SKIN ZONE

1. Single-glazed vertical glass panels [two]
Area: 11.70m^2 each
Construction: 6.0mm anti-sun glass
U-value: 5.44W/Km^2
Environment: exterior

2. Transparent BIPV panel
Active area of PV cells: 6.62m^2
Area of clear glass between PV cells: 2.05 m^2
Construction: 4.0 mm clear float glass
0.1 mm EVA + PV [mono-crystalline cells]
4.0 mm clear float glass
U-value: 5.31 W/Km^2
Environment: exterior

3. Maintenance grill
Area: 6.21m^2
Construction: 3.0mm galvanised metal
U-value: 5.62W/Km^2
Environment: double skin zone

PRE-HEAT ZONE [top of the double skin façade]
Area: 6.21m^2
Construction: all surfaces 6.0mm anti-sun glass
U-value: 5.44W/Km^2
Environment: exterior

CORRIDOR DUCT ZONE

All surfaces made of 3.0mm aluminium

U-value: 5.62W/Km^2

Environment: Constant temperature of 20°C

[static boundary conditions]

AIR HANDLING UNIT ZONE

Area: 20m^2

U-value: 5.62W/Km^2

Environment: Exterior

5.2 SUMMER CRITICAL WEEK THERMAL MODELLING

5.2.1 MODEL 1

'AS EXISTING'

NO DOUBLE SKIN FACADE

Model M1 represents the existing building with poor thermal properties of the external wall and roof [U-value = 1.48W/Km^2], and single-glazed windows, U-value = 5.44W/Km^2 Three options of the air-flow networks were tested. The first one, Option A, is the 'worst case scenario' where all office windows are closed and no natural ventilation is allowed, only background infiltration through crack openings in windows. The second one, Option B, had upper office windows open, to investigate the effect of natural ventilation on office temperature. The third one, Option C, had upper and lower office windows open, to investigate the effect of maximised natural ventilation on office temperatures.

Option A summer critical week simulation results [Fig. 5.9] have shown extreme peak mid-day temperature in offices between 40°C and 45°C. Temperatures on the 4th and 5th day are somewhat lower due to exclusion of casual gains during weekends, and coincidentally, somewhat lower ambient temperature. Also, temperature of Office_7 has lower temperature compared to other offices as a result of the top floor location with poor thermal properties of the roof and more surface area exposed to ambient conditions.

[Option B] results [Fig. 5.10] have shown that although very high peak mid-day temperature in offices is still evident, maximum levels are lowered by some 2-3K. Option C with all office windows open [Fig. 5.11], showed very little difference compared with Option B.

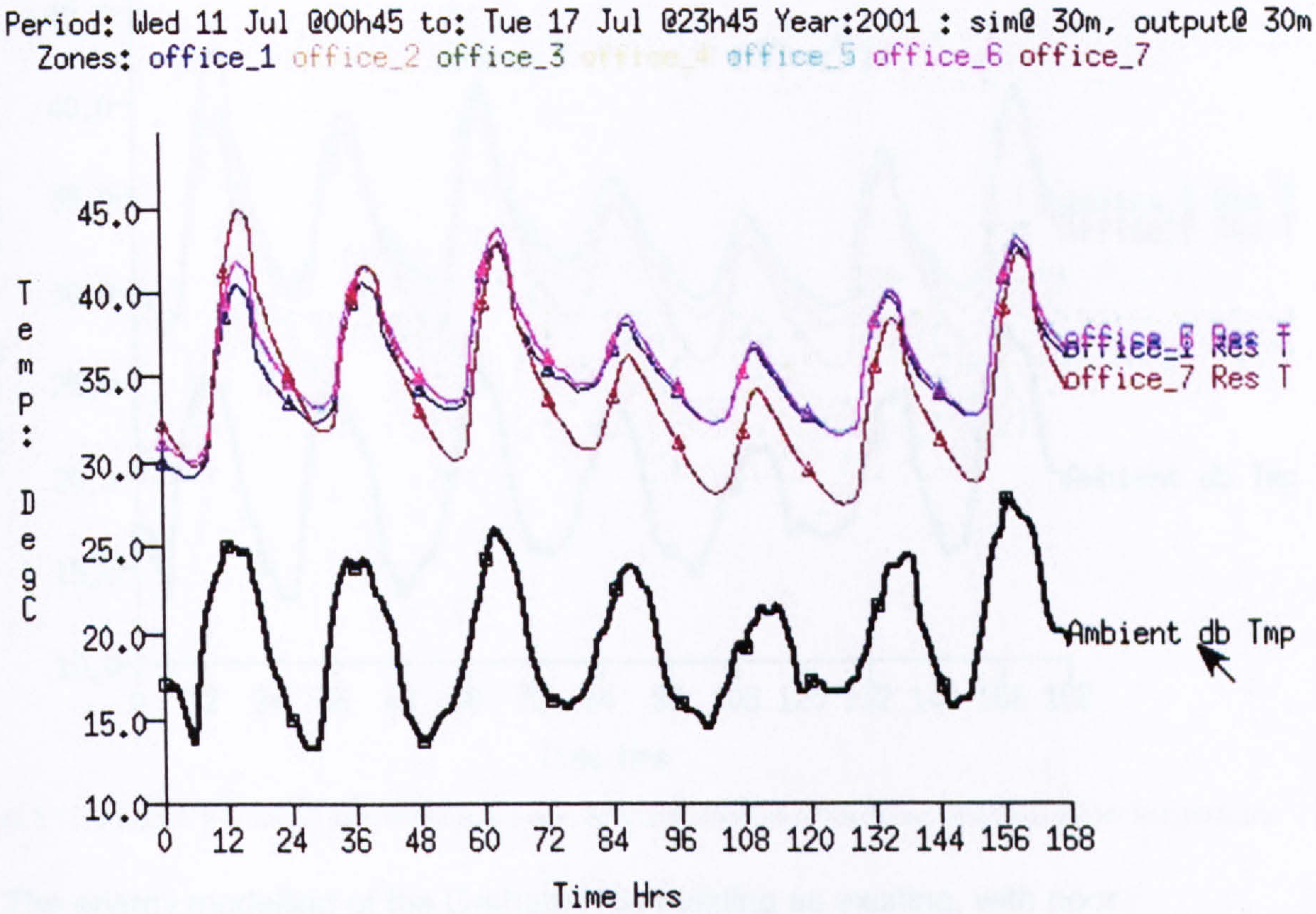

Fig. 5.9 M1model [Option A] summer critical week, temperature in all office zones and ambient air temperature.

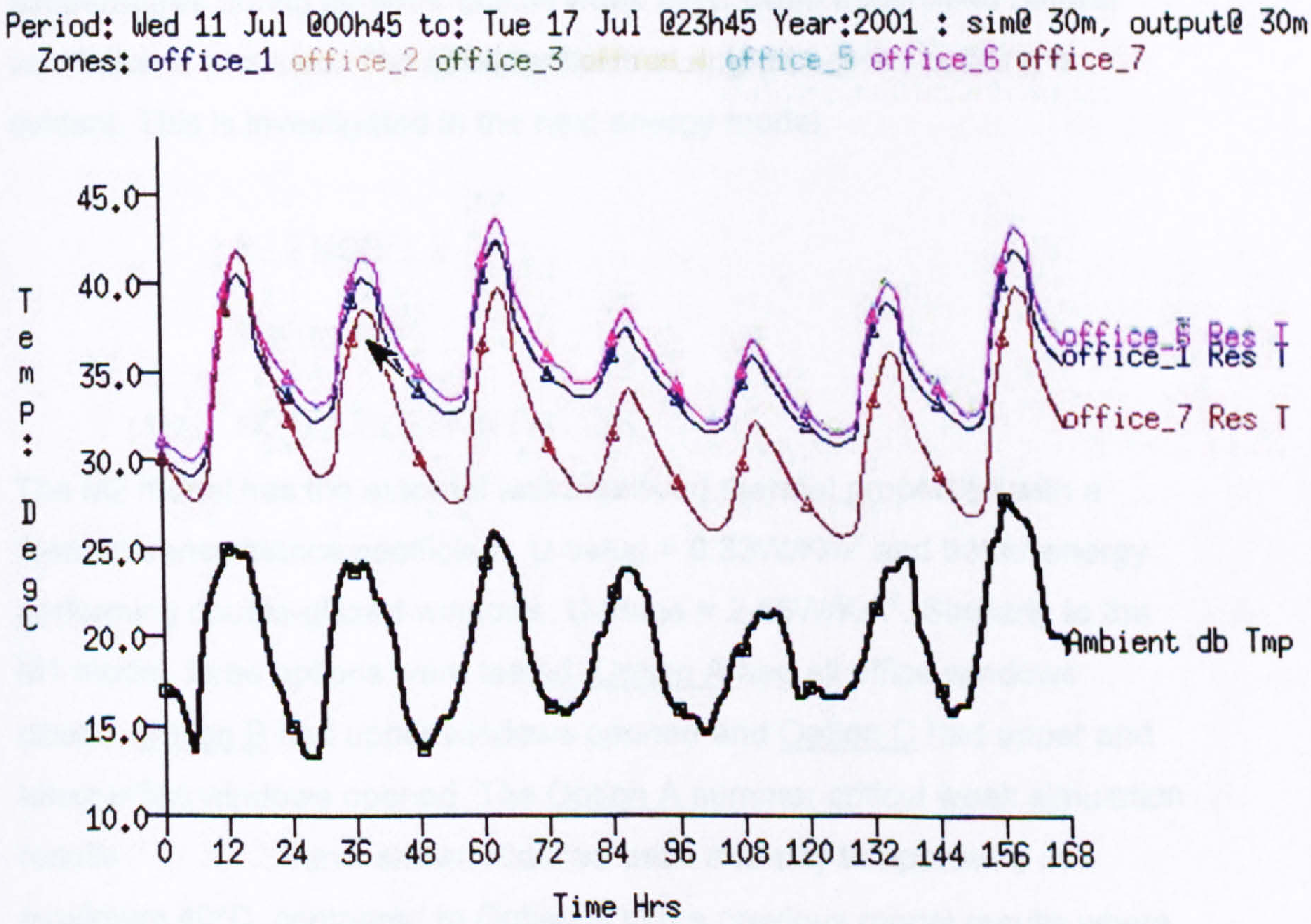

Fig. 5.10 M1model [Option B] summer critical week, temperature in all office zones and ambient air temperature.

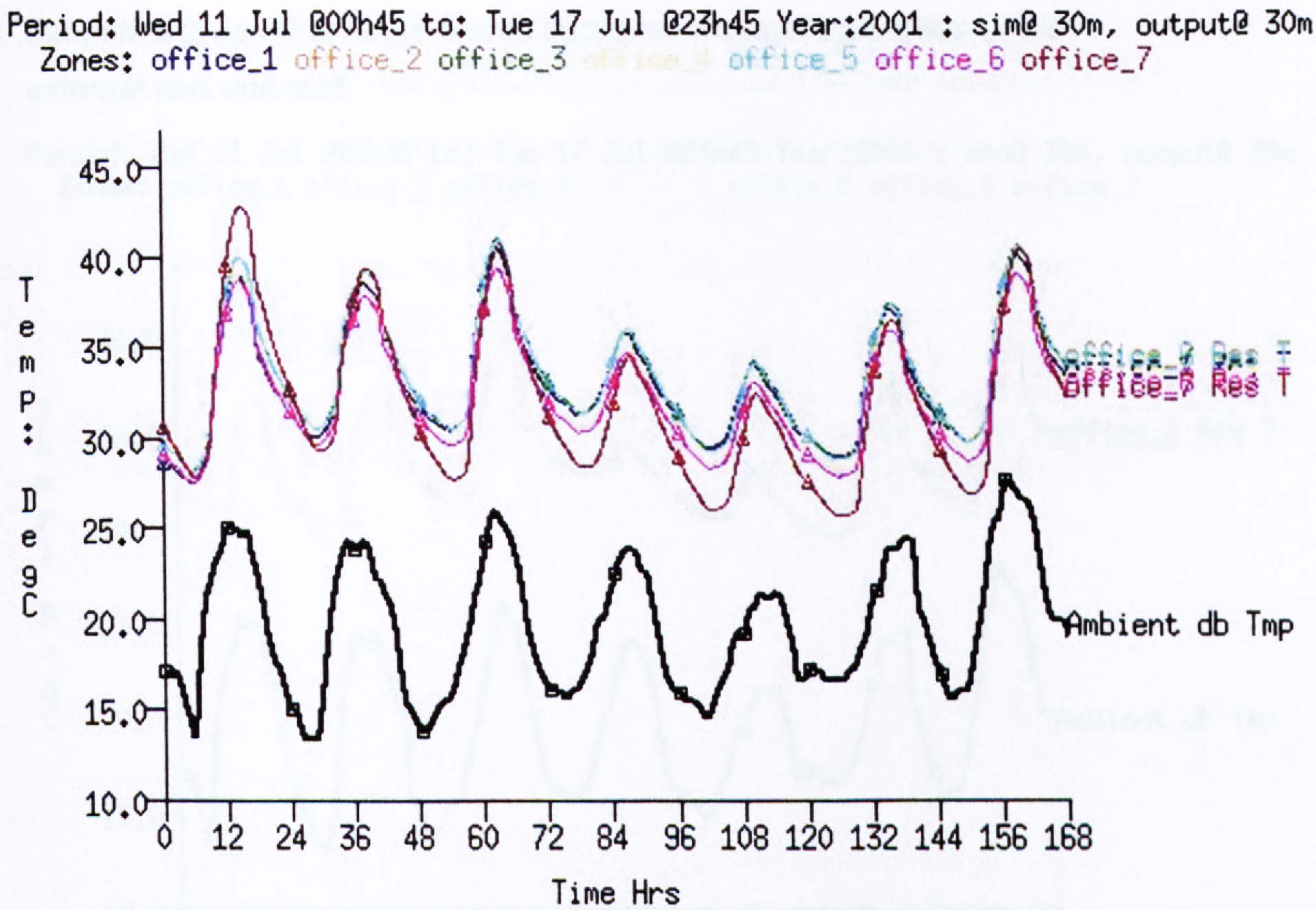

Fig. 5.11 M1model [Option C] summer critical week, temperature in all office zones and ambient air temperature.

The energy modelling of the Graham Hills building as existing, with poor thermal properties of the external envelope has shown very high office temperatures during summer critical week even when maximised natural ventilation is provided. The need for thermal upgrade of the building is evident. This is investigated in the next energy model.

5.2.2 MODEL 2

'IMPROVED'

NO DOUBLE SKIN FACADE

The M2 model has the external wall improved thermal properties with a thermal transmittance coefficient, U-value = 0.33W/Km^2 and better energy performing double-glazed windows, U-value = 2.56W/Km^2. Similarly to the M1 model, three options were tested. Option A had all office windows closed, Option B had upper windows opened and Option C had upper and lower office windows opened. The Option A summer critical week simulation results [Fig. 5.12] have shown reduced peak mid-day temperature of maximum 40°C, compared to Option A of the previous model results where maximum peak mid-day temperature in offices reached 45°C [Fig. 5.9 compared to Fig. 5.12]. Also, the top-floor office has now same internal temperature as other floors due to improved thermal properties of the external wall and roof.

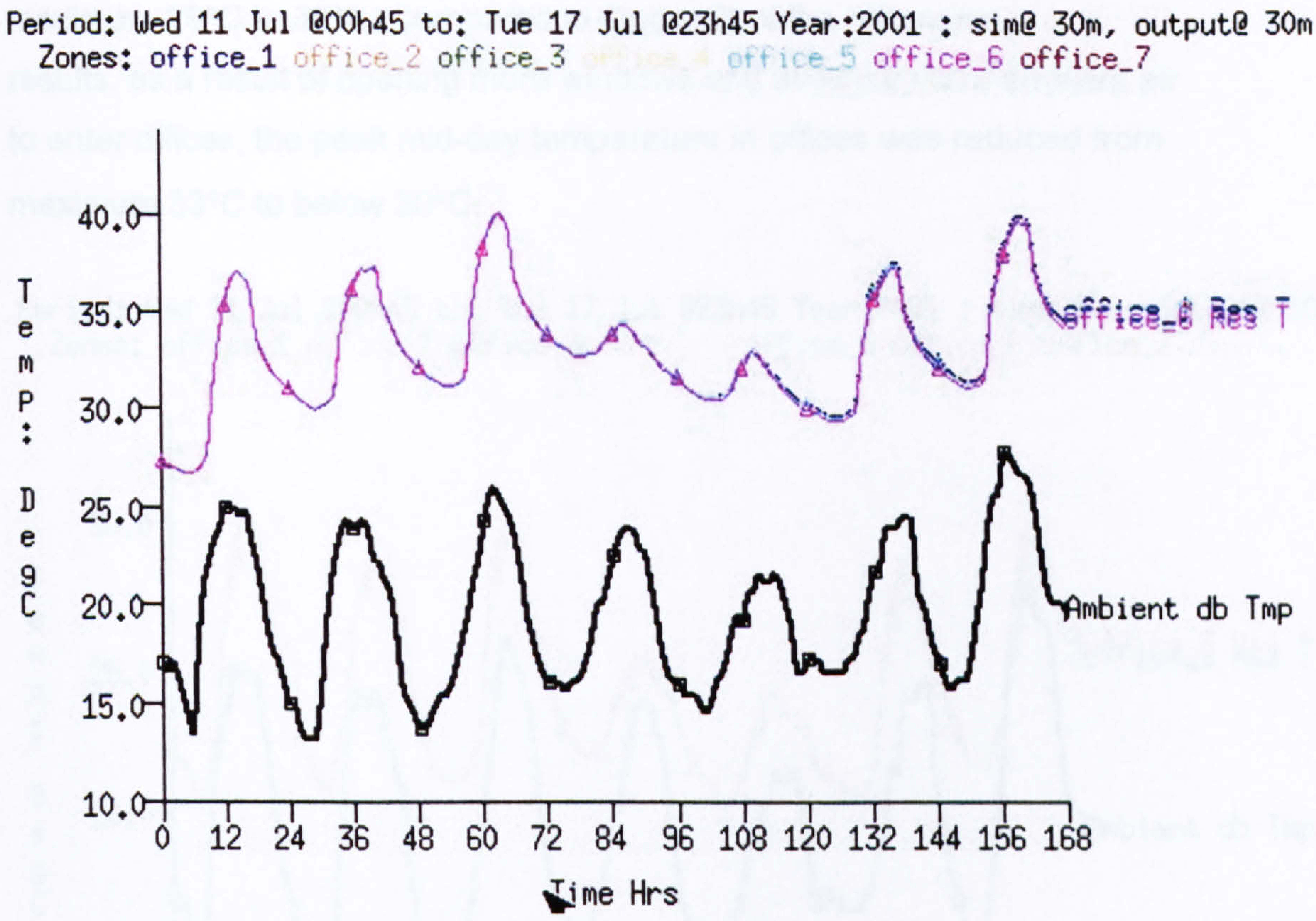

Fig. 5.12 M2model [Option A] summer critical week, temperature in all office zones and ambient air temperature.

With upper office windows opened, [M2 model Option B], peak mid-day temperature was reduced to maximum 33°C which compares to office temperatures of just above 40°C in the corresponding model without thermal improvement of the building fabric [Fig. 5.13 compared to Fig. 5.10].

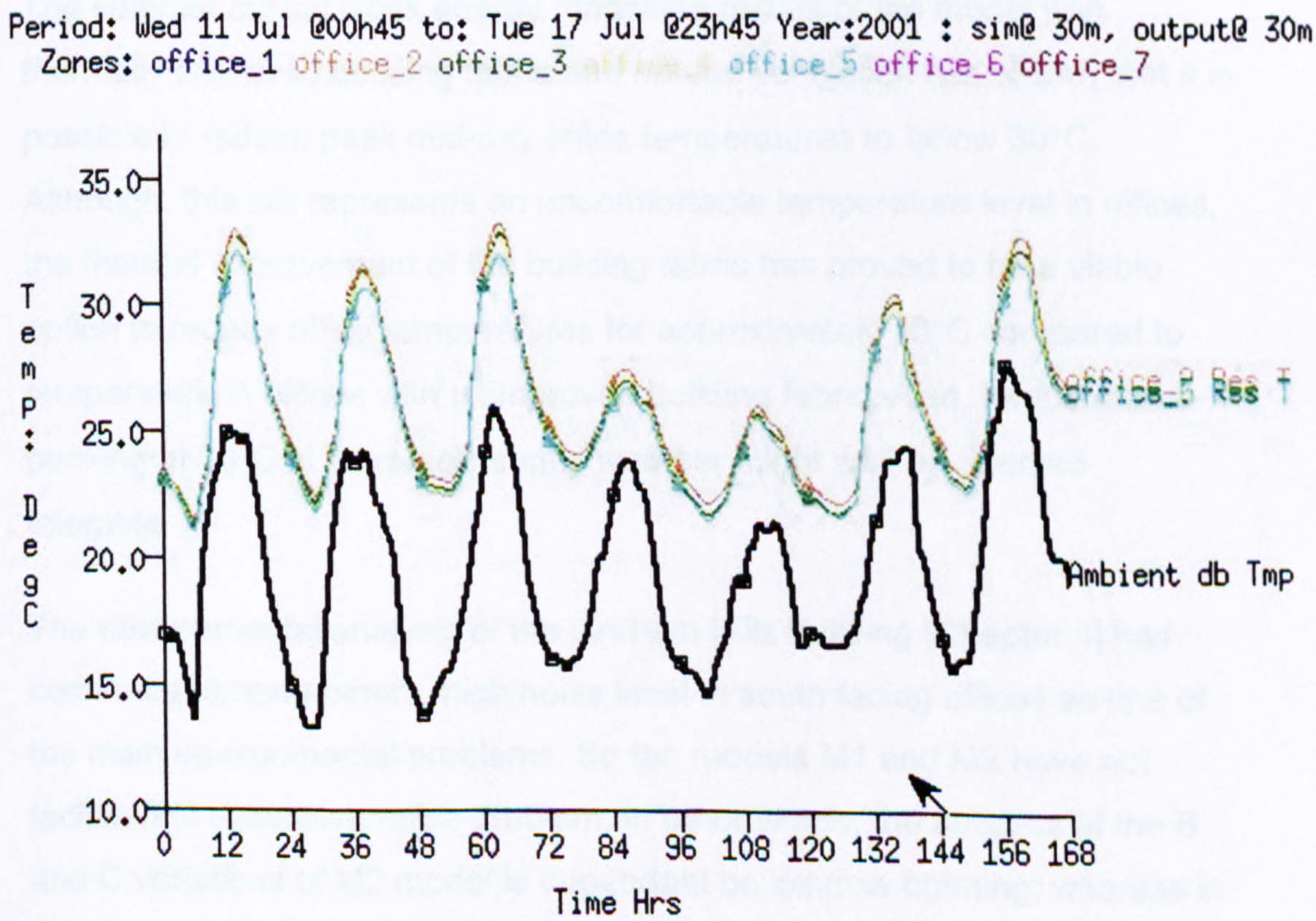

Fig. 5.13 M2model [Option B] summer critical week, temperature in all office zones and ambient air temperature.

M2 model Option C with all office windows open [Fig. 5.14] simulation results have shown further reduced peak mid-day office temperature to maximum 28°C to 30°C. Compared to Option B of the M2 model [Fig. 5.13] results, as a result of opening more windows and allowing more ambient air to enter offices, the peak mid-day temperature in offices was reduced from maximum 33°C to below 30°C.

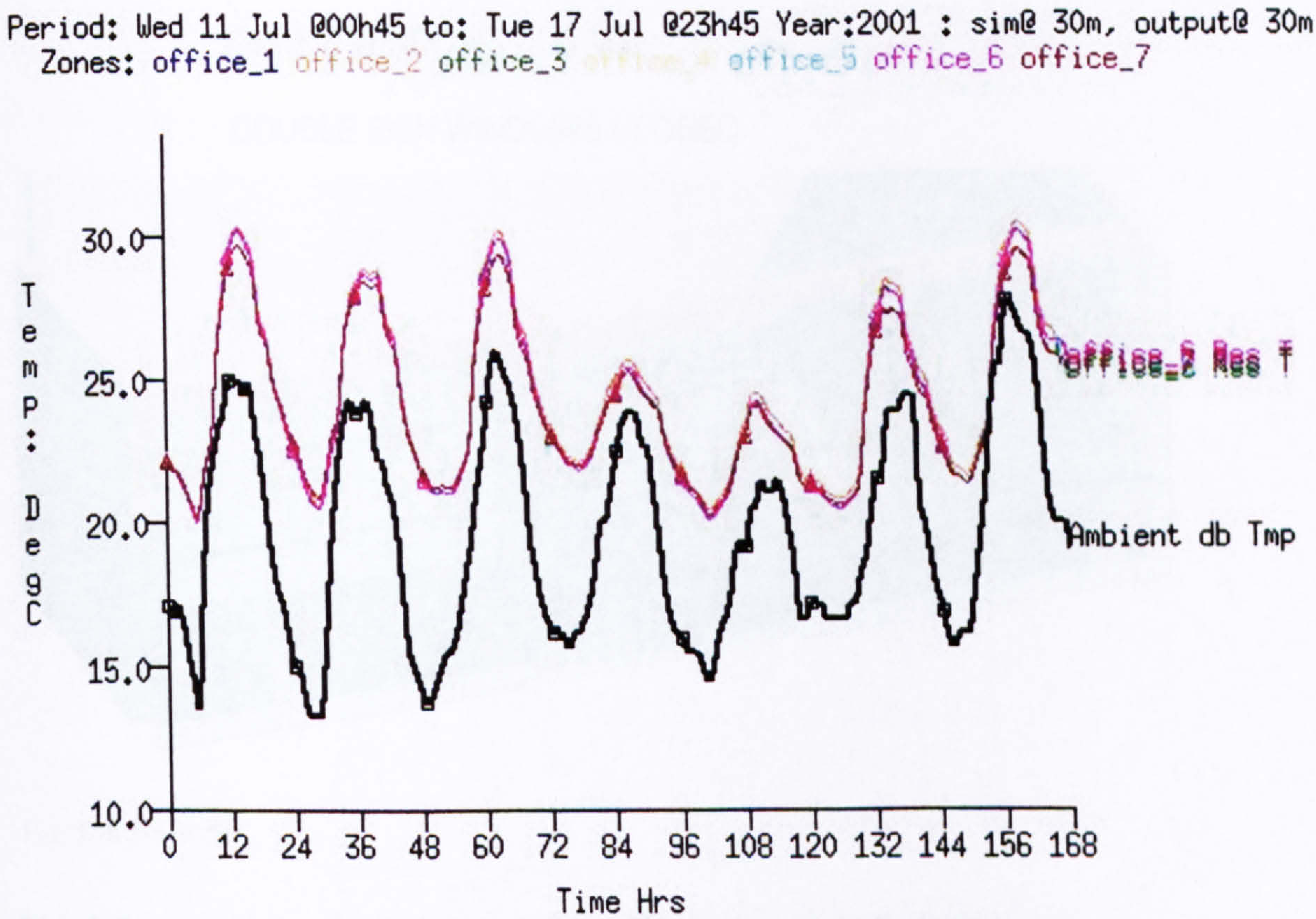

Fig. 5.14 M2model [Option C] summer critical week, temperature in all office zones and ambient air temperature.

The summer critical week energy modelling results of the model with thermally improved building fabric and natural ventilation has shown that it is possible to reduce peak mid-day office temperatures to below 30°C. Although, this still represents an uncomfortable temperature level in offices, the thermal improvement of the building fabric has proved to be a viable option to reduce office temperatures for approximately 10°C compared to temperature in offices with unimproved building fabric. Also, temperatures peaking at 30°C in extremely sunny weather might well be deemed tolerable.

The environmental analysis of the Graham Hills building [Chapter 4] has confirmed, among others, high noise level in south facing offices as one of the main environmental problems. So far, models M1 and M2 have not tackled the excessive noise problem. In other words, the success of the B and C variations of M2 model is dependant on window opening, whereas in reality, users are inhibited from doing this due to noise disturbance. The following models [M3 to M7] take the thermally improved model of the Graham Hills building as a starting point and investigate the addition of the double skin façade with BIPV, as a refurbishment package capable of tackling the noise problem.

5.2.3 MODEL 3

OFFICE WINDOWS CLOSED

DOUBLE SKIN WINDOWS CLOSED

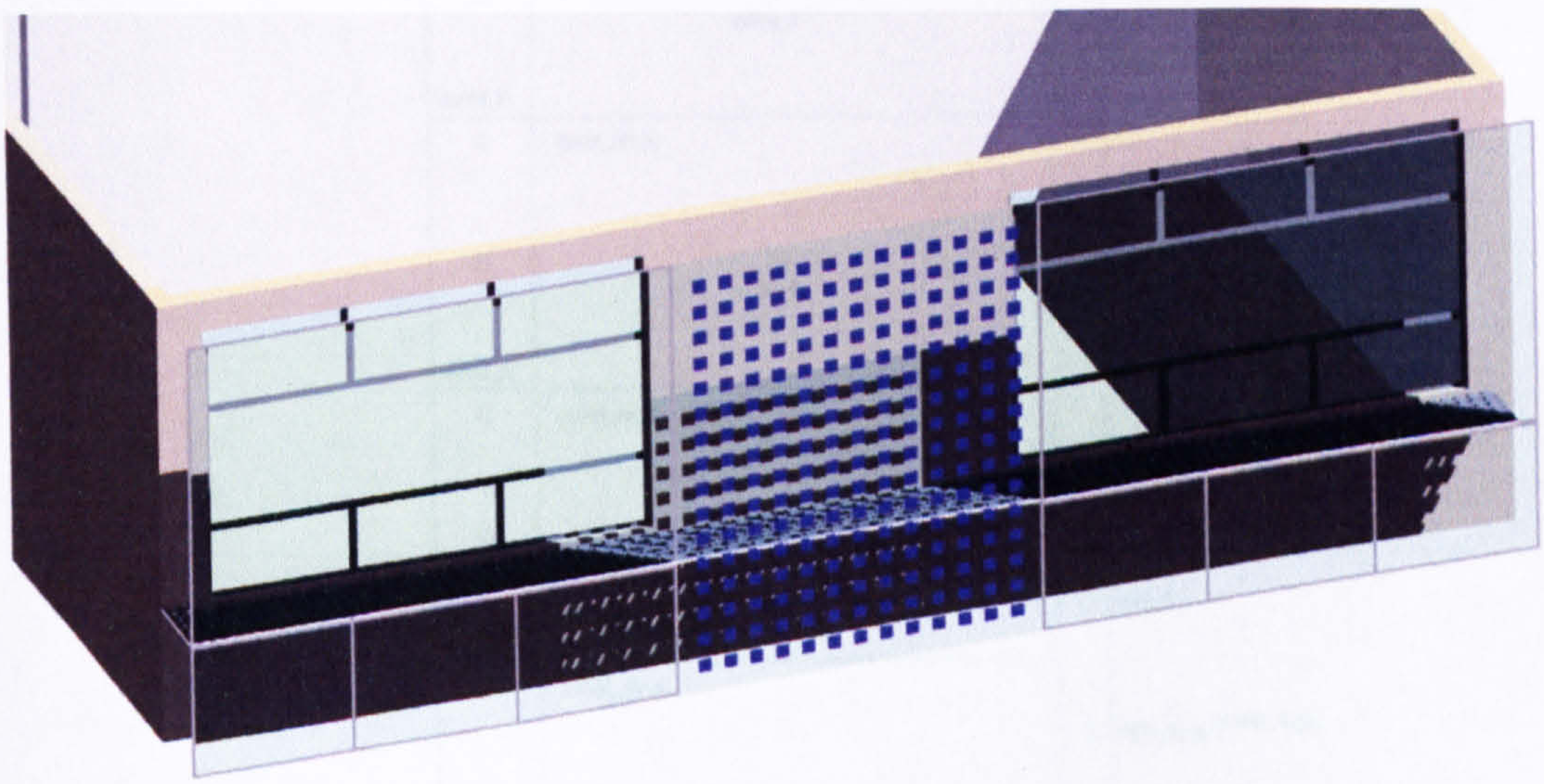

Fig. 5.15 M3 model

The M3 model has all windows on the office external wall closed and openings on the double skin façade closed. The air-flow diagram [Fig. 5.16] describes the building where all openings inside and outside are closed, casual gains in offices are included, and no ventilation is allowed, only background infiltration through small crack openings in windows. The background infiltration is important in this case as the outer vents are closed. The summer critical week 11^{th}–17^{th} July was simulated. The simulation results [Fig. 5.17] have shown extreme temperatures in all office and skin zones. In office zones, the peak mid-day temperatures are much higher than ambient temperature [Fig. 5.18]. They have risen to close to 50°C on weekdays, and to over 40°C during weekends [the fourth and the fifth days of the critical week]. This is due to the offices' internal gains being excluded and the ambient temperature being somewhat lower on those two days.

The temperatures in skin zones [Fig. 5.19] are also much higher than the ambient temperature, with peak mid-day temperatures of 45°C to 50°C, and the highest temperature of just below 60°C on the first day of the critical week when the incident solar radiation is highest. The graph also shows the correspondence between temperatures in skin zones and the incident solar radiation. When compared to the model M2 Option A, the presence of an unventilated double skin façade resulted in approximately 10°C higher office temperatures.

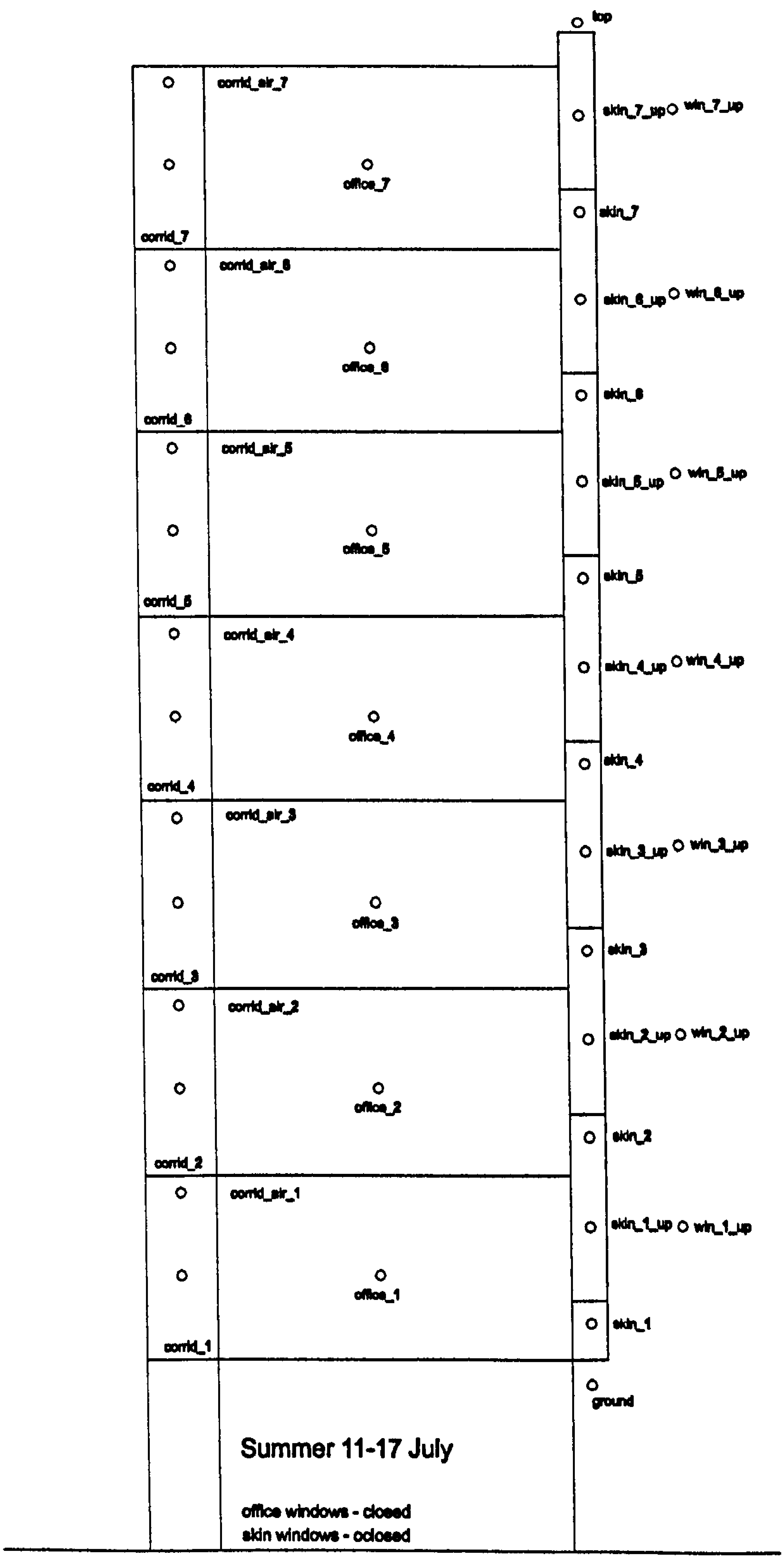

Fig. 5.16 M3 model air flow network

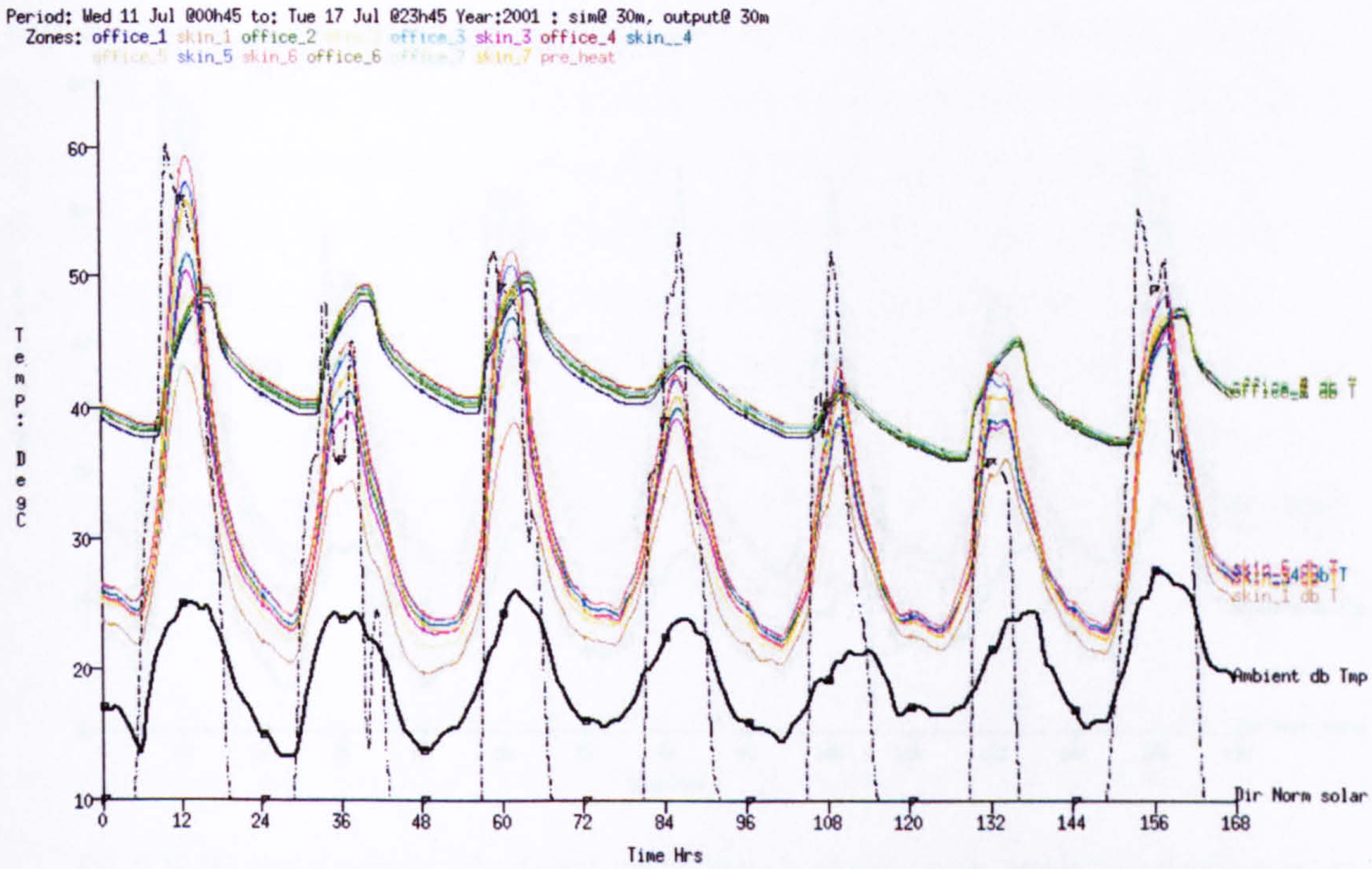

Fig. 5.17 M3 model summer critical week temperature in all zones, ambient air temperature and direct normal solar radiation

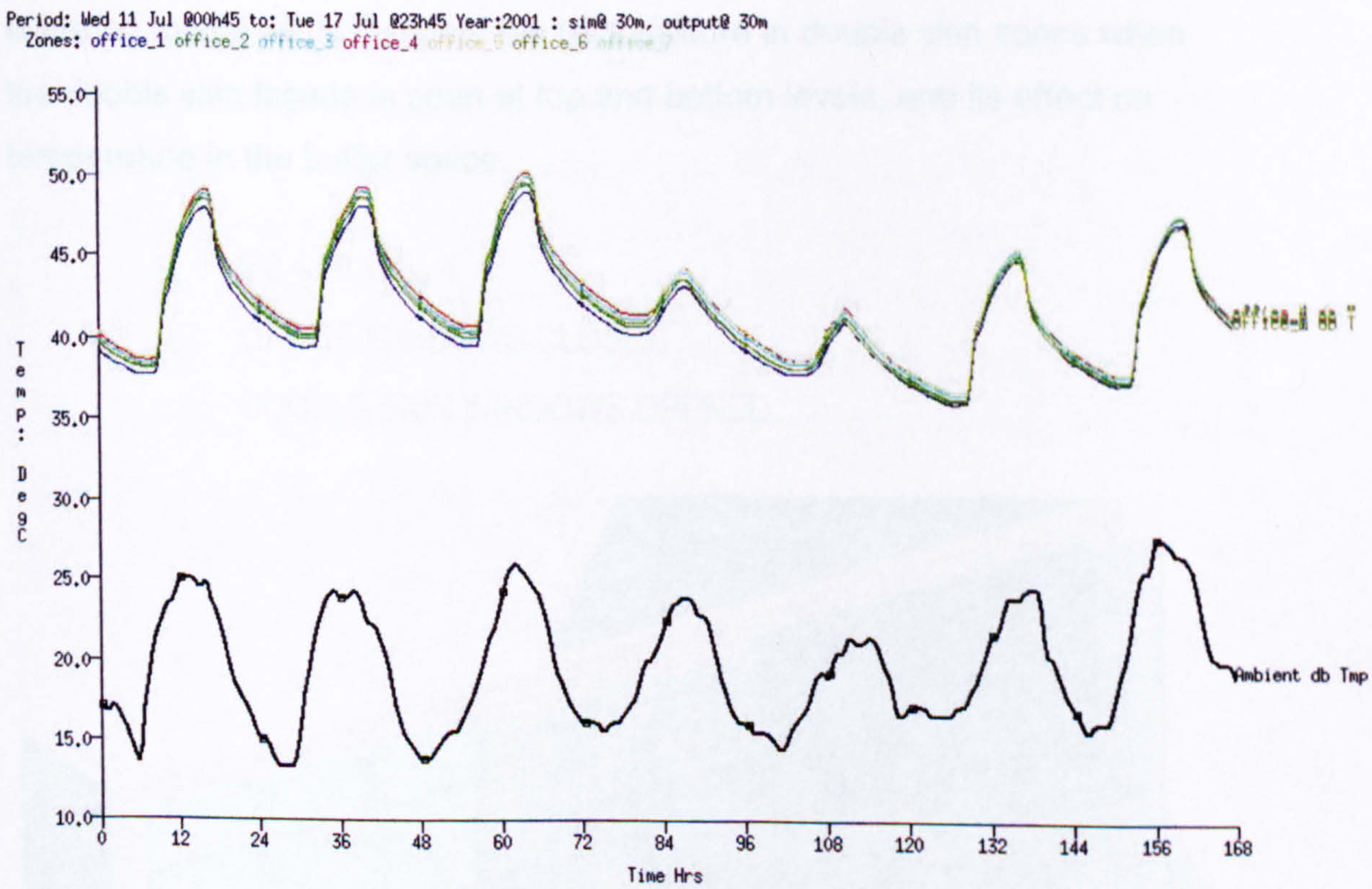

Fig. 5.18 M3 model summer critical week temperature in all office zones and ambient air temperature

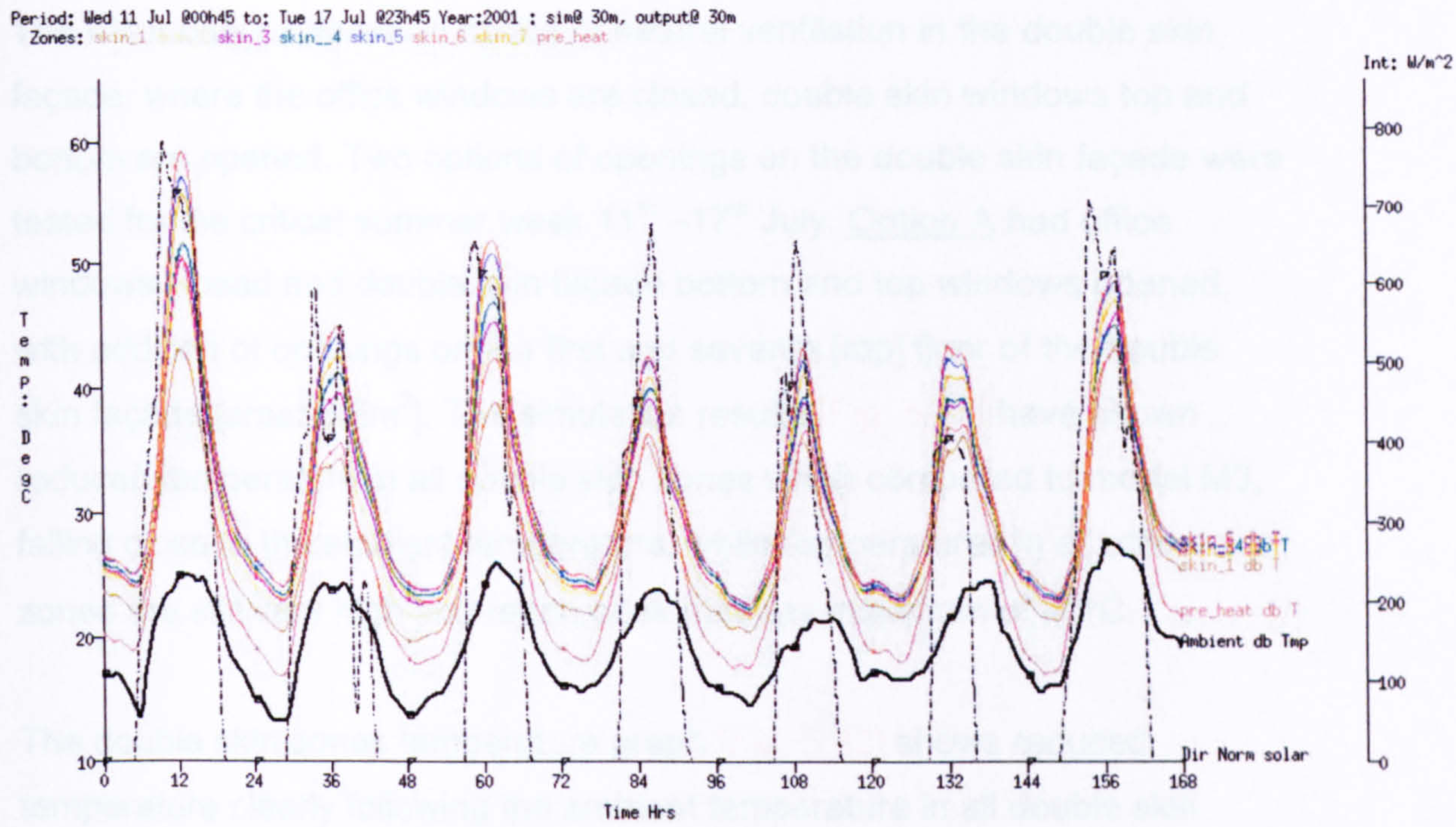

Fig. 5.19 M3 model summer critical week temperature in all skin zones, ambient air temperature and direct normal solar radiation

The results for the model M3 represent a theoretical worst-case scenario of the building, with very restricted ventilation. It was taken as a starting point for further exploration of the double skin façade thermal performance. The following model will investigate the temperature in double skin zones when the double skin façade is open at top and bottom levels, and its effect on temperature in the buffer space.

5.2.4 MODEL 4

OFFICE WINDOWS CLOSED

DOUBLE SKIN WINDOWS OPENED

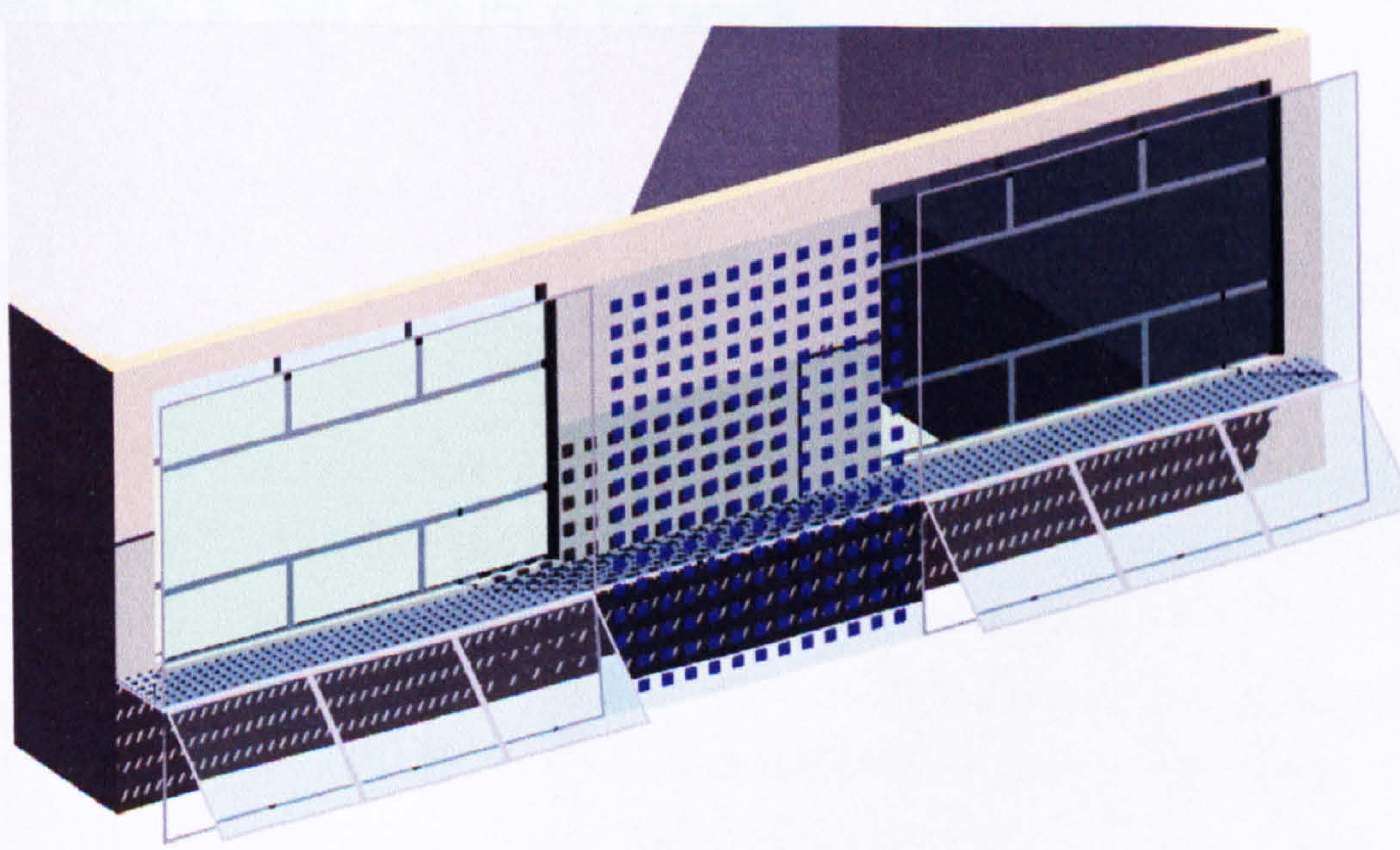

Fig. 5.20 M4 Model
Office windows closed / double skin windows opened

The M4 model explores an option of natural ventilation in the double skin façade, where the office windows are closed, double skin windows top and bottom are opened. Two options of openings on the double skin façade were tested for the critical summer week 11th –17th July. Option A had office windows closed and double skin façade bottom and top windows opened, with addition of openings on the first and seventh [top] floor of the double skin façade [area: 3.6m^2]. The simulation results [Fig. 5.21] have shown reduced temperature in all double skin zones when compared to model M3, falling close to the ambient temperature, while temperatures in all office zones are still very high and reach peak mid-day maximum of 45°C.

The double skin zones temperature graph [Fig. 5.22] shows reduced temperature clearly following the ambient temperature in all double skin zones, from the air-flow that is now provided by opening the double skin façade at top and bottom level. The highest peak mid-day temperature on the double skin zones of around 33°C is on the first day of the week, when the incident solar radiation is highest [reaching 800W/m^2], and falling to around or below 30°C peak mid-day temperature during the rest of the week. This noticeable difference in double skin façade temperatures between the M3 model and this model demonstrates the effectiveness of the natural ventilation by opening the double skin facade, to cool the air in the double skin buffer space. Also, the temperature profile of each double skin zone shows an incremental increase in temperature as one goes upwards from the skin zone on the first floor to the skin zone on the seventh floor. This confirms a stratification of warm air occurring in the buffer space, where the hottest air rises at the top of the façade.

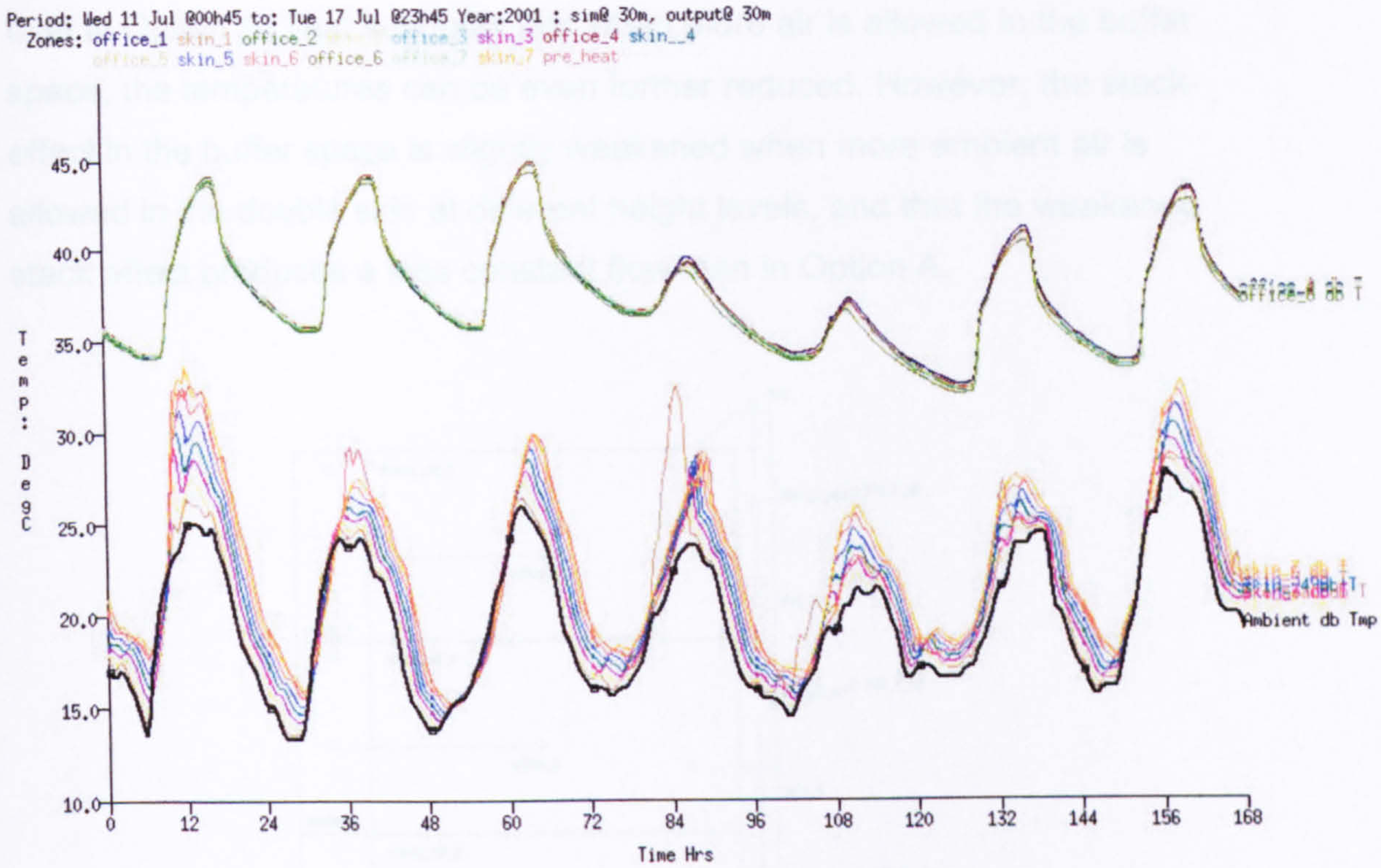

Fig. 5.21 M4 model [Option A] summer critical week temperature in all zones and ambient air temperature

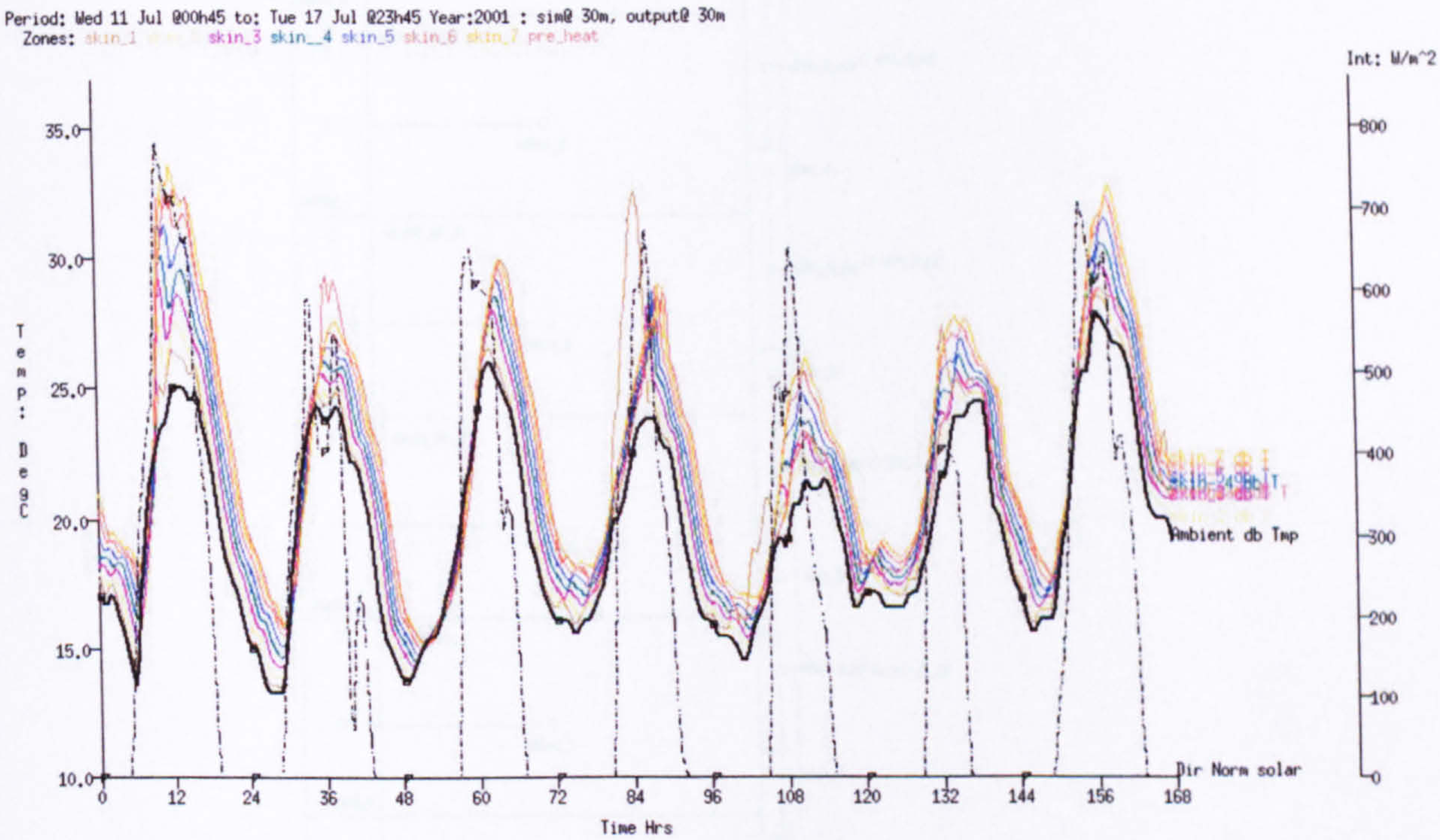

Fig. 5.22 M4 model [Option A] summer critical week temperature in all skin zones, ambient air temperature and direct normal solar radiation

Option B of this M4 model is similar to M4 model Option A, with the addition of double skin windows opened on all floors [office windows are all closed]. The air-flow network of this option is shown on the diagram [Fig. 5.23]. The idea behind this variation of the M4 model was to investigate the effect that by opening more area of the double skin façade has on temperatures in double skin façade zones. The simulation results [Fig. 5.24 and Fig. 5.25] have shown temperatures of the double skin zones generally slightly lower than in Option A. That suggests that when more air is allowed in the buffer space, the temperatures can be even further reduced. However, the stack-effect in the buffer space is slightly weakened when more ambient air is allowed in the double skin at different height levels, and that the weakened stack effect produces a less constant flow than in Option A.

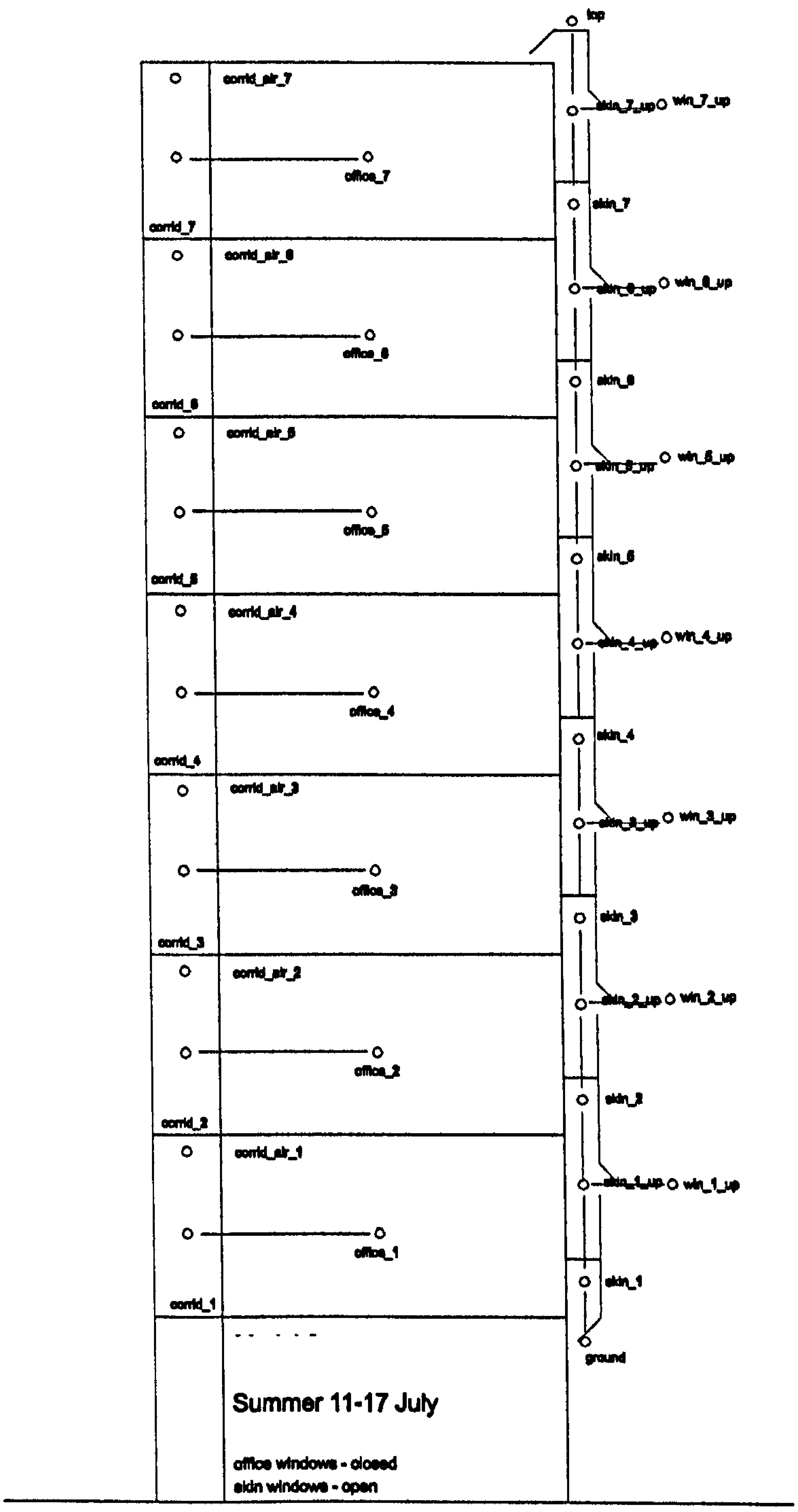

Fig. 5.23 M4 model [Option B] air flow network

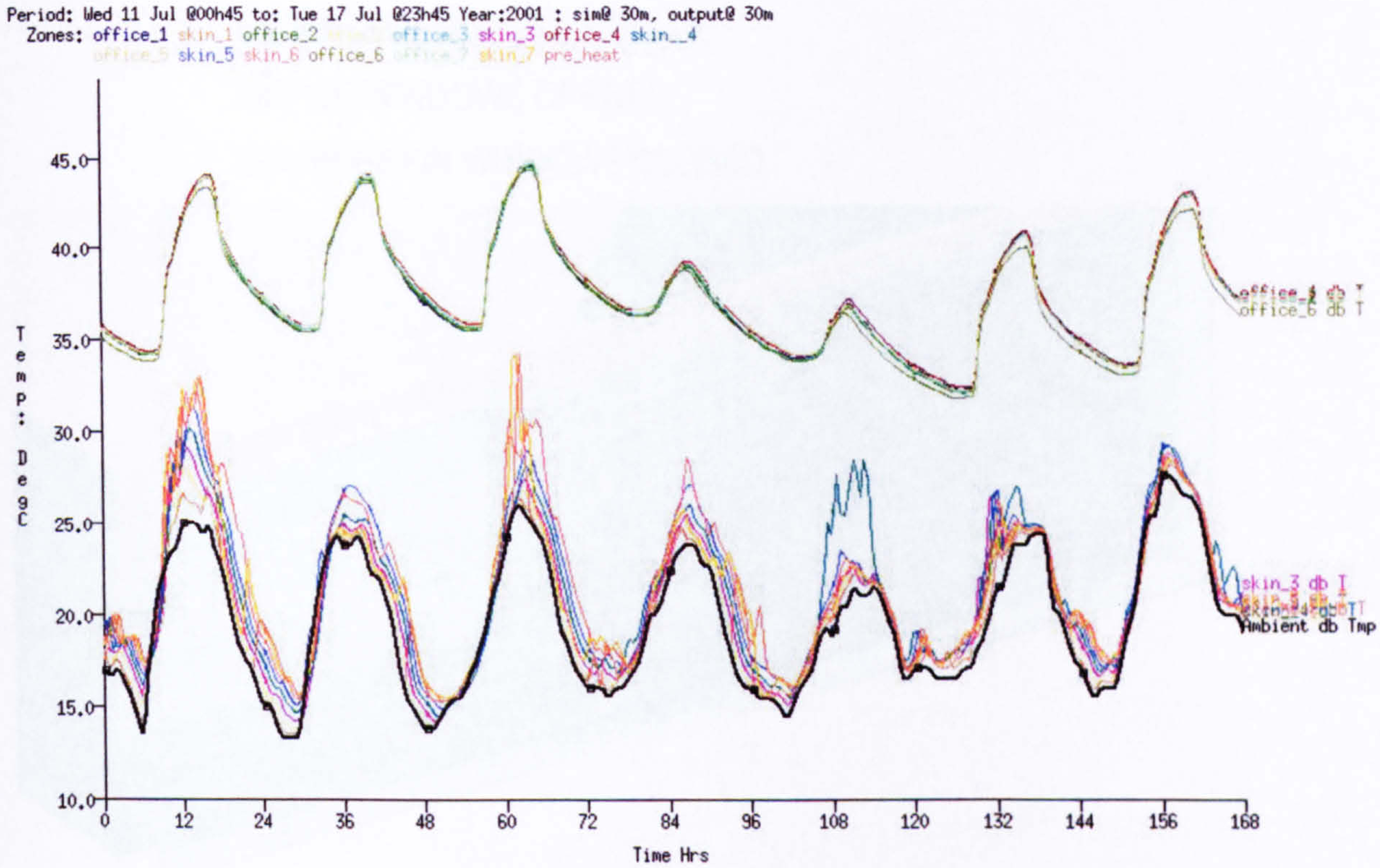

Fig. 5.24 M4 model [Option B] summer critical week temperature in all zones and ambient air temperature

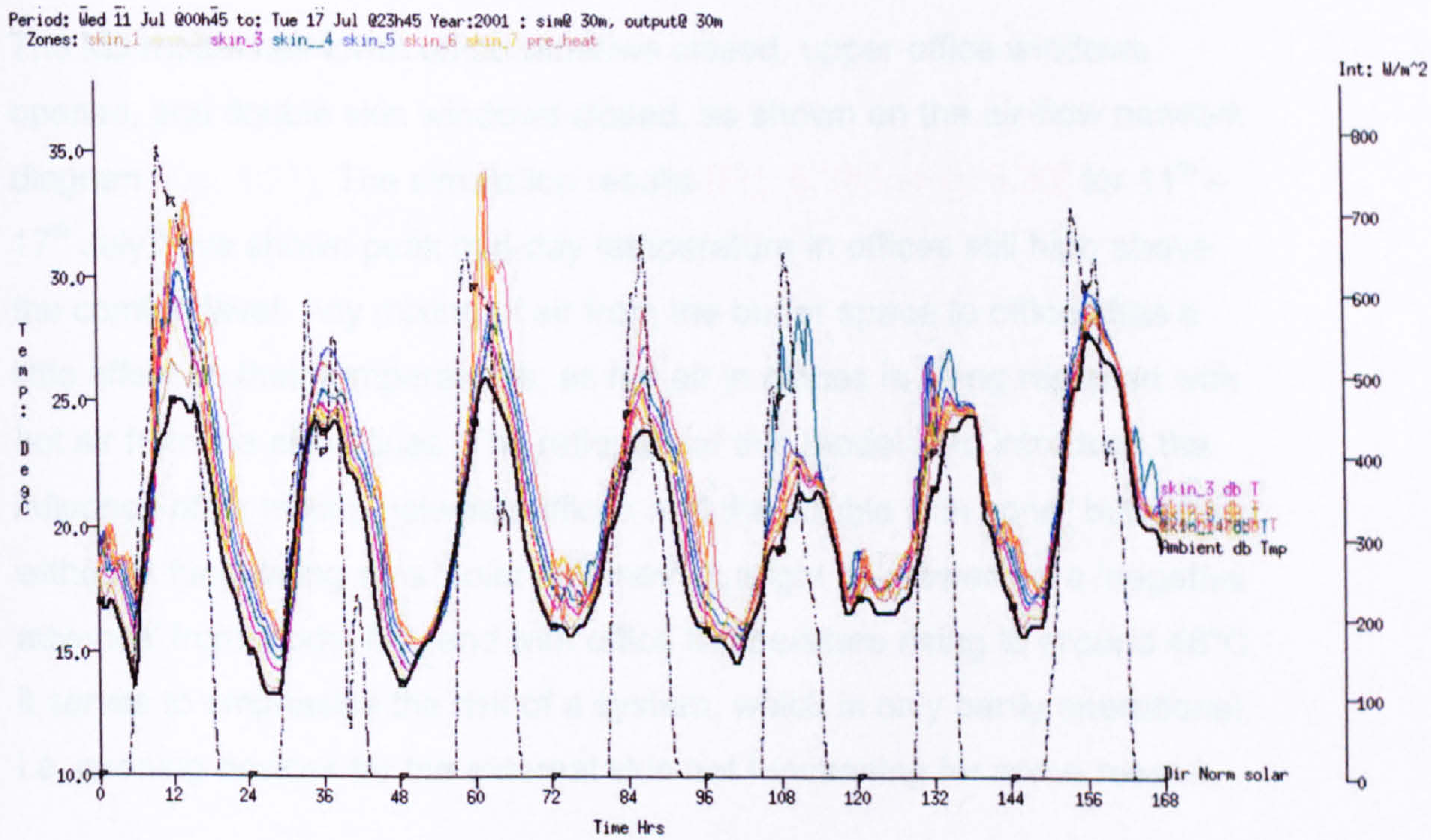

Fig. 5.25 M4 model [Option B] summer critical week temperature in all skin zones, ambient air temperature and direct normal solar radiation

5.2.5 MODEL 5
OFFICE WINDOWS OPENED
DOUBLE SKIN WINDOWS CLOSED

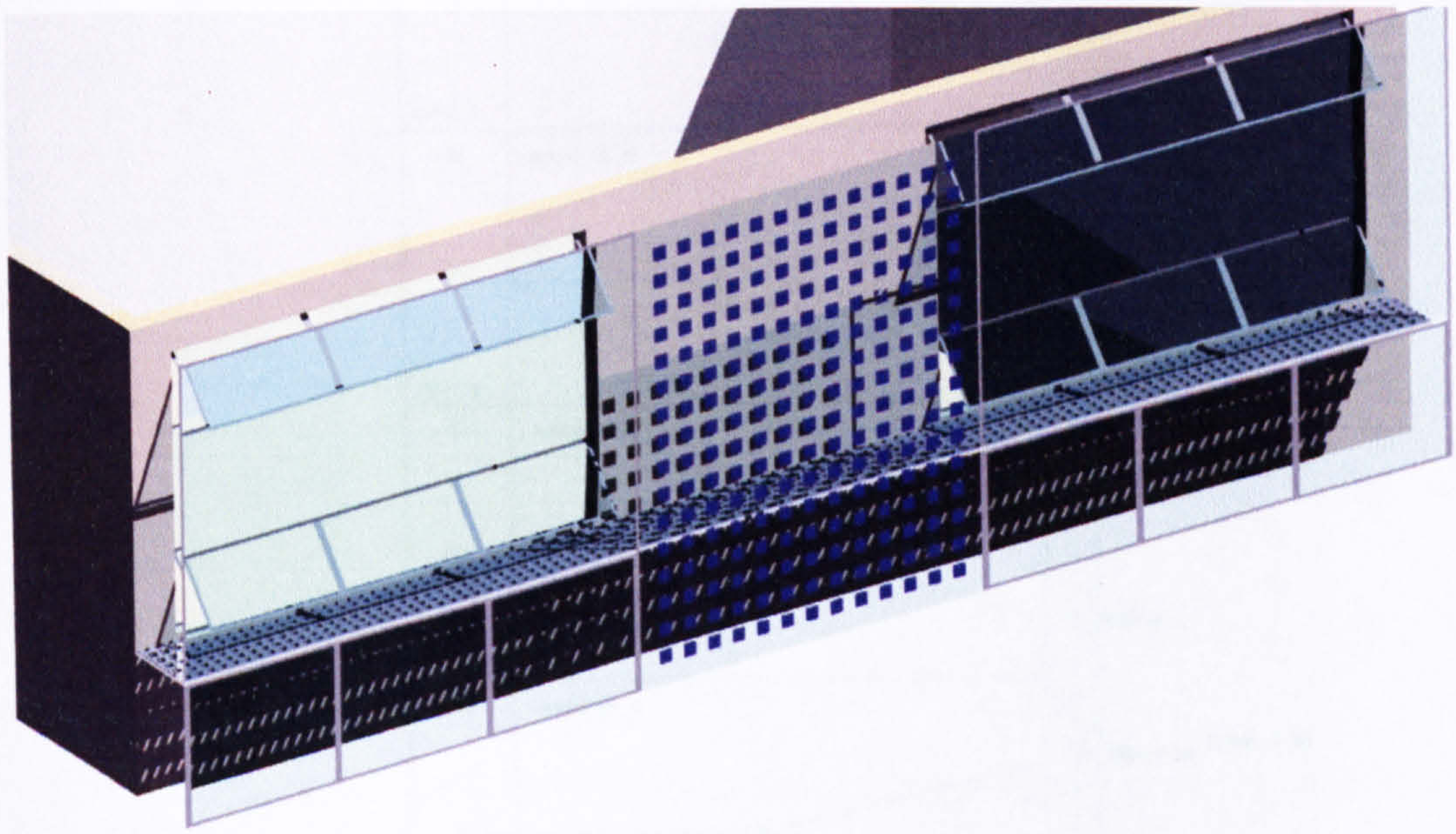

Fig. 5.26 M5 Model
Office windows opened / double skin windows closed

The M5 model has lower office windows closed, upper office windows opened, and double skin windows closed, as shown on the air-flow network diagram [Fig. 5.27]. The simulation results [Fig. 5.28 to Fig. 5.30] for 11th – 17th July have shown peak mid-day temperature in offices still high above the comfort level. Any mixing of air from the buffer space to offices has a little effect on their temperatures, as hot air in offices is being replaced with hot air from the skin zones. The rationale of this model is to introduce the influence of air mixing between offices and the double skin zone, but initially without it functioning as a 'solar chimney'. It might be viewed as a 'negative advance' from Model M4, and with office temperature rising to around 48°C, it serves to emphasise the risk of a system, which is only partly operational, i.e. opening devices for the external skin not functioning for some reason.

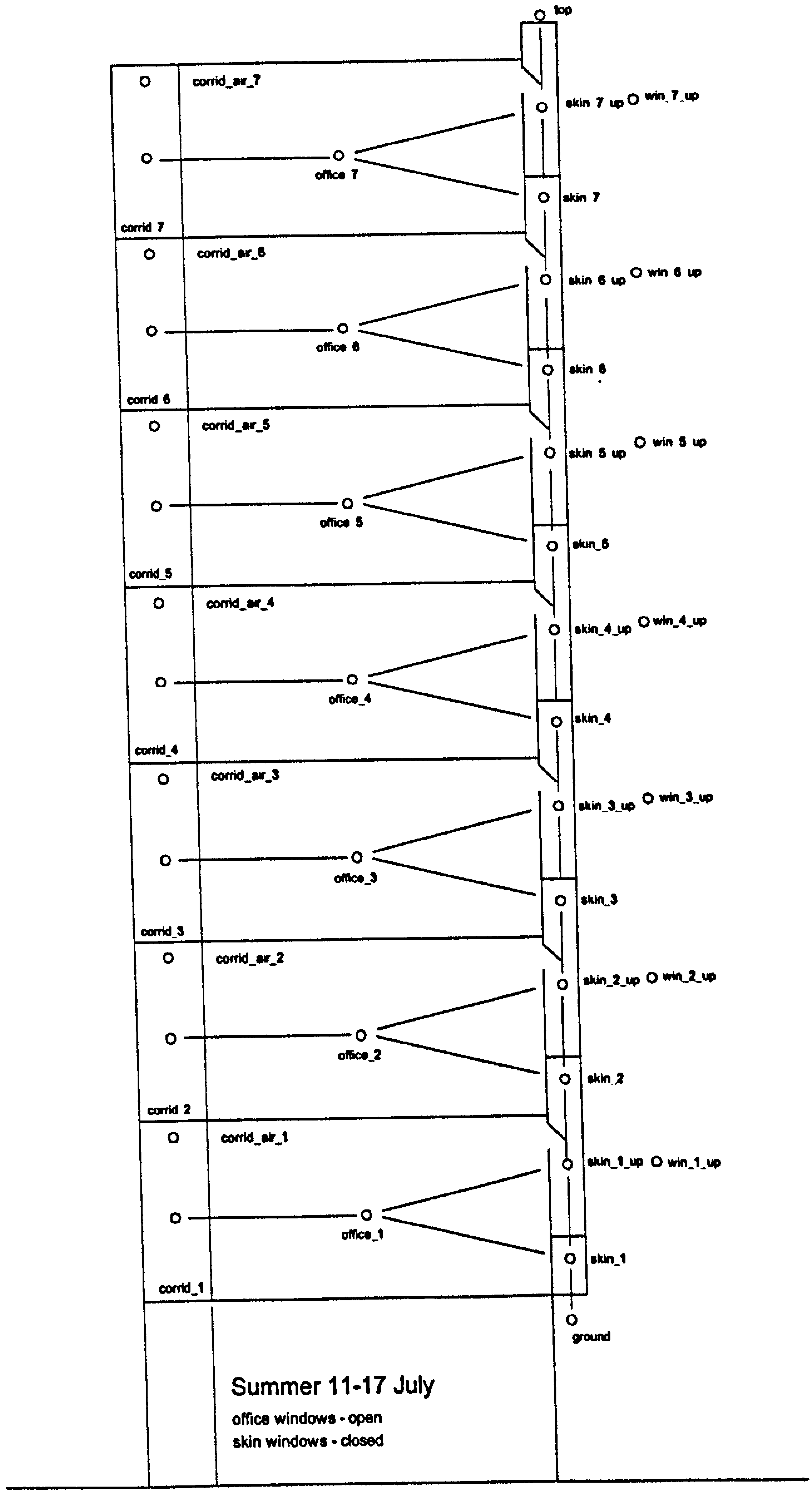

Fig. 5.27 M5 model air-flow network

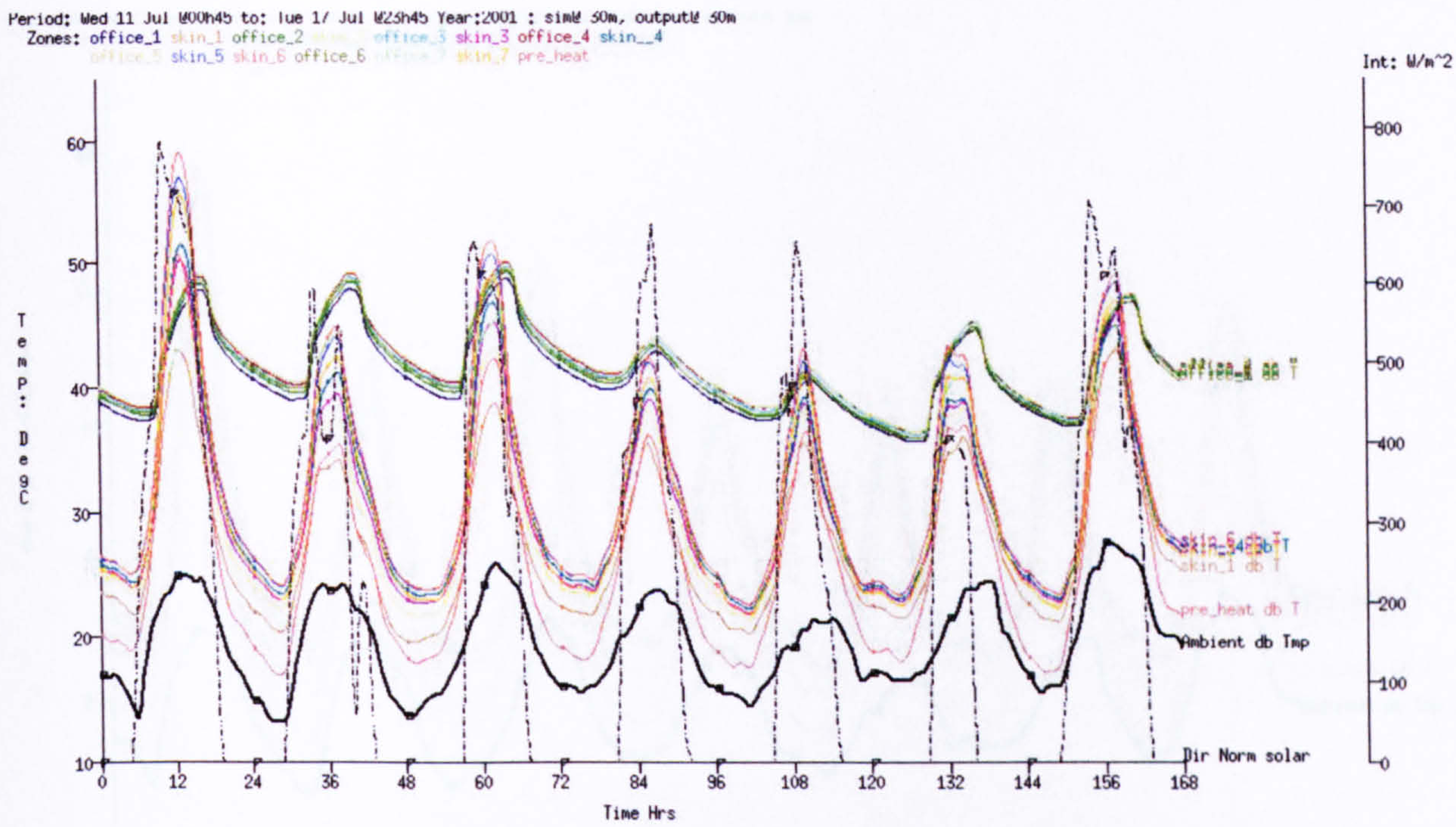

Fig. 5.28 M5 model summer critical week temperature in all zones, ambient air temperature and direct normal solar radiation

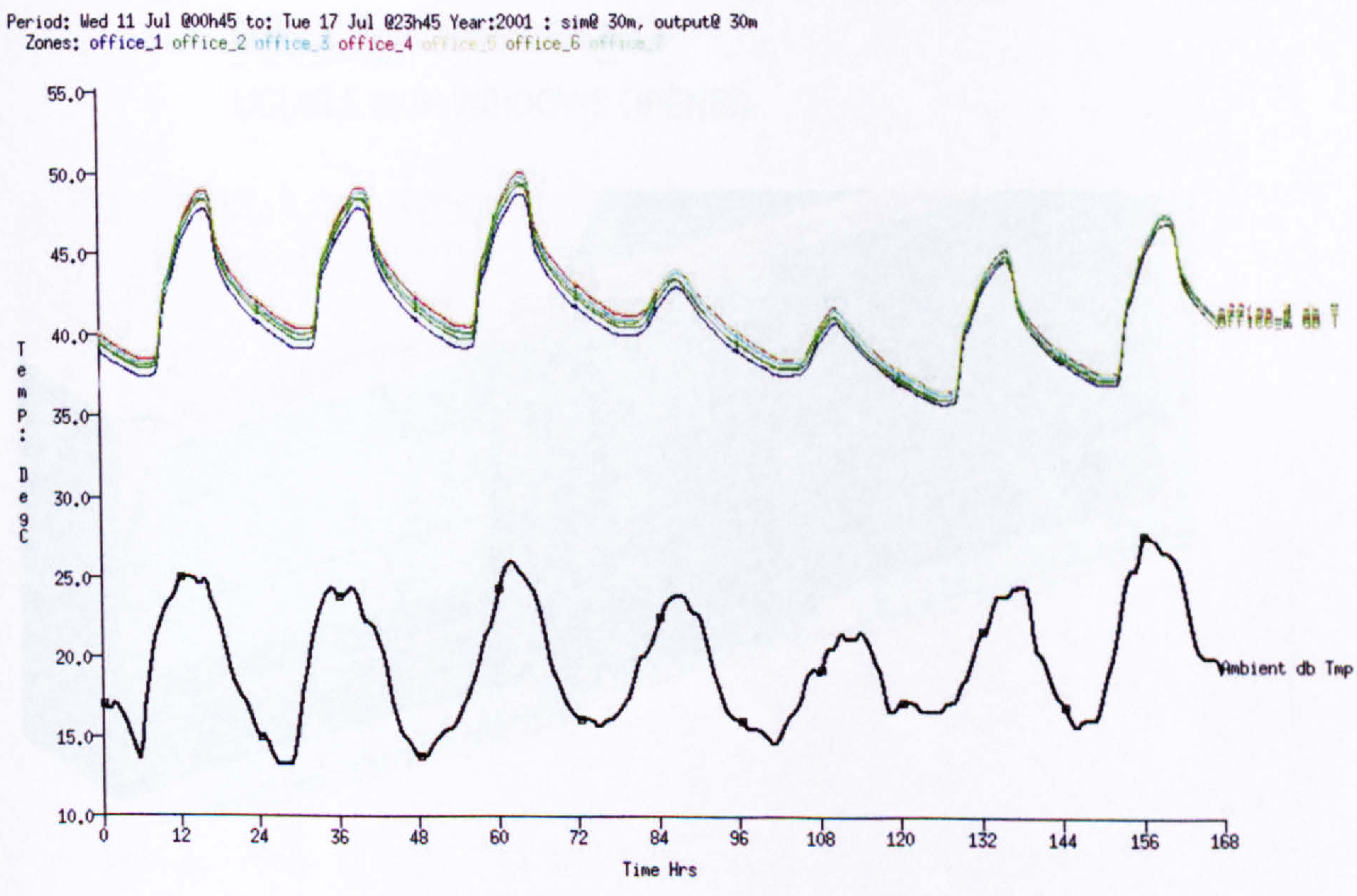

Fig. 5.29 M5 model
Summer critical week temperature in all office zones and ambient air temperature

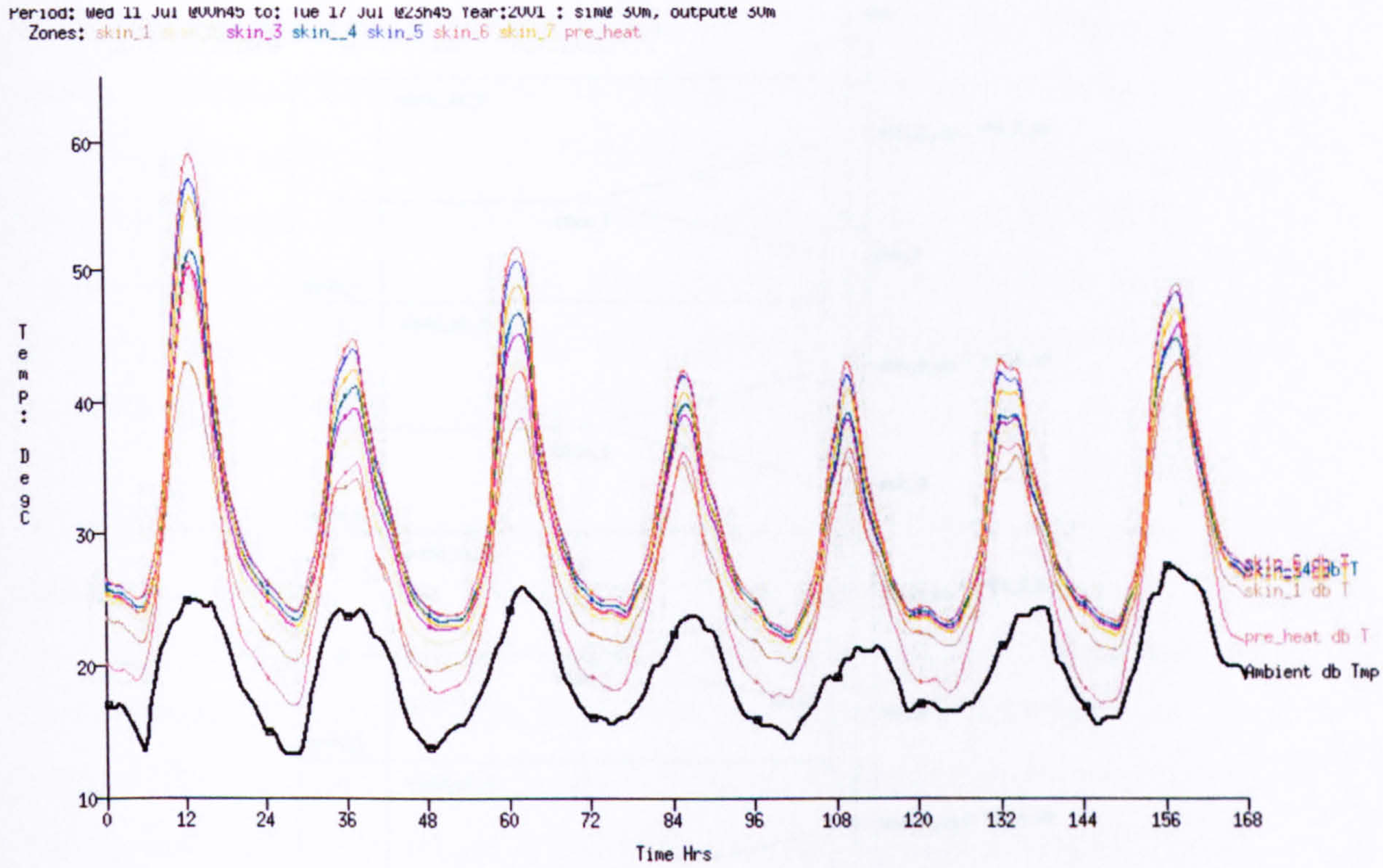

Fig. 5.30 M5 model summer critical week temperature in all skin zones and ambient air temperature

5.2.6 MODEL 6

OFFICE WINDOWS OPENED

DOUBLE SKIN WINDOWS OPENED

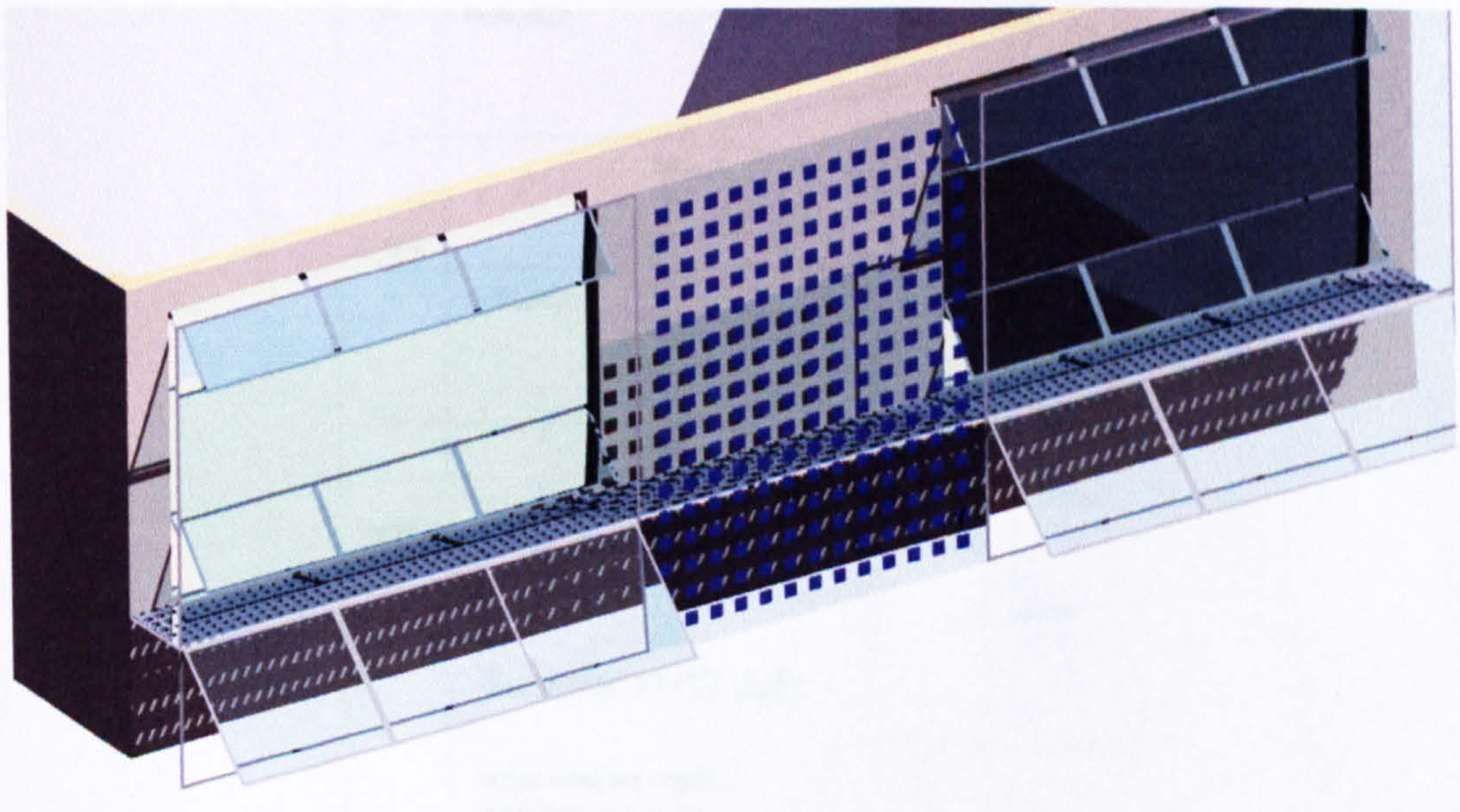

Fig. 5.31 M6 Model
Office windows opened / double skin windows opened

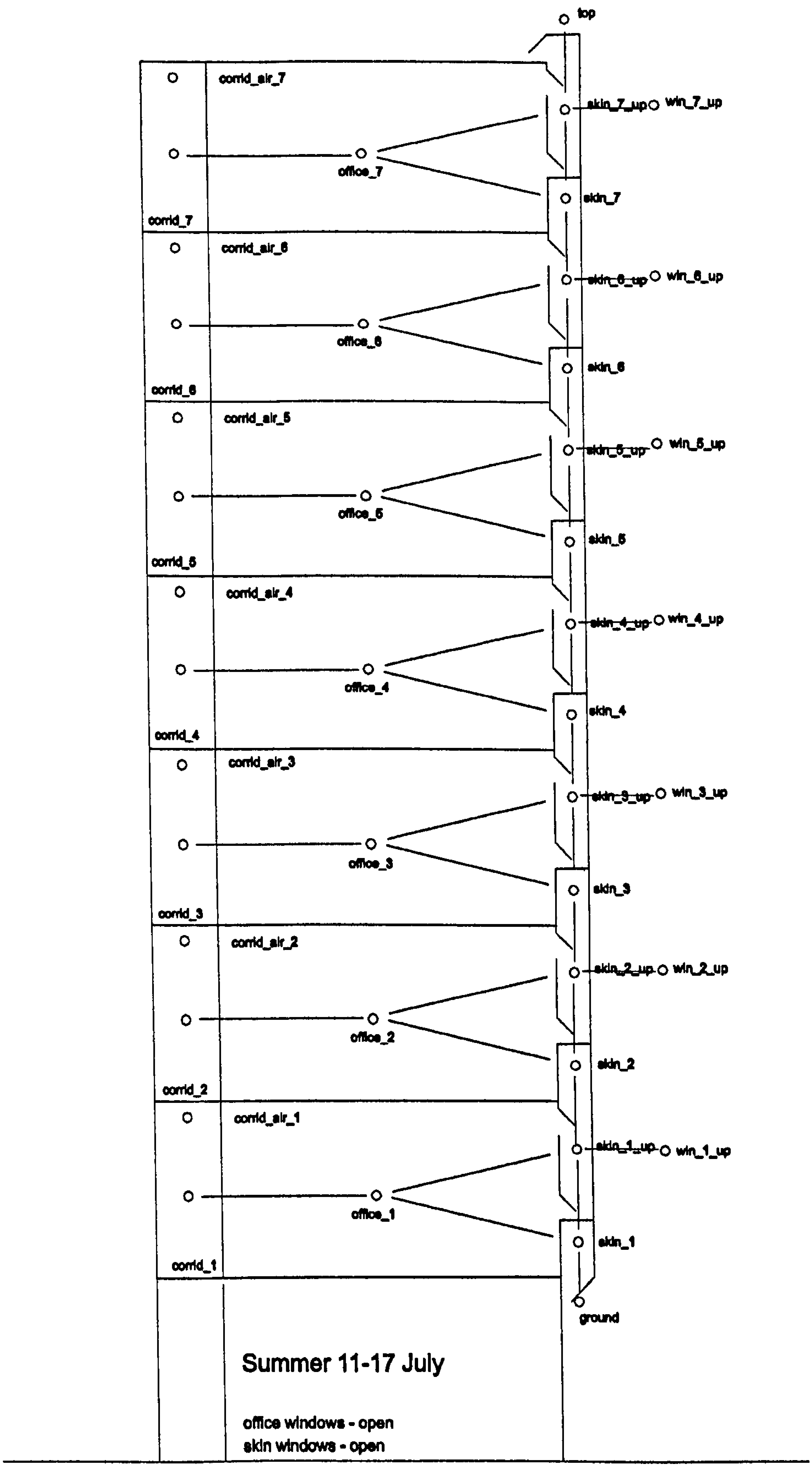

Fig. 5.32 M6 model air-flow network

The M6 model option combines an opening strategy for both office and double skin zones. The aim was to reduce temperature in all office and double skin zones with natural ventilation driven by the buoyancy effect in the buffer space. The model has the office lower and upper windows opened, and bottom and top openings in the double skin space opened [Fig.

5.32]. The summer week simulation results [Fig. 5.33 to Fig. 5.35] have shown office temperature profiles with reduced mid-day peaks of below 40°C, troughs between 25°C and 30°C, and the difference between the peak office and the peak double skin zone temperatures are on average 6-8°C. Compared with model M4 Option A, the reduction in office temperatures is approximately 5K, now more closely influenced by the temperature in double skin zones, which is similar to that in model M4.

When the model M6 is compared with model M2 Option C [having the same thermal properties of the building fabric as model M6, office windows opened, but without the addition of the double skin façade], the peak mid-day temperature in offices of the model with the double skin façade is just below 40°C, while peak mid-day temperature in offices without the double skin façade component, is just below 30°C. The presence of the double skin façade has resulted in higher peak mid-day temperature in offices to up to 10K [Fig. 5.34 compares to Fig. 5.14]. Consequently, one may conclude that the addition of the outer skin of glass is a factor in increasing the temperature in offices leading to excessively uncomfortable temperatures.

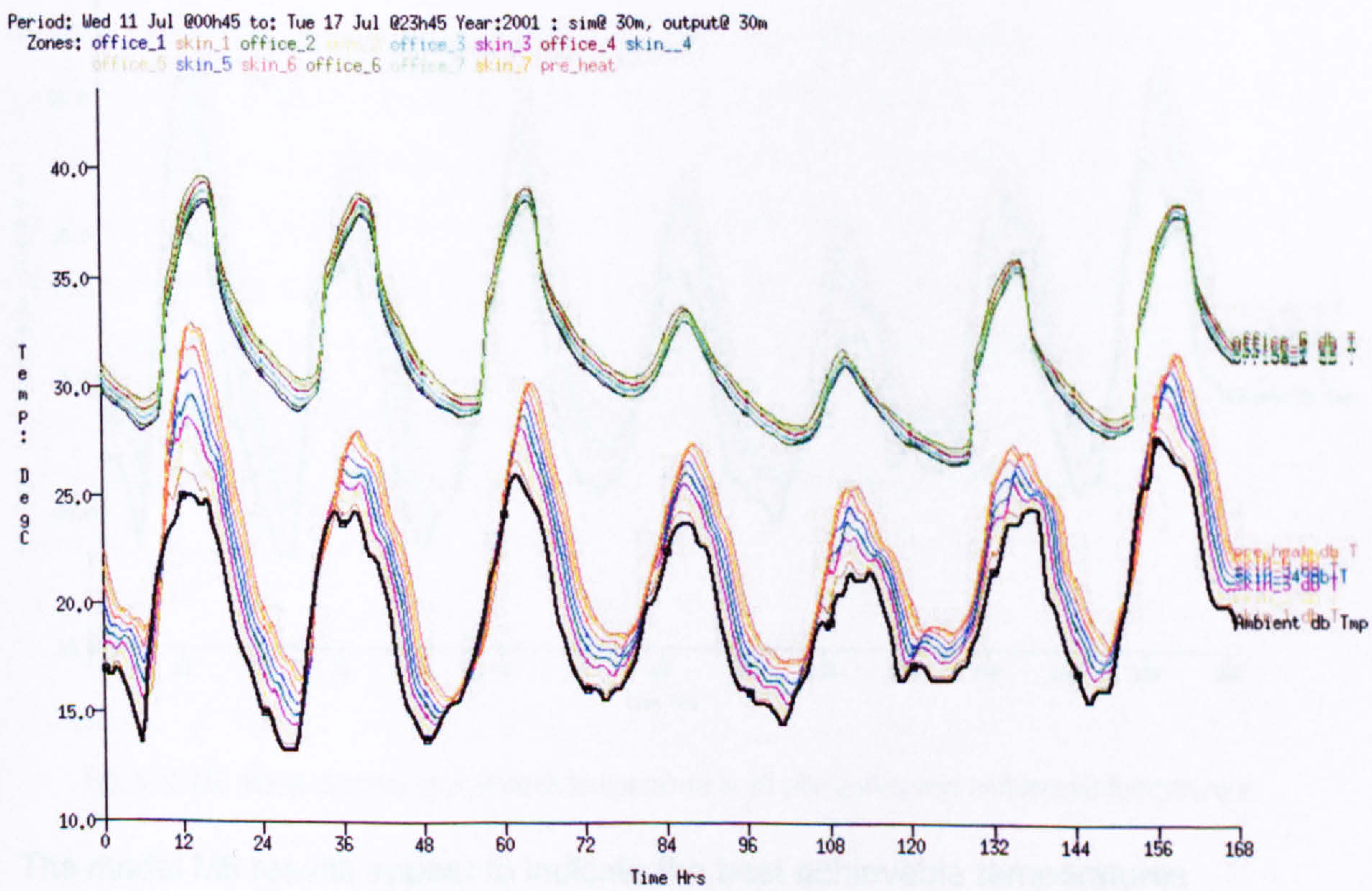

Fig. 5.33 M6 model summer critical week temperature in all zones and ambient air temperature

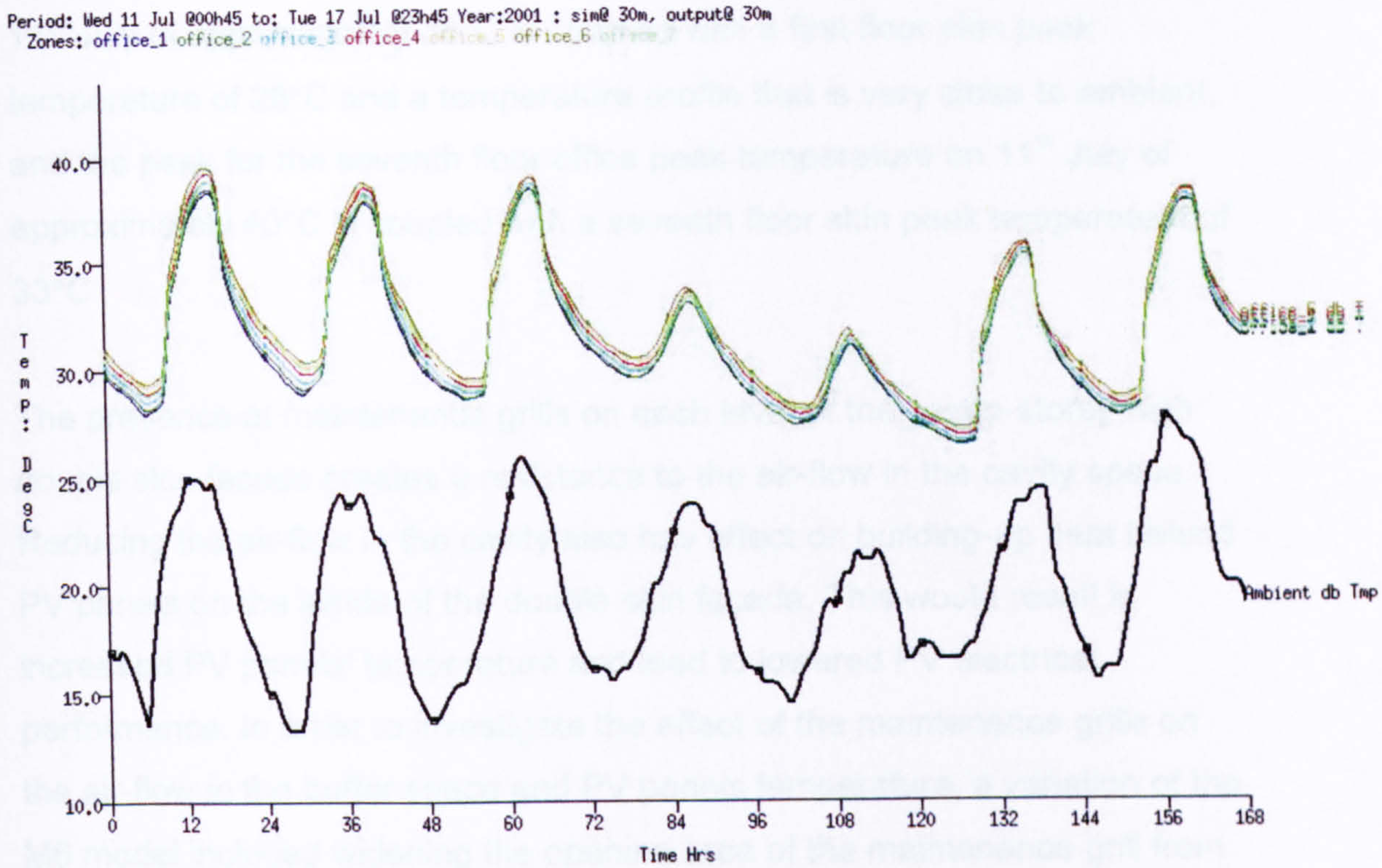

Fig. 5.34 M6 model summer critical week temperature in all office zones and ambient air temperature

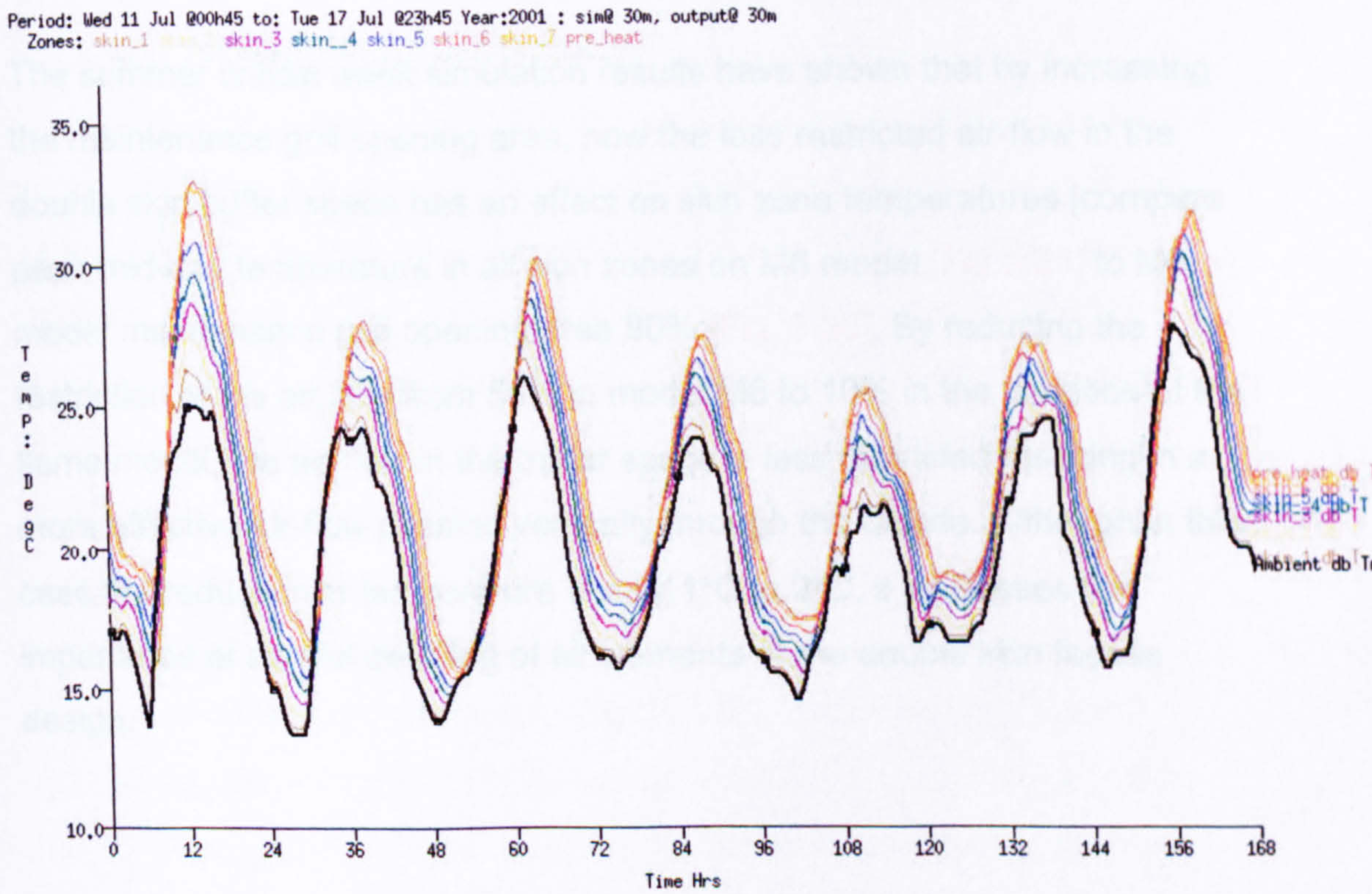

Fig. 5.35 M6 model summer critical week temperature in all skin zones and ambient air temperature

The model M6 results appear to indicate the best achievable temperatures in all zones by means of natural ventilation on hot days in summer. This is still well above acceptable limits for thermal comfort, and it is evident that although the peak skin temperature increases from lowest to highest floor level due to stratification of hot air on higher levels, the impact on office temperatures is marginal. For example, the peak for the first floor office on

11th July of approximately 38°C is coupled with a first floor skin peak temperature of 26°C and a temperature profile that is very close to ambient, and the peak for the seventh floor office peak temperature on 11th July of approximately 40°C is coupled with a seventh floor skin peak temperature of 33°C [Fig. 5.33].

The presence of maintenance grills on each level of the seven-storey high double skin façade creates a resistance to the air-flow in the cavity space. Reducing the air-flow in the cavity also has effect on building-up heat behind PV panels on the inside of the double skin façade. This would result in increased PV panels' temperature and lead to lowered PV electrical performance. In order to investigate the effect of the maintenance grills on the air-flow in the buffer space and PV panels temperature, a variation of the M6 model included widening the opening area of the maintenance grill from 50% to 90%, i.e. the opaque part of the maintenance grill was reduced from taking 50% of the buffer space area to 10%.

The summer critical week simulation results have shown that by increasing the maintenance grill opening area, now the less restricted air-flow in the double skin buffer space has an effect on skin zone temperatures [compare peak mid-day temperature in all skin zones on M6 model [Fig.5.33] to M6 model maintenance grill opening area 90% [Fig. 5.36]. By reducing the restriction of the air flow from 50% in model M6 to 10% in the variation of the same model, the air-flow in the buffer space is less restricted resulting in a more effective air-flow passing vertically through the façade. Although in this case the reduction in temperature is only 1°C to 2°C, it addresses the importance of careful detailing of all elements of the double skin façade design.

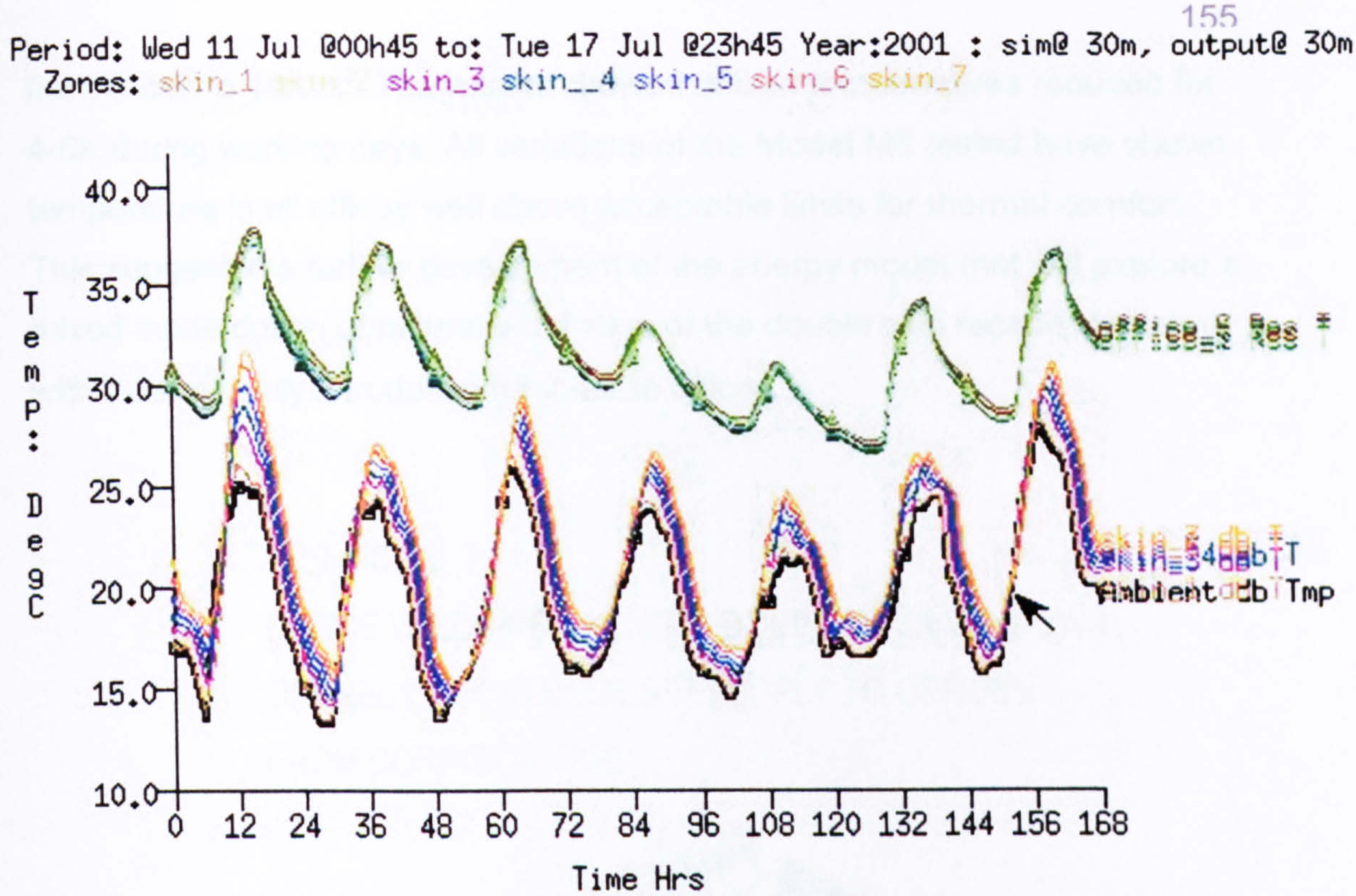

Fig. 5.36 M6 model [Maintenance grill with 90% opening] summer critical week temperature in all zones and ambient air temperature

Of interest here was also to compare the PV panels' temperature in the M6 model with 50% grill opening to the corresponding temperatures in the M6 model with 90% opening area. The results have shown slightly reduced PV temperatures in the model with increased grill opening area. For example, on the 11th July, the sunniest day of the week with 800W/m^2 direct solar radiation, wind speed of max 5 m/s and wind direction of North-east, the inside face PV temperatures at the top of the double skin façade, [i.e. 6th floor] reached maximum temperature of 64.2°C at 12.45am, a minimum 14.6°C at 03.45am and a mean day value of 27.7°C. When the grill openings were increased to 90%, the inside face of 6th floor PV panels showed a maximum temperature of 63.8°C at 12.45am, a minimum of 14.1°C at 03.45am and the mean day value was 27.2°C. These results suggest reduced temperature of the PV panels by approximately 0.5°C when the maintenance grills have less resistance to the air-flow in the buffer space. However, such a small difference in temperature would have a minimal impact on the efficiency of the cells.

Another variation of the model M6 was also tested. This included a double skin façade with larger area of the buffer space top opening, increased maintenance grill opening area and casual gains from artificial lighting reduced for 80% [assuming much lower demand for lighting during long summer days]. The top opening area of the 'solar chimney' was enlarged from $6.2m^2$ to $10.0m^2$. The results showed offices temperatures reduced for 4-5K during working days. All variations of the Model M6 tested have shown temperature in all offices well above acceptable limits for thermal comfort. This suggested a further development of the energy model that will explore a mixed mode option of natural ventilation of the double skin façade, assisted with mechanically introduced fresh air to offices.

5.2.7 MODEL 7
OFFICE WINDOWS OPENED / DOUBLE SKIN WINDOWS OPENED / MECHANICAL AIR SUPPLY TO OFFICES FROM CORRIDOR SIDE

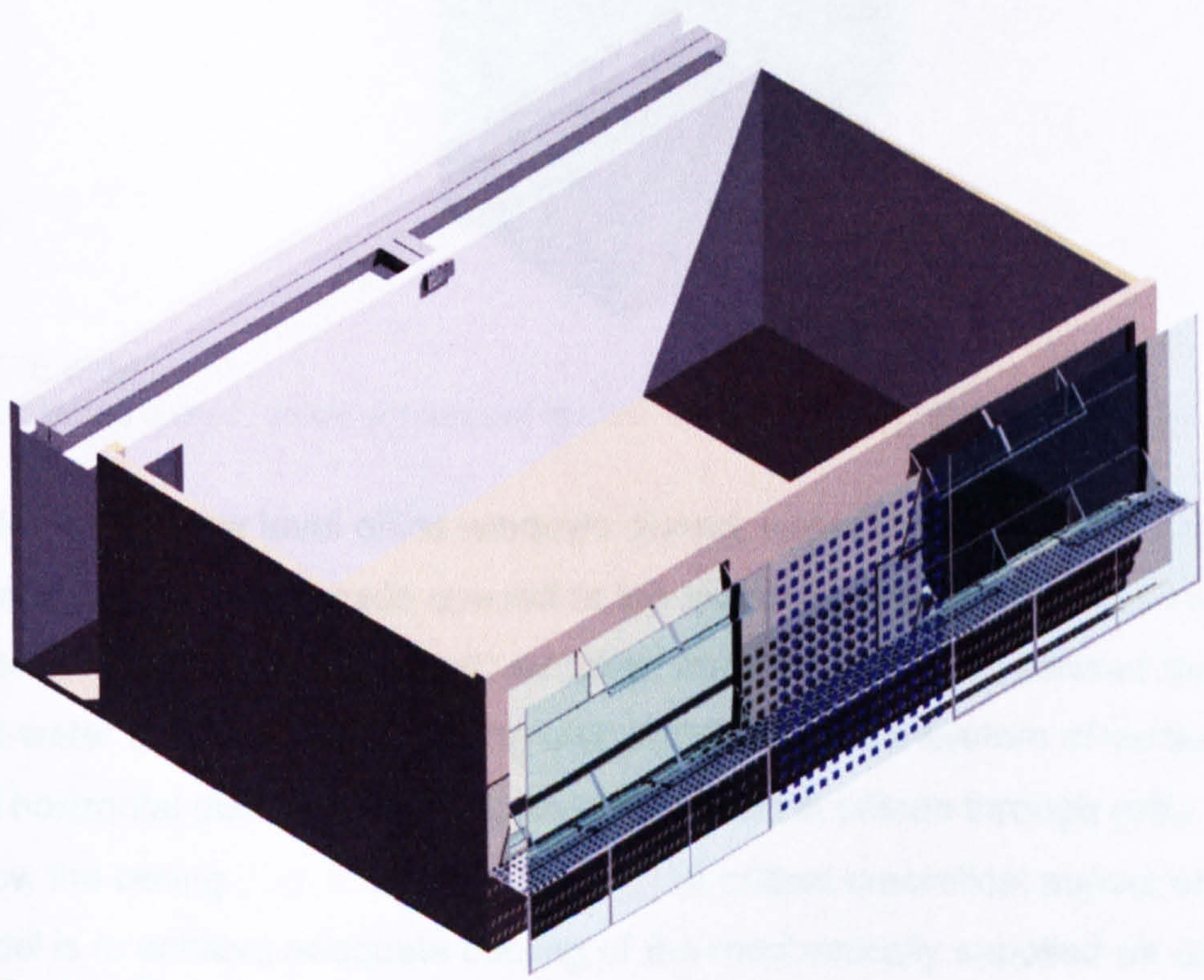

Fig. 5.37 M7 model
Office windows opened / double skin windows opened / corridor air supply

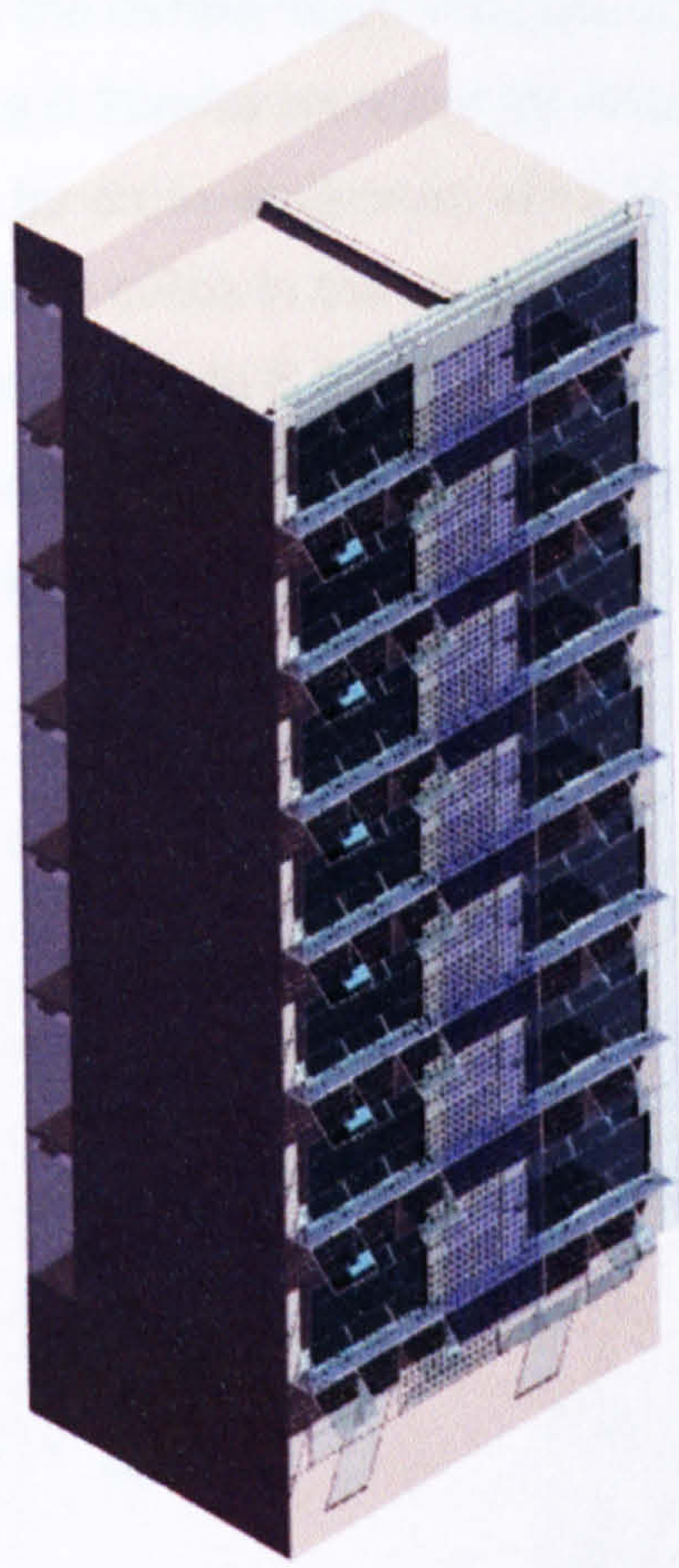

Fig. 5.38 Model 7
Office windows opened / double skin windows opened / corridor air supply, segment of the case study building modelled

Model M7 has low level office windows closed, upper level office windows opened, double skin façade opened at top and bottom and at the first and seventh floor, and fresh ambient air taken from the roof level, passed though cold-water coils in the air-handling unit, distributed via a system of vertical and horizontal ducts in corridors, and introduced in offices through grills below the ceiling [Fig. 5.39 and Fig. 5.40]. A critical theoretical aspect of this model is to achieve adequate cooling of the mechanically supplied air during peak summer conditions without resorting to full air conditioning.

In the air-handling unit, the ambient air temperature when passed through cold-water coils, is assumed to be reduced to 20°C at the point of delivery to the offices. Taking the peak ambient temperature of about 27°C, and mains water in summer at about 12°C, a reasonably efficient 'air to water' heat exchanger should be able to reduce the air temperature to 18°C or less. Allowing for some rise between the exchange and delivery point, 20°C is thus considered a reasonable target. The control system was defined for the air-handling unit zone. On weekdays, it is set as free-floating from 0.00 am – 9.00 am. During office hours, 9.00am – 6.00pm, the air delivered to offices is at a temperature of 20°C. After 6.00pm until 0.00am the control is again free-floating. In offices, when the temperature reaches 23°C, the air at 20°C temperature is introduced at a $0.32m^3/s$ constant air-flow rate to each office on weekdays only [e.g. 4m/s for cross-sectioned area of $0.08m^2$], between 9.00am and 6.00pm. Since each office in the simulation is $186m^3$, the volume flow rate of supply translates to 6.2ac/h. If all of this supply passes out through the window, without any air from the 'solar chimney' entering the room, this will constitute the total ventilation rate for the room.

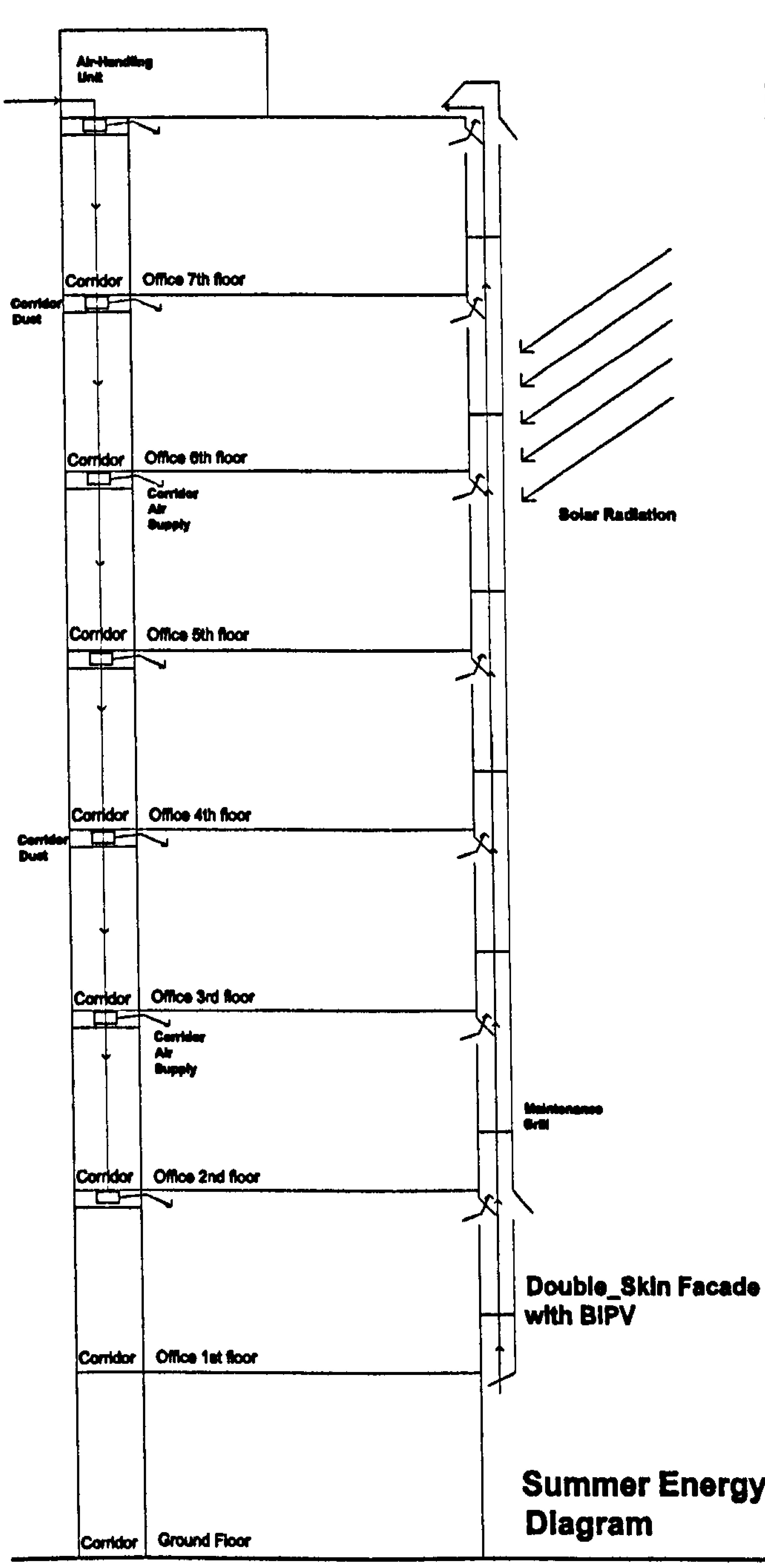

Fig. 5.39 M7 model summer energy diagram

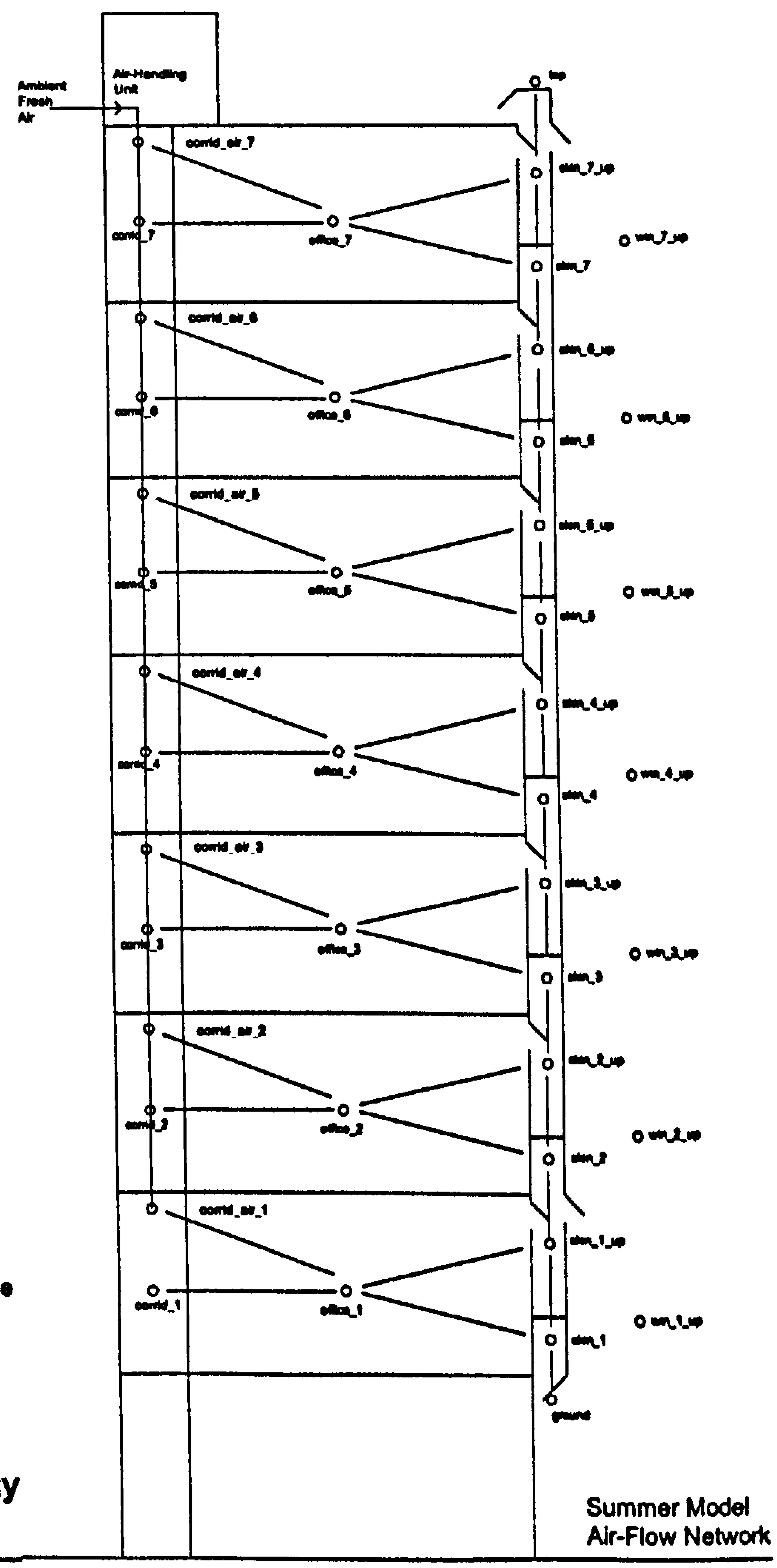

Fig. 5.40 M7 model summer air flow network

The simulation results [Fig. 5.41 and Fig. 5.42] have shown that the mid-day temperature in offices is reduced to close to 25°C. They have hence indicated that with a combination of a naturally ventilated buffer space and additional fresh air supply to offices from the corridor side, passively cooled by water supplied at normal 'summer mains' temperature, it is possible to keep office internal temperature in the upper level of a comfort zone during hot summer conditions.

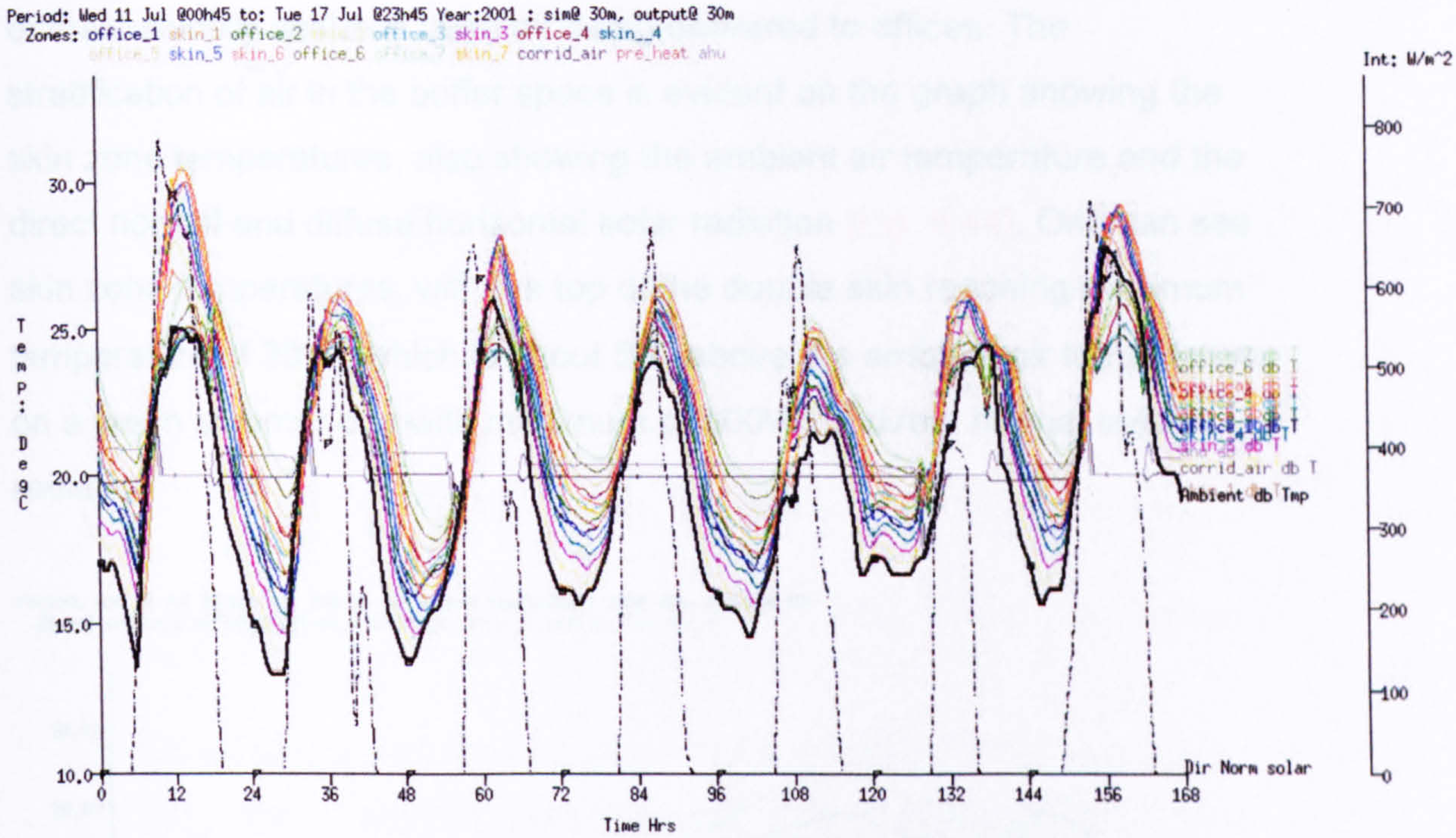

Fig. 5.41 M7 model summer critical week temperature in all zones, ambient air temperature and direct normal solar radiation

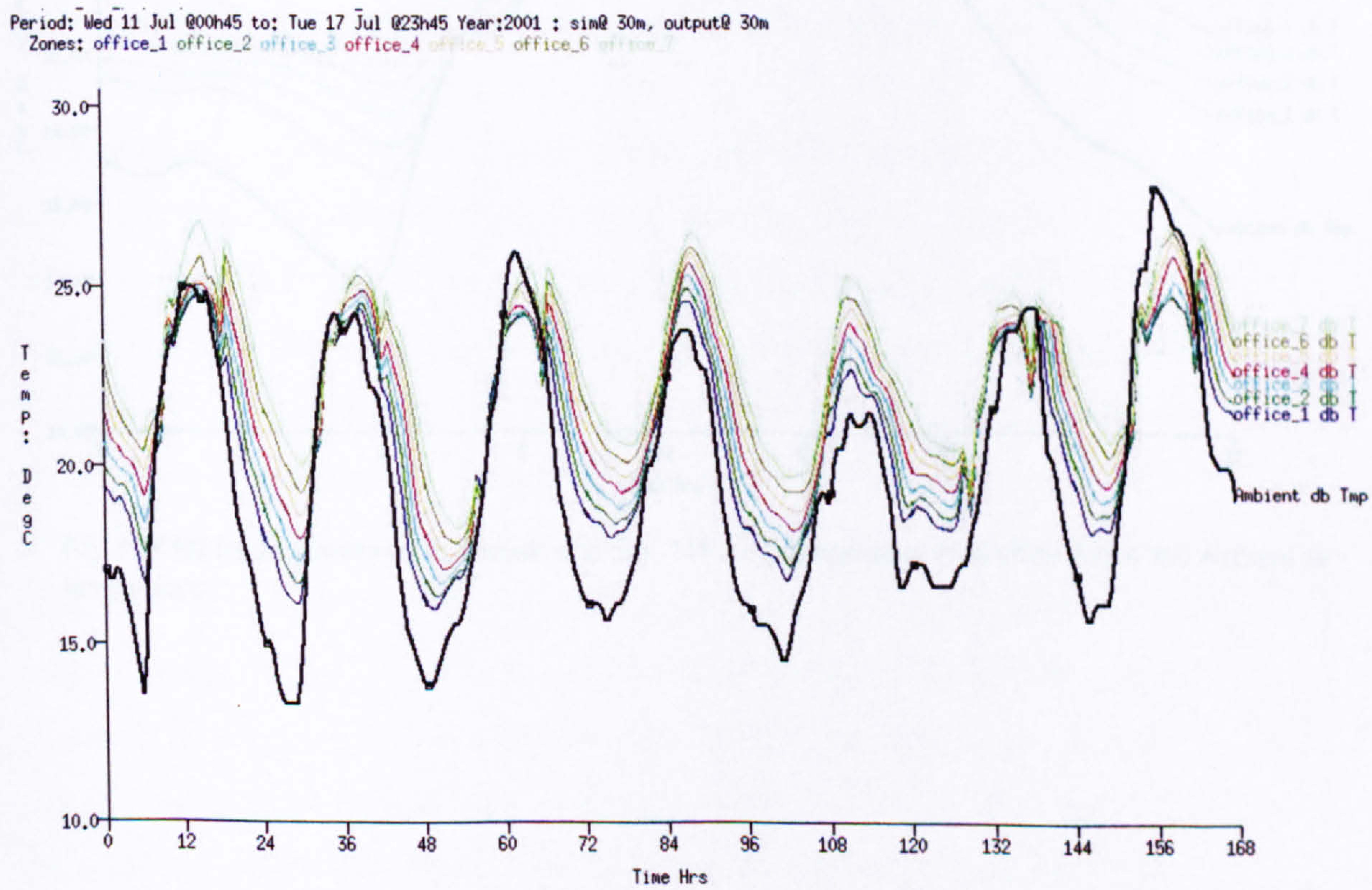

Fig. 5.42 M7 model summer critical week temperature in all office zones and ambient air temperature

A closer look on the one-day [11th July] temperature profiles [Fig. 5.43] in all office zones shows offices temperatures reaching 25°C to 26°C during working hours. One can also see offices temperatures slightly rising from the first to the top seventh floor as a result of the stratification effect in the double skin buffer space, from where some air entering offices through office windows is mixed with office air, having an effect on the offices temperature. This is more noticeable outside working hours, which coincides with the lack of mechanically assisted fresh air being delivered to offices. The stratification of air in the buffer space is evident on the graph showing the skin zone temperatures, also showing the ambient air temperature and the direct normal and diffuse horizontal solar radiation [Fig. 5.44]. One can see skin zone temperatures, with the top of the double skin reaching maximum temperature of 30°C, which is about 5°C above the ambient air temperature on a warm summer day with maximum of 800W/m^2 direct normal solar radiation.

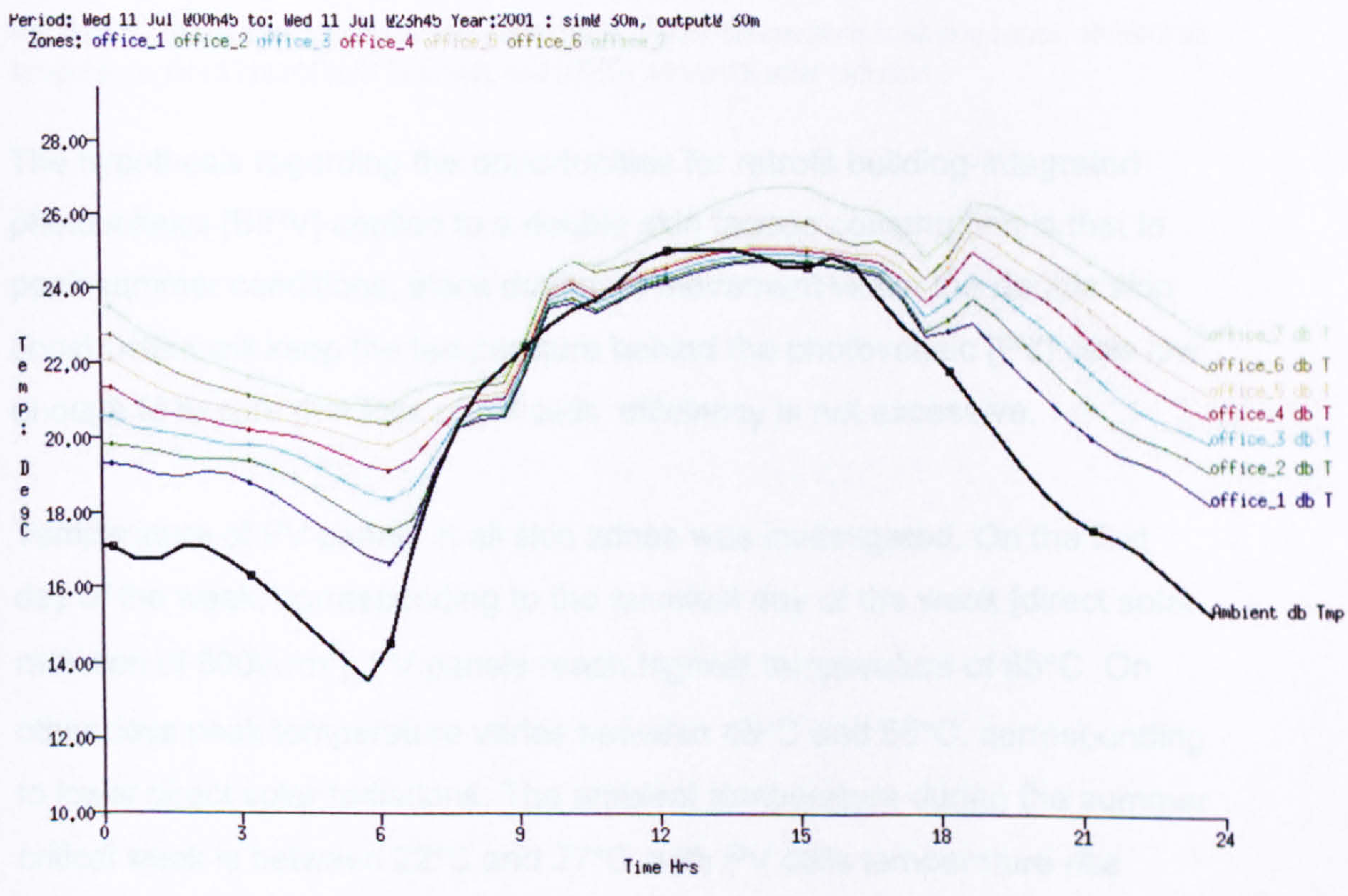

Fig. 5.43 M7 model summer critical week, one day, 11th July, temperature in all office zones and ambient air temperature

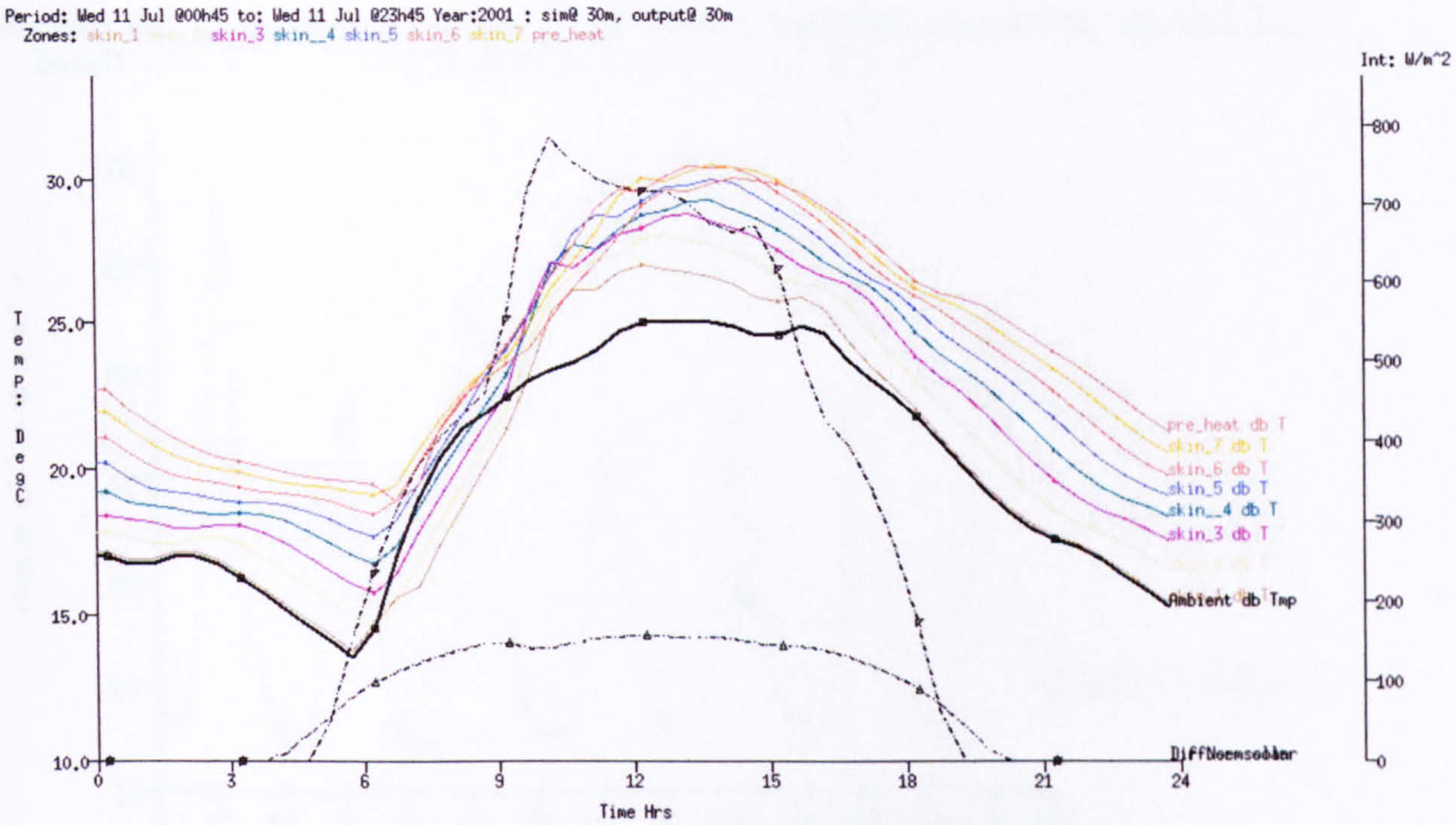

Fig. 5.44 M7 model summer critical week, one day, 11th July, temperature in all skin zones, ambient air temperature, direct normal solar radiation, and diffuse horizontal solar radiation

The hypothesis regarding the opportunities for retrofit building-integrated photovoltaics [BIPV] applied to a double skin façade construction is that in peak summer conditions, stack driven air movement within the double skin construction will keep the temperature behind the photovoltaic [PV] cells low enough to ensure that loss of PV cells' efficiency is not excessive.

Temperature of PV panels in all skin zones was investigated. On the first day of the week, corresponding to the sunniest day of the week [direct solar radiation of 800W/m^2], PV panels reach highest temperature of 65°C. On other days peak temperature varies between 45°C and 55°C, corresponding to lower direct solar radiations. The ambient temperature during the summer critical week is between 22°C and 27°C, with PV cells temperature rise above ambient temperature mainly about 20°C to 25°C, with exception of days with high direct solar radiation. If one takes that mono-crystalline PV cells efficiency is just below 14% for cells temperature of 45°C, followed by above 12% efficiency for cells temperature of 55°C, and efficiency of just below 12% for cells temperature of 65°C [CIBSE, 2000, p.4], then the theoretical loss in PV efficiency due to PV temperature in the case of the double skin façade in summer is about 2%. One could conclude that stack driven air movement within the double skin construction does not cause excessive loss in BIPV efficiency, given that the typical Scottish summer seldom corresponds to the conditions of this test week.

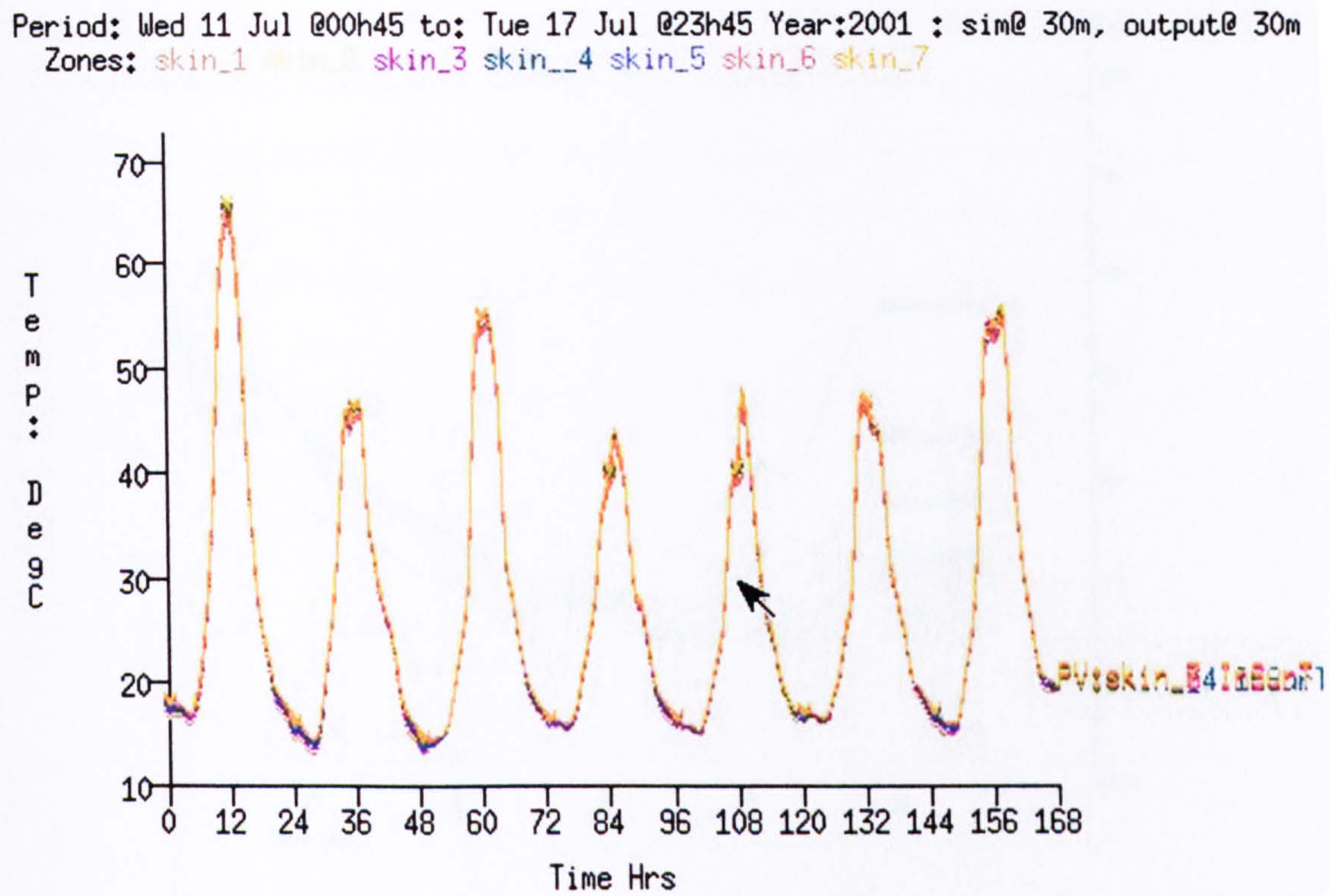

Fig. 5.45 M7 model summer critical week, PV cells temperature.

The model M7 has shown temperature in offices in the upper level of a comfort zone during hot summer conditions. Another aspect of the comfort level in rooms is the relative humidity [relative humidity = vapour pressure divided by the saturated vapour pressure]. Figure 5.45 shows the relative humidity in each office zone, and the ambient relative humidity during the working day. One can see the relative humidity in offices during working hours is between 50% and 70%, [Fig. 5.46, Psychometric chart], which goes above the area of recognised optimal humidity, of between 50% and 60%. However, the highest level of relative humidity in offices is at the beginning of the working hours, and is reduced to around 60% at midday, and further to 50% by the end of the working day. Although the relative humidity level is rather high, it is probably tolerable as it is occurring for a part of the day, and assuming some 'adaptive opportunity' from the occupants, e.g. desk fans increasing movement of air, or a solution of passive fans.

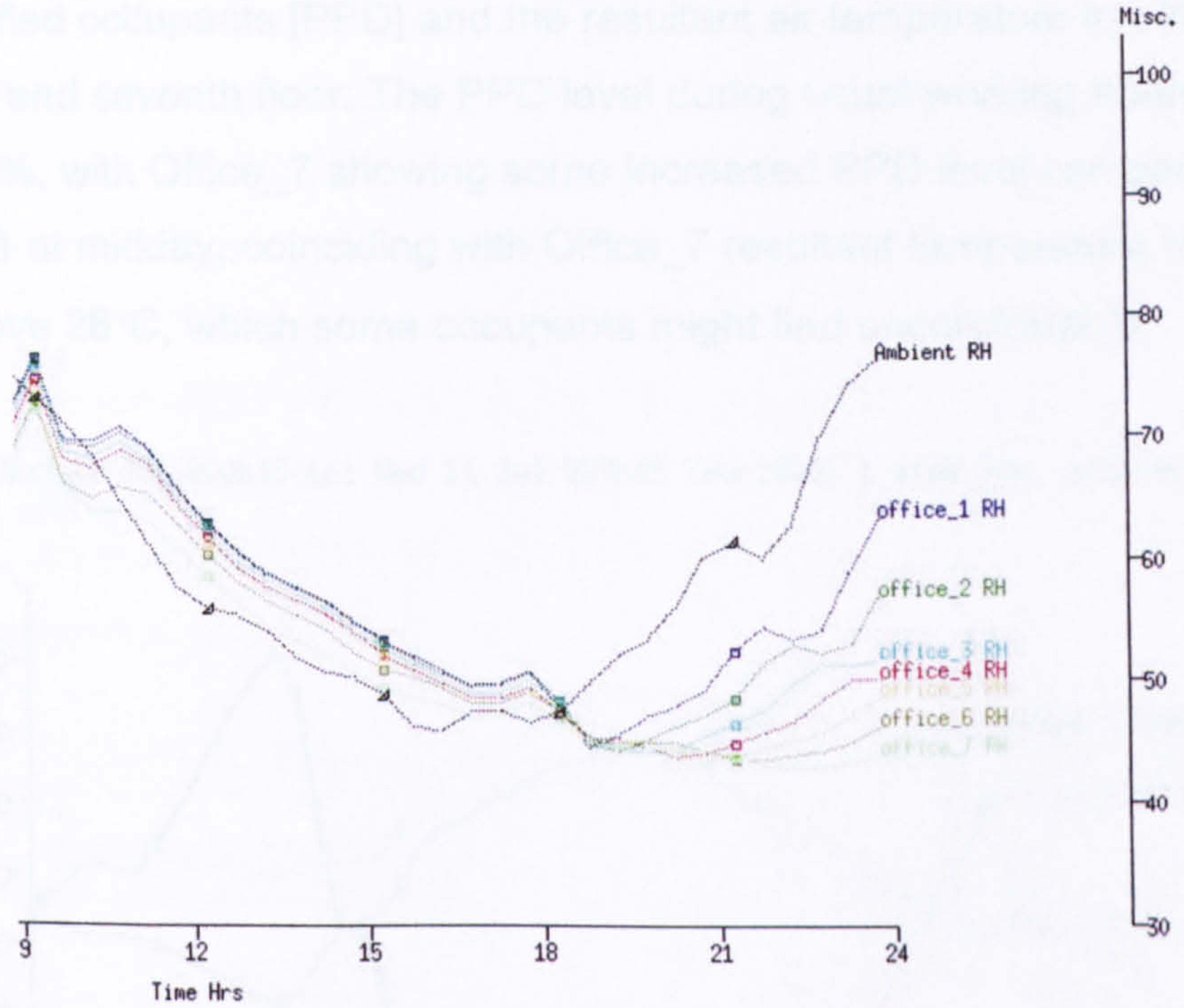

Fig. 5.46 M7 model summer critical week, one day, 11th July, relative humidity in all office zones and ambient air relative humidity

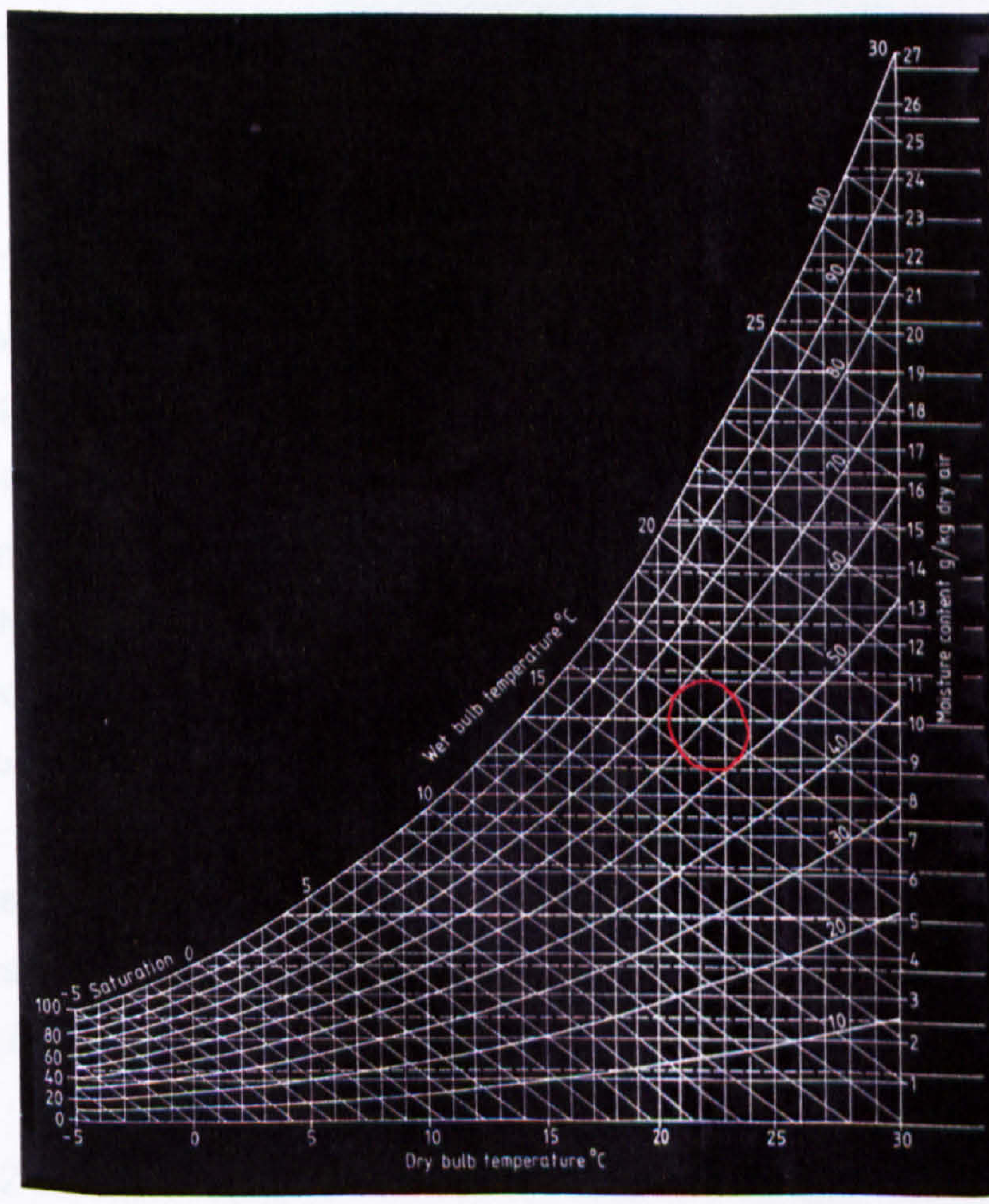

Fig. 5.47 M7 model summer critical week, one day, 11th July, Psychometric chart of relative humidity in all office zones

In terms of number of people being potentially dissatisfied from offices thermal conditions, Fig. 5.47 graphically shows the percentage of dissatisfied occupants [PPD] and the resultant air temperature in offices on the first and seventh floor. The PPD level during usual working hours is less than 20%, with Office_7 showing some increased PPD level compared to Office_1 at midday, coinciding with Office_7 resultant temperature reaching just above 26°C, which some occupants might find uncomfortable.

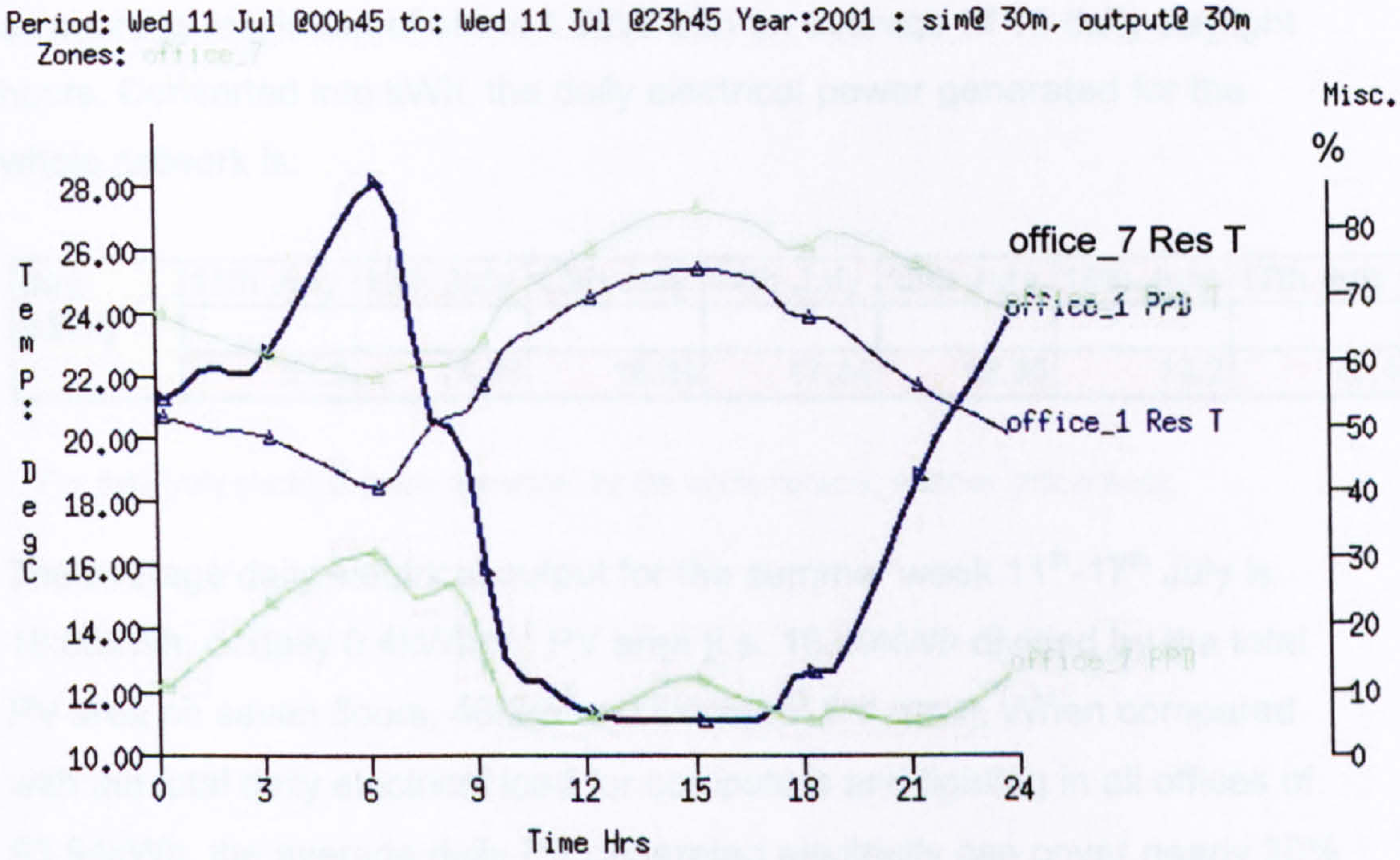

Fig. 5.48 M7 model summer critical week, one day, 11th July, Percentage Dissatisfied in Office_1 and Office_7 zones, and Resultant Air Temperature in Office_1 and Office_7 zones

The modelling results of the model option with naturally ventilated double skin façade and offices with additional mechanical supply of fresh air to offices, for the summer critical week, have shown office temperatures reaching maximum 25°C to 26°C during office working hours. It is therefore reasonably to assume that temperature in offices during the whole summer season would be within the comfort zone, with only few days with office temperatures reaching the upper level of the comfort zone.

Another, similar option of the Model 5 was tested, with lower office windows opened as well as upper. The results were not significantly different, therefore it is not necessary here to show the temperature graph.

5.2.8 SUMMER ELECTRICAL CONTRIBUTION FROM BIPV

The BIPV electrical network was simulated for the summer critical week. The network was developed to represent the electrical network of the BIPV panels, enabling simulations for the electricity generated from PV panels integrated in the double skin. The electrical network can be described as a collection of nodes [control volumes], which represent the junction between conducting elements and/or points where power is added or extracted, and nodes that are connected by electrical components such as cables, lines, transformers, switchers, inverters, etc. [Kelly, 2000, pp.2029-2032].

The PV electrical network simulation results for the summer critical week [Fig. 5.48] have shown an energy flow generated from the whole network of an average maximum of about 1.2kW with an average of 15 daily daylight hours. Converted into kWh, the daily electrical power generated for the whole network is:

Day [kWh]	11th July	12th July	13th July	14th July	15th July	16th July	17th July
	21.9	16.93	18.84	17.44	16.95	14.2	20.4

Fig. 5.49 Daily electrical power generated for the whole network, summer critical week

The average daily electrical output for the summer week 11^{th}-17^{th} July is 18.09kWh, or daily 0.4kWh/m^2 PV area [i.e. 18.09kWh divided by the total PV area on seven floors, 46.2m^2 = 0.4kWh/m^2 PV area]. When compared with the total daily electrical load for computers and lighting in all offices of 93.94kWh, the average daily PV generated electricity can cover nearly 20% of the electrical load defined in 5.1.3. However, if one omits 80% of the lighting load on the basis of daylight use in summer, this proportion would rise to 33%.

The average PV system efficiency, based on the summer critical week PV electrical network simulation results was also calculated, as a sum of the total weekly PV electrical output multiplied by 100 and divided by the total incident solar radiation falling on the vertical PV surface. The results were an average PV system efficiency of 10.9% and a maximum PV system efficiency of 12.4%. Having in mind that high efficiency, BP Solar Saturn, mono-crystalline PV cells were used in the modelling of the PV system network, and their expected theoretical efficiency due to PV cells temperature, the system efficiency results seems reasonable. However, they might be optimistic, if one has in mind the experience of the monitoring of PV installations applied on buildings described in Chapter 2. The examples have shown that PV systems predictions were always higher than measured. The urban reality of over-shading, air pollution, the PV system components performance [or the so called Balance of the System, B.O.S. accounting in cases to up to 20% loss in efficiency], and maintenance, all

have an effect on the efficiency, and should be considered when predicting the performance of a photovoltaic system.

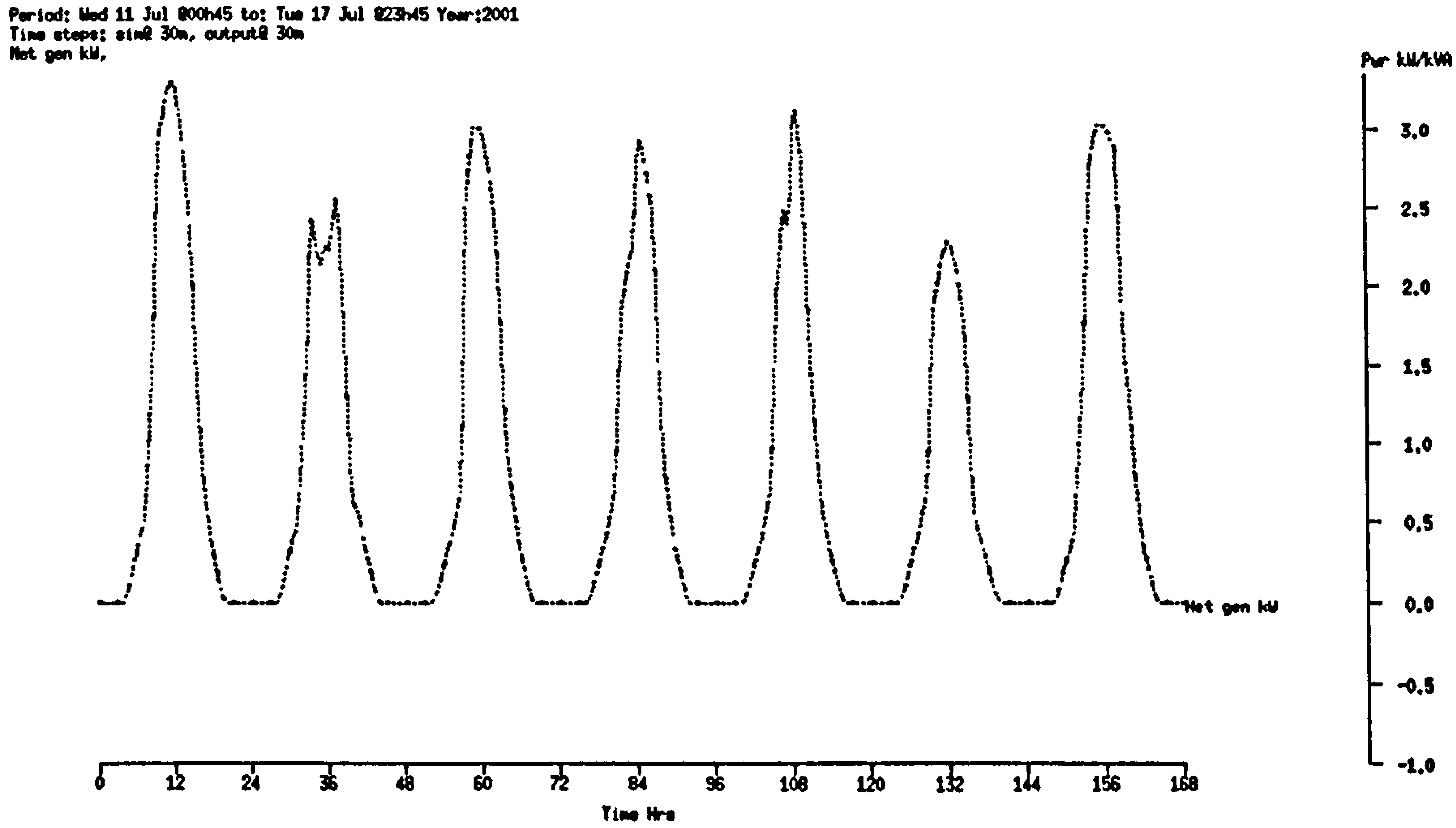

Fig. 5.50 Whole network results of the BIPV electrical network summer critical week simulation

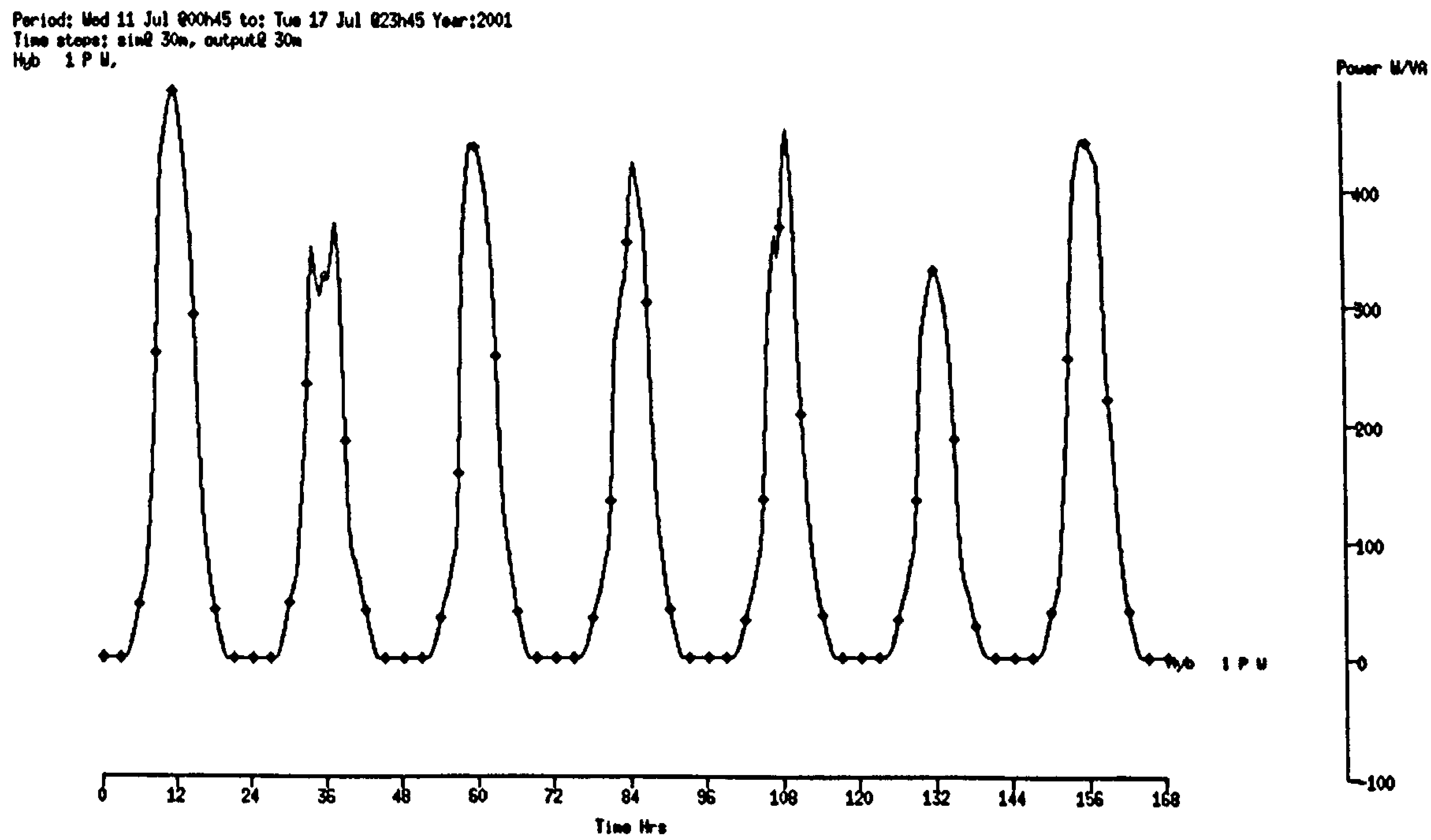

Fig. 5.51 One array results of the BIPV electrical network summer critical week simulation

5.3 CHAPTER 5 THERMAL AND ELECTRICAL SUMMER CRITICAL WEEK MODELLING RESULTS SUMMARY

- The summer critical week modelling of the existing, non-refurbished Graham Hills building [model M1] showed very high office temperatures both without and with natural ventilation provided.

- The summer critical week modelling of the improved Graham Hills building, but without the double skin façade with BIPV [model M2], showed up to 10°C reduced office temperatures compared to the non-refurbished case. However, office temperatures were still high above the comfortable level.

- The results of the improved Graham Hills building with the double skin façade with BIPV [model M3] and no windows open, represents a theoretical worst-case scenario of the building, with very restricted ventilation. It was taken as a starting point for further exploration of the double skin façade thermal performance.

- The model M4 explores an option of natural ventilation in the double skin façade, where the office windows are closed and double skin windows top and bottom are opened. The simulation results have shown reduced temperature in all double skin zones when compared to model M3, falling close to the ambient temperature, while temperatures in all office zones are still very high and reach peak mid-day maximum of 45°C. The temperature profile of each double skin zone shows an incremental increase in temperature as one goes upwards from the skin zone on the first floor to the skin zone on the seventh floor. This confirms a stratification of warm air occurring in the buffer space, where the hottest air rises at the top of the façade

- The model M5 has lower office windows closed, upper office windows opened, and double skin windows closed. The simulation results have shown peak mid-day temperature in offices still high above the comfort level. The rationale of this model is to introduce the influence of air mixing between offices and the double skin zone and serves to emphasise the risk of a system, i.e. opening devices for the external skin not functioning for some reason.

- The model M6 has the office lower and upper windows opened, and bottom and top openings in the double skin space opened. The addition of the double skin façade with BIPV on the thermally improved Graham Hills building energy model showed summer critical week office temperatures 10°C higher than in the case without the double skin façade component. Consequently, one may conclude that the presence of the double skin façade is a serious factor for summer overheating in offices. However, the advantage of the double skin façade structure is in reducing the noise level in offices so that users can open windows without disturbance. The summer critical week modelling of the model M6 showed that with only a means of natural ventilation, the peak day temperatures in offices reach below 40°C. This made the case for combining the natural ventilation of the double skin and offices, with additional mechanically introduced fresh air into offices from the corridor side

- The modelling of the naturally ventilated double skin façade with mechanically supplied air to offices at 20°C [model M7], proved to be able to reduce temperature in offices during working hours to 25°C to 26°C. The supply temperature of 20°C is considered achievable on a hot summer day without resorting to use of chillers, but using mains water at normal temperature as the cooling agent. Having in mind that the modelling was the 'worst case' summer scenario, it is therefore reasonable to assume that the temperature in offices throughout the whole summer season would stay within a comfortable thermal zone. In favour of this ventilation strategy is the dual function of air-handling units, also valuable for ventilation preheat in winter. The benefit of this strategy, apart from achieving comfort in offices, is improved air quality in corridors, and the use of PV generated electricity to run the fans for the air supply. This mixed-mode ventilation strategy, combined with the double skin façade technique and improved external envelope thermal performance has tackled one of the most serious environmental problems of the case study building, the severe overheating in the south facing offices. [The modelling has shown that overheating would occur with or without the extra glass skin in the absence of mechanical assistance].

- The hypothesis regarding the opportunities for retrofit building-integrated photovoltaics [BIPV] applied to a double skin façade construction is that in peak summer conditions, stack driven air movement within the double skin construction will keep the temperature behind the photovoltaic [PV] cells low enough to ensure that loss of PV cells' efficiency is not excessive. The investigation of PV cell temperature in all skin zones of the last model has shown that the highest temperature is 65°C on the sunniest day of the week [direct solar radiation of 800W/m^2], and temperatures are between 45°C and 55°C during the rest of the week, corresponding to lower direct solar radiation. If one takes that mono-crystalline PV cells efficiency is just below 14% for cells temperature of 45°C, followed by above 12% efficiency for cells temperature of 55°C, and efficiency of just below 12% for cells temperature of 65°C [CIBSE, 2000, p.4], then the theoretical loss in PV efficiency due to rise in PV temperature in this case is about 2%. One could conclude that stack driven air movement within the double skin construction does not cause excessive loss in their electrical performance.

- The PV cells integrated in to the double skin façade performed well during summer. The generated electricity could be directly used in offices due to the good match between the solar availability, and demand for electricity during offices working hours. The modelling showed that up to 20% of the daily electrical load for computers and lighting in offices [excluding fans delivering fresh air to offices], or the whole energy needed to run fans and part of the computers and lightings load could come from the PV system. The PV electrical network modelling results showed the PV system efficiency, over the summer critical week, to have an average 10.9% and maximum 12.4%. For the PV cells specified, the results falls within the theoretical PV efficiency due to operating temperature. However, it should be born in mind that the monitoring results of other European buildings have shown lower PV system efficiency than is usually predicted when based on computer simulations.

The following part of this thesis continues with testing the double skin façade with BIPV refurbishment solution and focuses on the thermal and electrical energy modelling for winter critical week.

5.4. CHAPTER 5 REFERENCES

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TESTING THE DOUBLE SKIN FAÇADE WINTER MODELLING

6

CHAPTER 6

TESTING THE DOUBLE SKIN FAÇADE

WINTER CRITICAL WEEK MODELLING

CLIMATE DATA

A winter critical week was selected from the typical year climate data for Kew 1967, and modified for Glasgow with a longitude difference –4.10 and latitude 56.0. The winter critical week is from 3rd to 9th January with a lowest mid day temperature on 8th January of –1.9°C [Fig. 6.1].

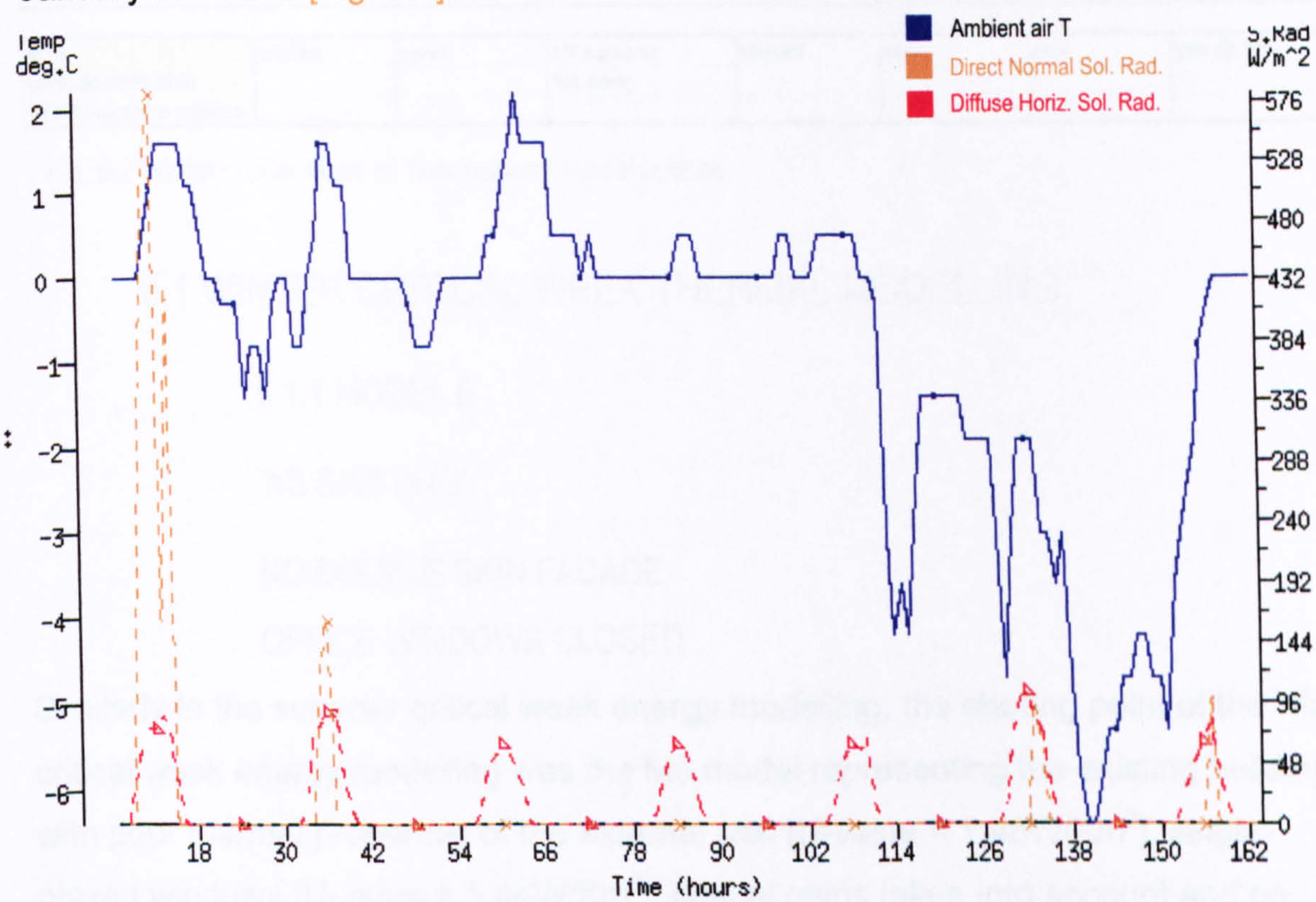


Fig. 6.1 Winter critical week [3rd – 9th January] ambient air temperature, direct normal and diffuse horizontal solar radiation [W/m²]

AIR-FLOW NETWORKS

The winter critical week thermal performance of the Graham Hills building was tested with three air-flow network models representing various model options, as shown in [Fig. 6.2]. The model M8 'as existing', represents the non-refurbished option with poor thermal properties of the typical office with the same surface attributes as in the M1 'As existing' model of the summer critical week energy modelling (weekend days on the fourth and fifth day of the critical winter week) [Chapter_5]. The model M9 'improved', represents the refurbished option with improved insulation, higher performance windows of the typical office and no double skin façade [same surface attributes as per summer model M2 'improved', Chapter_5]. Models M10 and M11 represent the refurbished option with addition of the double skin façade and correspond to surface attributes of models M3 to M7 in the summer energy modelling.

MODELS WINTER	Office low wdws	Office upper wdws	Skin top/down	Skin wdws	Casual Gains	AH_unit to Corridor_Air	Corrid_air_supply to Offices	Controls
M8 'As existing' no double skin	closed	closed	n/a	n/a	yes	no	no	no
M9 'Improved' no double skin	closed	closed	n/a	n/a	yes	no	no	no
M10 with double skin	closed	open	1/3 open at 1st floor	closed	yes	no	no	no
M11 with double skin pre-heat air to offices	closed	open	1/3 open at 1st floor	closed	yes	yes	yes @ 23C	yes

Fig. 6.2 Winter critical week air flow network model options

6.1 WINTER CRITICAL WEEK THERMAL MODELLING

6.1.1 MODEL 8

'AS EXISTING'

NO DOUBLE SKIN FACADE

OFFICE WINDOWS CLOSED

Similarly to the summer critical week energy modelling, the starting point of the winter critical week energy modelling was the M8 model representing the existing building with poor thermal properties of the external wall [U-value = 1.48W/Km^2], single-glazed windows [U-value = 5.44W/Km^2], casual gains taken into account and no double skin facade. The air-flow network had all office windows closed and background ventilation allowed only through crack openings in windows.

The winter critical week 'free-floating' simulation results (without heating) [Fig. 6.3] have shown peak mid-day temperature in offices reaching 20°C on 3rd January, which was a cold but sunny day [600W/m^2 direct solar radiation], and 11°C on other working days with low ambient temperature and very low direct solar radiation. The temperature of the Office_7 has a significantly lower temperature compared to other offices as a result of the top floor location and a roof exposed to ambient conditions.

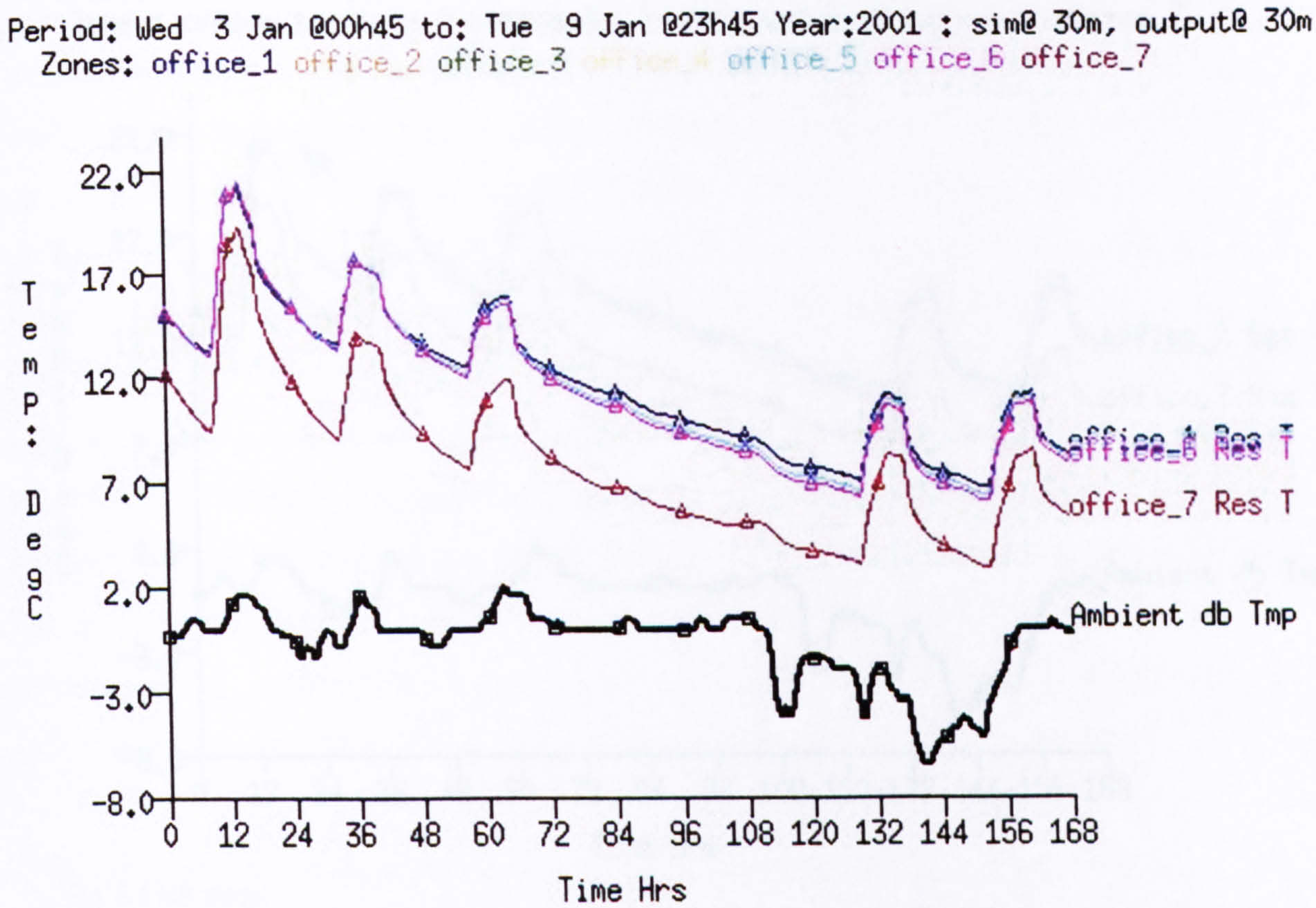


Fig. 6.3 M8 model
Winter critical week, temperature in all office zones and ambient air temperature.

6.1.2 MODEL 9

'IMPROVED'

NO DOUBLE SKIN FAÇADE

OFFICE WINDOWS CLOSED

The model M9 has the external wall thermally improved with U-value = 0.33W/Km^2 and better energy performing double-glazed windows with U-value = 2.56W/Km^2. The air-flow network had again specified all office windows closed and background ventilation allowed only through crack openings in windows. Specifying the same air-flow network as in the M8 model was deliberate to find out the temperature difference in offices due to thermal improvement of the building fabric. Fig. 6.4 shows the winter week energy simulation results. Compared to previous model M8 [without the thermal improvements], the temperature in offices in this model M9 is noticeably, but not significantly, higher throughout the whole winter week. On the 3rd January, peak mid-day temperature is 22°C and on 5th January peak mid-day temperature is 19°C. The temperature of the top-floor office is again lower than temperature in other offices, but nevertheless, higher than in the non-refurbished case of the model M8.

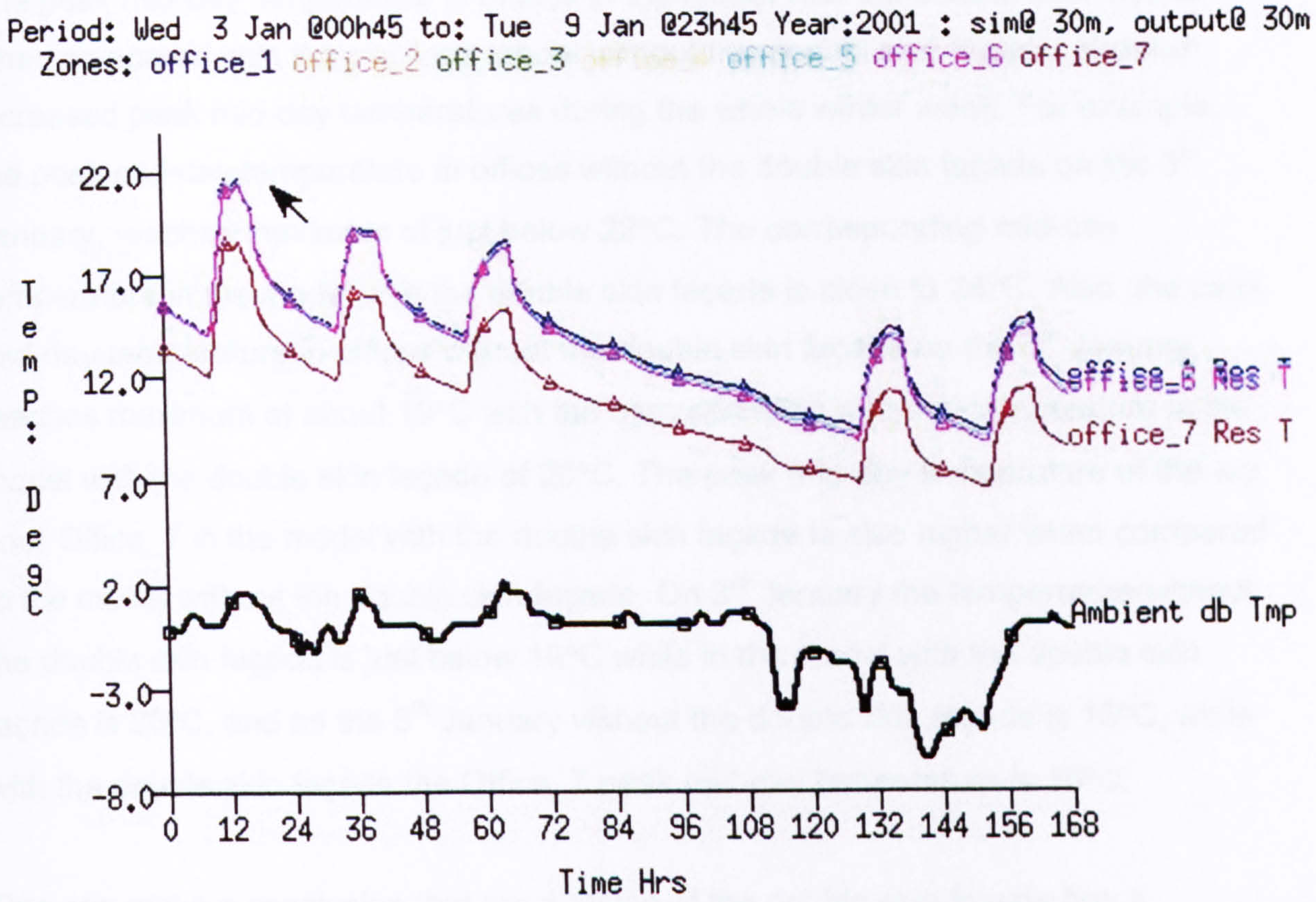


Fig. 6.4 M9 model
Winter critical week, temperature in all office zones and ambient air temperature.

6.1.3 MODEL 10

WITH DOUBLE SKIN FAÇADE

The model M10 was a natural progression of the M9 model, with the same specification of improved thermal properties, but with addition to the double skin façade. The winter critical week simulation and a comparison with the model M9 results showed difference in offices temperatures due to addition of the secondary skin construction in front of the offices' south façade. Here, the double skin construction was specified as a passive buffer, without taking the pre-heat air from the double-skin façade. The air-flow network had lower office windows closed but upper office windows opened towards the double skin façade buffer space. Air mixing was allowed between offices and the double skin only, while background infiltration was allowed only through crack openings of the double skin façade and ambient air.

The simulation results [Fig. 6.5] have shown temperature in offices and double skin zones slightly rising from lower to upper floors as a result of the stratification effect in the double skin buffer space, from where some air entering offices through upper office windows is mixed with office air, having some effect on offices temperature.

The peak mid-day temperature in offices in the model with the double skin façade when compared with the previous model without the double skin façade, showed increased peak mid-day temperatures during the whole winter week. For example, the peak mid-day temperature in offices without the double skin façade on the 3rd January, reaches maximum of just below 22°C. The corresponding mid-day temperature in the model with the double skin façade is close to 24°C. Also, the peak mid-day temperature in offices without the double skin façade on the 5th January, reaches maximum of about 19°C with the corresponding mid-day temperature in the model with the double skin façade of 20°C. The peak mid-day temperature of the top floor Office_7 in the model with the double skin façade is also higher when compared to the model without the double skin façade. On 3rd January the temperature without the double skin façade is just below 19°C while in the model with the double skin façade is 20°C, and on the 5th January without the double skin façade is 15°C, while with the double skin façade the Office_7 peak mid-day temperature is 16°C.

One can make a conclusion that the addition of the double skin façade has a moderately positive effect on the thermal performance of offices in winter, with higher office temperatures due to reduced heat loss than in case with no double skin façade. This modelling also showed that temperature in all skin zones is constantly above the ambient air temperature, suggesting that the glazed cavity with southern exposure traps solar radiation the same way as a greenhouse or an atrium. This energy can be used for pre-heating supply air which is the subject of the next energy model. In other words we are moving from 'free floating' simulations, which clearly indicate a demand for heating, to a simulation where it is hoped that the air supply from the double skin, augmented by a heating coil, will provide the necessary load of comfort.

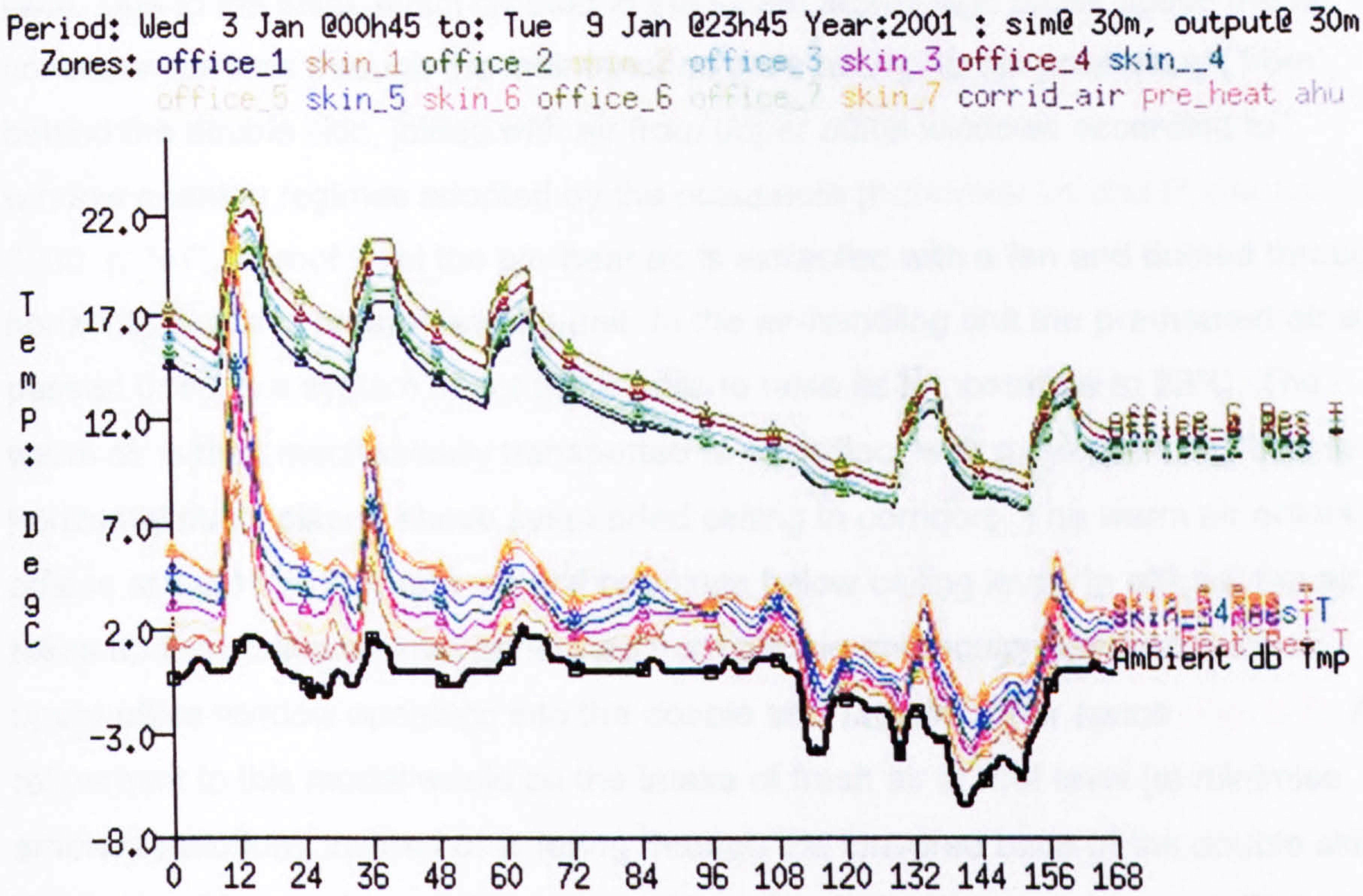


Fig. 6.5 M10 model
Winter critical week, temperature in all office zones and ambient air temperature.

6.1.4 MODEL 11

WITH DOUBLE SKIN FAÇADE / PRE-HEAT AIR SUPPLY TO OFFICES FROM CORRIDOR SIDE

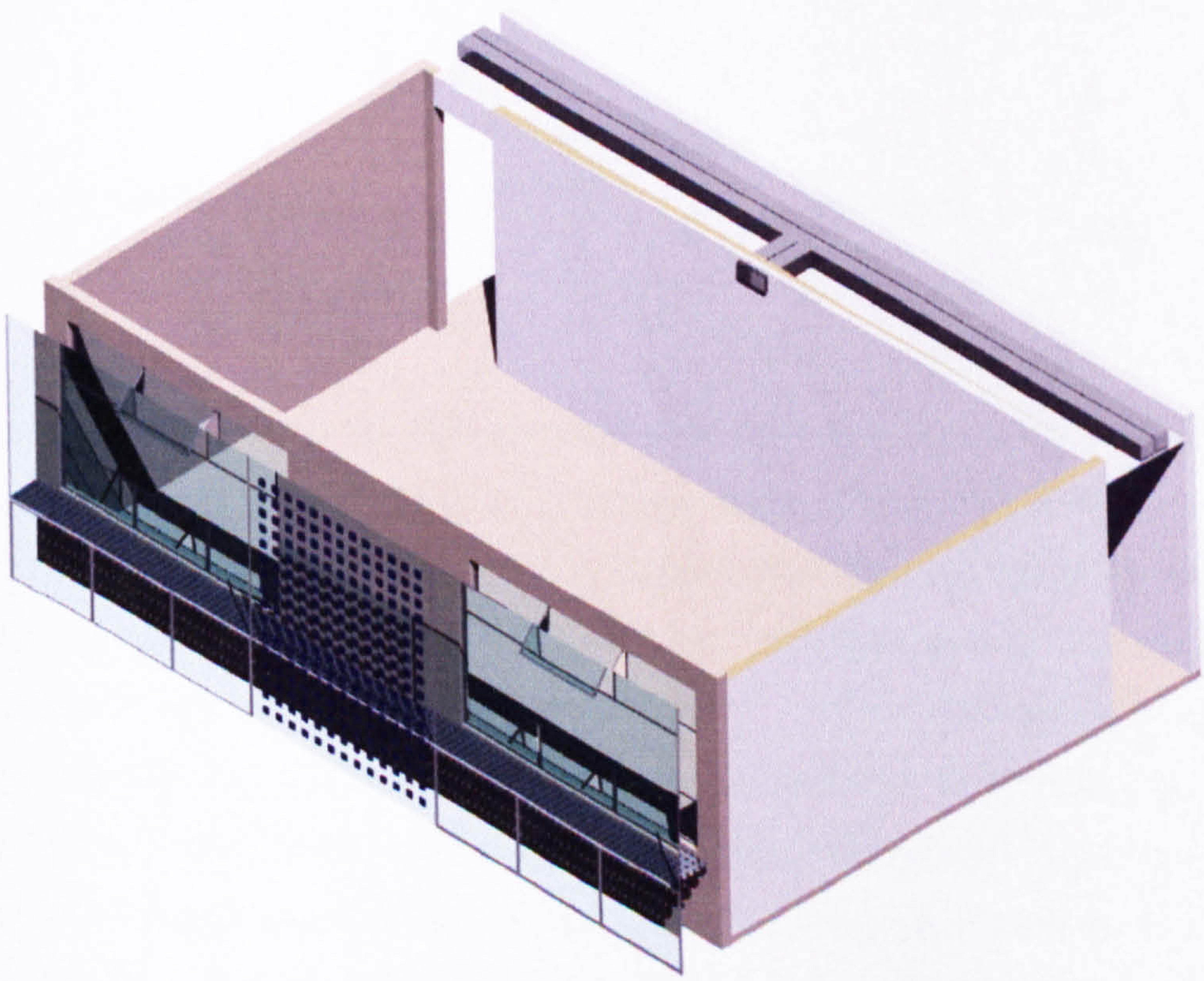


Fig. 6.6 M11 model

The incoming ambient cold air enters through the base of the double skin at first floor level. Due to the stack effect created in the seven storey high buffer space the air convects upwards through the maintenance grills taking up the pre-heat air from behind the double skin, joined with air from upper office windows according to window opening regimes adopted by the occupants [Kondratenko and Porteous, 2000, p.247]. At roof level the pre-heat air is extracted with a fan and ducted through horizontal ducts to an air-handling unit. In the air-handling unit the pre-heated air is passed through a system of hot water coils to raise its temperature to 23°C. The warm air is then mechanically transported to each floor with a system of vertical and horizontal ducts placed above suspended ceiling in corridors. The warm air enters offices at $0.32m^3/s$ flow rate via grill openings below ceiling level. In offices, the air takes up the additional heat generated from people and equipment and exits via upper office window openings into the double skin façade buffer space [Fig. 6.7]. A refinement to this model would be the intake of fresh air at roof level [to minimise ambient pollution], instead of entering through the louvered base of the double skin. However, although this would improve air quality, it would reduce energy efficiency.

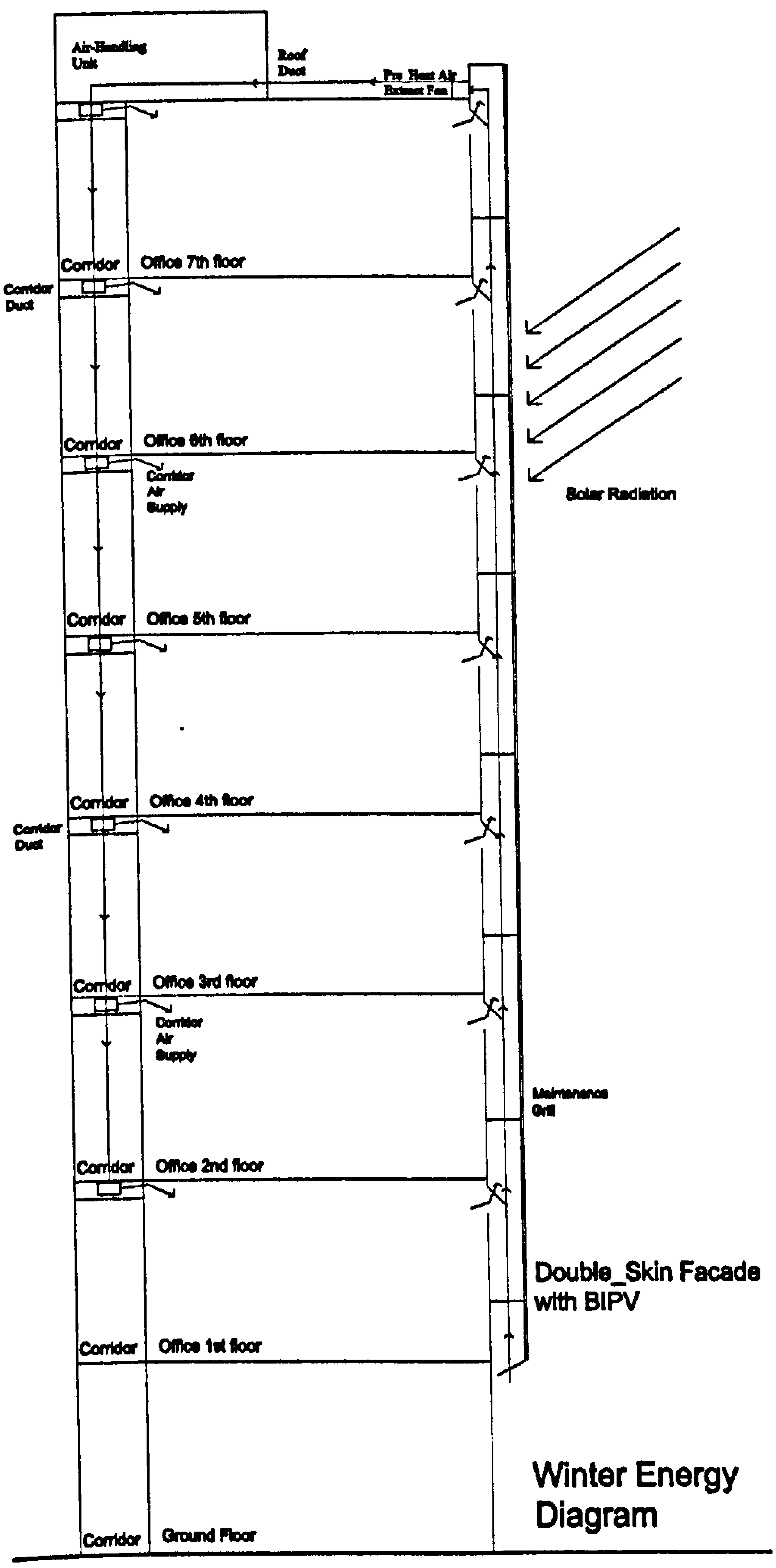


Fig. 6.7 M11model energy diagram

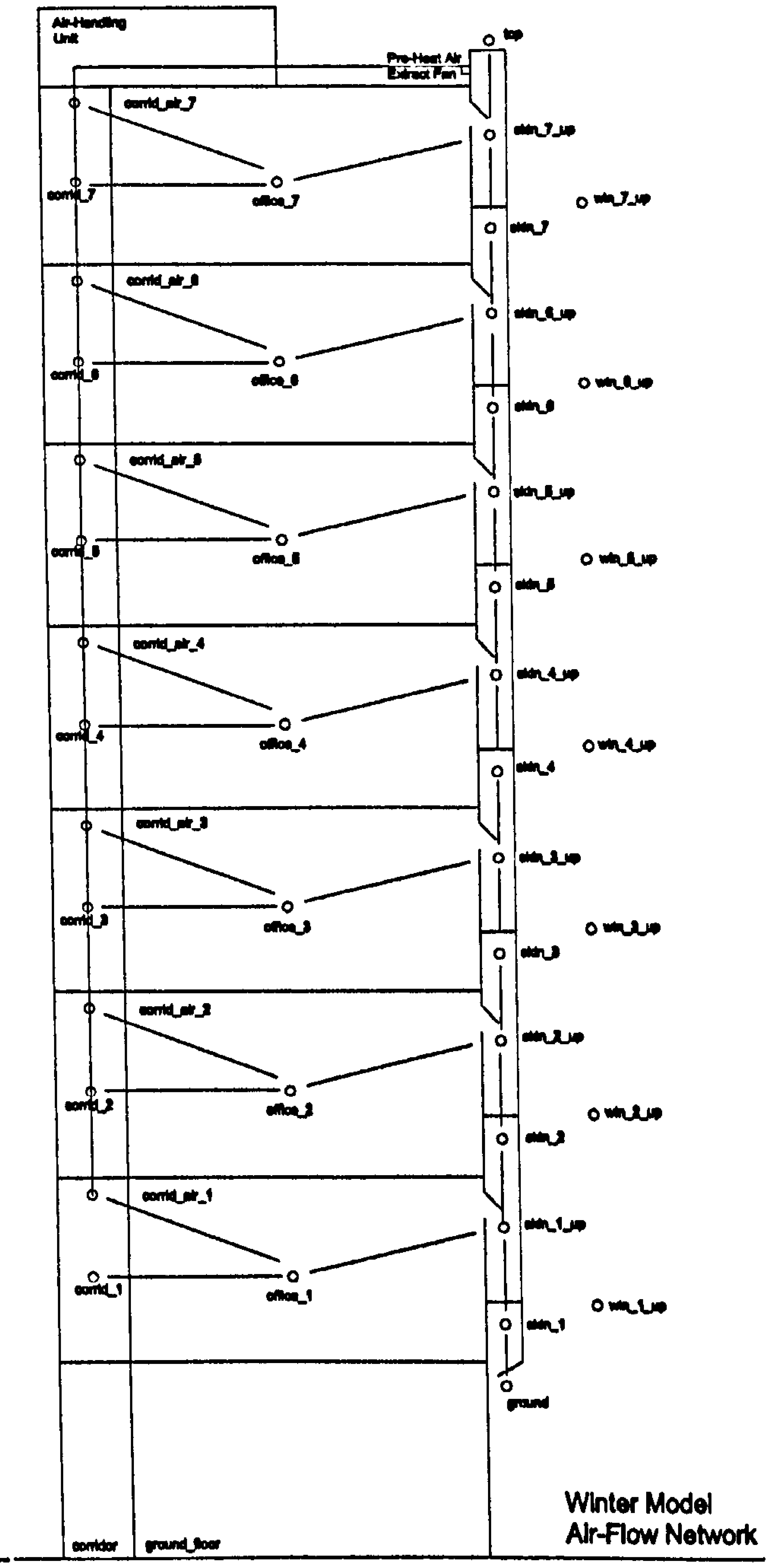


Fig. 6.8 M11 model air-flow network

An elaborated winter air-flow network was developed to represent the air movement between the outside and the double skin zone; between the skins on each floor up to the top level; between the pre-heat air extracted from the top of the double skin façade and the air-handling unit on the roof; and the warm air from the air-handling unit and corridor air-supply to offices [Fig. 6.8]. The control system was defined for the air-handling unit zone. On weekdays, it is set as free-floating from 0.00am – 7.00am. From 7.00am – 9.00am the air delivered to offices is pre-heated to 18°C. During office hours 9.00am – 6.00pm the air delivered to offices at an air rate of 0.32m^3/s and is heated to 23°C. After 6.00pm until 0.00am the control is again free-floating. The winter critical week thermal performance of the double skin façade component was tested with the winter model option as shown.

6.1.5 Model M11 RESULTS – OVERALL PREHEATING

Several model options of the model M11 were tested in ESP-r to both evaluate the pre-heat contribution from the double skin façade in winter and to isolate the thermal contribution from the BIPV relative to the overall pre-heat contribution. The first model M11 option simulates the pre-heat contribution of the double skin façades with BIPV panels with a winter-mode air-flow network as described in Fig. 6.8. The winter critical week simulation result graph [Fig. 6.9] shows the temperature in all zones of the model, the ambient air temperature, and the direct solar radiation. It can be seen that the 3rd January is a cold but particularly sunny day with direct solar radiation of close to 600W/m^2. On the other hand, the 5th January is a cold and overcast day with little direct solar radiation. The zones temperatures in all zones are lower on the fourth and the fifth day of the week due to weekend days, when offices casual gains are set to zero and the when air delivery system is non-operational. Also, the temperature of the skin on the first floor [graph skin 1] and the skin zone at the top of the double skin [preheat], has the lowest of all skin zones temperatures, due to being connected to the outside ambient air through a louvered base of the double skin at the first floor, and a glass surface at the top of the façade.

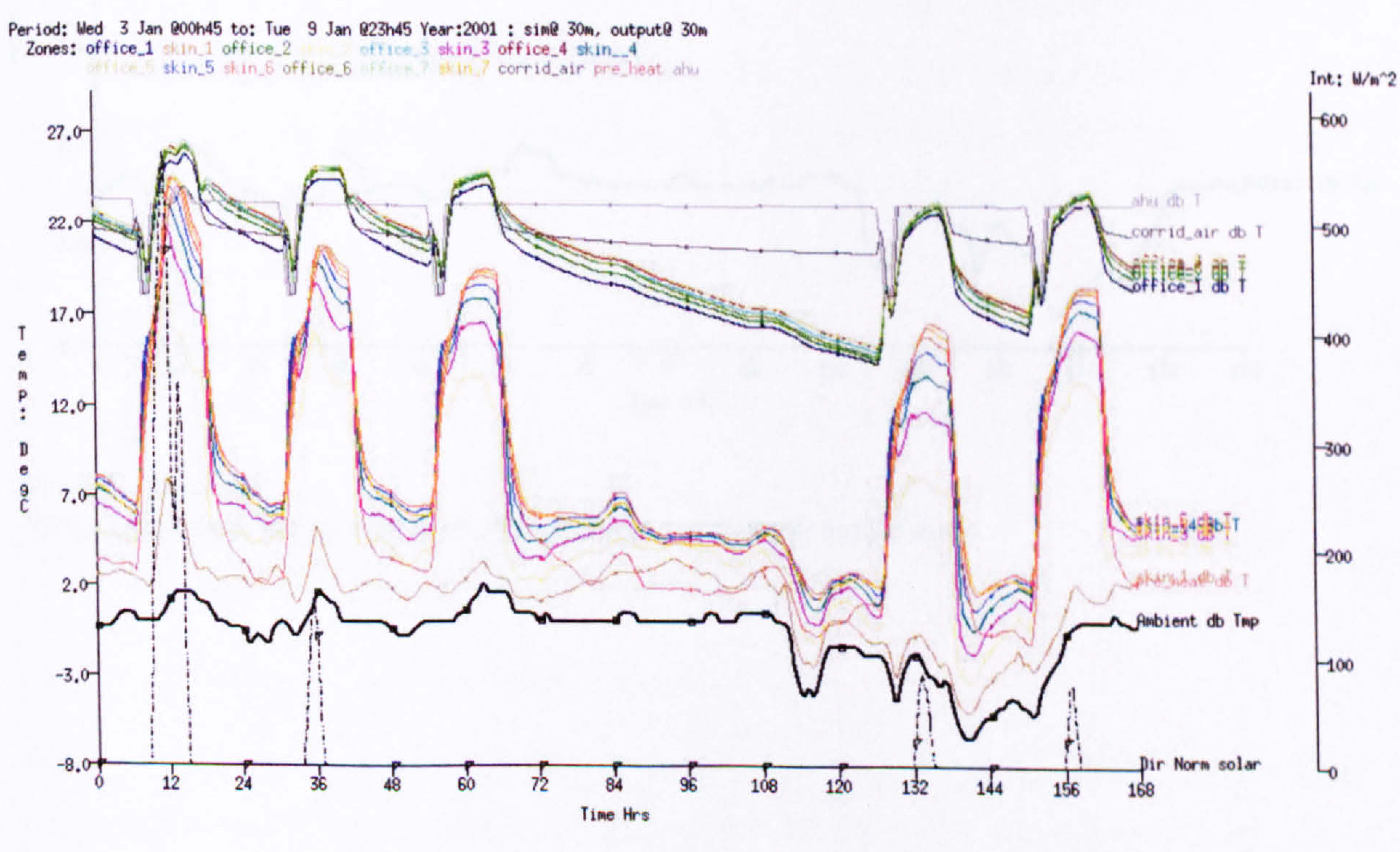


Fig. 6.9 M11 model
Winter critical week temperature in all zones, ambient air temperature and direct normal solar radiation

The temperature graph of all office zones [Fig. 6.10] shows temperature in all offices during weekdays working hours of up to 25°C, that is several degrees higher than necessary due to a combination of solar and casual gains. This suggests a refined demand control in the heating coil might be viable, for example a weather sensor to lower the setting in sunny conditions. The temperature profiles of all skin zones [Fig. 6.11] shows highest peak temperature of above 22°C on the first day of the simulation, 3rd January, when the solar radiation is particularly high for a winter day. On other weekdays, the peak skin zone temperatures are between 17°C and 21°C, which is also well above the ambient temperature even on days with very modest direct solar radiation. That suggests that the greatest part of the warm air in the double skin space comes from the offices, as air being lost into the buffer space through office windows.

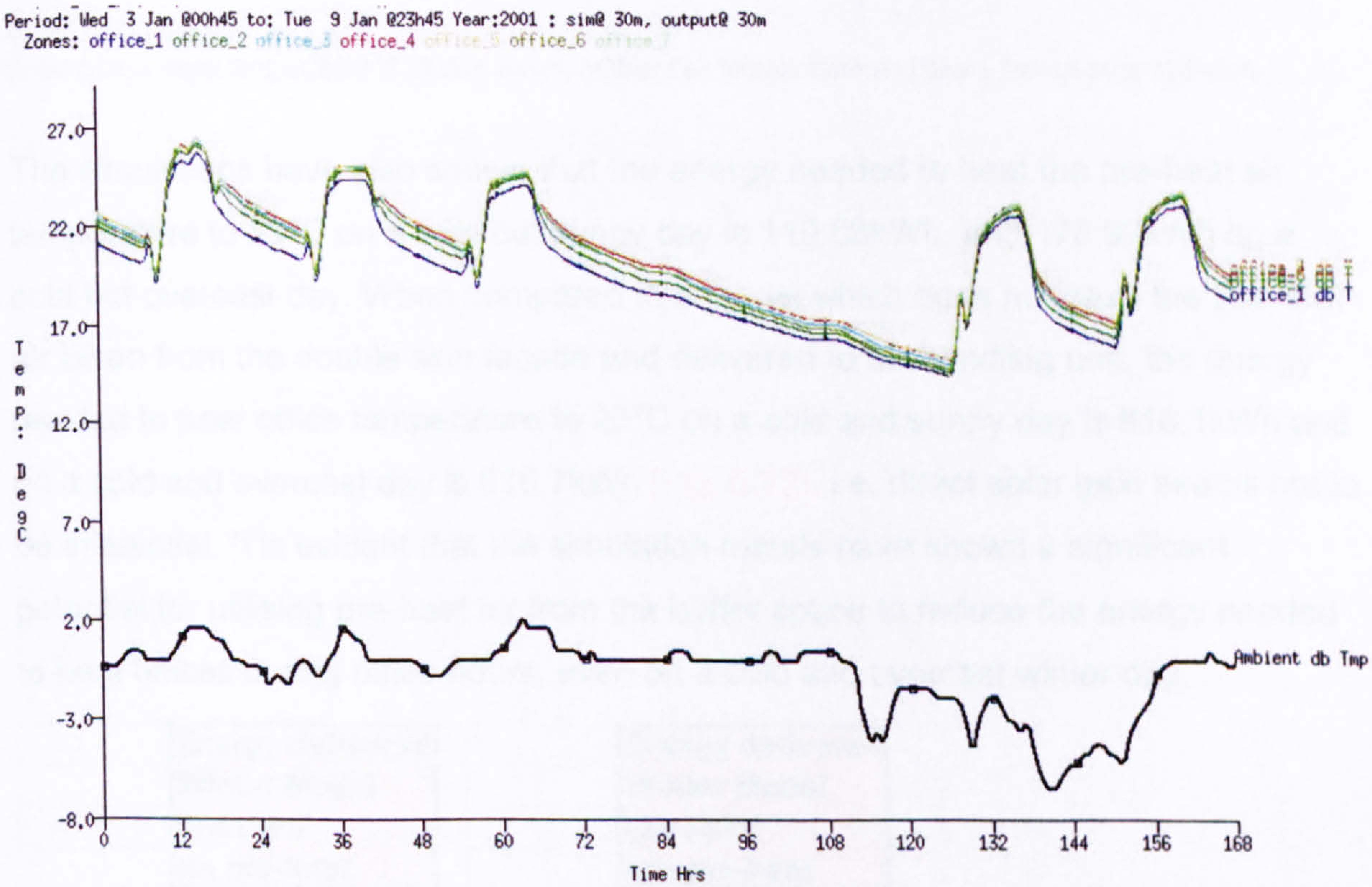


Fig. 6.10 M11 model
Winter critical week temperature in all office zones and ambient air temperature

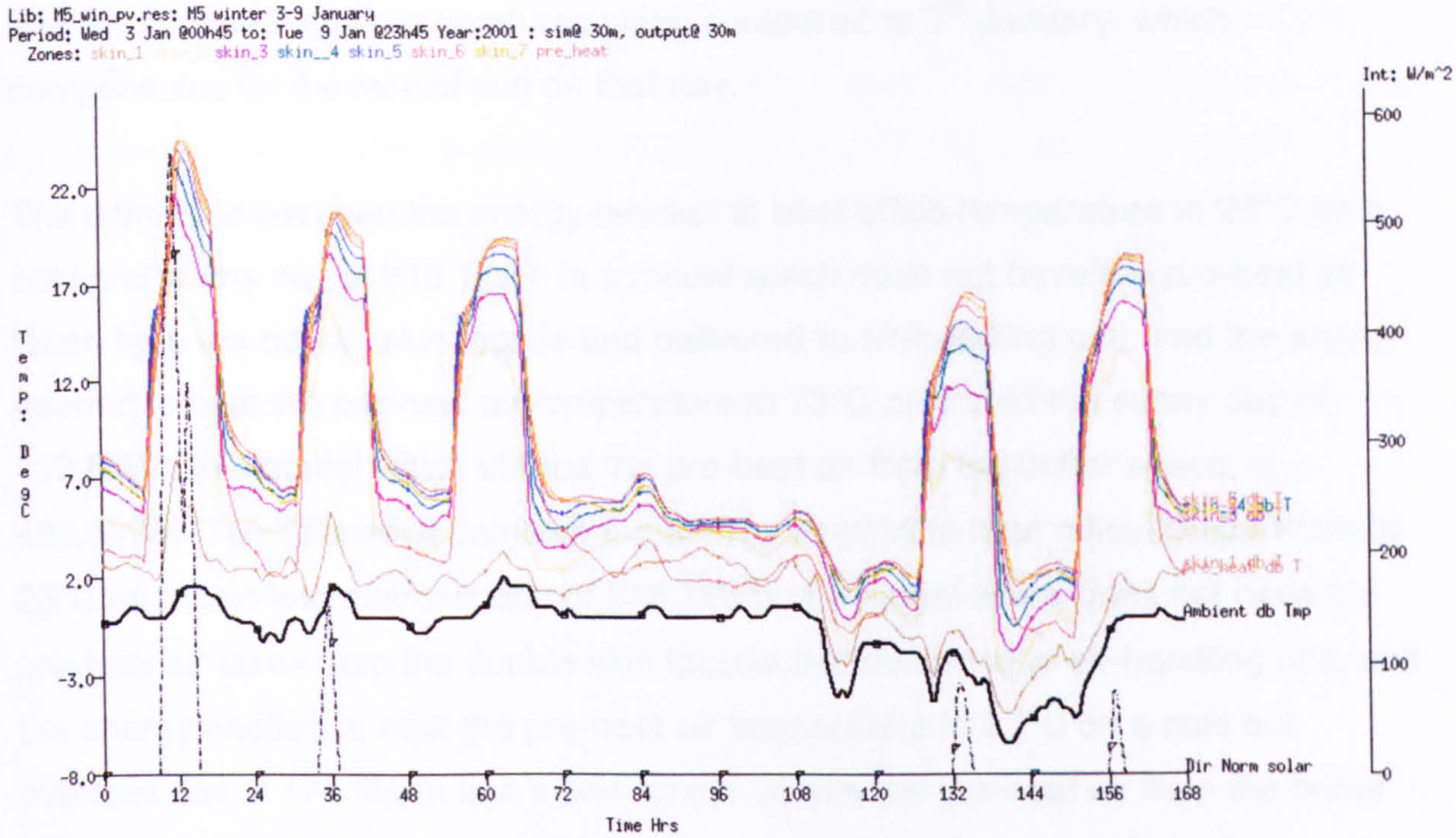


Fig. 6.11 M11 model
Winter critical week temperature in all skin zones, ambient air temperature and direct normal solar radiation

The simulations have also shown that the energy needed to heat the pre-heat air temperature to 23°C on a cold but sunny day is 119.58kWh, and 178.92kWh on a cold but overcast day. When compared to a model which does not have the pre-heat air taken from the double skin façade and delivered to air-handling unit, the energy needed to heat office temperature to 23°C on a cold and sunny day is 616.1kWh and on a cold and overcast day is 616.7kWh [Fig. 6.12], i.e. direct solar gain seems not to be influential. It is evident that the simulation results have shown a significant potential for utilising pre-heat air from the buffer space to reduce the energy needed to heat offices during office hours, even on a cold and overcast winter day.

	Energy delivered Winter Model yes BIPV no pre-heat
Day	
3rd Jan	616.1kWh
5th Jan	616.7kWh

	Energy delivered Winter Model yes BIPV yes pre-heat
Day	
3rd Jan	119.5kWh
5th Jan	178.9kWh

Fig. 6.12 Winter Models
Energy delivered with and without preheated air from double skin.

Although one would expect the difference between the energy needed to heat office temperature to 23°C on a cold and sunny day [616.1kWh] to be higher than on a cold and overcast day [616.7kWh], the explanation lies in the fact that the 5th January, despite being a dull day, has a smaller temperature difference between the maximum and the minimum day temperatures when compared to 3rd January, which compensates for the lack of sun on that day.

The difference between the energy needed to heat office temperature to 23°C on a cold and sunny day of 616.1kWh in a model which does not have the pre-heat air taken from the double skin façade and delivered to air-handling unit, and the energy needed to heat the pre-heat air temperature to 23°C on a cold but sunny day of 119.6kWh in a model which utilises the pre-heat air from the buffer space, is 496.6kWh. The difference between the energy needed to heat office temperature to 23°C on a cold and overcast day of 616.7kWh in a model which does not have the pre-heat air taken from the double skin façade and delivered to air-handling unit, and the energy needed to heat the pre-heat air temperature to 23°C on a cold but overcast day of 178.9kWh in a model which utilises the pre-heat air from the buffer space, is 437.8kWh [Fig. 6.13]. It means that when comparing a cold and sunny day with a cold and overcast day, the 58.7kWh difference is attributed mainly to the solar preheat. From this it is evident that majority of the heat is recovered from the buffer space rather than the solar preheat, which seems to account for approximately 1/8 of the total. However, as noted above, the slightly less severe temperatures on the overcast day must also exert some influence, partly eclipsing the solar contribution.

	Winter Model yes BIPV no pre-heat	Winter Model yes BIPV yes pre-heat	Energy saved
Day			
3rd Jan	616.1kWh -	119.5kWh =	496.5kWh
5th Jan	616.7kWh -	178.9kWh =	437.8kWh

Fig. 6.13 Winter Models
Energy savings gained using pre-heat air with BIPV.

For a total office area in the energy model of 435m^2, [62.1m^2 floor area of one office x 7 floors = 435m^2], the daily saving on a cold and sunny day is 1.14kWh/m^2 floor area, [i.e. 496.5kWh divided by 435m^2]. The daily saving on a cold and overcast day is 1.0kWh/m^2 floor area, i.e. 437.8kWh divided by 435m^2.

	Difference between Energy Delivered in Winter Models	Office Total Area	Daily Demand
Day			
3rd Jan	496.5kWh :	435m2 =	1.14kWh/m2
5th Jan	437.8kWh :	435m2 =	1.0kWh/m2

Fig. 6.14 Winter Models
Daily savings attributable to preheat with BIPV.

The energy load on a model which does not have the pre-heat air taken from the double skin façade and delivered to air-handling unit is 1.42kWh/m^2 on both cold and overcast days [616.1kWh divided by 435m^2, and 616.7kWh divided by 435m^2]. Compared to the energy load of 1.42kWh/m2, the cold and sunny day results with 80% savings of the energy load, and a somewhat lower of 70% on a cold and overcast day [Fig. 6.15]. This difference appears to indicate that the solar preheat contribution is some 10% of the overall energy savings. However, again the modest difference in respective temperature regimes must play a part in the respective savings, i.e. if the overcast day had had precisely the same temperature profile as the sunny day, the saving would have dropped below 1.0kWh/m^2.

	Winter Model yes BIPV no pre-heat	Office Total Area	Daily Demand
Day			
3rd Jan	616.1kWh :	435m2 =	1.42kWh/m2
5th Jan	616.7kWh :	435m2 =	1.42kWh/m2

Fig. 6.15 Winter Model
Daily energy demand without preheat.

As stated above, the modelling results with a preheat air introduced in offices at 23°C, have shown that during the critical winter week, the temperature in offices reaches 25°C to 26°C, suggesting that the temperature of the air introduced in offices could have been even lower than 23°C [to about 21°C], and still maintain good thermal conditions in offices during the heating season. The lower delivery temperature would mean decreased space heating load, i.e. it would shorten the heating season, but it would also in turn reduce opportunity for recovery.

The one-day analysis of the 3rd January, as a cold and sunny day [Fig. 6.16 to Fig. 6.19], has also revealed that between 12am and 3pm, the temperature at the top of the double skin is above 23°C. That is higher than the temperature of the air delivered to offices. It means that the pre-heat air from the double skin façade during this period of that day is preheated in the buffer space to a temperature that does not require additional heating in the air-handling unit and can be directly delivered to offices.

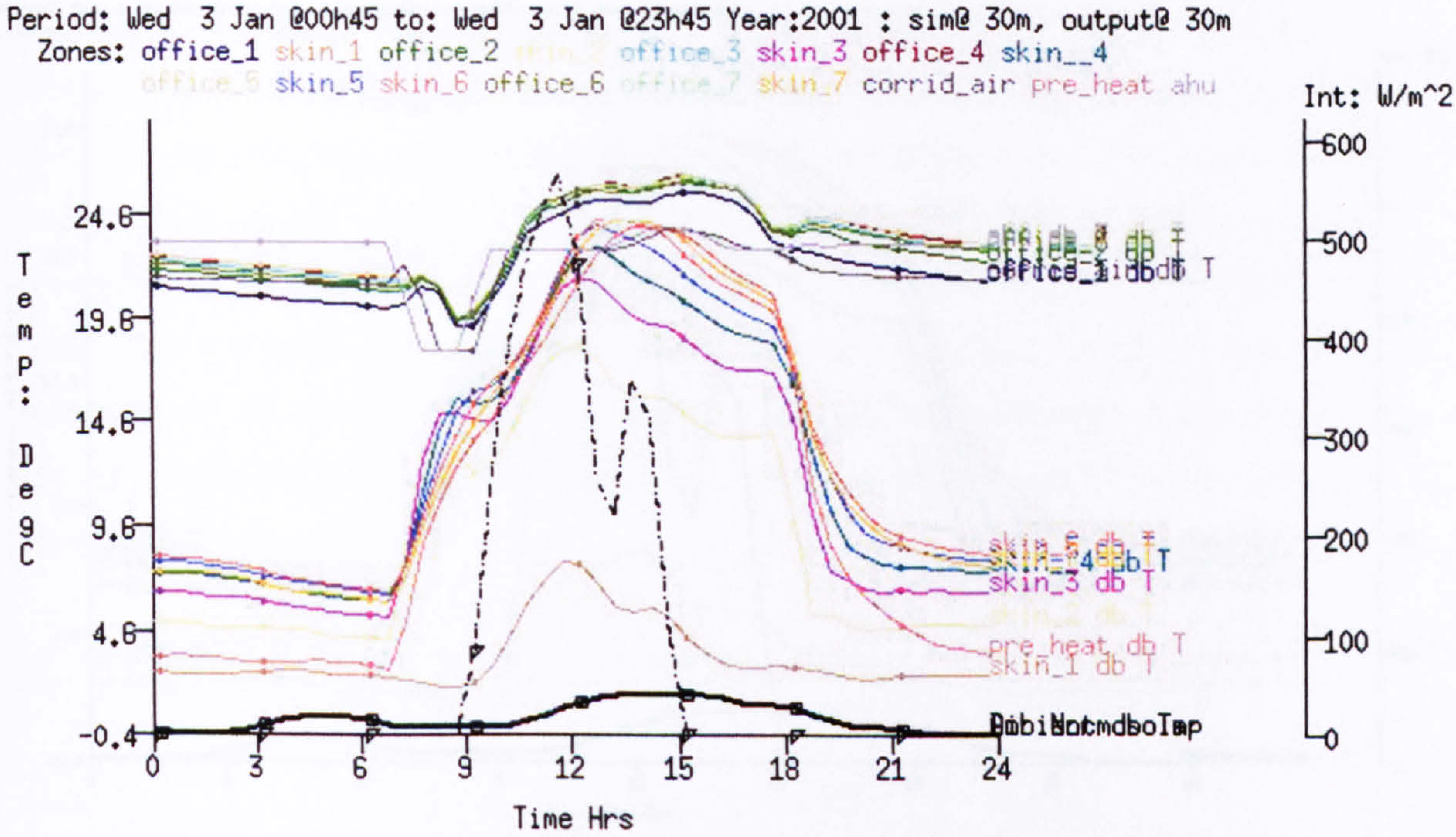


Fig. 6.16 M11 model
Winter critical week, one day 3rd January, temperature in all zones, ambient air temperature and direct normal solar radiation

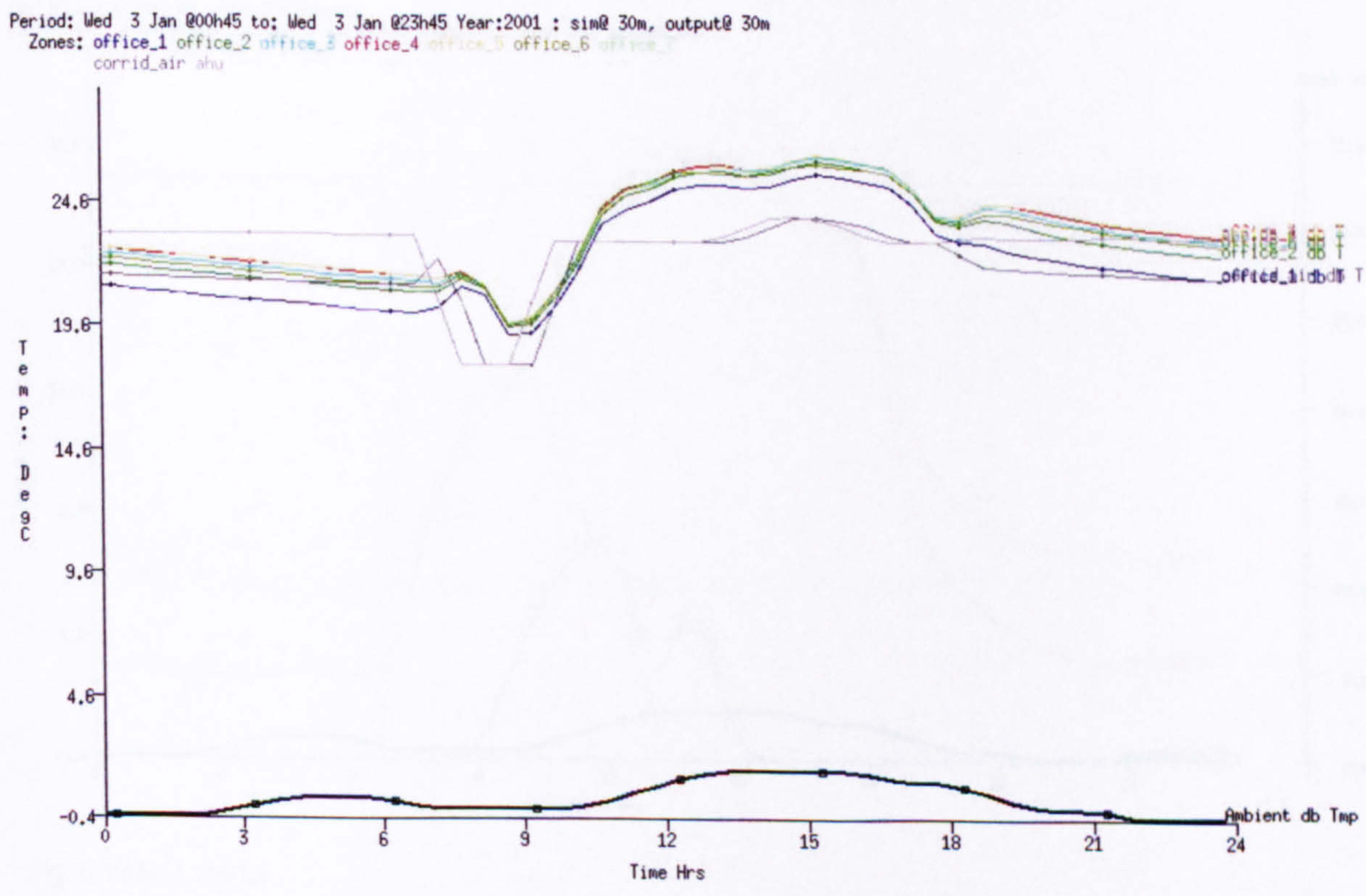


Fig. 6.17 M11 model
Winter critical week, one day 3rd January, temperature in all offices zones, temperature in the air-handling unit and corridor air supply to offices zones and ambient air temperature

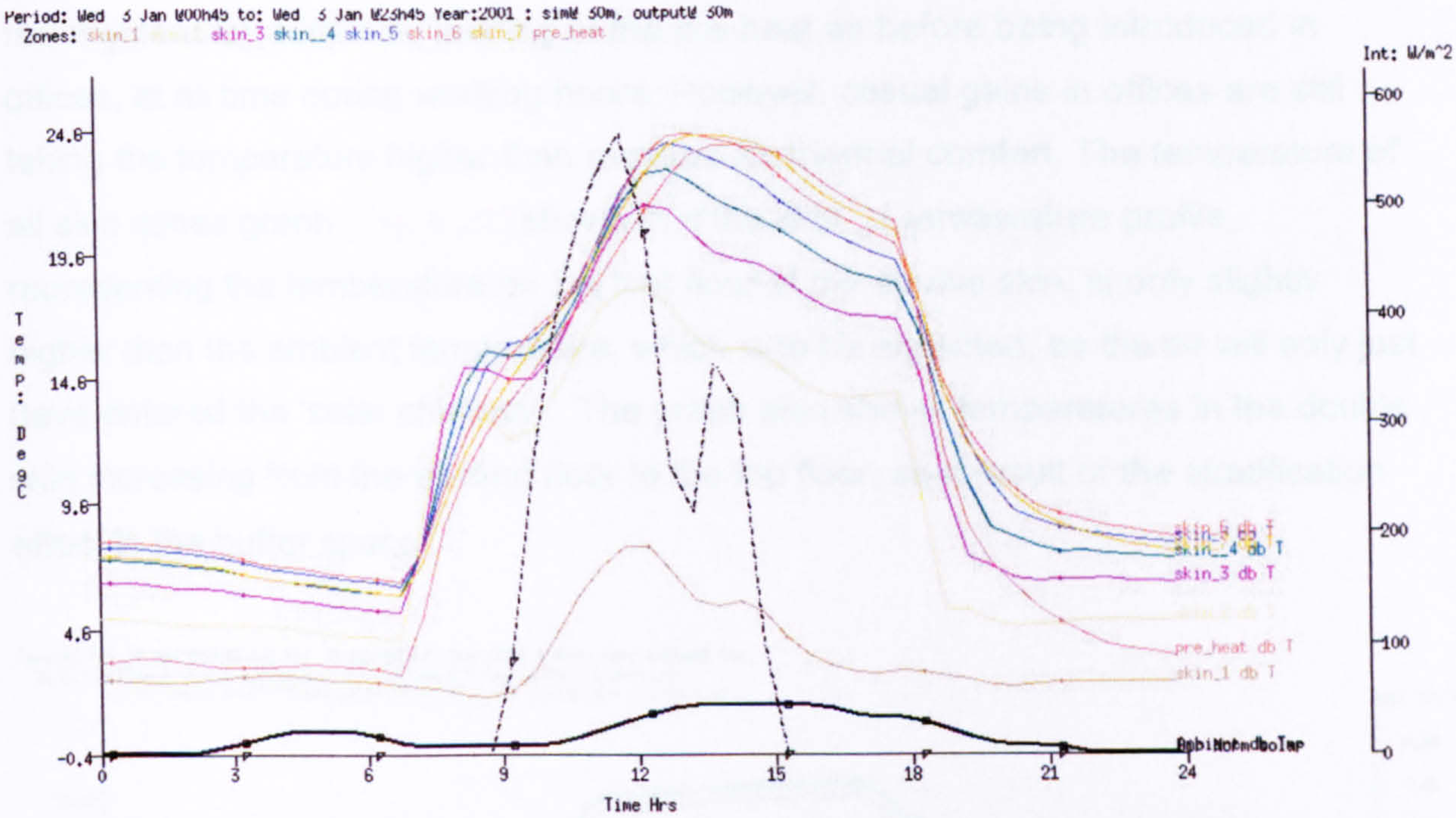


Fig. 6.18 M11 model
Winter critical week, one day 3rd January, temperature in all skins zones, ambient air temperature, and direct normal solar radiation

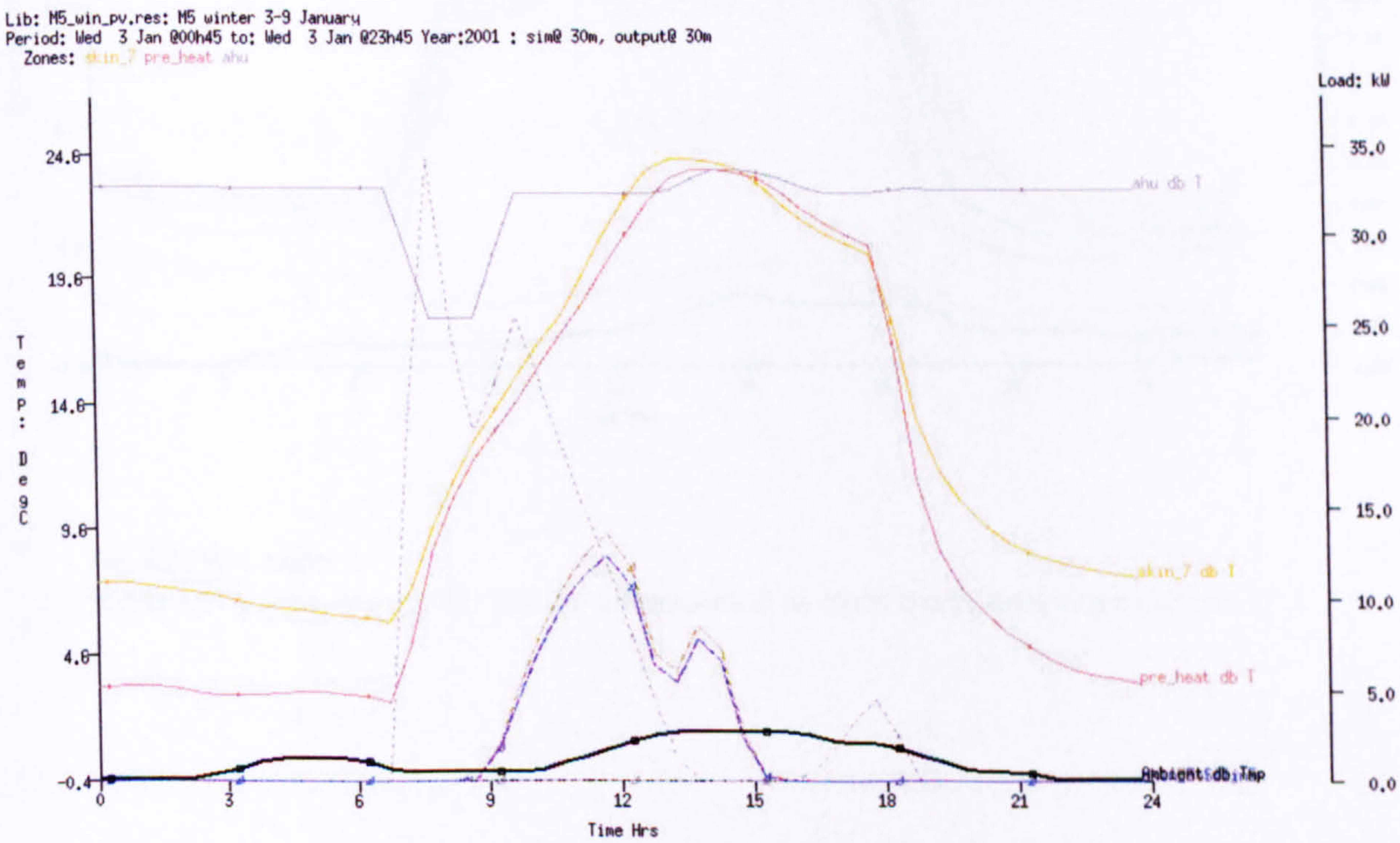


Fig. 6.19 M11 model
Winter critical week, one day 3rd January, temperature in skin_7, pre_heat, and air_handling unit zones, ambient air temperature, sensible heating load, and skin_1, skin_3 and skin_5 solar absorbed in zone

The one-day analysis of the 5th January, a cold and overcast day, has shown peak temperature reaching 19°C at the top of the double skin façade [Fig. 6.20]. The temperature in the buffer space being lower than 23°C, shows a theoretical requirement for additional heating of the pre-heat air before being introduced in offices, at all time during working hours. However, casual gains in offices are still taking the temperature higher than required for thermal comfort. The temperature of all skin zones graph [Fig. 6.22] shows that the skin _1 temperature profile, representing the temperature on the first floor of the double skin, is only slightly higher than the ambient temperature, which is to be expected, as the air will only just have entered the 'solar chimney'. The graph also shows temperatures in the double skin increasing from the second floor to the top floor, as a result of the stratification effect in the buffer space.

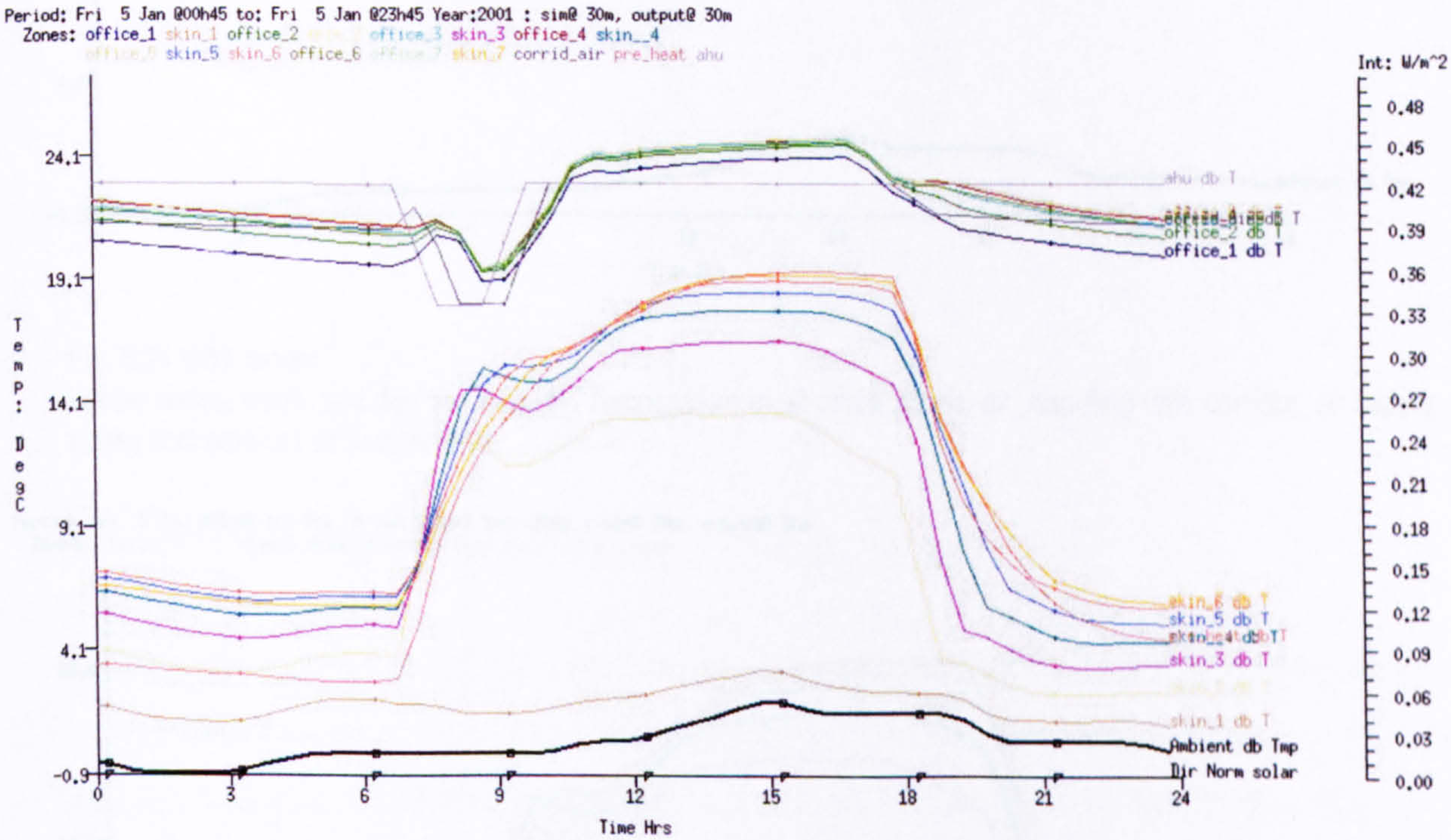


Fig. 6.20 M11 model
Winter critical week, one day 5th January, temperature in all zones and ambient air temperature

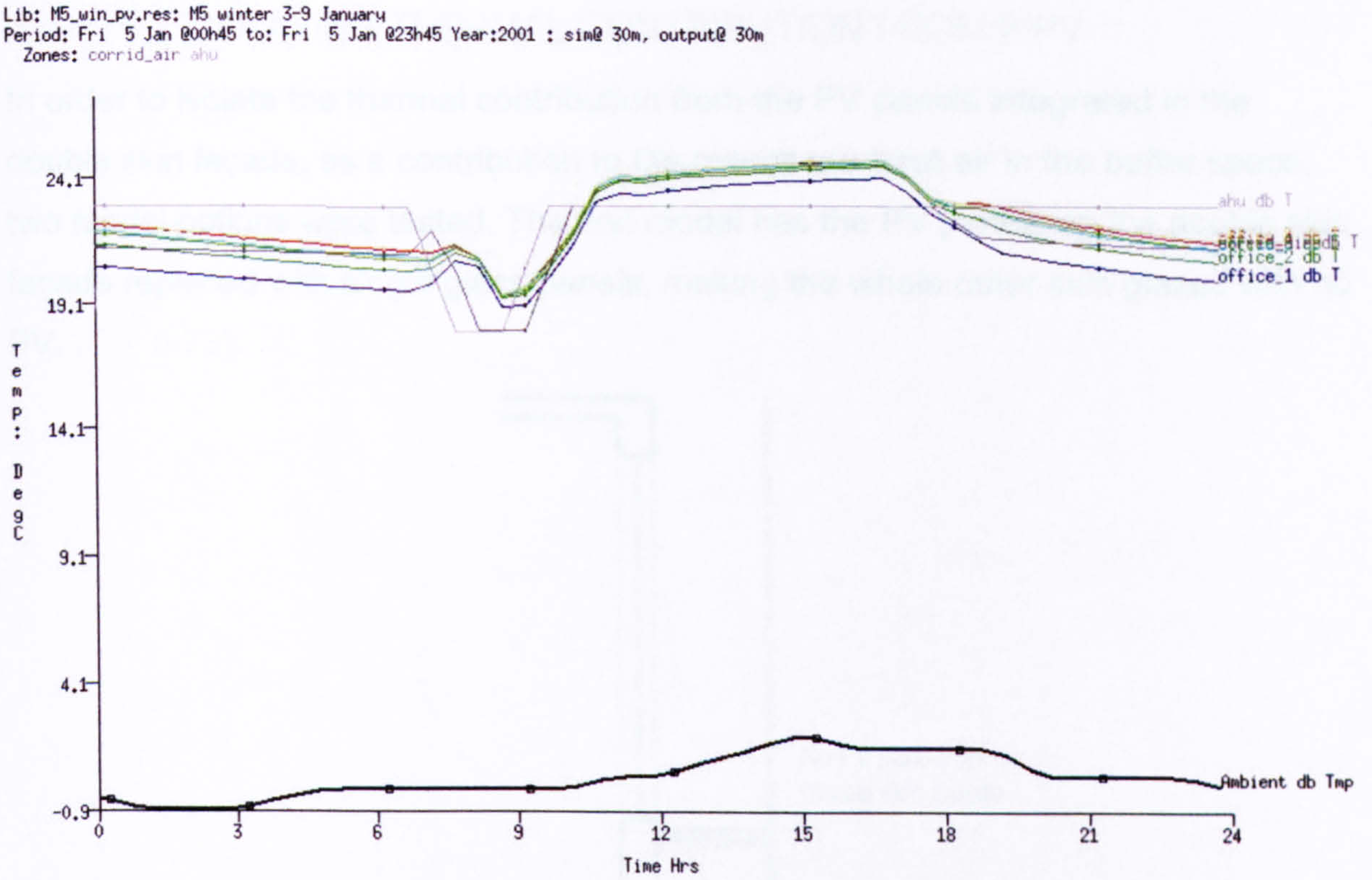


Fig. 6.21 M11 model
Winter critical week, one day 5th January, temperature in all office zones, air_handling unit, corridor_air supply zones and ambient air temperature

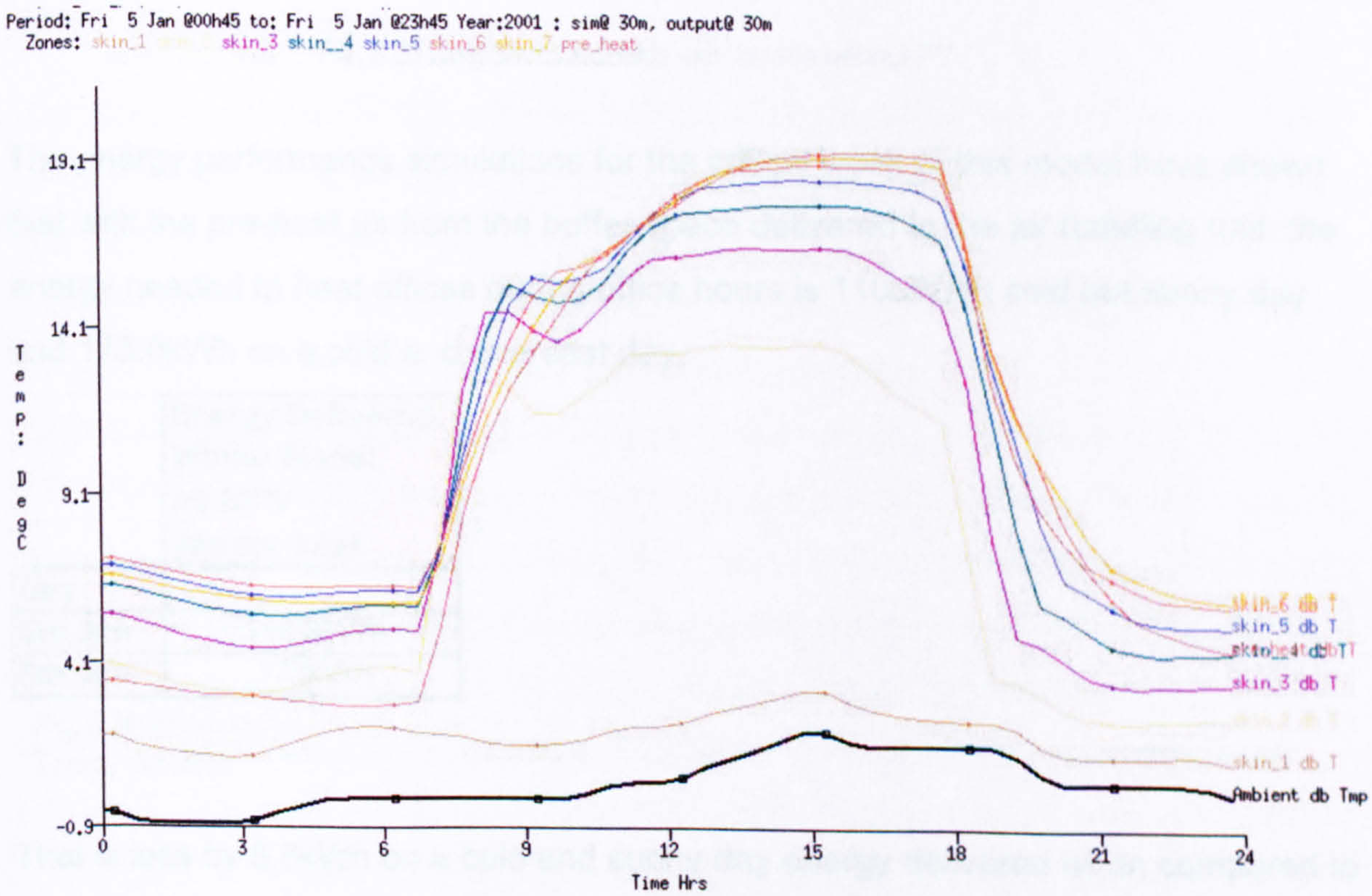


Fig. 6.22 M11 model
Winter critical week, one day 5th January, temperature in all skin zones and ambient air temperature

6.2 ISOLATING THERMAL CONTRIBUTION FROM BIPV

In order to isolate the thermal contribution from the PV panels integrated in the double skin façade, as a contribution to the overall pre-heat air in the buffer space, two model options were tested. The first model has the PV panels on the double skin façade replaced with single glass panels, making the whole outer skin glazed with no PV, [Fig. 6.23].

Fig. 6.23 Diagram of a double skin façade without PV

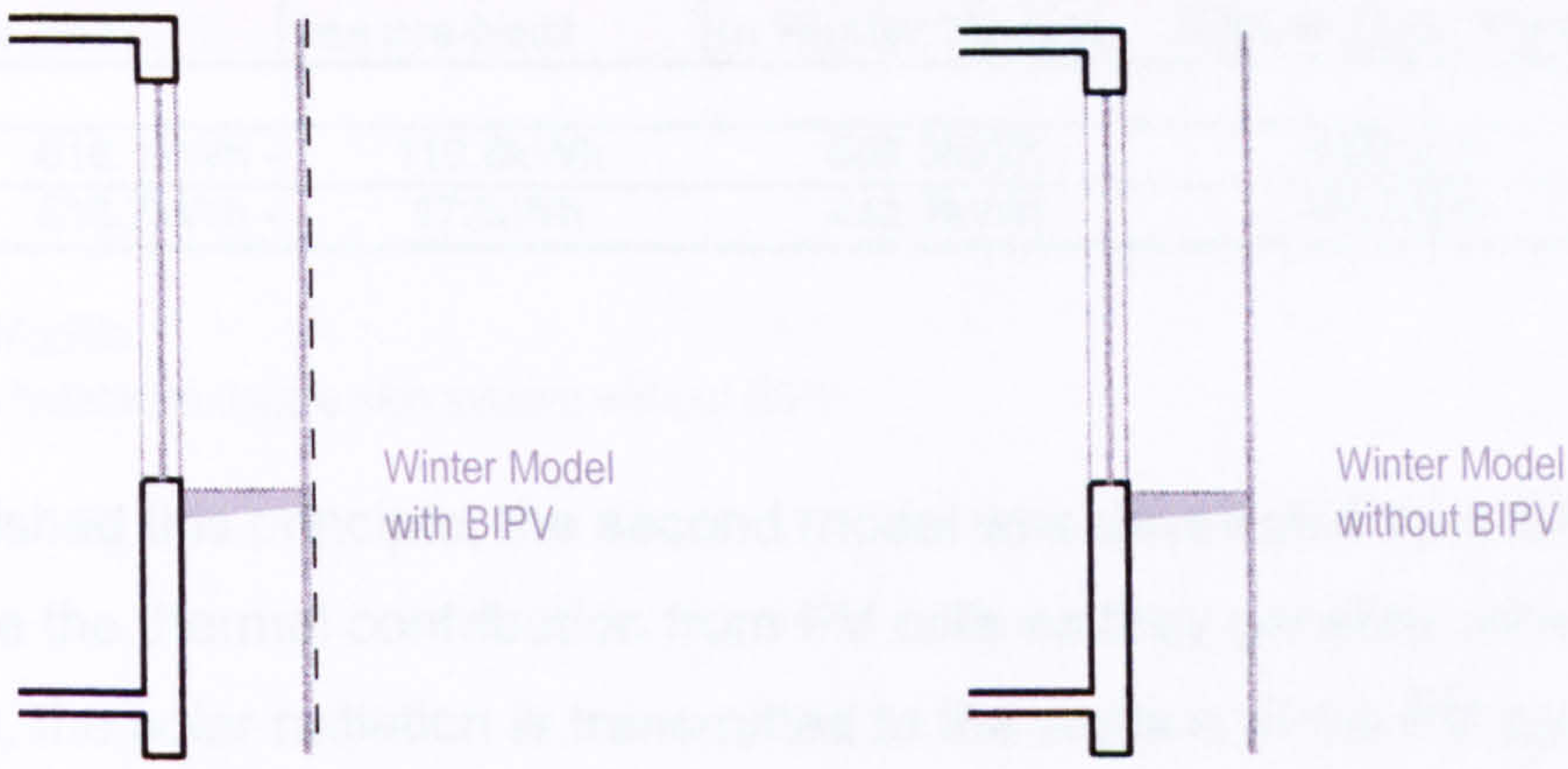
The energy performance simulations for the critical week of this model have shown that with the pre-heat air from the buffer space delivered to the air handling unit, the energy needed to heat offices during office hours is 110.8kWh cold but sunny day and 173.0kWh on a cold and overcast day.

	Energy Delivered Winter Model no BIPV yes pre-heat
Day	
3rd Jan	110.8kWh
5th Jan	173kWh

Fig. 6.24 Winter Model
Energy delivered

That is less by 8.8kWh on a cold and sunny day energy delivered when compared to the similar winter model with the PV panels on the outer skin [119.6kWh - 110.8kWh], and 5.9kWh on a cold and overcast day energy delivered, compared to the similar winter model with the PV panels on the outer skin [178.9kWh – 173.0kWh]. Having lower energy requirement to heat offices, on both sunny and overcast sky days, in the model without the PV panels on the façade, confirms that there will be more solar gains through all glazed surfaces than when the PV panels are on the façade.

Space heating load [Energy Delivered]
Winter Model with BIPV – Winter Model without BIPV



	Energy Delivered in Winter Model with BIPV	Energy Delivered in Winter Model without BIPV	Difference
Day			
3rd Jan	119.6kWh -	110.8 =	8.8kWh
5th Jan	178.9kWh -	173kWh =	5.9kWh

Fig. 6.25 Winter Models
Energy savings gained using pre-heat air

The presence of the PV cells will inevitably block out some transmitted solar gains to the buffer space, and as one would expect, that effect is more evident on the sunny day. Also, even though PV cells are located in front of opaque parts of the façade, transmission into offices will also be reduced depending on time of day, i.e. the more the solar azimuth moves away from normal to the façade.

Thus on the sunny day the net combined effect of relating extra thermal heat from the PV cells and a relatively large reduction in transmitted solar gain is 8.8kWh extra. It then seems, that on the overcast day, the smaller thermal gain from the PV cells and the smaller loss in diffuse gain through the glazing result in a net effect of 5.9kWh extra. Thermally, in winter conditions, the option without BIPV performs better than when PV panels are integrated on to the façade of the skin. However, expressed relative to total offices floor area [435m^2] this difference is marginal, approximately 0.02kWh/m^2 in each case, bringing the daily savings up to 1.16kWh/m^2 and 1.02 kWh/m^2 respectively [N.B. previously 1.14kWh/m^2 and 1.0kWh/m^2]. 616.1kWh – 110.8kWh = 505.3kWh, divided by total floor area 435m^2 = 1.16kWh/m^2, on a cold and sunny day, and 616.7kWh – 173.0kWh = 443.7kWh, divided by total floor area 435m^2 = 1.02kWh/m^2, on a cold and overcast day.

	Energy Delivered Winter Model yes BIPV no pre-heat	Energy Delivered Winter Model no BIPV yes pre-heat	Difference between Energy Delivered in Winter Models	Office Total Area	Daily Demand
Day					
3rd Jan	616.1kWh -	110.8kWh	505.3kWh :	435m2 =	1.16kWh/m2
5th Jan	616.7kWh -	173kWh	443.7kWh :	435m2 =	1.02kWh/m2

Fig. 6.26 Winter Models
Daily savings attributable to double skin system without BIPV.

Having established this principle, the second model was developed as a theoretical study to isolate the thermal contribution from PV cells as they generate electricity. In the PV panels, the solar radiation is transmitted to the surface of the PV layer through the glass cover. The calculation of the intensity of solar radiation incident on the glass surface is handled by ESPr's solar processing algorithm and as a function of the surface geometry, site location, shading and weather parameters prevailing at a particular simulation time step [Kelly, 2000, pp.2029-2032]. Within the PV layer, not all the absorbed solar radiation is converted to heat. A proportion is converted to electrical energy, resulting in a reduced layer temperature. This temperature is calculated by ESP-r's conduction model, while the light generated current is calculated as a function of the solar energy absorbed in the PV layer [Kelly, 2000, pp.2029-2032]. In this model, the glass properties of PV panels were altered to zero daylight transmittance to block out the directly transmitted solar heat gain and the thermal contribution from PV cells generated as they convert light into electricity. The effect is as if the PV cells are black squares with zero light transmittance, and hence zero short-wave solar gain, as well as no electricity generation, and hence no thermal gain as a by-product of this process.

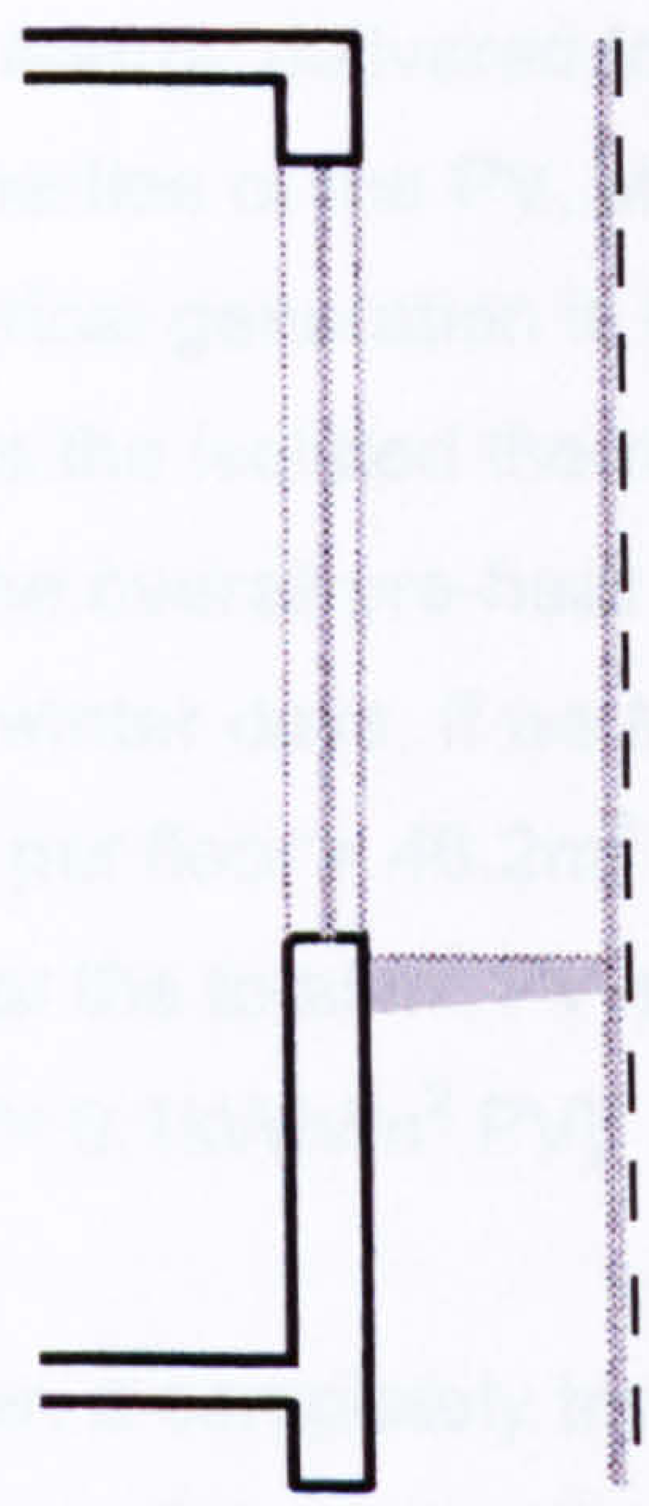
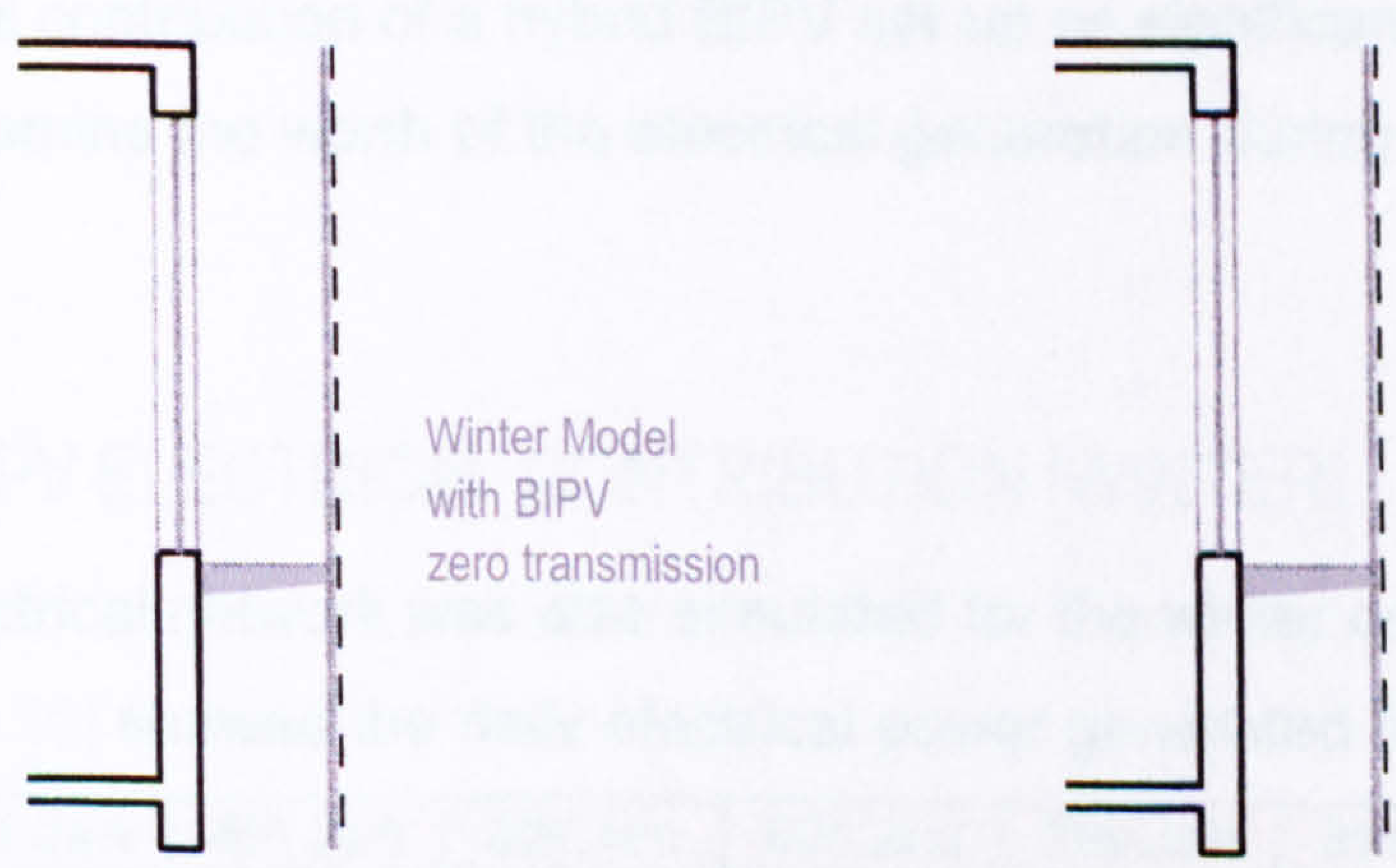


Fig. 6.27 Diagram of a double skin façade with BIPV panels with zero daylight transmittance

The simulations have shown that the energy delivered to heat up the pre-heat air to 23°C on a cold and sunny day is 125.8kWh. That is 6.2kWh higher than energy delivered in the model option with PV panels with unchanged glass properties [125.8kWh compares to 119.6kWh]. It has also shown that the energy delivered to heat up the pre-heat air to 23°C on a cold and overcast day is 182.2kWh. That is 3.3kWh higher than energy delivered on the same day in the model option with PV panels with unchanged glass properties [182.2kWh compares to 178.9kWh].

Space heating load [Energy Delivered]
Winter Model with BIPV zero transmission– Winter Model with BIPV



	Energy Delivered in Winter Model zero Transmission 'BIPV'	**Energy Delivered in Winter Model with BIPV**	**Difference**
Day			
3rd Jan	125.8kWh -	119.6kWh =	6.2kWh
5th Jan	182.2kWh -	178.9kWh =	3.3kWh

Fig. 6.28 Winter Models
Isolating the thermal contribution of PV cells.

Having increased the need for energy delivered to offices on both winter days in the model with changed glass properties of the PV, shows that the thermal gain from PV panels as a by-product of electrical generation is being excluded. The difference of 6.2kWh and 3.3kWh represents the isolated thermal gain from operating PV panels, of respective contributions to the overall pre-heat saving [Fig. 6.13] of 1.25% and 0.75% on sunny and overcast winter days. If we take an average of 4.5kWh during January and PV area of 6.6m^2 per floor = 46.2m^2 on all floors, the mean monthly daily PV thermal contribution for the total m^2 PV area is approximately 0.1kWh/m^2 PV [4.5kWh divided by 46.2m^2 PV= 0.1kWh/m^2 PV].

One can conclude that in winter, a completely transparent façade without PV would perform thermally better than with PV, as the PV blocks out the solar gain more than it contributes thermally by virtue of generating electricity. However, the contribution from the PV cells as they generate electricity does partially make up for this loss. Moreover, the thermal net loss of 0.02kWh/m^2 [Figures 6.14 and 6.26] is not very significant, and compared to the overall benefit of the preheat air with BIPV on a sunny day [Fig. 6.13: 496.5kWh divided by 435m^2 = 1.14kWh/m^2] it is 1.75% rising to just below 2% on an overcast day. Again, the point is clearly made that in a cold winter week, regardless of variations in solar gain and the overall thermal input of PV, the principal donor to the buffer space is energy being lost from the heated offices. Having identified the specific thermal contribution of PV as insignificant, but the overall thermal contribution of a hybrid BIPV set-up as significant, the next section goes on to examine the worth of the electrical generation during the same winter week.

6.3 BIPV ELECTRICAL CONTRIBUTION [WINTER]

The BIPV electrical network was also simulated for the winter critical week. The results [Fig. 6.29] showed the daily electrical power generated for the whole network

Day [kWh]	3rd Jan	4th Jan	5th Jan	6th Jan	7th Jan	8th Jan	9th Jan
	12	2.77	0.693	0.651	0.742	2.21	1.41

Fig. 6.29 Daily electrical power generated for the whole network, winter critical week

The average daily electrical output for the winter week 3rd to 9th January is 2.92kWh, or 0.063kWh/m^2 total PV area daily [i.e. 2.92kWh divided by the total PV area on seven floors, 46.2m^2 = 0.063kWh/m^2 PV].

The average PV system efficiency, based on the winter critical week PV electrical network simulation results was also calculated [sum of the total weekly PV electrical output multiplied by 100, and divided by the total incident solar radiation falling on the vertical PV surface]. This gave an average PV system efficiency of 10.0% and a maximum PV system efficiency of 12.7%.

As in the summer critical week modelling, the temperature of PV panels in all skin zones was investigated. On the first day of the week, corresponding to the sunniest day of the week [direct solar radiation of 600W/m^2], PV panels reach highest temperature of 50°C. On other days, the PV temperature is significantly lower corresponding to much lower solar radiation and maximum PV temperatures of 25°C [Fig. 6.30]. If one takes that the mono-crystalline PV cells efficiency is about 13% for cells temperature of 50°C, and PV cells efficiency of 15% for cells temperature of 25°C [CIBSE, 2000, p.4], then the theoretical loss in PV efficiency due to PV temperature in the case of the double skin façade in winter is about 2%. One could conclude that during winter, PV panels would not have excessive loss in efficiency due to their temperature, since the temperature of 50°C is only occasionally reached.

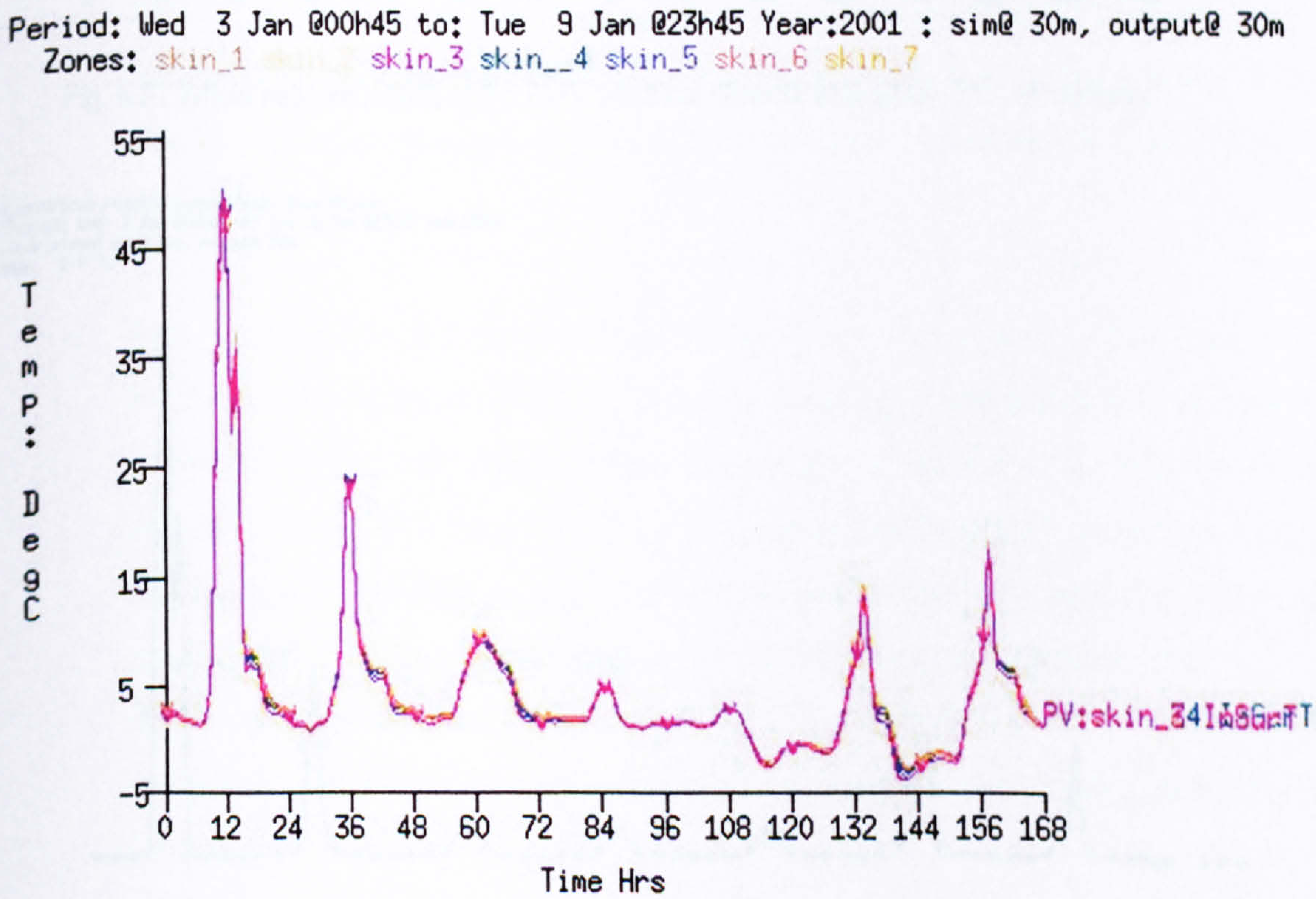


Fig. 6.30 M11 model winter critical week, PV cells temperature.

A calculation was done to find out the need for electricity to run all fans for the pre-heat and extract, delivery to air-handling unit and air supply to offices [i.e. the offices behind the area of PV modelled]. It was found that 2.7kWh/day electricity is needed for all fans in the pre-heat and heating air delivery system [assuming a duct diameter of 750mm at 5m/s air velocity at the air-handling unit, and a 300W fan]. Thus, compared to the daily average PV energy flow output of 2.92kWh, the PVs generate enough electricity to supply the electrical energy for the fans in a January week.

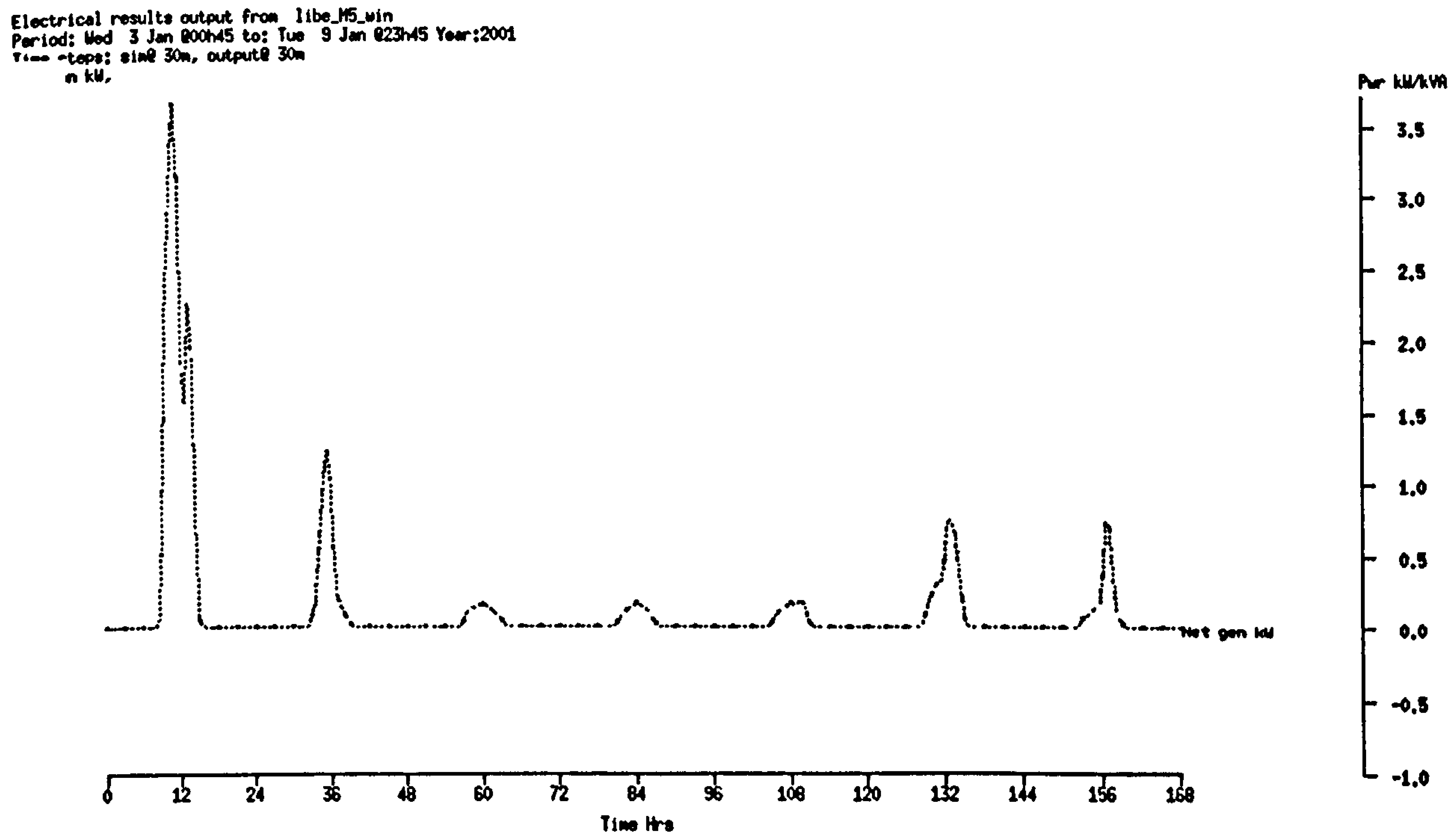


Fig. 6.31 Whole network results of the BIPV electrical network simulation, 3rd – 9th January

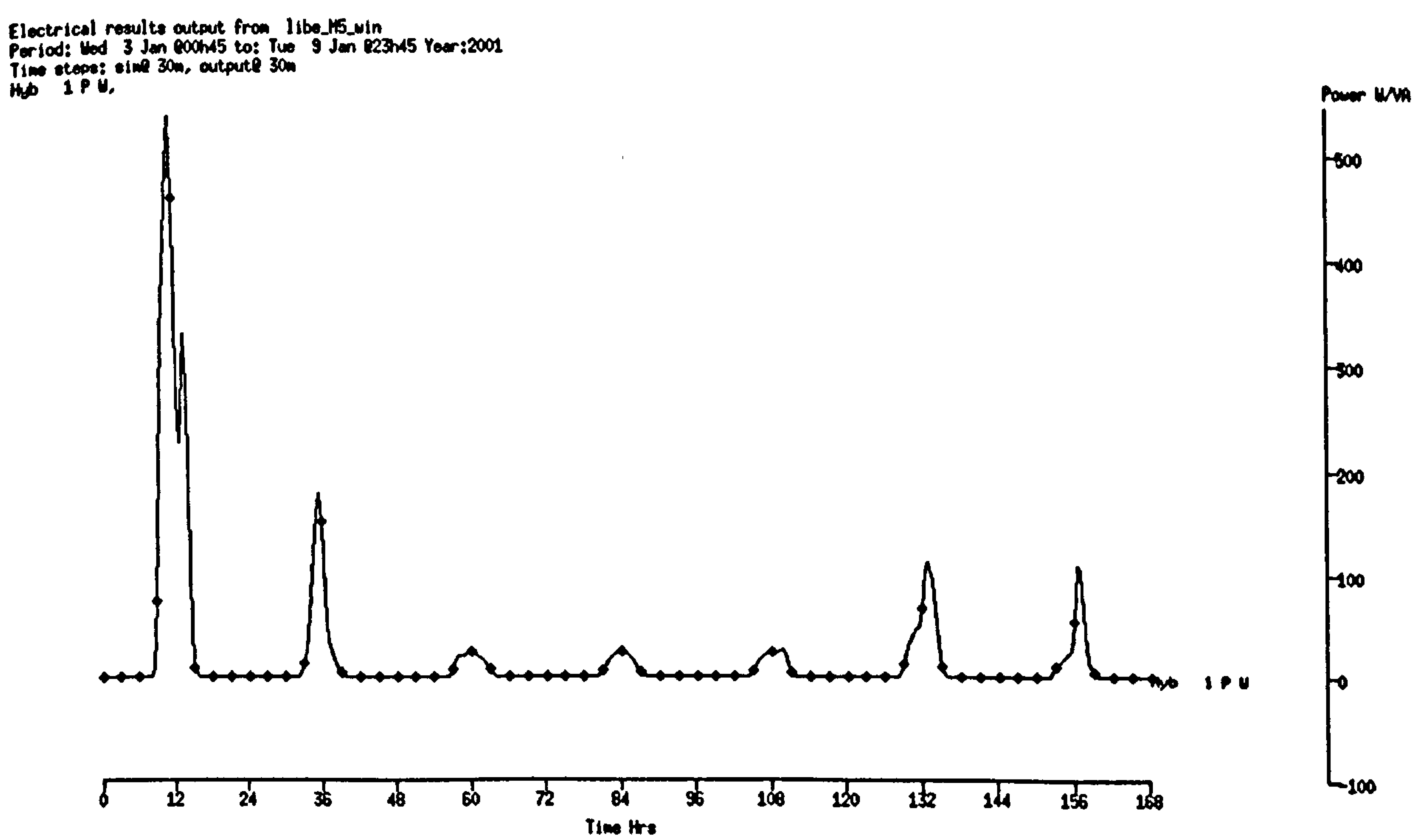


Fig. 6.32 One-array results of the BIPV electrical network simulation, 3rd – 9th January

6.4 CHAPTER 6 THERMAL AND ELECTRICAL WINTER CRITICAL WEEK MODELLING RESULTS SUMMARY

- The winter critical week 'free floating' modelling of the existing, non-refurbished Graham Hills building [model M8] showed poor thermal performance in offices with peak mid-day temperature in offices reaching 20°C on a cold but sunny day [600W/m^2 direct solar radiation], and 11°C on days with low ambient temperature and very low level of solar radiation. The temperature of Office_7 had lowest temperature as a result of the top floor location and poor thermal properties of the roof.

- The equivalent winter energy modelling of the improved Graham Hills building, but without the double skin façade with BIPV [model M9], showed thermal improvement in all offices with higher office temperature throughout the whole winter week. On the 3rd January, peak mid-day temperature was 22°C and on 5th January peak mid-day temperature was 19°C. The temperature of the top-floor office was again lower than temperature in other offices, but nevertheless, higher than in the non-refurbished case of the model M8.

- The results of the model M10 has shown that the addition of the double skin façade had a positive effect on the 'free floating' thermal performance of offices in winter, with higher office temperatures than in case with no double skin façade [as in model M9]. The modelling also showed temperature in all skin zones constantly above ambient air temperature, suggesting that the glazed cavity with southern exposure both traps solar radiation and accumulates some heat on its journew from inside to outside. This then indicates a possibility for this energy to be used for pre-heating supply air to offices.

- The model M11 winter critical week modelling results supported a ventilation strategy of preheat air extracted from the double skin façade buffer space and heated in the air handling unit to 23°C, before being delivered in offices. Indeed by heating to 23°C, is possible to achieve temperature in offices during working hours of around 25°C, i.e. rather higher than necessary. This modelling also showed that on a cold, but particularly sunny winter day, it is possible for the air temperature in the double skin façade space to reach 23°C or over, in which case additional heating in the air-handling unit is not required.

- The results of the PV thermal contribution have shown that in cold winter conditions, although a negative effect due to the PV blocking solar radiation from the space was identified, the thermal contribution from the PV cells as they generate electricity partially makes up for this loss. Nevertheless, both the solar heat gain through the outer glazing, and the heat given up to the buffer space as the PV cells generate electricity, are very minor compared with heat leaving the warm offices. Thus, the overall pre-heat contribution from the double skin façade is very worthwhile, resulting in energy loads at less than 30% on an overcast winter day, and less than 20% on a sunny winter day, of that needed for the same construction, but without its 'active' assistance.

- Isolating the thermal contribution of the PV in this BIPV context as respectively 1.25% and 0.75% on sunny and overcast winter days has provided a valuable new insight. Although the balance between solar preheat and heat recovery will alter towards solar in autumn and spring, it appears that in this hybrid PV application, the thermal gain which is solely attributable to the PV will play a minor role. On the other hand, it is significant that the BIPV electrical contribution on a sunny day is enough to run the fans, which supply air to offices. The average daily electrical output for the winter week 3rd to 9th January of almost 3kWh should also be viewed as displacing primary non-renewable electrical loads. The energy worth of this is significantly greater per consumed kWh, when compared with equivalent displacement of fossil fuel thermal loads, since the latter can attain relatively high efficiencies. Of course it also represents only a small 'slice' of the total.

- The temperature of PV panels showed highest temperature of 50°C on the first day of the week, [direct solar radiation of 600W/m^2]. On other days, PV temperature reached a maximum temperature of 25°C. The theoretical PV cells efficiency would be about 13% for cells temperature of 50°C, 15% for cells temperature of 25°C, resulting in overall PV efficiency loss of 2%. One could conclude that during winter the PV panels do not have excessive loss in efficiency due to their temperature. Therefore, the hypothesis stated in Chapter 1 regarding the winter performance of the retrofit double skin façade with BIPV, is confirmed. In cold winter conditions, although the thermal input of the photovoltaics is insignificant, the PV electrical contribution is useful relative to the power for fans operating a mechanical warm air supply with passive ventilation pre-heat and heat recovery.

6.5. CHAPTER 6 REFERENCES

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Kelly N., The Integrated Simulation of PV and Building Electrical Power Flow, in the proceedings of the *16th European Photovoltaic Solar Energy Conference*, 1st - 5th May 2000, Glasgow, UK, James and James [Science Publishers] Ltd., Vol. 2., London, UK, 2000, pp. 2029-2032.

7

DAYLIGHT MODELLING OF THE DOUBLE SKIN FAÇADE WITH BIPV

7.1 DOUBLE SKIN FAÇADE DAYLIGHT MODELLING IN RADIANCE

The purpose of the modelling in Radiance was to investigate the effect of the double skin façade component on the internal daylight environment of offices. The modelling also aimed to investigate the potential for energy saved for artificial lighting in the base case, i.e. existing situation, compared to an office with the added double skin component. The basic notion was that the PV cells in the double skin façade, on one hand generate electricity while the extra skin is also part of a thermal and acoustic problem-solving package; but on the other, the added glass structure in front of existing windows reduces the daylight entering in offices. The danger of this contradiction is increased need for the use of artificial lights in offices, which in turn could diminish the contribution from the clean electricity generated by the PV cells.

Radiance computer modelling programme used for this daylight modelling, was developed at the Lawrence Berkeley National Laboratory, California, as a research tool for predicting the distribution of visible radiation in illuminated spaces. It is a highly sophisticated lighting visualisation system with ability to accurately simulate light behaviour in complicated environments. Similar to the ESP-r programme, Radiance is run under a UNIX operating system. A detailed description of the solar office Radiance model is given in the Radiance Appendix [pp. 277-285].

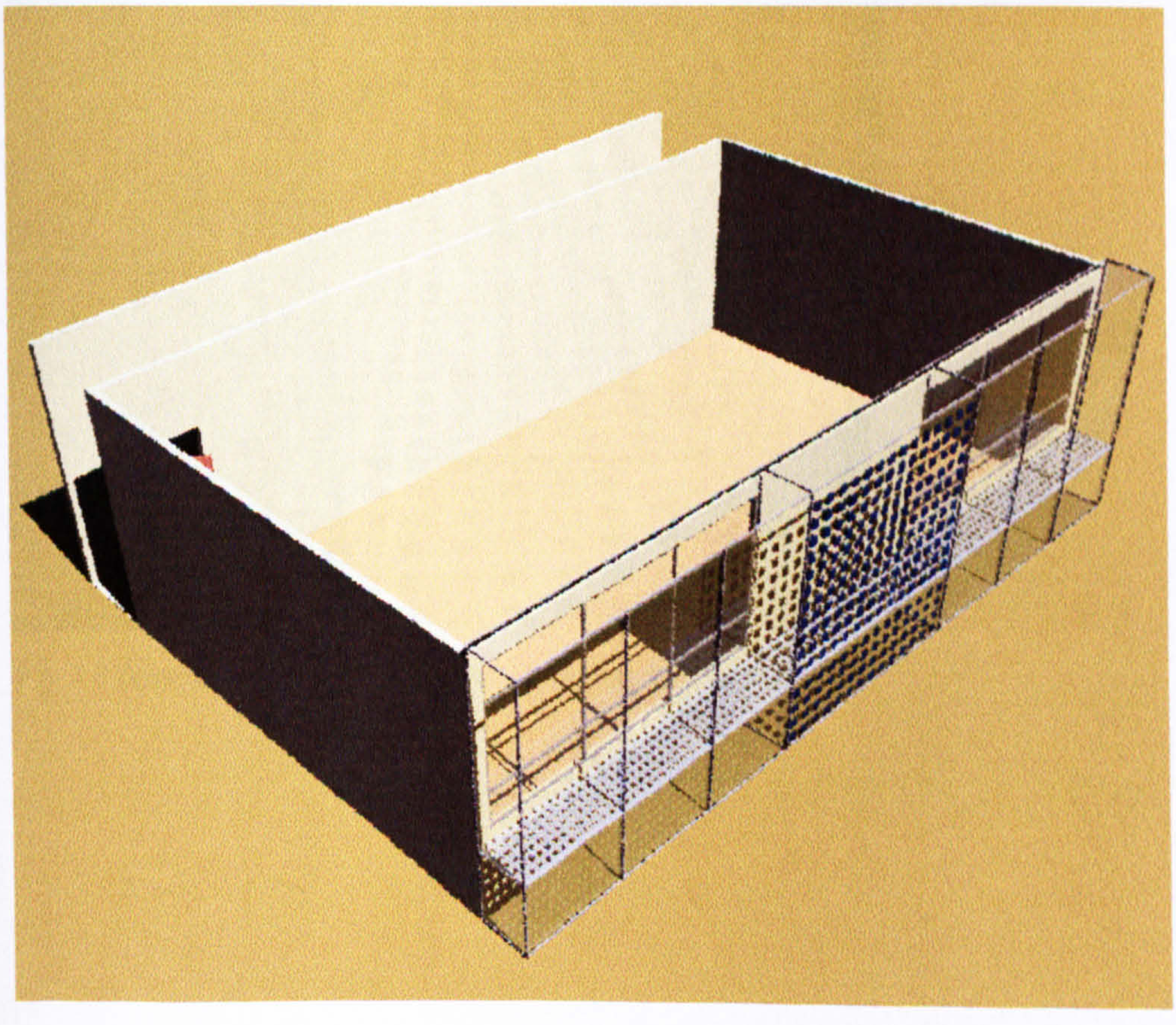


Fig. 7.1 Solar office Radiance model, view from south-west

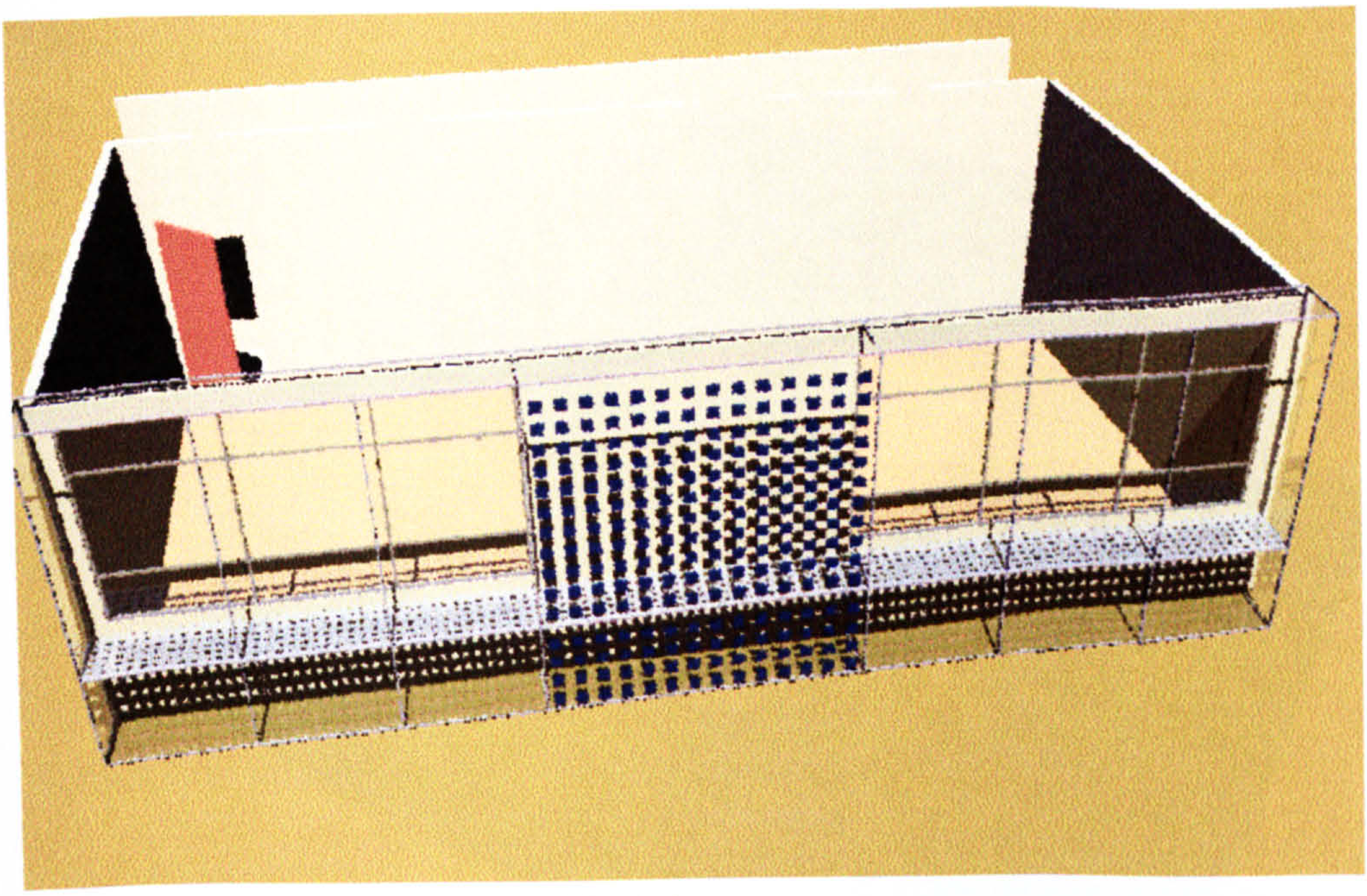


Fig. 7.2 Solar office Radiance model, front view

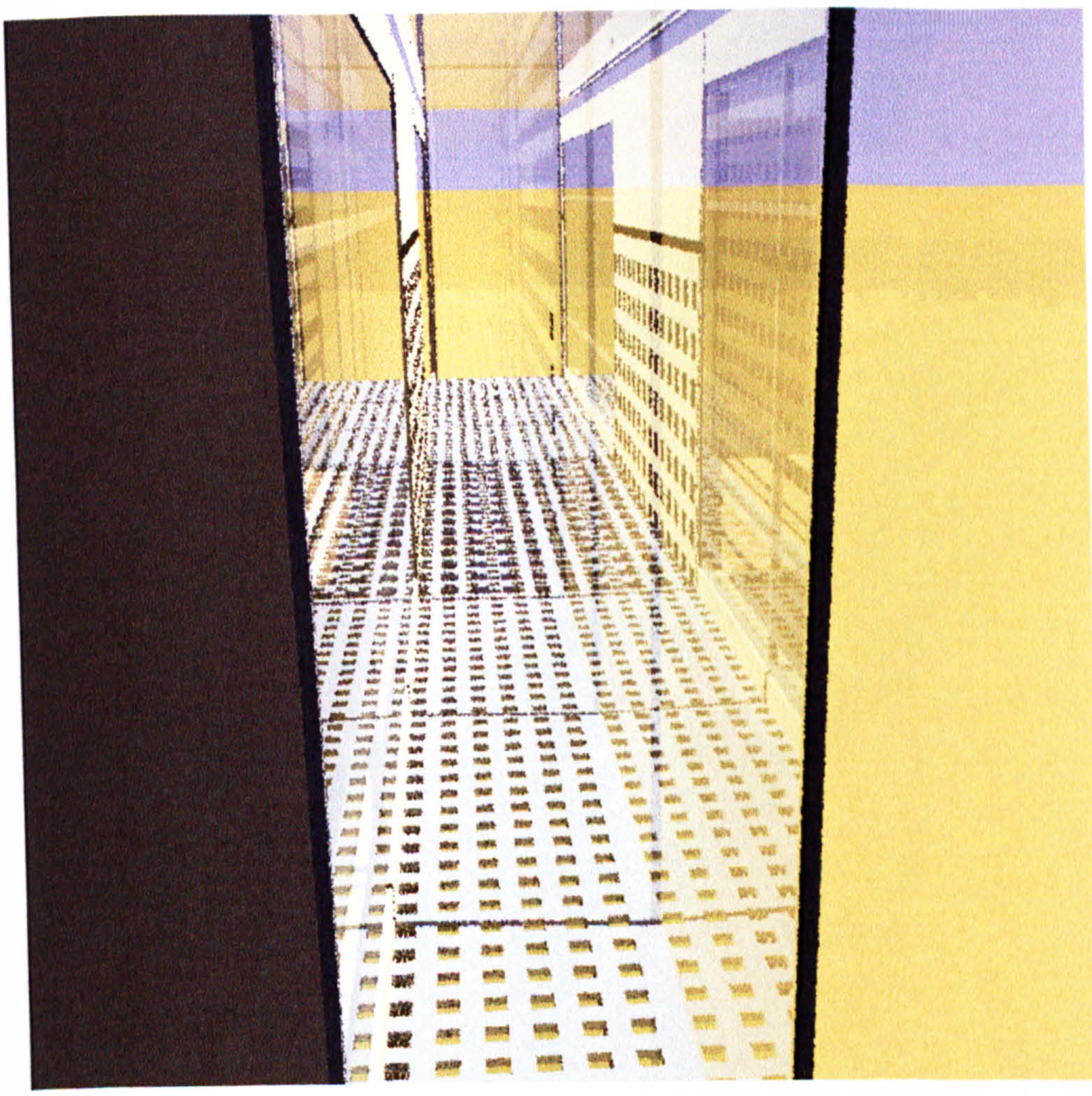


Fig. 7.3 Solar office Radiance model, inside double skin façade view

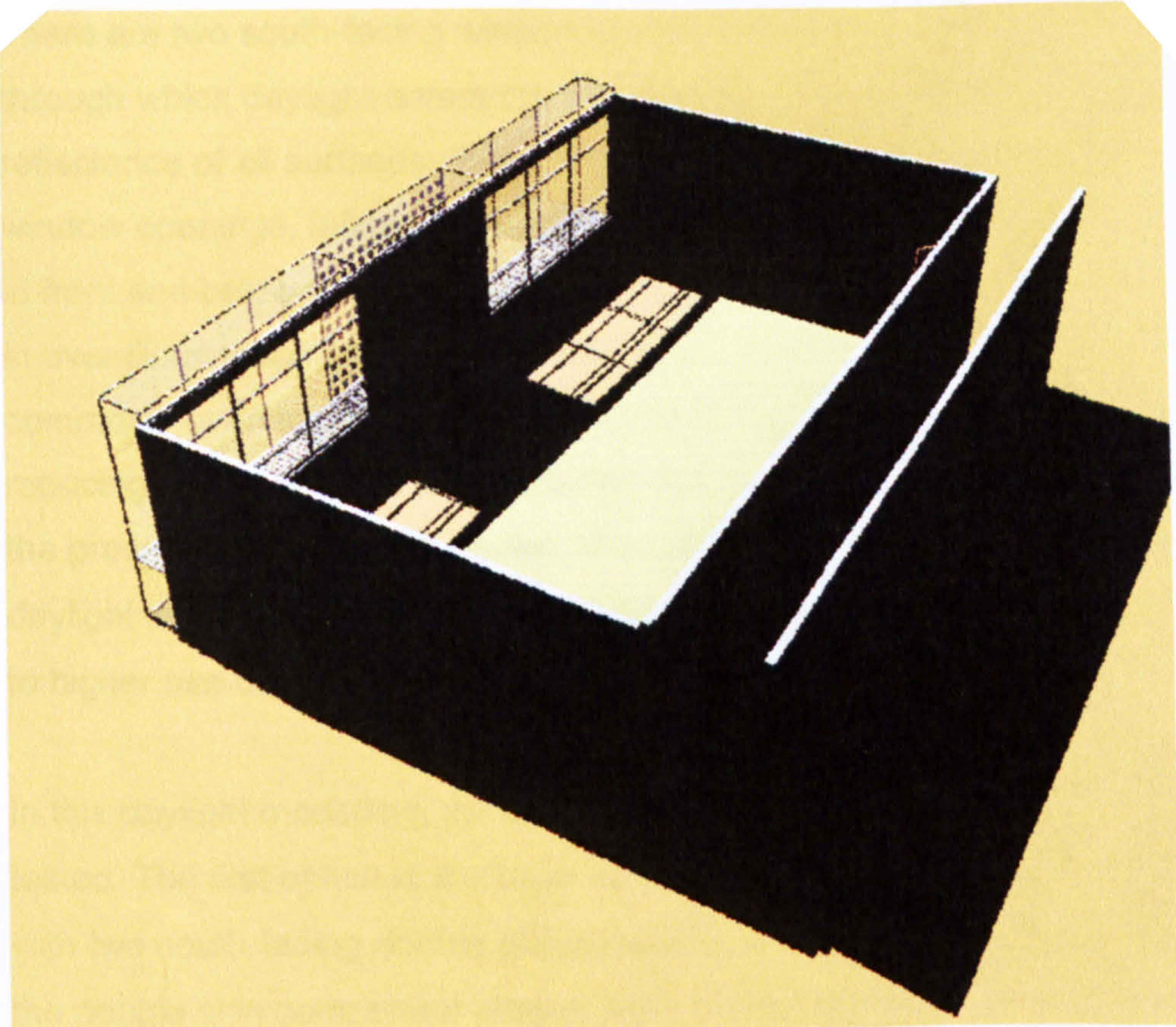
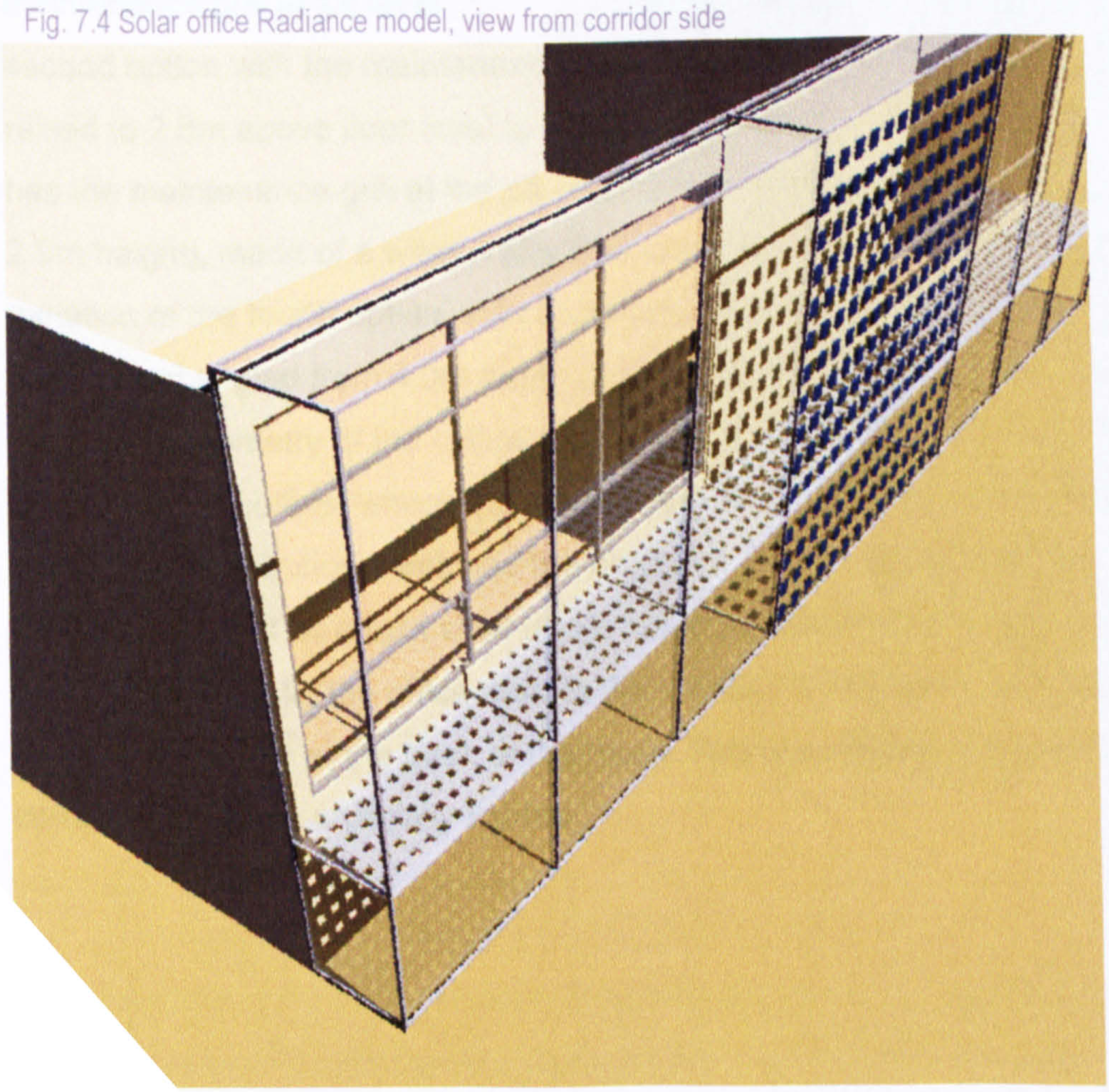


Fig. 7.4 Solar office Radiance model, view from corridor side



ce Radiance model, close view from south-west

There are two south-facing windows on the external wall of the office model through which daylight enters the office room. The shape of the room, reflectance of all surfaces, room height and depth, and the detail design of window openings, influence the intensity and distribution of daylight. The areas in front and below windows receive the strongest level of daylight that can result in over illumination of the front of the room. To avoid this, shading devices are commonly used to play an important role in reducing the solar heat gain, reducing strong daylight from entering the room, and reducing glare. However, the presence of a shading device, if inappropriately used when there is enough daylight available, may cause increased use of artificial lighting, in turn leading to higher use of electricity for lighting.

In this daylight modelling, six options of the solar office Radiance model were tested. The first option is the base case model of the typical office as existing, with two south-facing double glazed windows [Fig. 7.6]. The second option has the double skin component placed 0.6m in front of the existing façade, with the maintenance grill at sill level [Fig. 7.7]. The third option is a variation of the second option with the maintenance grill platform of the double skin component raised to 2.6m above floor level to act as a light shelf [Fig. 7.8]. The fourth option has the maintenance grill at the sill level and suspended horizontal ceiling [at 2.9m height], made of a white, reflective material [Fig. 7.9]. The fifth option is a variation of the fourth option, with a ceiling suspended 0.2m from the existing ceiling, and angled from 4.0m depth of the room to the back of the room [Fig. 7.10]. The geometry of the ceiling was modified to assist distributing daylight deeper into the office, where it is expected to be lower than at the front of the room. The sixth option combines the third and the fifth option, with the maintenance grill as a light shelf and a reflective suspended angled ceiling [Fig. 7.11]. In all models, the office door to the corridor is half open, allowing some extra light to enter at the back of the room. This is a realistic assumption, as corridors would be artificially lighted.

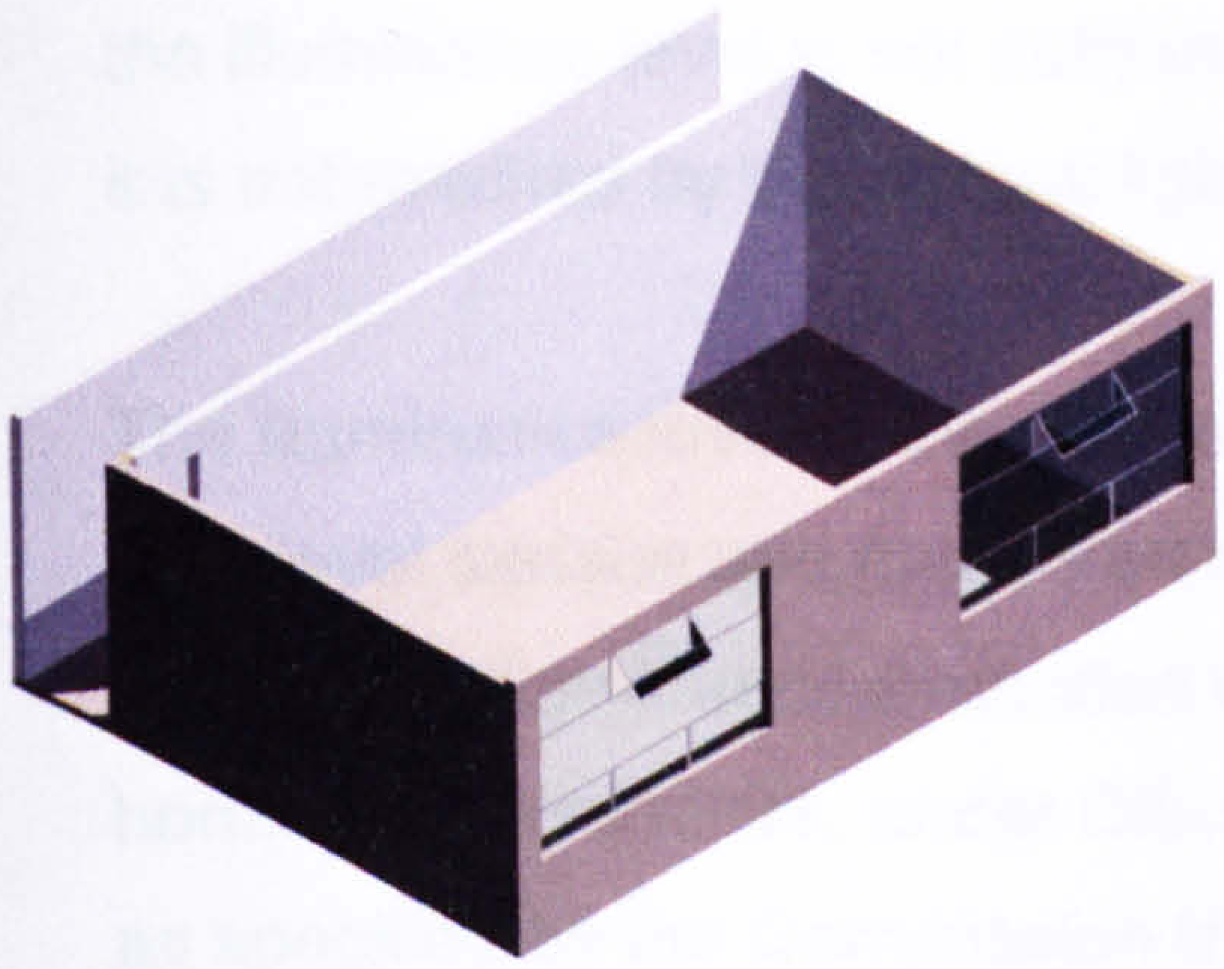


Fig. 7.6 Option 1: Office as existing

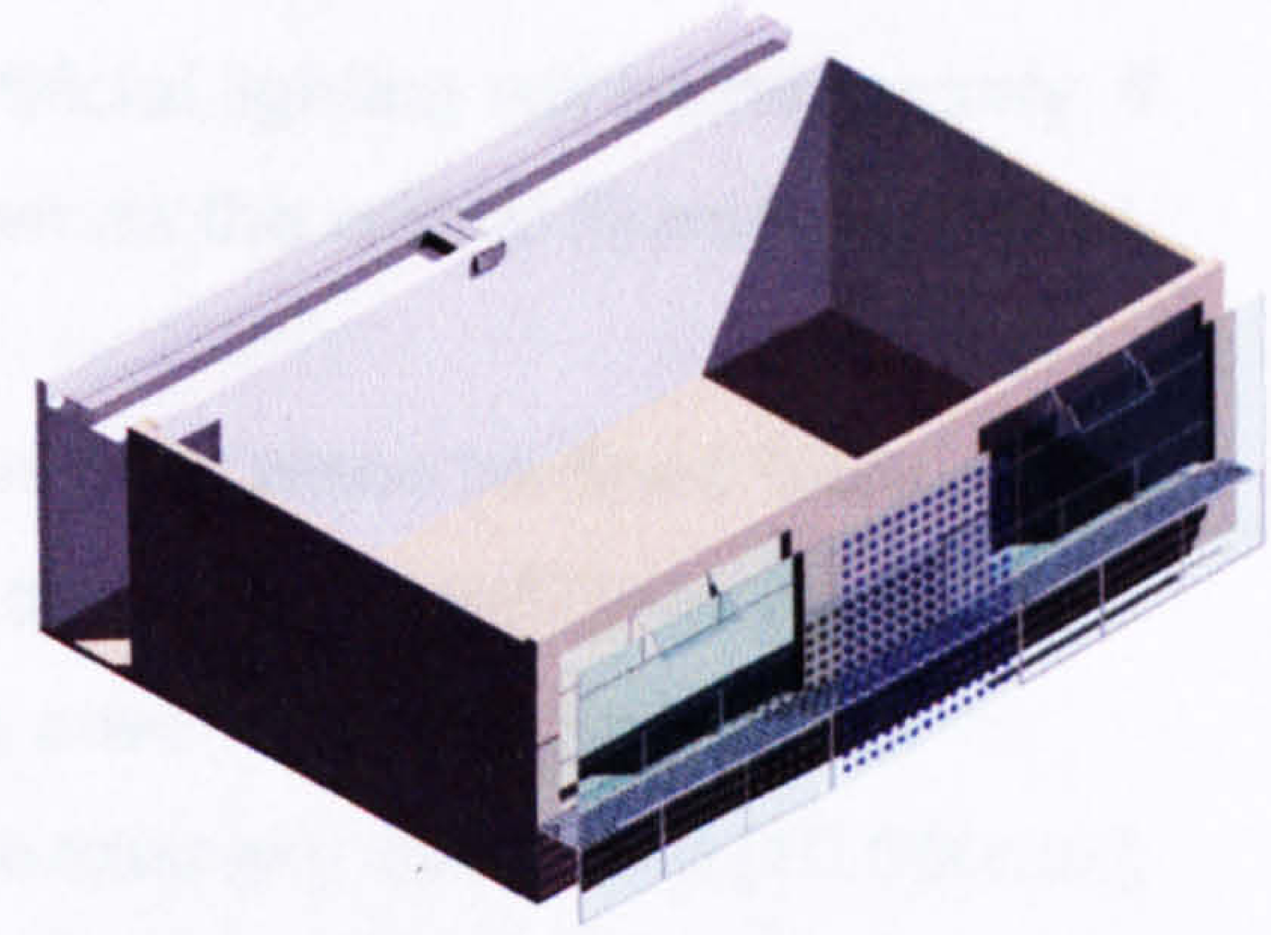


Fig. 7.7 Option 2: Office with double skin façade and maintenance grill at sill level

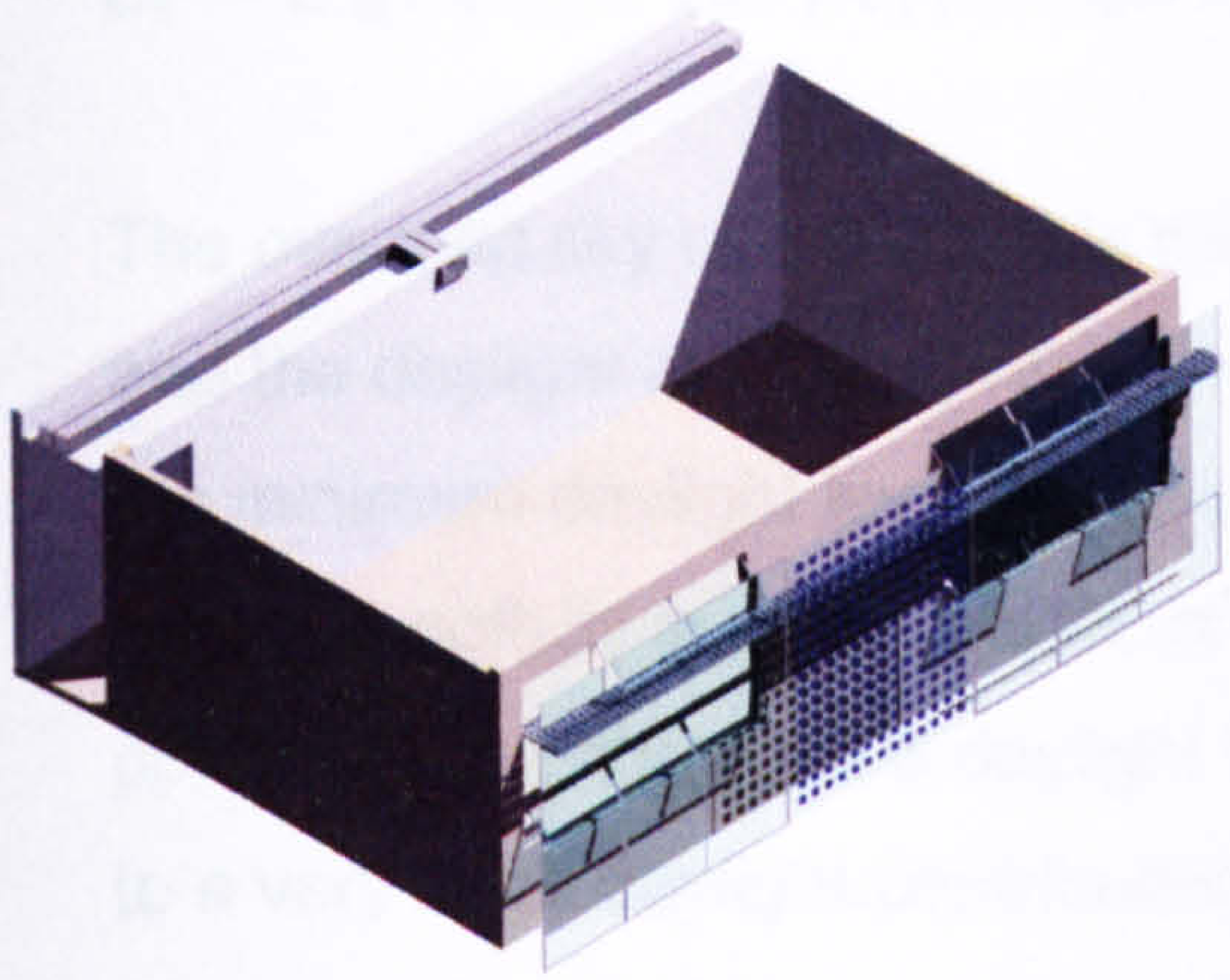


Fig. 7.8 Option 3: Office with double skin façade, maintenance grill as a light shelf

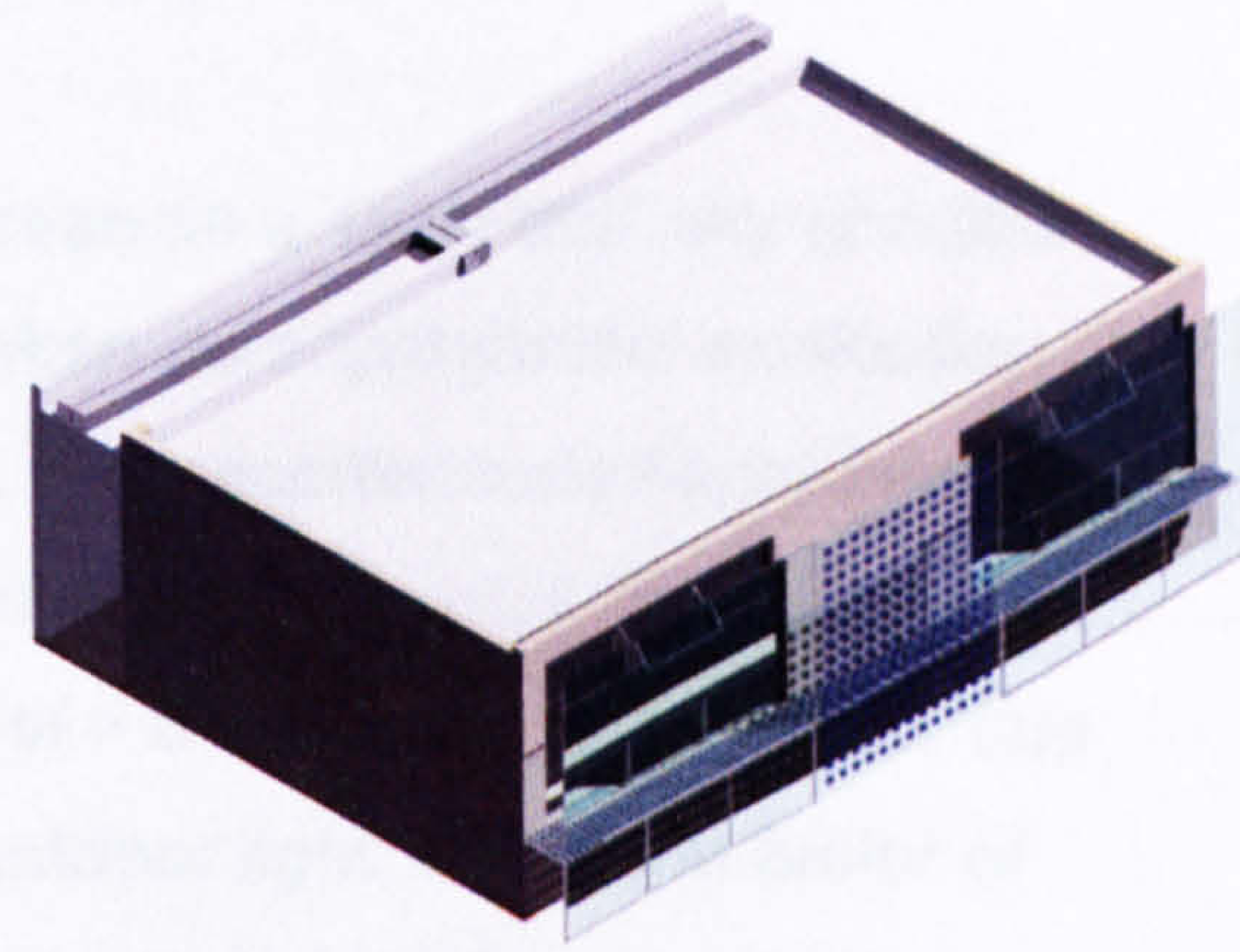


Fig. 7.9 Option 4: Office with double skin façade, maintenance grill at sill level and suspended reflective ceiling [horizontal]

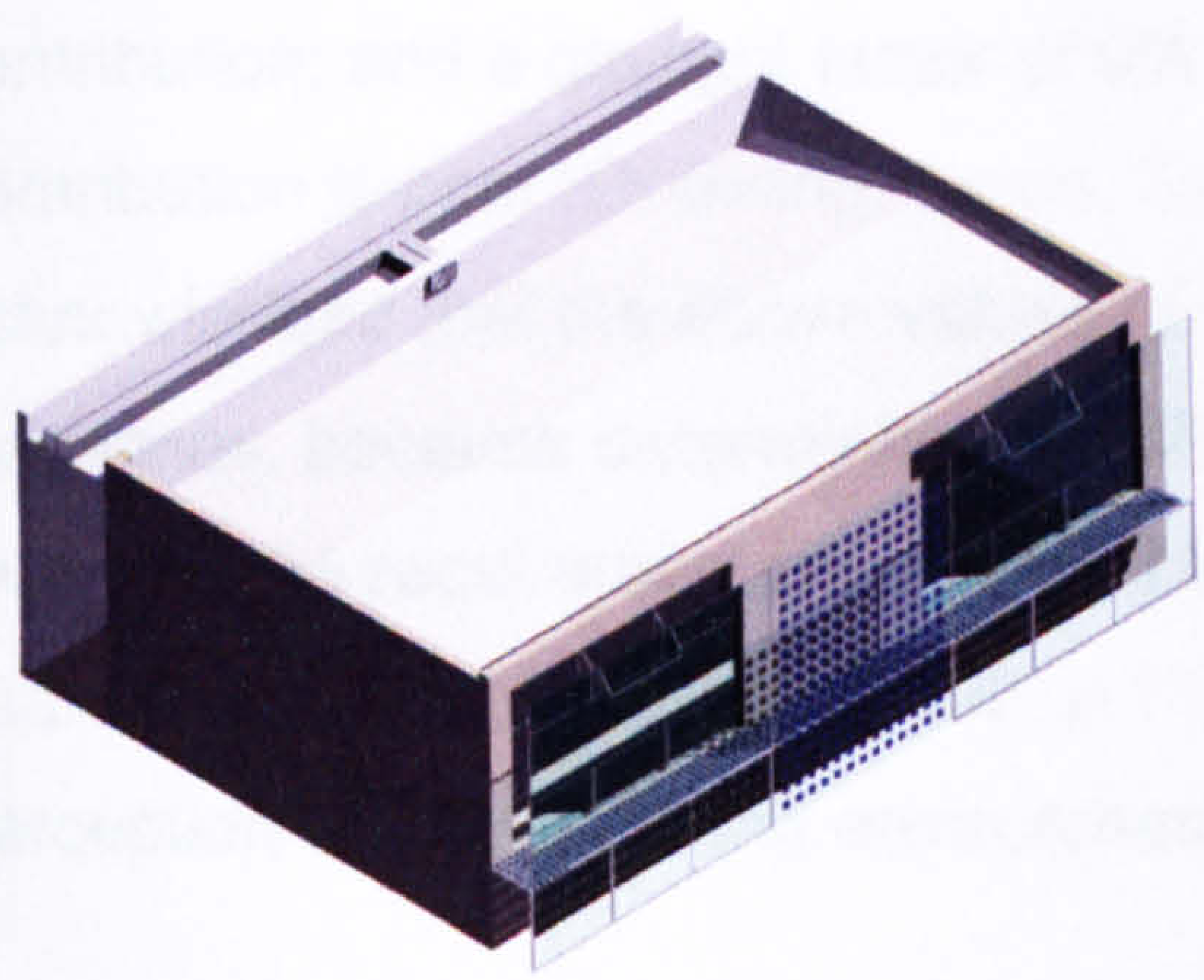


Fig. 7.10 Option 5: Office with double skin façade, maintenance grill at sill level and suspended reflective ceiling [angled]

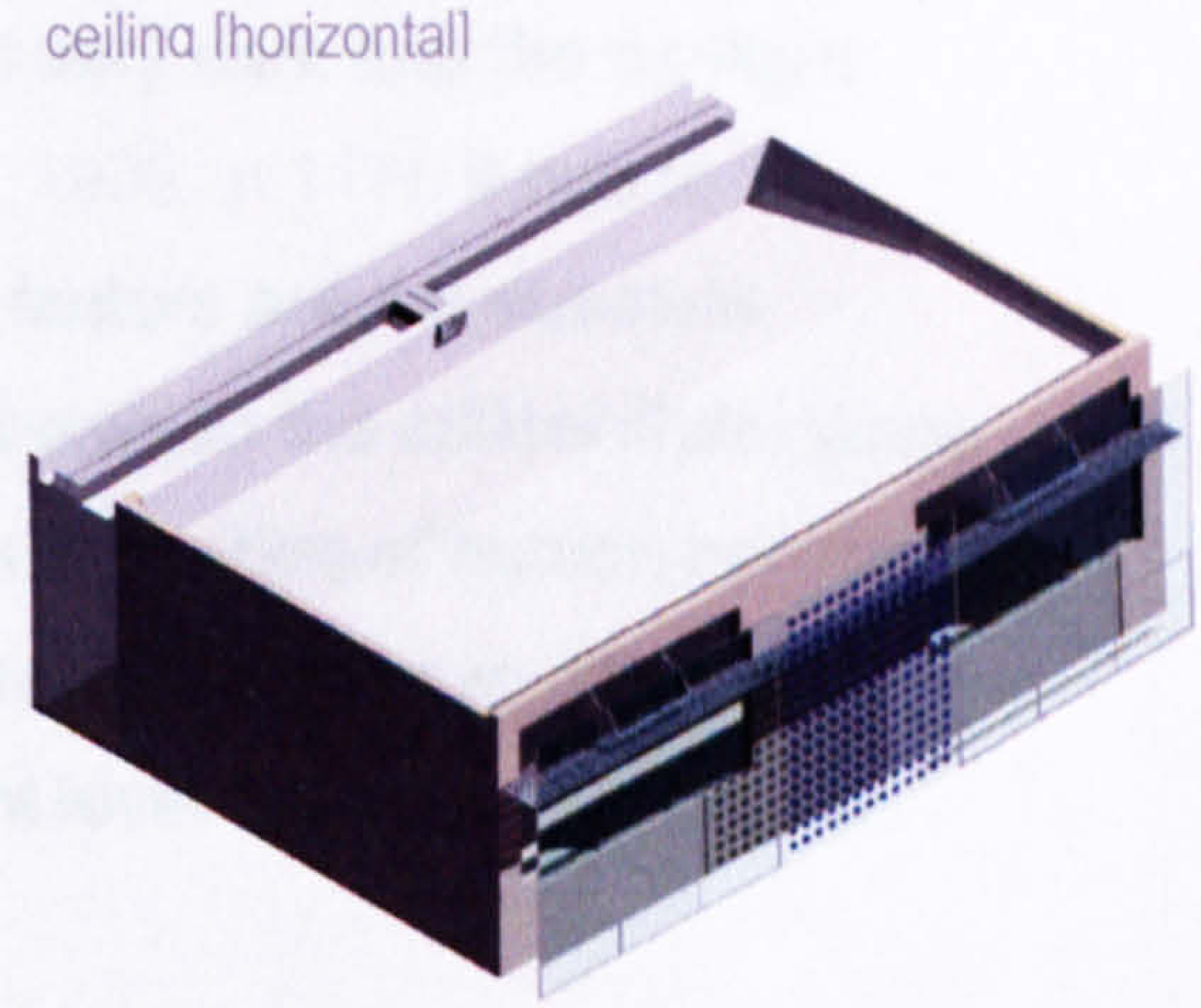


Fig. 7.11 Option 6: Office with double skin façade, maintenance grill as a light shelf and suspended reflective ceiling [angled]

7.1.1 SOLAR OFFICE DAYLIGHT MODELLING

The objective of the daylight modelling in Radiance was to evaluate the interior illuminance level [Lux], the daylight factor [DF], and the percentage of saved energy for artificial lighting that would otherwise been used to lit the room, when the Lux level on the office work plane falls below the lighting design level recommended for offices of 500Lux. The critical point at the work plane at which the illuminance level is not sufficient and an artificial lighting will be necessary, if it is not reached by the natural lighting, is known as the critical illuminance level.

The illuminance level is the daylight striking the work plane [defined 0.8m above floor level surface and measured in Lux]. The daylight factor [DF] is the ratio of the interior illuminance evaluated at a point on a work plane to the global horizontal illuminance, under CIE standard overcast sky conditions [10,000Lux], as specified by the Commission Internationale de l'Eclairage (CIE), [Goulding, Lewis, Steemers, 1992, p.117]. The DF is expressed with the formula:
$DF = E_{in} / E_{out} \times 100$ [%] [Larson *et al*, 1998, p.348].

The overcast sky chosen in this modelling represents a 'fairly dull' sky condition, and the daylight modelling results should be taken as a 'pragmatic' evaluation of the minimum daylight level in the office model. The recommended light intensity for office activity is around 500Lux [Randal and Max Fordham & Partners, 1999, pp.95-96]. An area with a daylight factor level of > 6% is considered bright, due to a very large daylight contribution from the outdoor light; a daylight factor of between 3% and 6% is considered average with a good outdoor daylight contribution; a daylight factor of 1% to 3% appears dark and has fair daylight contribution; and a daylight factor of 0% to 1% is very dark and the daylight contribution is poor [Goulding, Lewis, Steemers, 1992, p.117]. It has to be acknowledged that the above values of daylight factors are not absolute guidelines, because determining the difference between the critical illuminance level and the requirements for artificial lighting is a function of human behaviour [Goulding, Lewis, Steemers, 1992, p.116]. Different people have different perception for their working environment daylight level.

The general rule, when the daylight enters a space through south-facing window [as in the case of the office model], is that the depth of a space for adequate natural illumination should be in a range of 2 to 2.5 times the window height. This means that for a window height of 2.0m the maximum depth that daylight will enter is maximum 5.0m. In the case of the office room tested, the room depth is 6.0m and windows are 2.0m high, falling close to the general rule, with an assumption that daylight will nearly penetrate the entire space. However, a good daylight design must provide both visual comfort and energy conservation. Saving energy for artificial lighting also signifies a reduction in the heat load generated from artificial light, thereby reducing the cooling load in summer months.

Saving energy for lighting in offices depends strongly on patterns of use of artificial lighting. In the paper "From Feedback to Strategy" [Bordass and Leaman, 1997], some of the findings of the Probe studies on the subject of the performance of eight British buildings from energy, environmental and occupant perspectives are discussed. The automatic lighting controls design and performance are qualified in most case study buildings as disappointing with lights switched 'on' for long hours. The paper suggests that a key to better performance and occupant satisfaction is control, where control allows:

> "systems to operate more efficiently according to need; management and occupants to intervene where necessary to adjust programmes and settings; and individuals to obtain the services they require, when they require them, and to take action if they experience a crisis of discomfort".

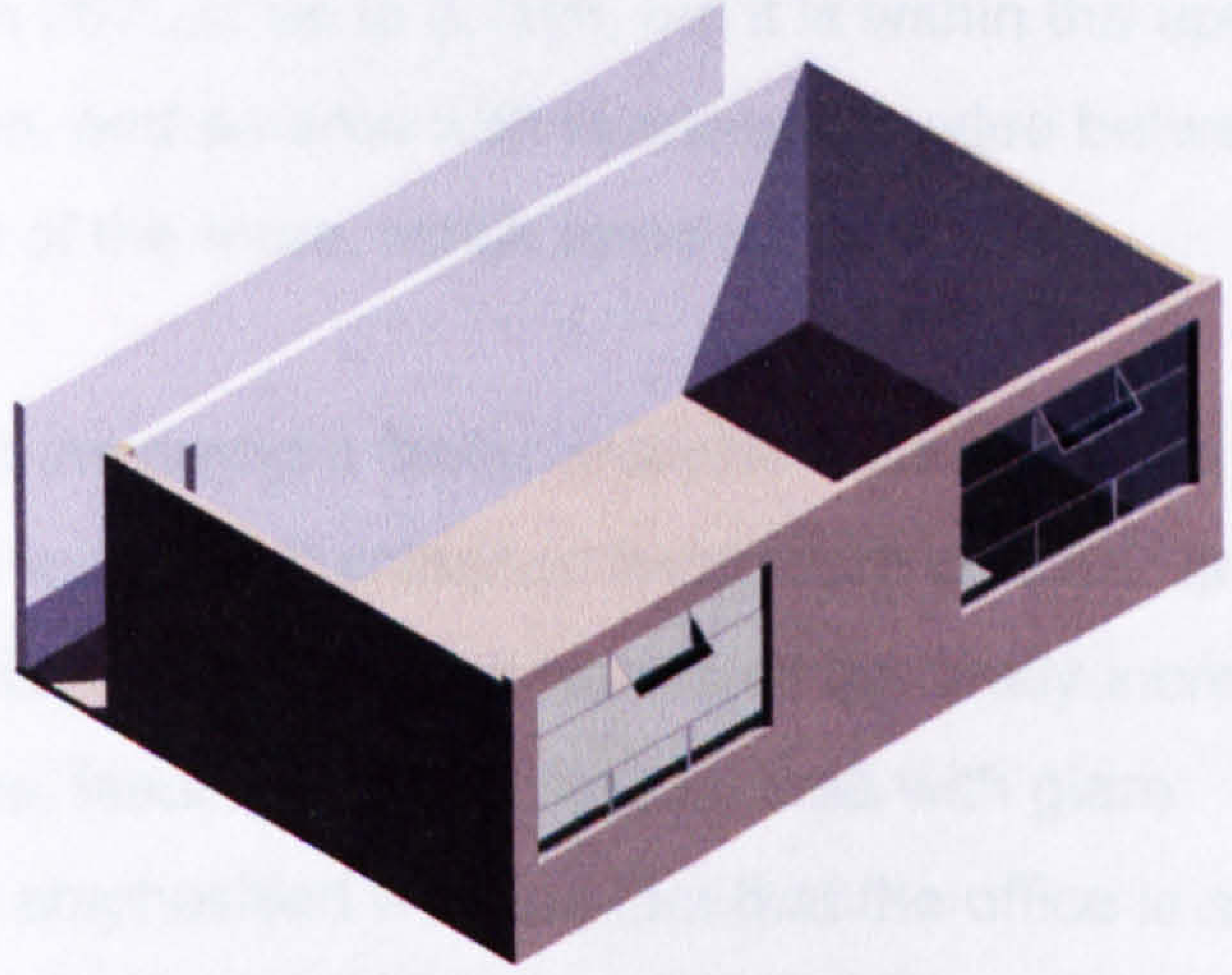
In terms of lighting strategy, the paper suggest as essential, the ability for users to over-ride automatic operations in switching lights, moving blinds or opening windows, with following recommendations:

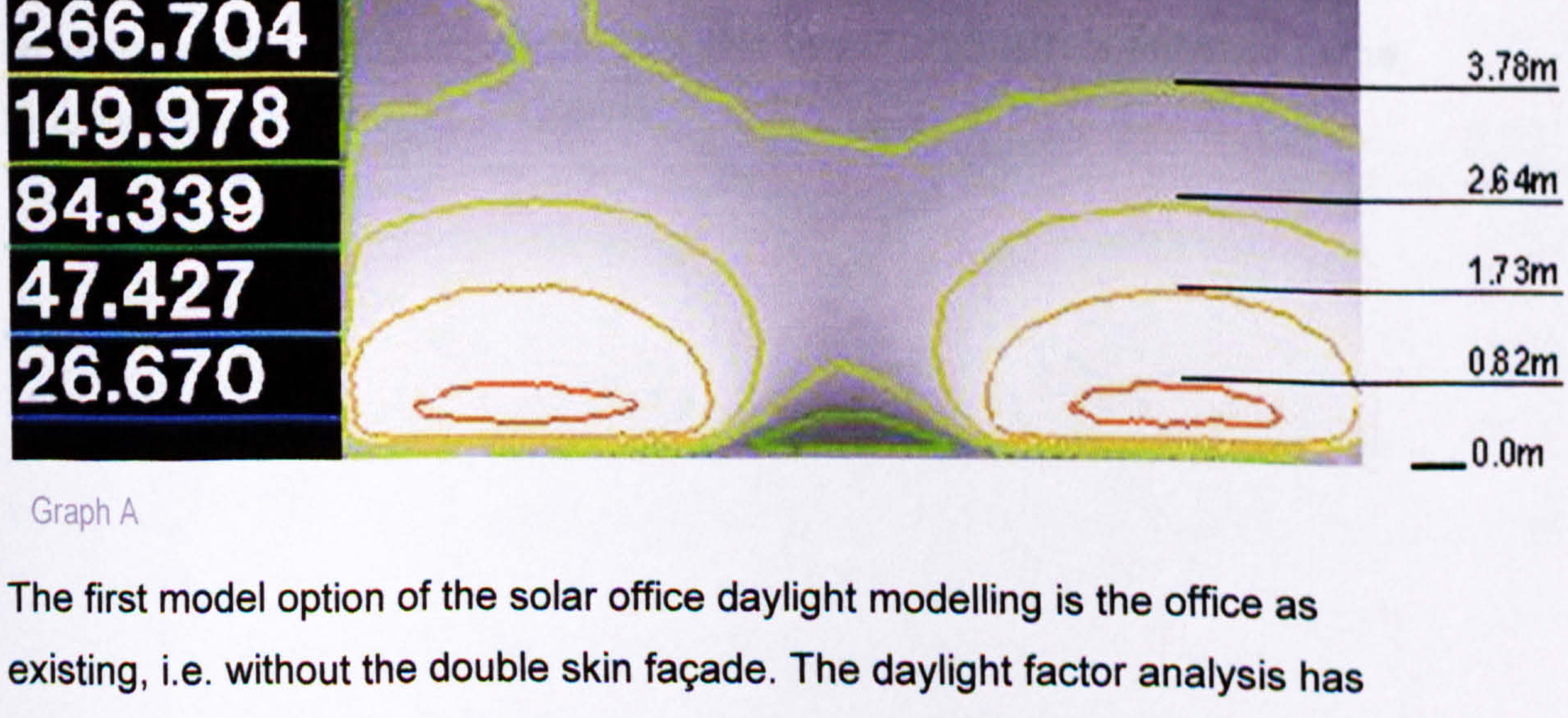
- To avoid lights being switched 'on' unnecessarily when users do not need them, the possible solution is to include manual 'on' switches, include manual 'off' switches, in addition to occupancy-sensed lighting in offices.
- For the measure of automatically dimmed lighting, which reduces artificial illuminance level when daylight is sufficient, the recommendation is to bring lights 'on' at a low but reasonable level, in combination with given opportunities for the users to increase brightness of the lights when required.

7.1.2 DAYLIGHT MODELLING RESULTS

The daylight factor analysis was based on the DAYFACT lighting analysis tool in Radiance [more information given in the Radiance Appendix]. This tool is an interactive script to compute illuminance values, daylight factors and the potential for saving energy on a given lighting design level [500Lux in this case], and on a work plane specified as 0.8m above the office floor level. Results for each model option tested are presented as graphs, where the contour plots of work plane illuminance values is shown on Graph A, work plane daylight factors are shown on Graph B, and potential for saving energy on a given lighting design level is shown on Graph C. On the left-hand side of each graph, a label shows the measurement units, Lux, DF, and % for the illuminance level, daylight factor value and saving energy percent, respectively. The contour line colours, superimposed over office work plane are a two-dimensional representation of isolux or iso-daylight factor lines, corresponding to the Lux and Daylight Factor curves on the work plane, and assigned values for each contour line colour shown on the left-hand side. On the right-hand side, there is a scale in metres [m], showing the depth of the office room, from 0.0m on the internal side of the external wall, to 6.0m at the back wall, as well as scale lines showing contour line distances from the front wall.

OPTION 1 Office as existing



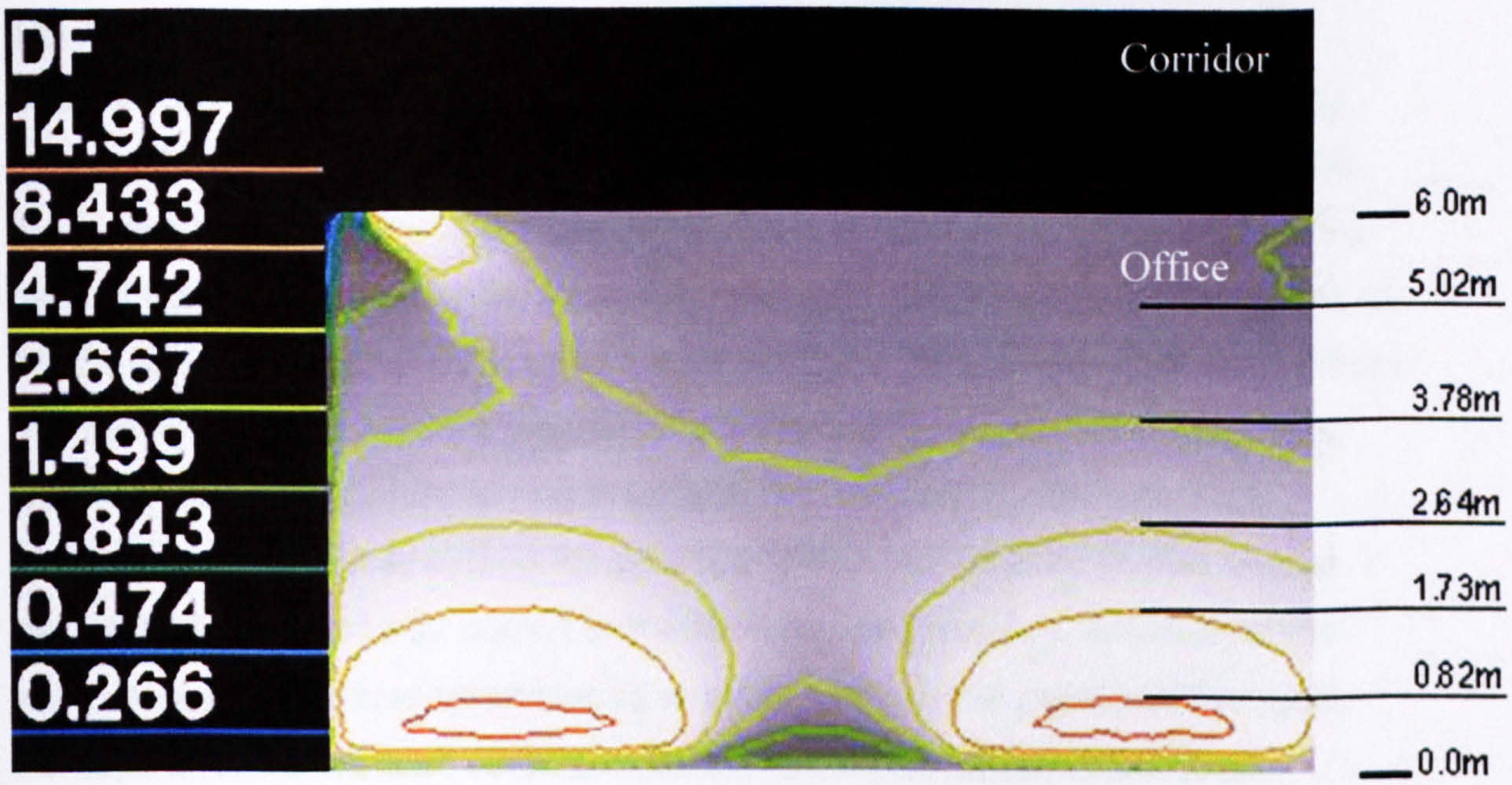


Graph A

The first model option of the solar office daylight modelling is the office as existing, i.e. without the double skin façade. The daylight factor analysis has shown areas with highest illuminance values on the work plane in front and below windows. The illuminance level [Graph A] has a value of 1,500Lux up to

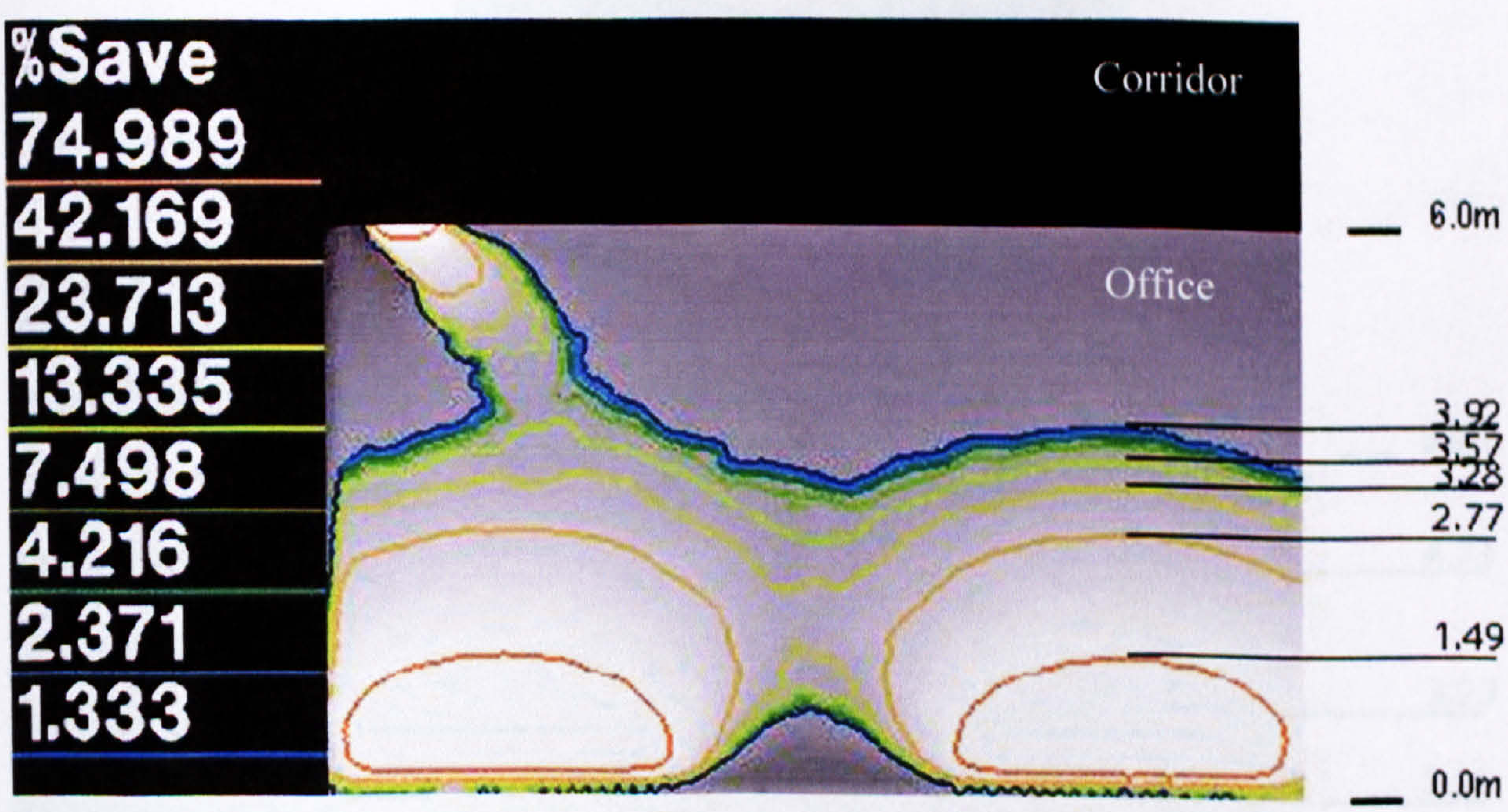
0.82m from the front wall, which is 3 times the recommended value [500Lux] for offices. Further from the external wall, the intensity of illuminance value is nearly halved to 843Lux up to 1.73m distance from the front wall. That suggests that under overcast sky conditions of 10,000Lux, the illuminance level in the front area directly below windows is very bright, above the recommended values for offices, and it is a source of glare. In the middle of the room, the daylight level reaches 474Lux up to 2.64m distance from the façade. It is evident that the illuminance level on the work plane is reduced three fold from the front to just below the middle of the office room, and it is within the optimum daylight level for offices. From the middle of the room to the back wall, the daylight level falls below recommended value, with 267Lux up to 3.78m, but it is within the upper range of fair daylight contribution, and an area with illuminance value between 267Lux and 150Lux at the back of the room, which appears dark.

Having said all this, the fact that the daylight factor analysis is based on an overcast scenario, under higher external illuminance level, such as clear and sunny skies, it is expected the daylight level in offices would generally increase throughout the whole work plane, leading to an increased area with glare problem in the front zone, [also emphasised with the fact that the office is south oriented], and also increased daylight values throughout the work plane. In terms of a visual comfort, the strong contrast between the illuminance levels at the front and the back of the room suggests an environment with strong variation of the daylight intensity and therefore poor visual comfort. To avoid glare, fine tuning with a system of daylight shading elements such as adjustable blinds, is recommended. The danger of this situation is the blinds staying down over a period of time when there is enough external daylight available, increasing unnecessary the use of electricity. This was found to be a frequent case in the Probe studies.



Graph B

The daylight factor results graph [Graph B], shows a daylight factor of 15% directly below windows, 8.43% up to 1.73m distance from front wall, 4.74% up to nearly the middle of the room up to 2.64m, 2.67% up to 3.78m, and 1.5% beyond 3.78m distance, up to the back wall. N.B. The DF graph and Lux level graph result values correspond directly because they have been calculated with a 10,000Lux global horizontal illuminance. The daylight factor values confirms that the front of the room directly in front of windows is too bright, the middle of the room has good daylight availability, and the back of the room appears dark.

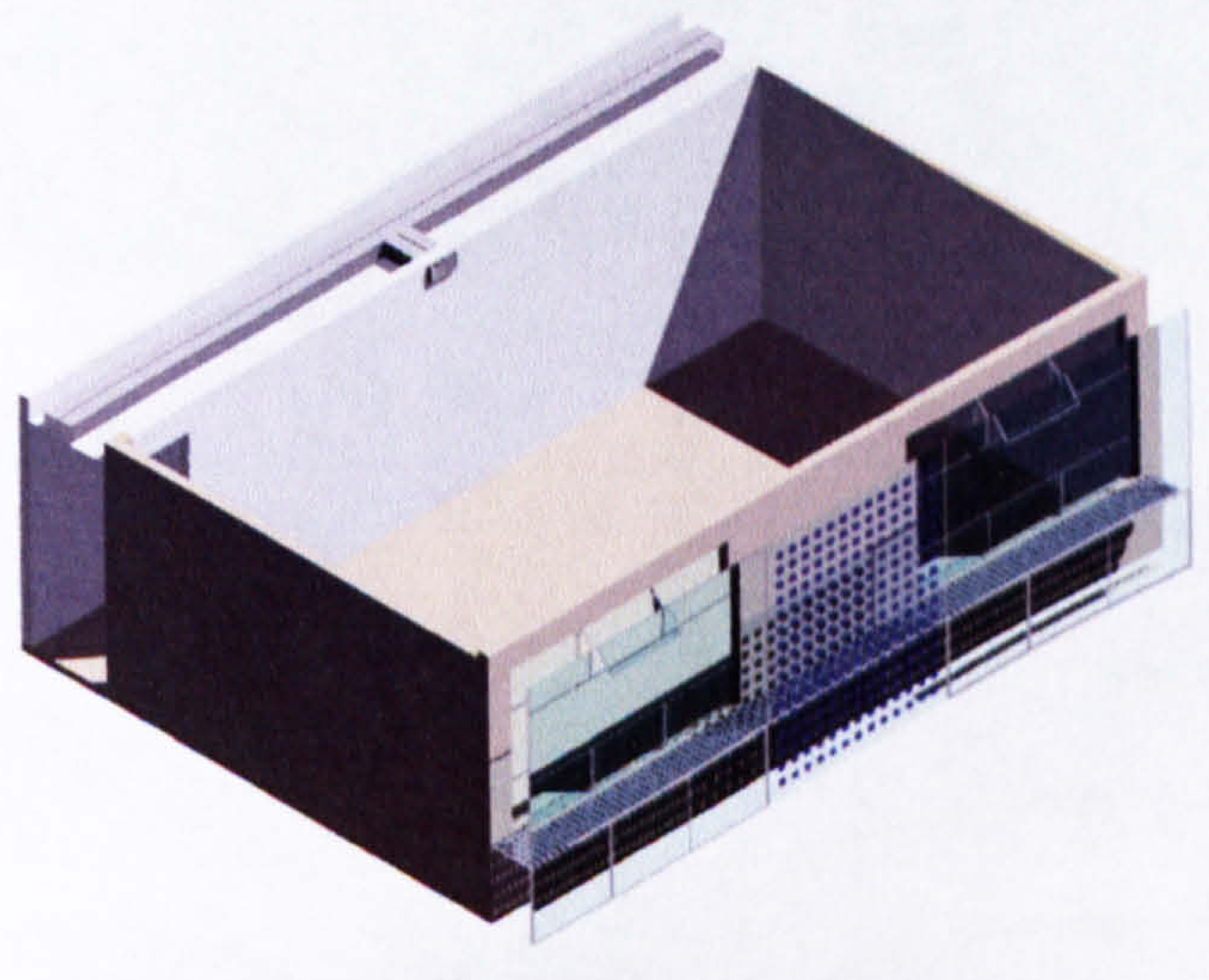


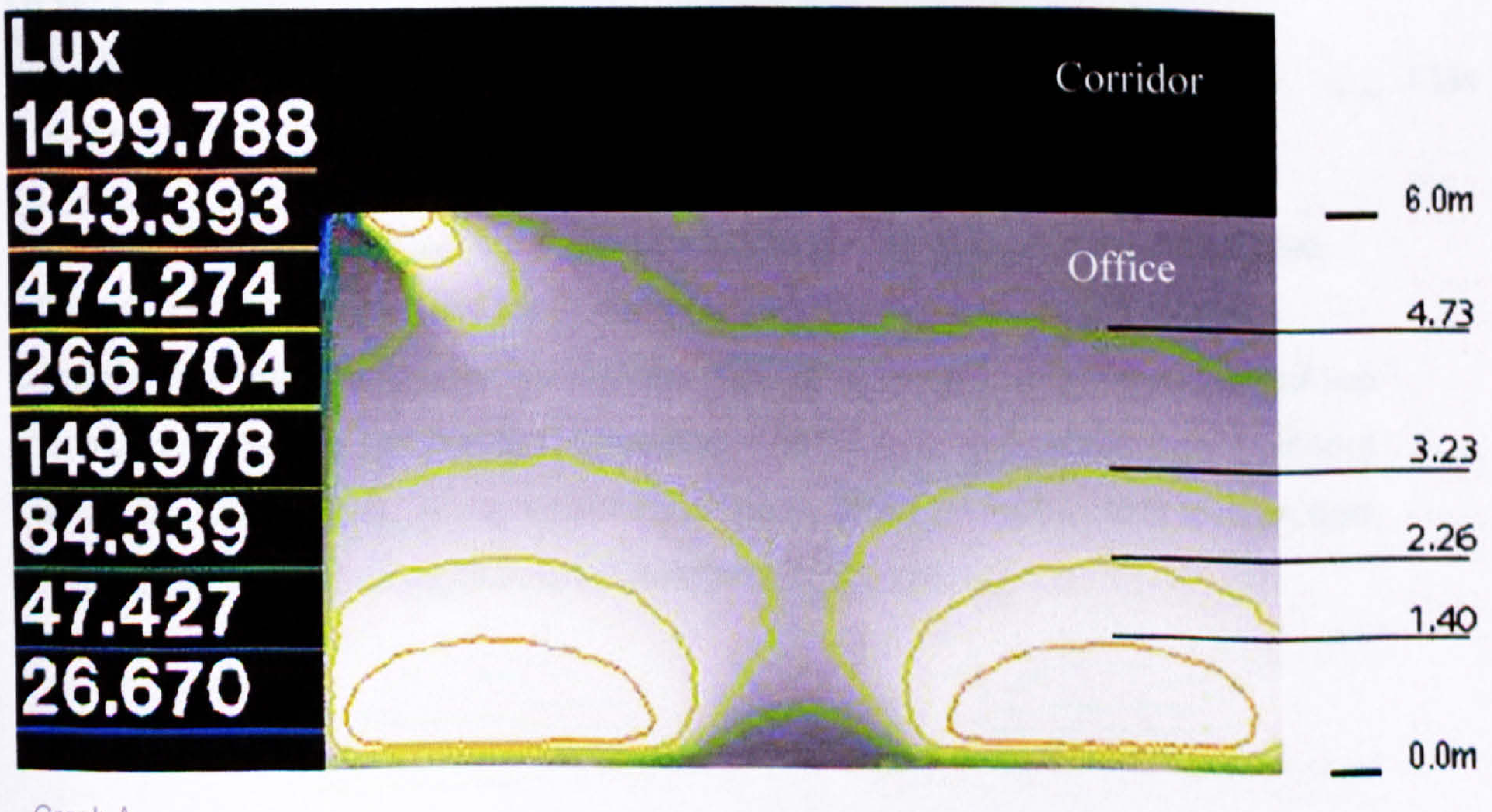
Graph C

Fig. 7.12 Daylight factor modelling results. Model 1: Office as existing

The saving energy graph [Graph C] shows the brightest area in front of windows, up to 1.49m from the front wall, with the highest potential for saving energy of 75%. In the middle of the room, up to 2.77m distance from front wall, the saving energy potential is reduced to 42.1%. Further from the middle to the back of the room, the potential for saving energy is 23.7% up to 3.28m, falling to 13.3% up to 3.57m and 1.3% up to 3.92m distance. This means that further from the middle of the room, the potential for saving energy is around 20% or less, with very little potential for saving energy in the area below 267Lux. This situation would suggest a need for an office layout, with activities that require higher daylight level to be placed in the front half of the office, while personal computers and monitors to be placed to avoid glare in the middle of the room. Perhaps a relaxation area could be located to the rear of the room. Thus activities with lower and higher light demand could correspond to the daylight supply, and hence will minimise the need for artificial lighting.

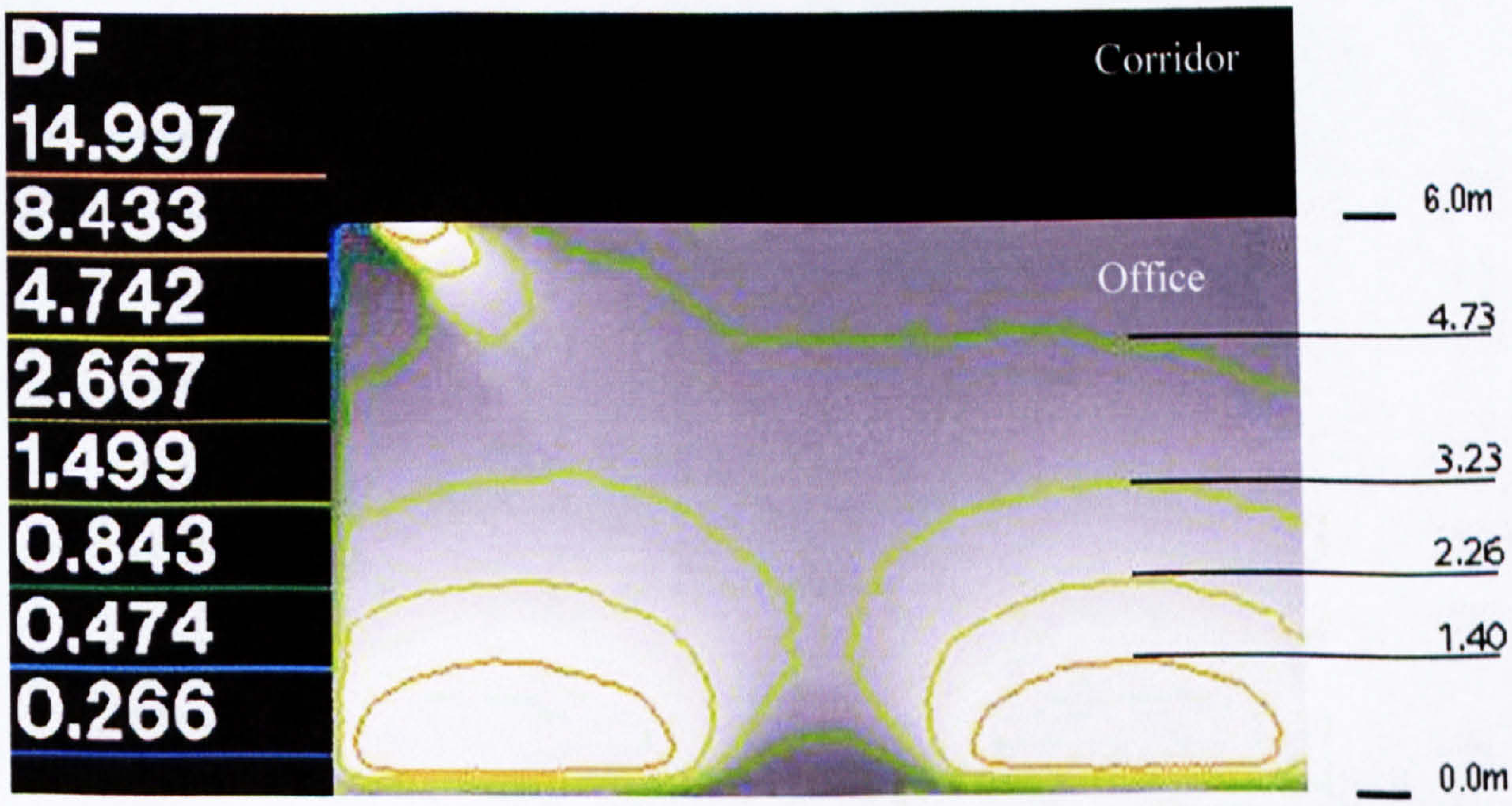
OPTION 2 Office with double skin façade and maintenance grill at sill level





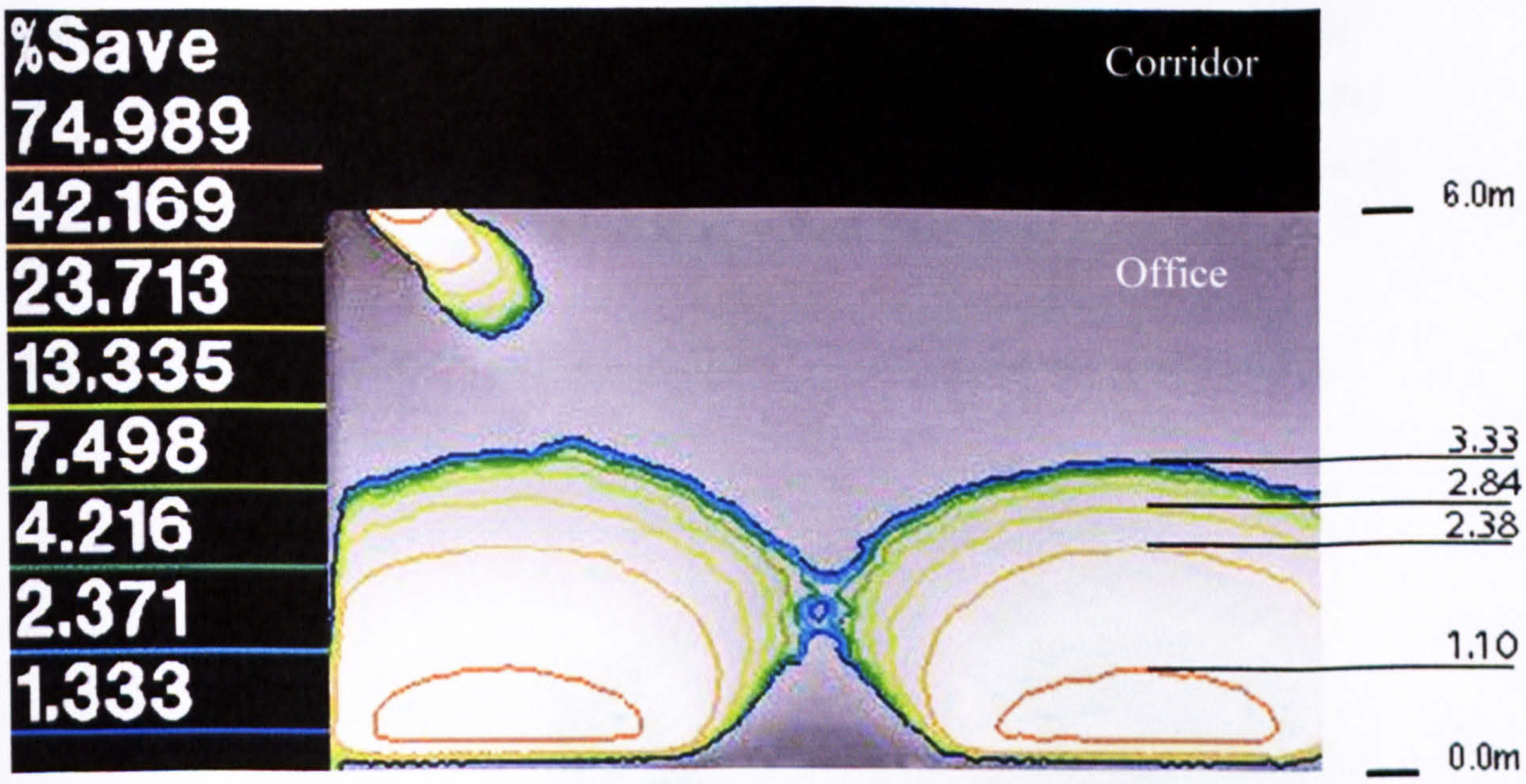
Graph A

The second model option investigates the effect of the single glass structure of the double skin façade on the internal daylight values, when placed in front of existing office model. The illuminance value results [Graph A], shows illuminance level of 843Lux in the area up to 1.40m distance from windows. Compared to the base case model of the office without the double skin façade, the daylight level is reduced, i.e. there is no area with illuminance level higher than 843Lux directly below windows, as in the case of the first model, and the distance of the area with 843Lux is narrowed from up to 1.73m in the first model, to 1.40m distance when the skin component is added. A similar effect follows in the rest of the room, with the contour line of 474Lux being narrowed by 0.38m compared with the same contour line of the previous model, [i.e. 2.64m to 2.26m], and the 267Lux contour for 0.55m, compared with the contour line of the first model. Finally, the area with less than 150Lux near the back wall is evidently increased, starting from 4.73m distance from front windows.



Graph B

Since the DF graph corresponds directly to the Lux level graph, as calculated with a 10,000Lux global horizontal illuminance, the daylight factor values confirms that the Daylight Factor directly in front of windows, in the middle of the room and at the back of the room is reduced compared to the first model without the double skin façade, which effectively means that the double skin façade had reduced the level of daylight throughout the whole room.



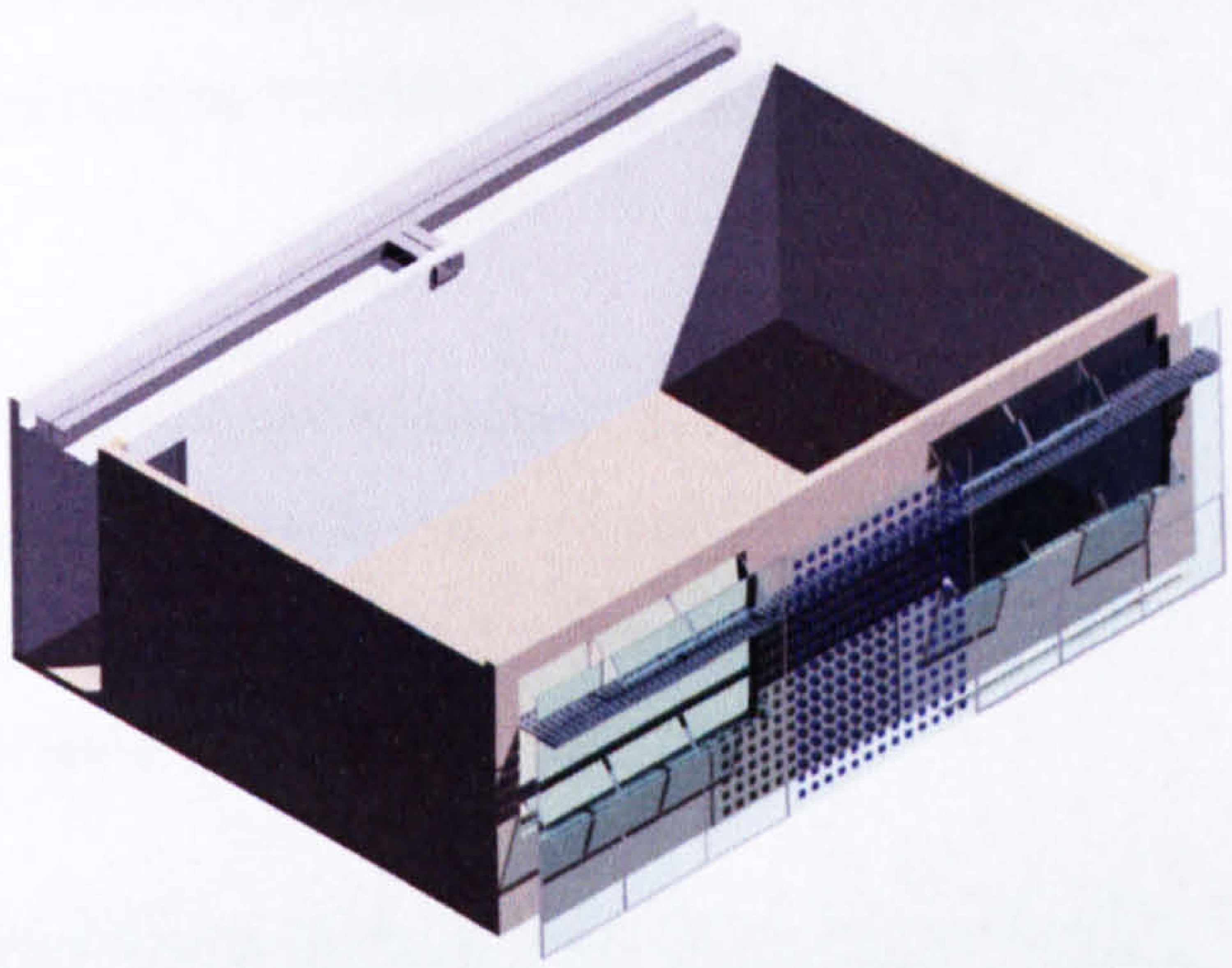
Graph C

Fig. 7.13 Daylight factor modelling results. Model 2: Office with double skin façade and maintenance grill at sill level

In terms of the percentage for saving energy, [Graph C], the area with highest percentage of 75% savings is reduced from up to 1.49m to 1.10m from the front wall, compared to the first model. The area with 42.1% savings is also shifted from up to 2.77m in the first model, to 2.38m in this model. In the middle of the room, the area with 23% saving energy is also narrowed, from up to 3.28m distance from front windows in the first to 2.84m in the second model. The area with the lowest percentage of saving energy of 1.3% now starts at 3.33m, compared to 3.92m in the base case model. It is evident that the double skin façade reduces the illuminance level in the office room, and consequently, the potential for saving energy is reduced throughout the whole office. In other words, there is a need for more artificial lighting to be provided in the model with the double skin façade to maintain an internal lighting environment with 500Lux level.

Although, this model has shown that the double skin façade reduces the daylight level on the office work plane, leading to less potential for saving energy for artificial lighting at the back of the room, it has also shown a positive effect from the double skin façade at the front of the room, where the area with highest daylight level is reduced. Therefore, the potential for glare is also reduced, also reducing the contrasts between the area with highest illuminance level at the front with the rest of the room, resulting in a more uniform spread daylight within the office and therefore better visual comfort. In favour for the double skin façade daylight performance is the notion that under clear and sunny skies, the daylight level penetrating the office will increase, with the double skin façade screening out part of the unwanted high illuminance level at the front, while the illuminance levels at the middle and back of the room would increase, all this of course, with a reasonable use of blinds to protect from direct sunshine.

OPTION 3 Office with double skin façade and maintenance grill as a light shelf

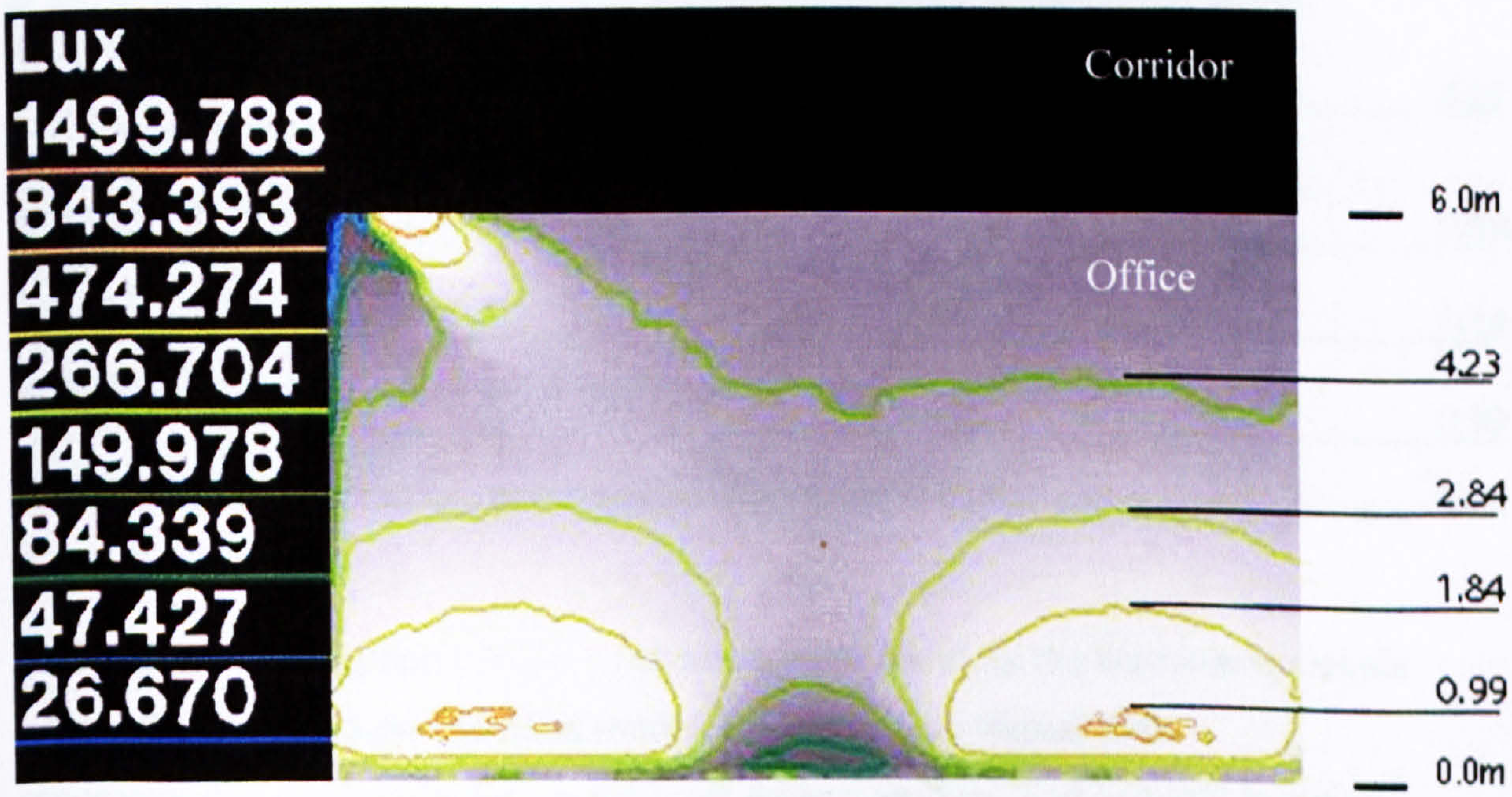


The third model option investigates the effect of the maintenance grill being raised to 2.6m above floor level and acting as a light shelf. As shown in the previous two models, the daylight intensity is reduced from the front of the room to the back of the room, showing a range of daylight levels, with a stronger contrast in the model without the double skin than in the model with the double skin façade. To help reducing this variation of light intensity even further and to reduce the high intensity daylight in the front zone, light shelves could be used partly to act as shading device and partly to redistribute daylight deeper into the room.

The redistribution effect of the light shelf is influenced by several factors including: shelf geometry, position, material properties, and the reflectance properties of the ceiling surface, and the ceiling's height and geometry. A fixed light shelf positioned below the ceiling will shade the lower part of the window, in both sunny and overcast conditions, and it will reflect and redirect some daylight further back into the room. The down side of this is that because the fixed light shelf is not geometrically selective, it reduces direct sunlight on sunny sky conditions, but it also may reduce diffuse light during overcast sky conditions. That may in cases result in under-illuminated conditions on overcast days leading to increased demand for artificial lighting.

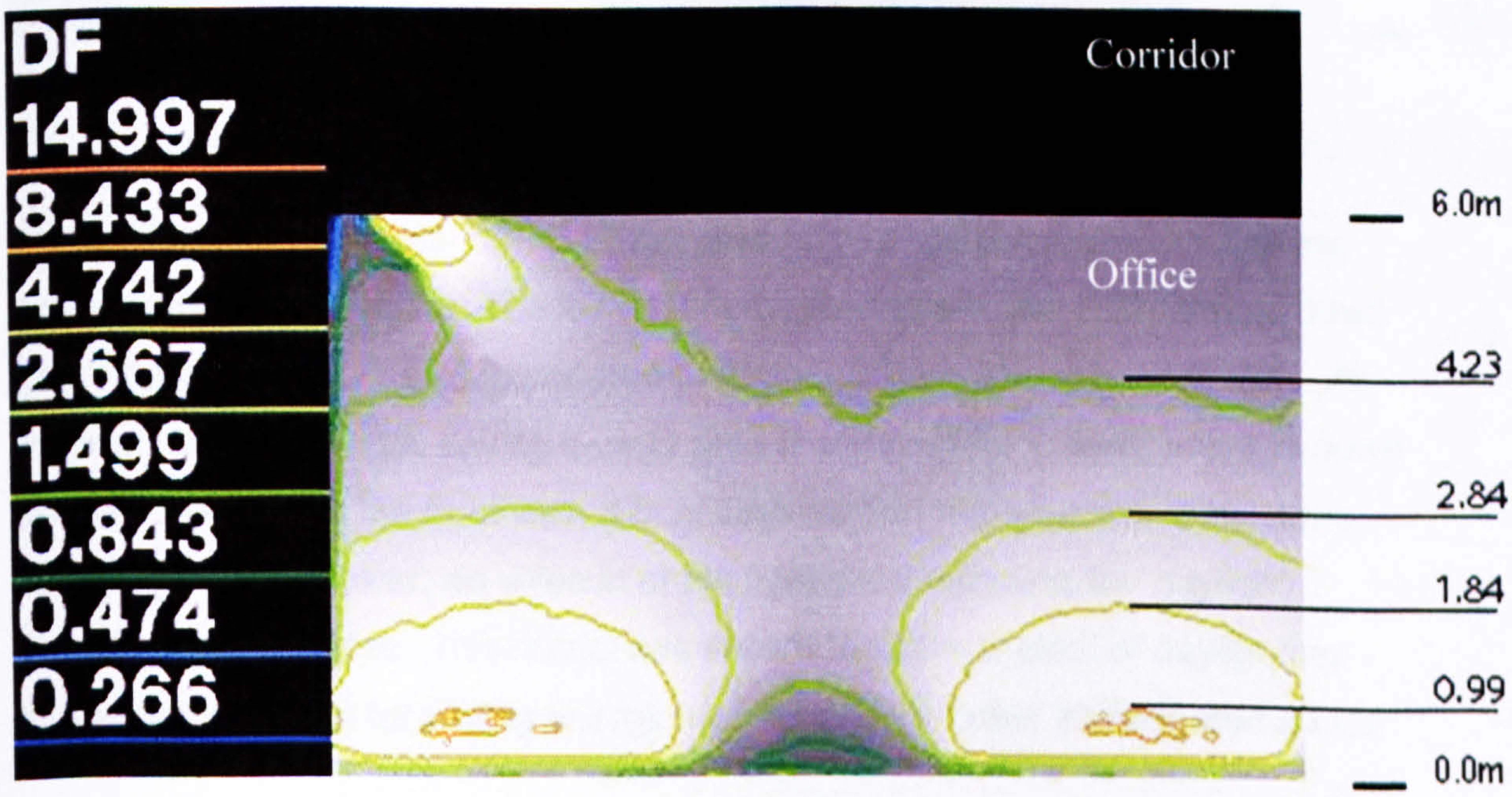
An earlier study on the subject of the impact of daylighting systems [including a light shelf], on visual performance and visual comfort in office rooms [van Bochoven *et al*, 1999, pp.379-384], has concluded that under an overcast sky, an office room with light shelf showed highly decreased illuminance values on work plane level near the façade. It also showed that it is difficult to increase the illuminance values on work plane level at the back of the room, and no savings of energy for artificial lighting could be achieved. However, the study concludes that the use of light shelf will improve the uniformity of daylight in the room under overcast sky conditions.

The following model investigates the maintenance grill, part of the double skin façade component, performing an additional function as a light shelf. N.B. For the modelling of this option, the ceiling position, geometry, and material properties have remained the same as in the first two models.



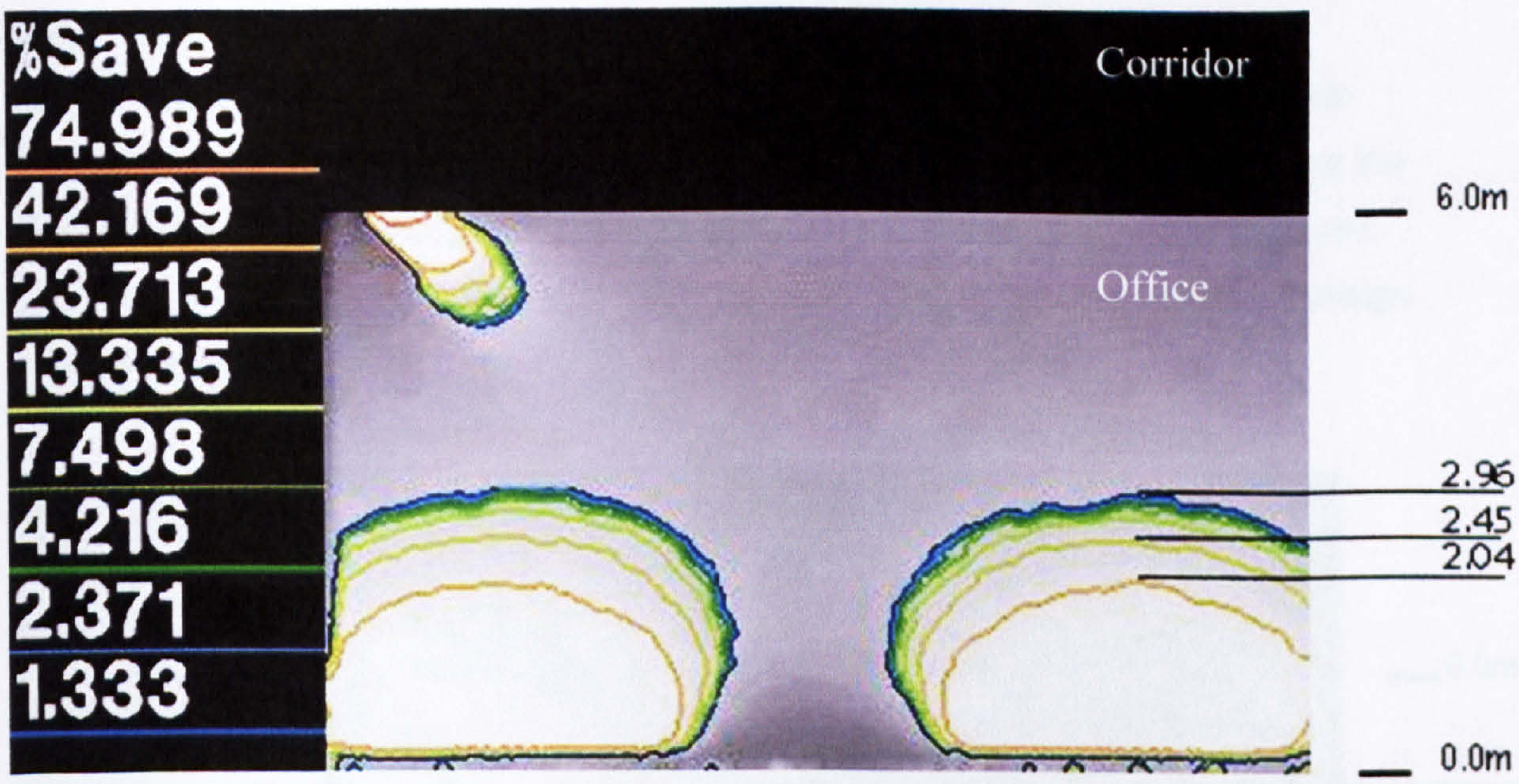
Graph A

The illumination level result graph [Graph A] of the third model, shows an area with 843Lux is reduced in size and location, compared to the double skin façade model, i.e. from up to 1.40m distance from front window in the second model, to only 0.99m in this model, proving the fact that under overcast sky conditions, the light shelf does shade the area directly below windows. Also, the area with 474Lux level is also narrowed by 0.42m compared to the second model, and the contour line marking the area with 267Lux is also reduced by 0.39m, compared to their position in the second model. So far, the effect of the added double skin façade and the light shelf on the office daylight has been that both reduce the illuminance level falling on the work plane at the front and the middle of the office. At the back of the office, the model with the light shelf has the darkest area increased by 0.5m, compared to the second model, suggesting that the light shelf has an overall negative effect to the office daylight environment, by reducing the daylight on whole office work plane, and without a significant effect on redistributing the illuminance deeper into the office. The lack of illuminance redistribution effect at the back of the room might be due to the fact that in this model the properties of the ceiling have stayed unchanged. That led to developing options for different ceiling properties, geometry, which is the subject of the next two model options.



Graph B

The daylight factor graph [Graph B] shows similar trend as the illuminance levels graph. Compared to the previous model, the areas with higher than recommended daylight factor values have been narrowed and brought forward closer to the front wall, while the area with low daylight factor at the back of the room has increased in area.

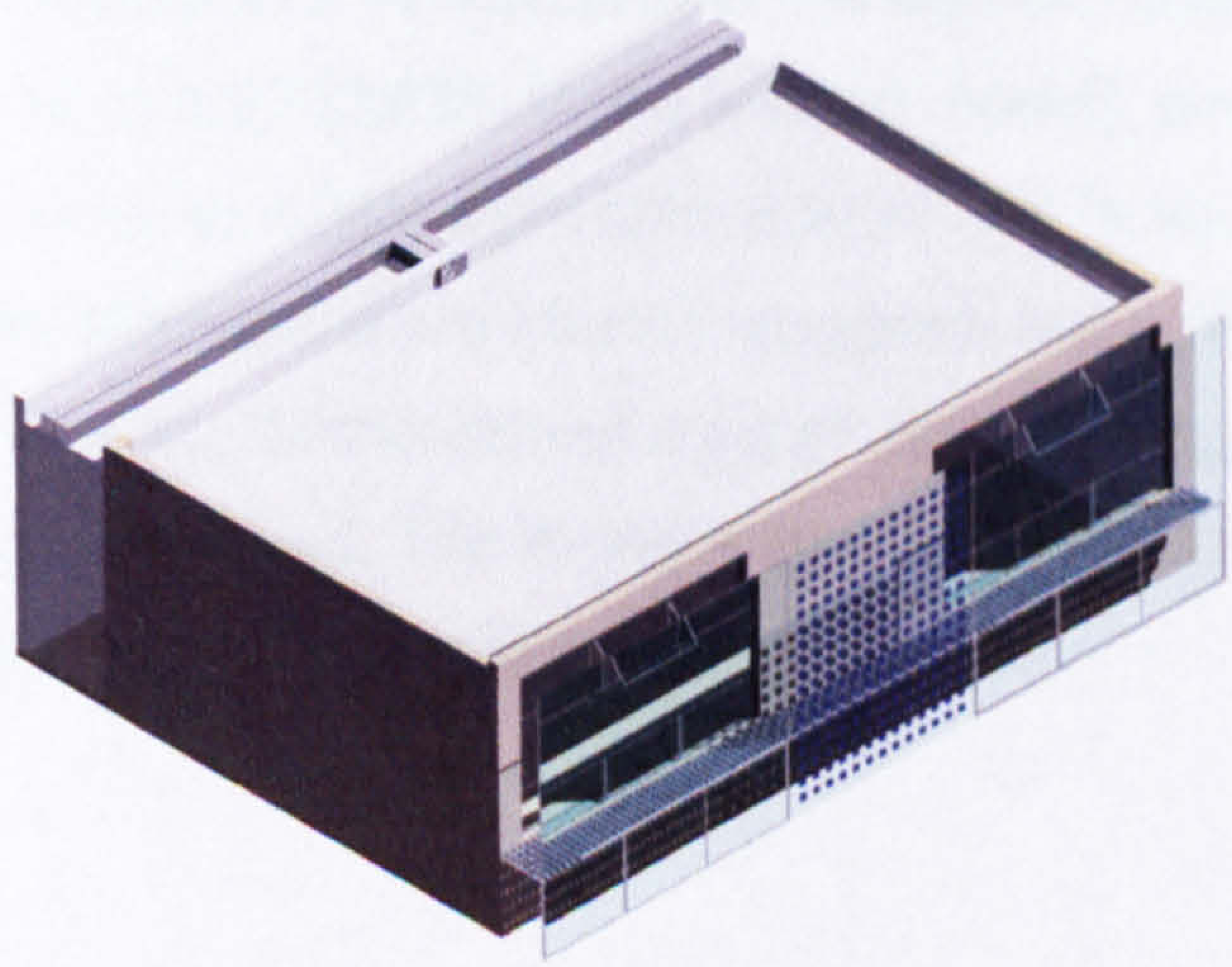


Graph C

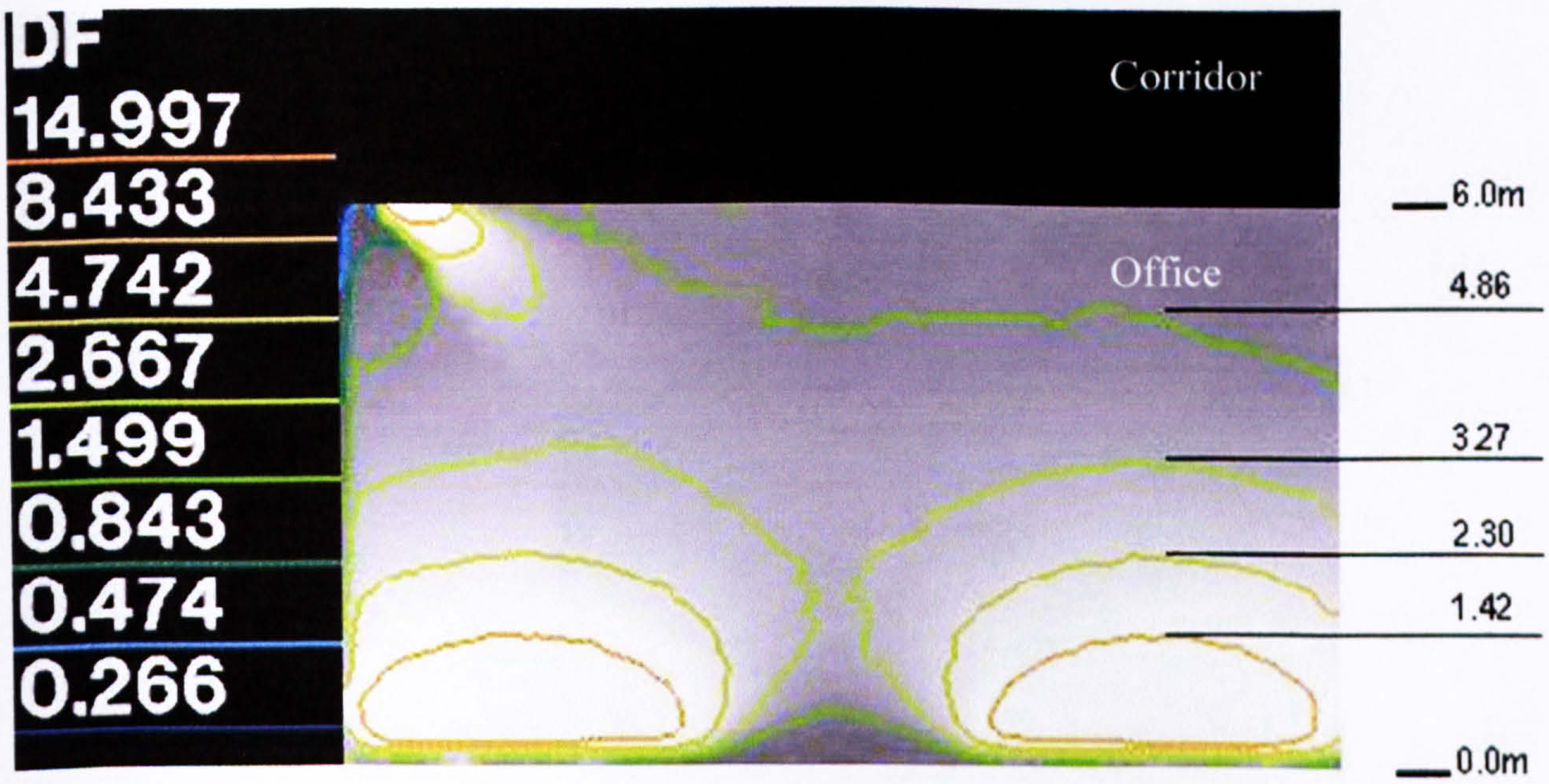
Fig. 7.14 Daylight factor modelling results. Model 3: Office with double skin façade and maintenance grill as a light shelf

The saving energy graph [Graph C] has also shown the poorest results of the three model options so far. The lowest energy saving area of 1.3% is now down up to 2.96m from front wall [compared to up to 3.33m in the second model]. At the front wall, the 42.1% saving energy area is reduced for 0.34m, and it is down to up to 2.04m from the front wall. It is noticeable that the area with 75% does not appear in this model, as a result of the light shelf reducing the daylight directly below windows. This model has shown the lowest level of daylighting and lowest potential for saving energy from all three models investigated so far.

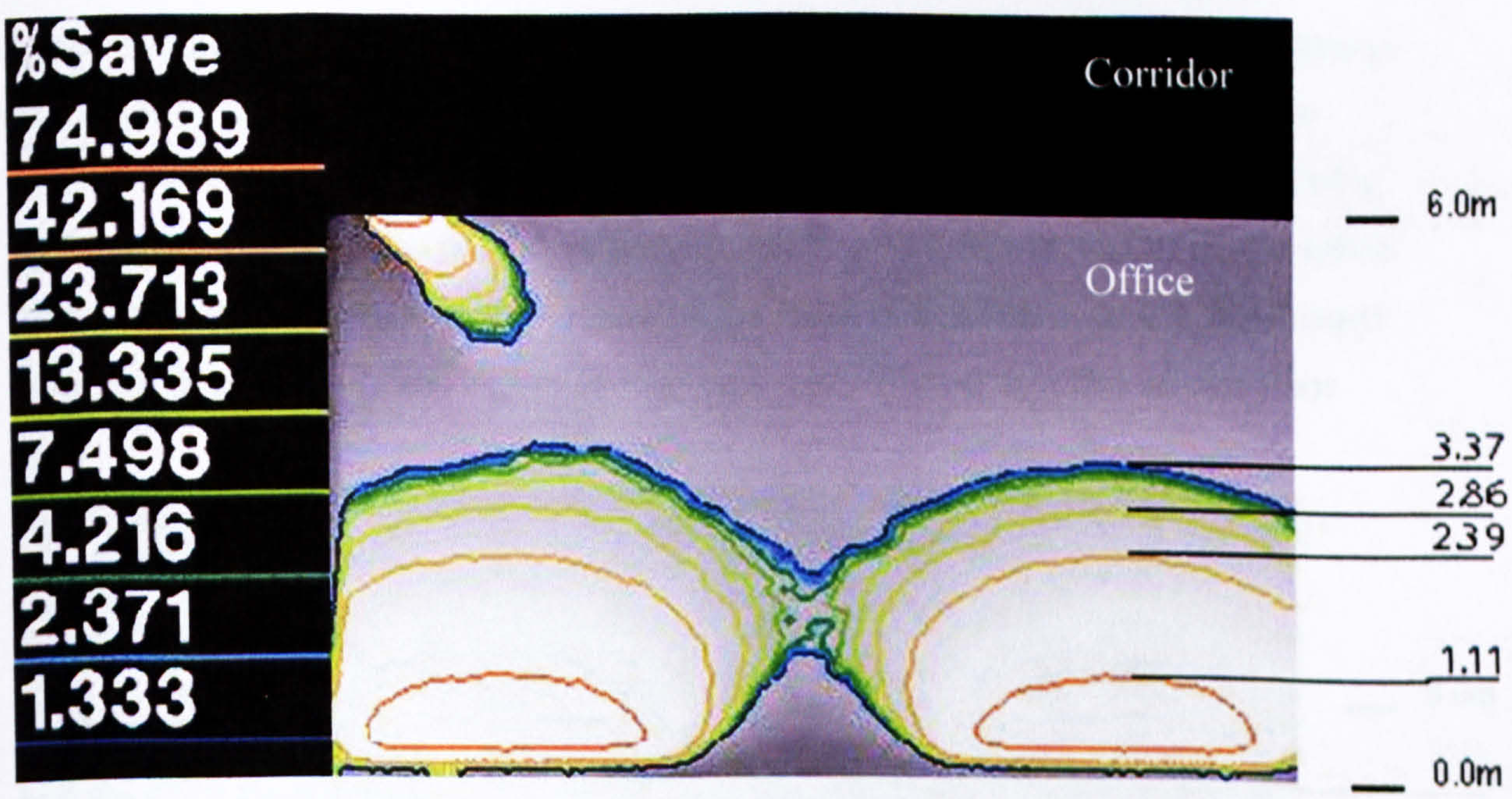
OPTION 4 Office with double skin façade, maintenance grill at sill level and suspended reflective ceiling [horizontal]



The fourth model option has a white, horizontal ceiling surface, suspended 0.2m below the existing ceiling. The rational behind this model option was to see the



Graph B

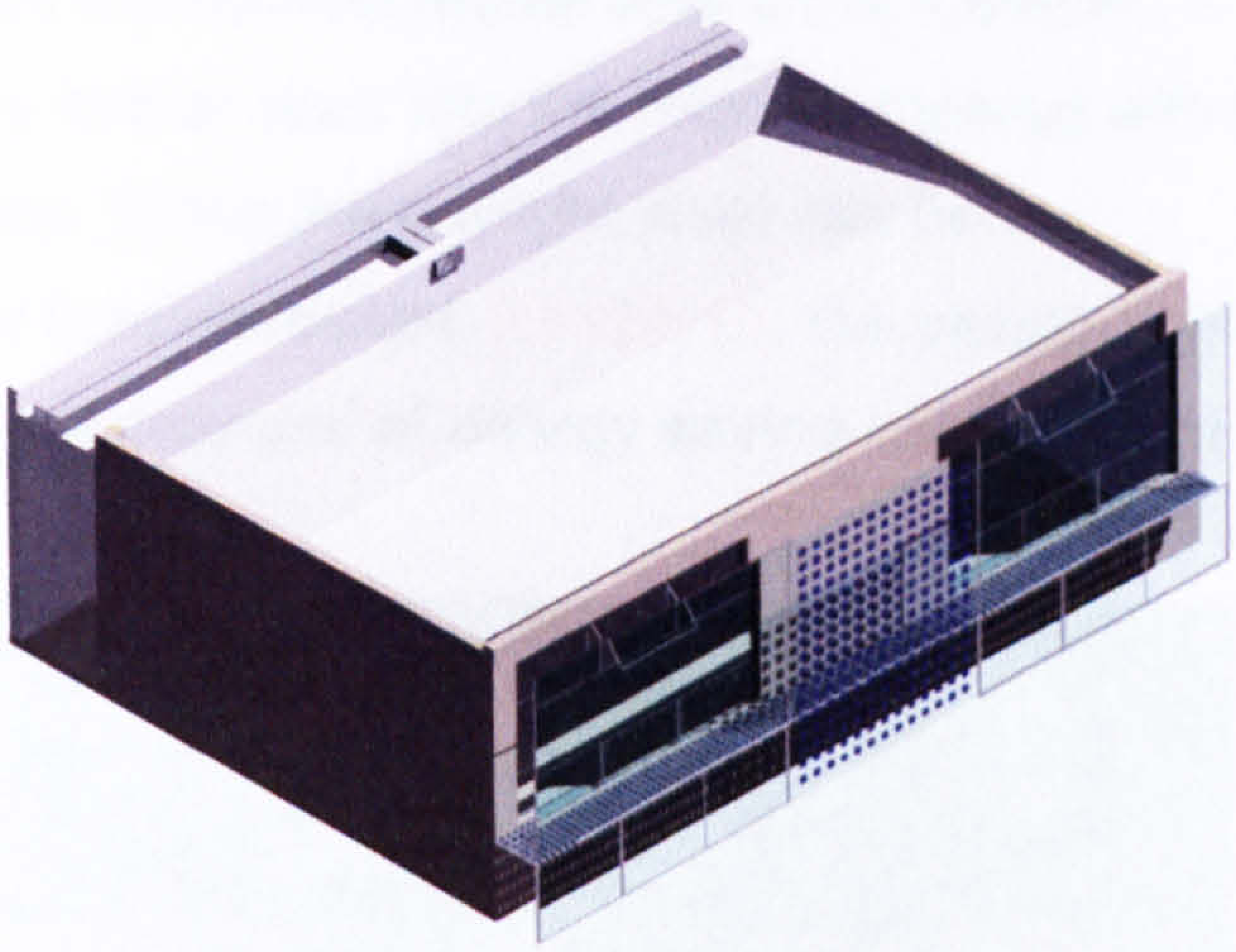


Graph C

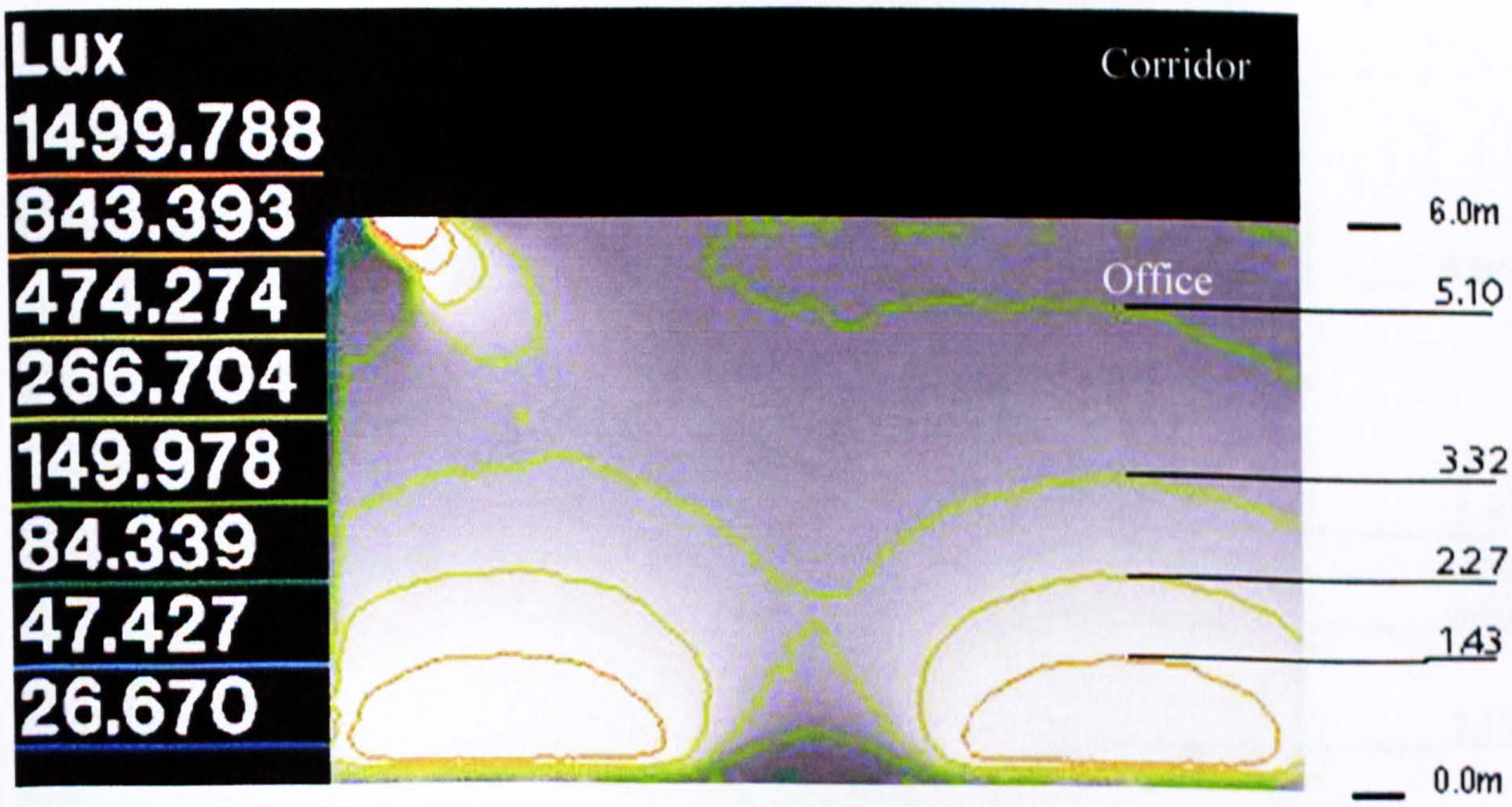
Fig. 7.15 Daylight factor modelling results
Model 4: Office with double skin façade, maintenance grill at sill level and suspended reflective ceiling [horizontal]

The saving energy graph [Graph C] shows contour lines with an area with 75% saving energy up to 1.11m from front windows [1.10m in the second model], 42.1% at up to 2.39m [2.38m in the second model], then 23.7% at up to 2.86m [compares to 2.84m], and 1.3% at up to 3.37m [3.33m in the second model]. Despite the small differences in energy saving graph, nevertheless, this model has a somewhat better quality of light distribution on the work plane.

OPTION 5 Office with double skin façade, maintenance grill at sill level and suspended reflective ceiling [angled]

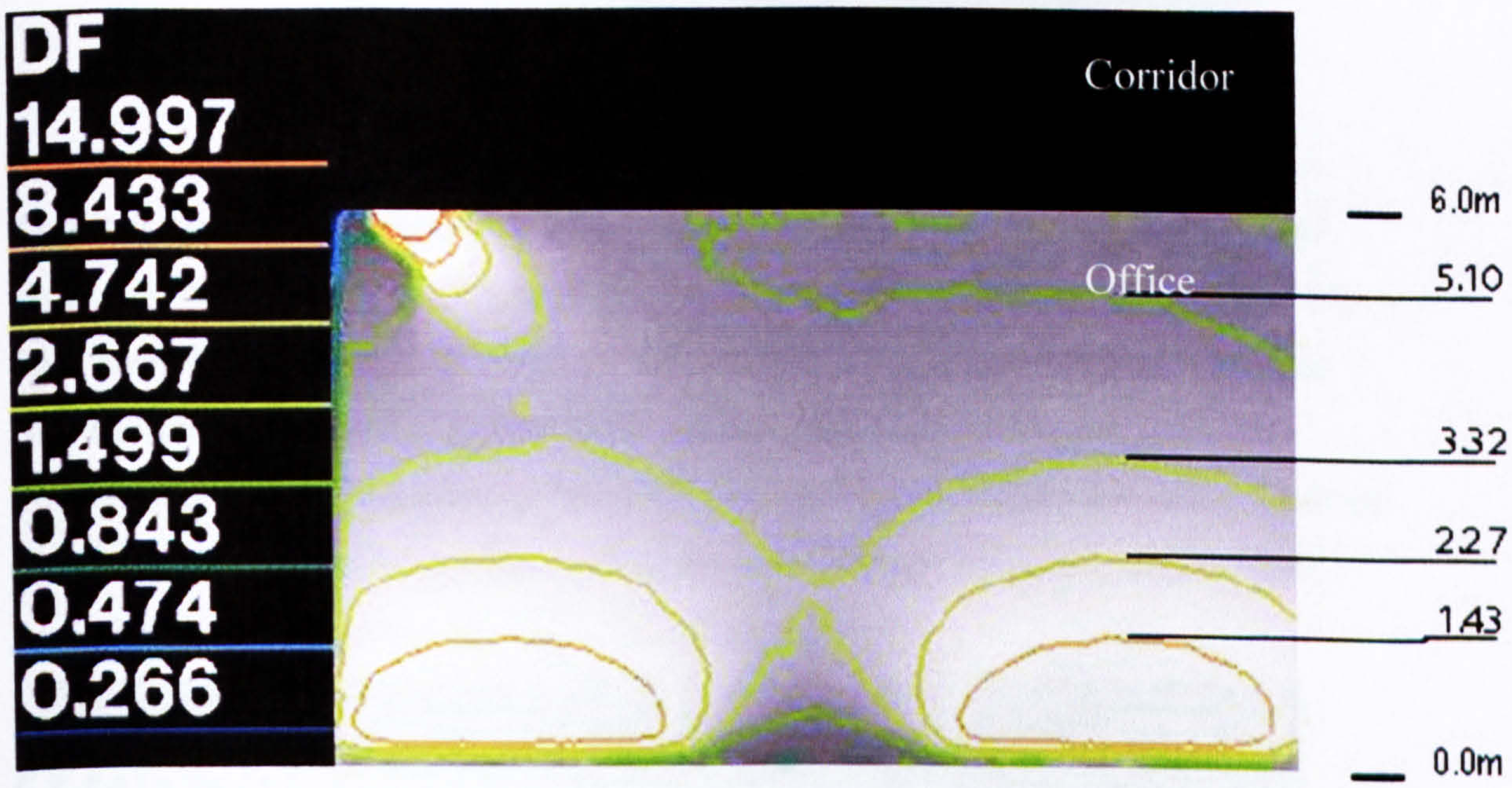


The positive results of the fourth model have led to further developing the suspended ceiling model option and to modify the ceiling geometry in an attempt to further emphasise the effect of redistributing daylight from the front of the office further back in the office. The ceiling geometry in this model consists of a white, suspended horizontal surface, 4.0m wide, and 2.9m raised from the office floor, starting from the front wall towards the back of the room, and a downward tilted surface, starting from 4.0m to the back wall, ending at 2.5m above floor level.

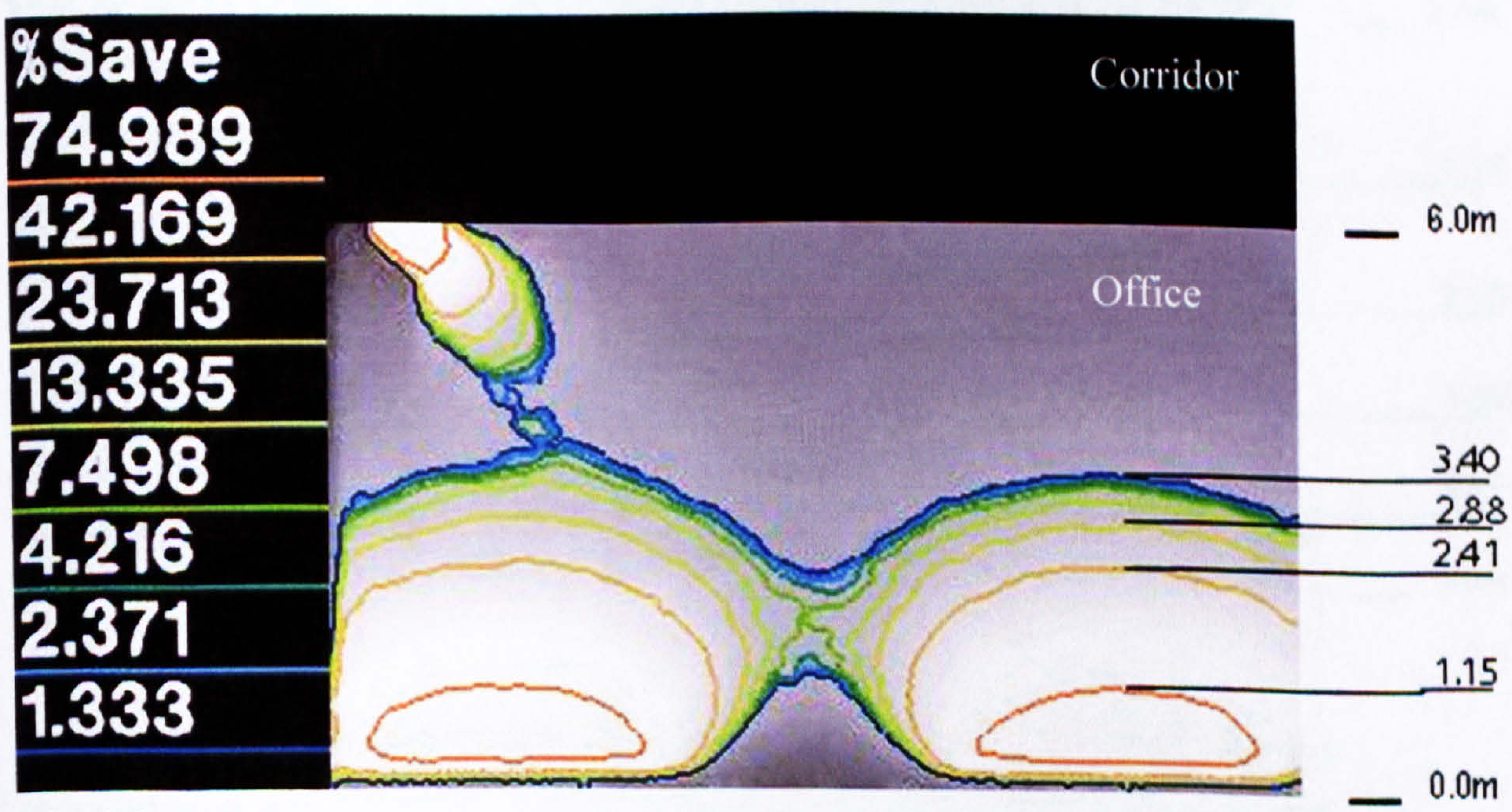


Graph A

Compared to the model with a horizontal suspended ceiling, the front area below windows has very small changes in the illuminance distribution. A stronger change is noticeable at the back of the room, where the area with an illumination value of 150Lux is increased from 4.86m distance from the front in the previous model to 5.10m distance in this model [Graph A]. That is to say, that the altered ceiling geometry has an effect on the redistribution of daylight in the back of the office, where it is needed. Indeed it is the first model where the 1.5%DF threshold has moved fractionally further back into the room compared with the base case without the double skin. Since the daylight level has been redistributed in the office, rather than increased, [Graph B], the saving energy graph [Graph C], shows only small changes of energy saving contour lines towards the back of the room.



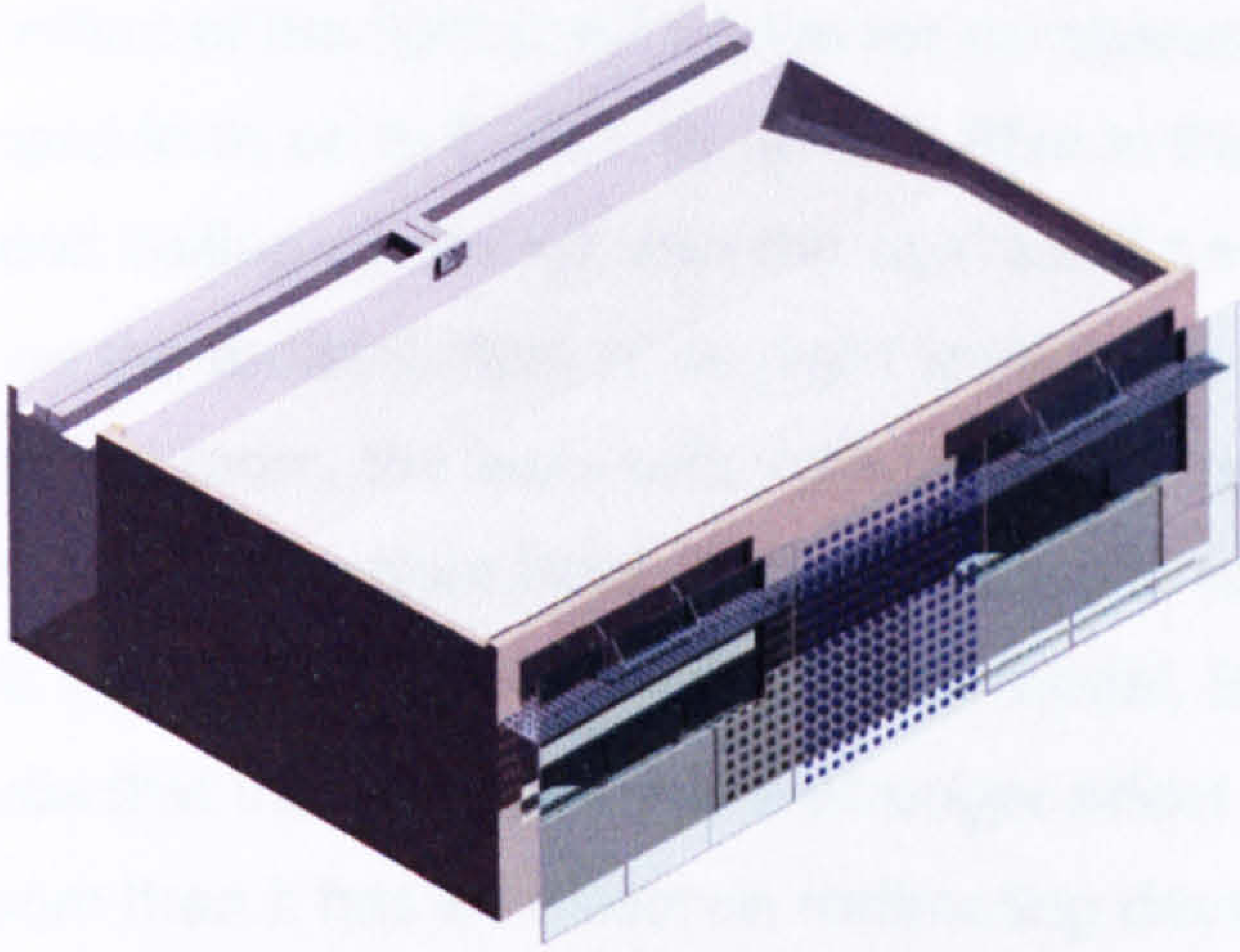
Graph B



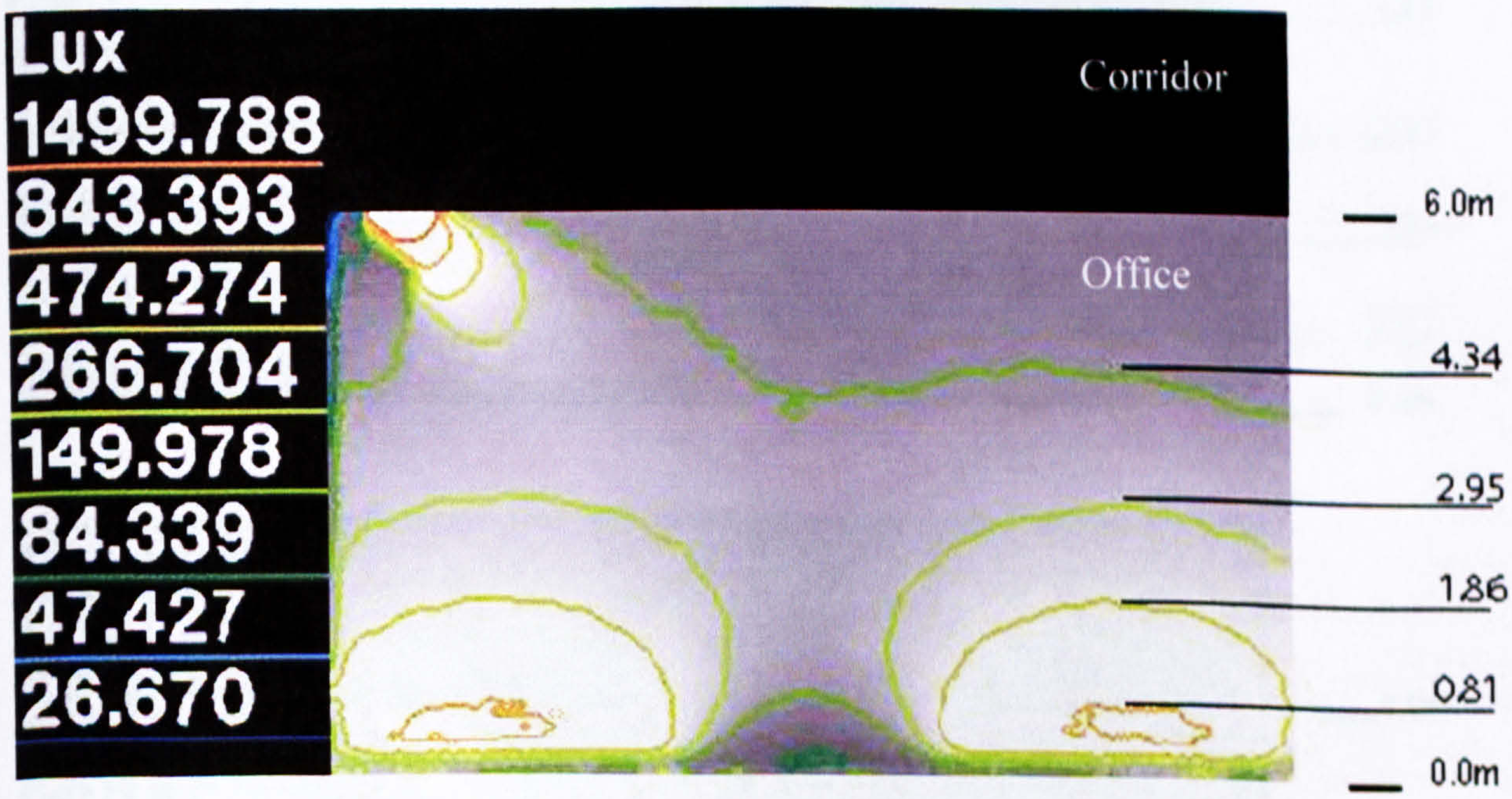
Graph C

Fig. 7.16 Daylight factor modelling results
Model 5: Office with double skin façade, maintenance grill at sill level and suspended reflective ceiling [angled]

OPTION 6 Office with double skin façade, maintenance grill as a light shelf and suspended reflective ceiling [angled]



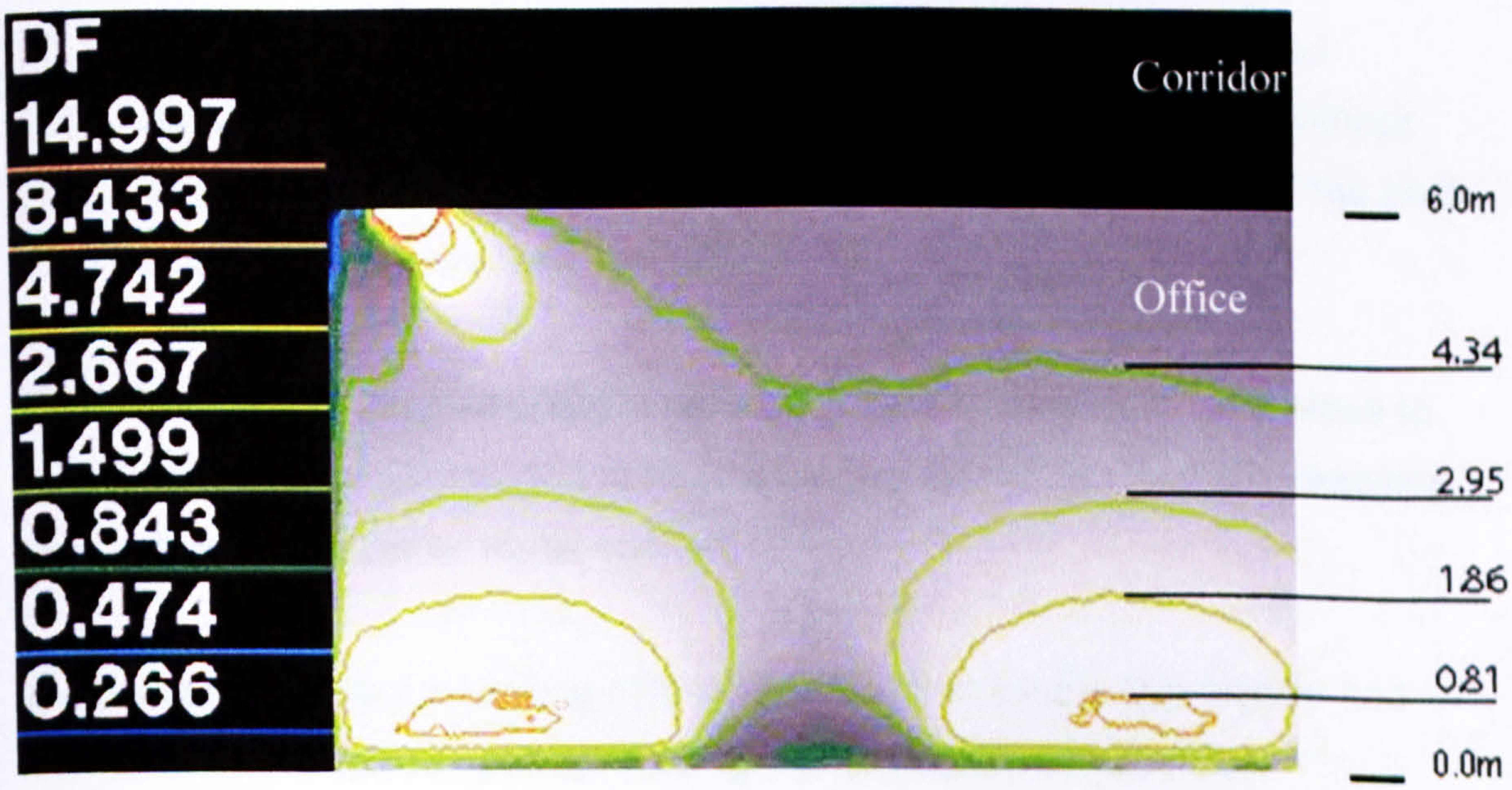
The last model option combines the strategy of a maintenance grill as a light shelf and angled suspended ceiling. The idea was to combine the effect of the light shelf on reducing the intensive illuminance level at the front of the office, and therefore reduce the potential for glare, while in combination with the suspended and angled ceiling, more daylight will be redistributed at the back of the room, where the third model [maintenance grill raised up as a light shelf], has shown largest area with lowest illuminance level.



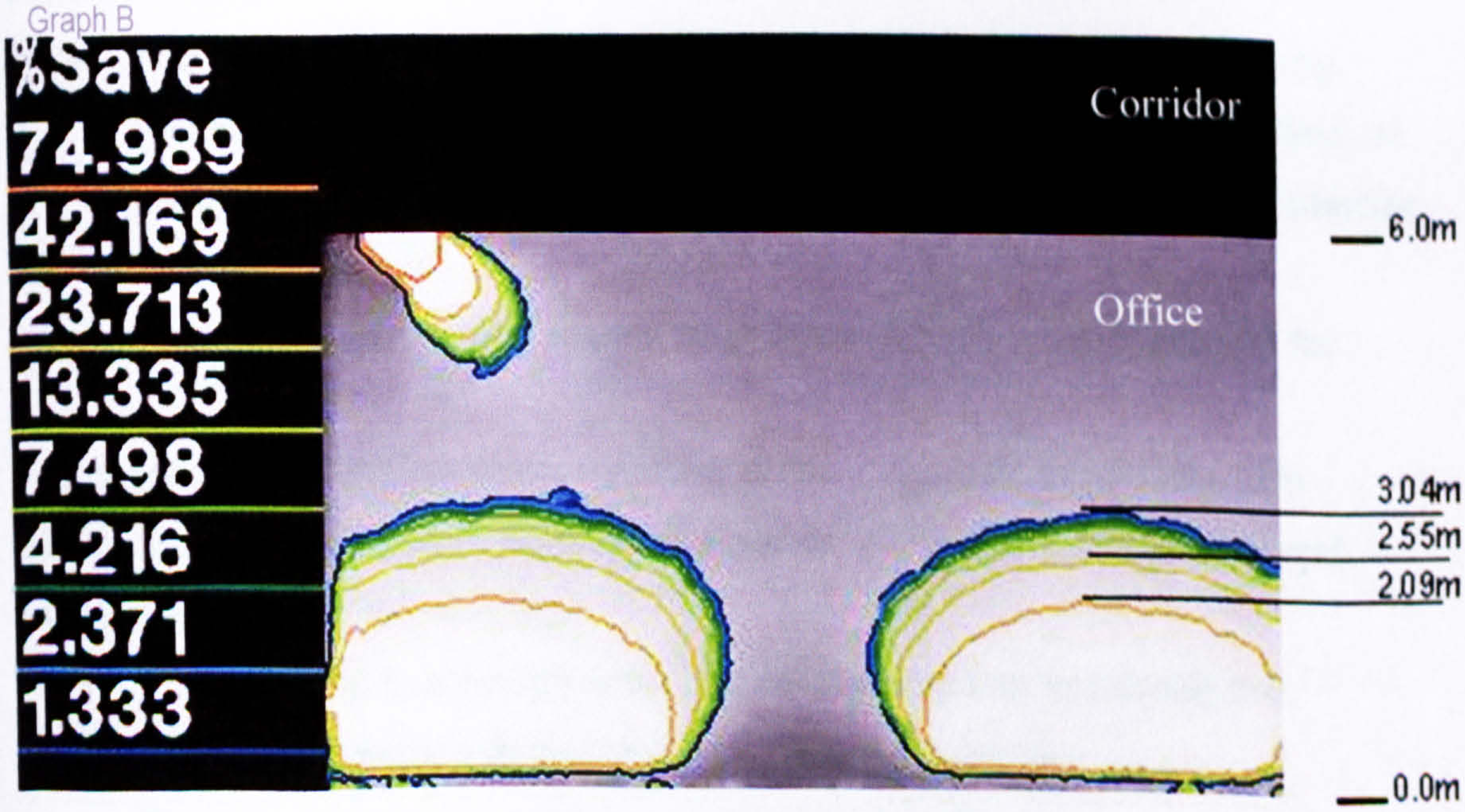
Graph A

Similarly to the results of the third model, the results [Graph A] have shown a reduced area with illuminance level of 843Lux at the front of the room below windows, due to presence of the maintenance grill raised up as a light shelf.

The area with 474Lux level is very little enlarged compared to the third model, from up to 1.84m distance from front windows in the third model to up to 1.86m distance in the sixth model. The 267Lux area, as one would expect, is smaller compared with the fifth model, from up to 3.23m in the fifth model to up to 2.95m in this model due to the shading effect of the light shelf. However compared to the third model, the area is enlarged from up to 2.84m, to up to 2.95m in this model, showing that the suspended ceiling combined with the light shelf has some, although small, influence on the redistribution of daylight level in the middle of the room. At the back of the room, the area with 150Lux is reduced by 0.11m, and starts from up to 4.34m distance from front wall, compared to up to 4.23m in the third model, and it is significantly less than in the fifth model. Based on these results, one can conclude that the light shelf has a stronger effect on reducing daylight entering the room than it has an effect on redirecting daylight deeper in the room, even when combined with a suspended ceiling with modified geometry to help redistributing daylight at the back of the room.



Graph B



Graph C

Fig. 7.17 Daylight factor modelling results
Model 6: Office with double skin facade, maintenance grill as a light shelf

7.1.3 DAYLIGHT MODELLING CONCLUSIONS

The main conclusions regarding the daylight modelling of the office as existing [Option 1], i.e. without the double skin façade, under overcast sky conditions, are:

- The illuminance level on the work plane in front and below windows is up to three times higher than recommended level and it is a source of glare.
- The middle of the office has sufficient daylight level.
- The back of the office room receives daylight below recommended value of 500Lux. However, it has a fair daylight contribution.

The main conclusions regarding the daylight modelling of the office with the double skin façade [Option 2] are:

- The daylight level and the potential for saving energy are reduced throughout the whole office work plane, compared to the office without the double skin façade, and the area with low level of daylight at the back of the room is increased.

- However, a positive effect is reduced potential for glare in area close to windows, less contrast and more uniformly distributed daylight, resulting in generally better visual comfort.

In case of the daylight modelling of the office with the double skin façade and maintenance grill raised up to act as a light shelf [Option 3], the main conclusions are:

- The light shelf has an overall negative effect on the office daylight by reducing the daylight throughout the office, without a significant effect on redistributing daylight deeper in the room, and also reducing the potential for saving energy.
- The model has poorest results of all three options investigated so far.

The conclusions of the daylight modelling of the office with the double skin façade, maintenance grill at sill level and the horizontal, white, reflective and suspended ceiling [Option 4] are:

- The ceiling has, although small, a positive effect on improving the daylight distribution throughout the office work plane.
- The effect on saving energy potential is insignificant.

The daylight modelling conclusions of the office with the double skin façade, maintenance grill at sill level and a white, reflective, suspended ceiling with modified geometry [Option 5] are:

- The altered ceiling geometry has a positive effect on redistributing daylight in the back of the room, where needed.

- If one assumes an office layout with activities requiring around 500Lux level being concentrated in the first half of the office plan, and the redistributed daylight at the back of the room providing better visual comfort, than the office daylight environment of this model has best performance out of all options tested so far with double skin façade. From a design point of view, a ceiling surface with an uneven geometry and higher reflectance material property might add to the aesthetic quality of the office interior, and a challenge to incorporate the artificial lighting design by also taking an advantage of the ceiling reflectance and geometry.

The main conclusions regarding the daylight modelling of the office with the double skin façade, maintenance grill as a light shelf, and a white, reflective, suspended ceiling with modified geometry [Option 6] are:

- The light shelf has stronger effect on reducing daylight entering the room at the front. It is expected that under clear and sunny sky condition, the light shelf would shade the front area, reducing the potential for glare and reducing the contrast. However it has effect on reducing daylight level throughout the office, rather than having a positive effect on redistributing daylight at the back of the room.

- From the point of view of a design decision, this option of a maintenance grill acting as a light shelf, combined with a suspended angled ceiling, would perhaps be justified if the maintenance grill for aesthetic, functional or other reasons is found better to be raised up from the sill level. In those circumstances, this model option would provide reduced glare at the front, [which could also be achieved by using blinds], accepting also the negative effect of the light shelf of generally reducing daylight.

- Overall, the design decision to have the maintenance grill at sill level, with a suspended and angled ceiling [Option 5] would give most evenly daylight distribution throughout the offices. This solution also has the highest opportunity for saving energy for the case of the single glass façade added in front of double glazed office windows. Here, suggested strategies of occupancy-sensed lighting, opportunities for manual switch 'on' and switch 'off' and automatically dimmed lighting, with given opportunity for users to increase brightness of lights, is seen as an integral part of creating an office environment with good lighting comfort and efficient use of electricity.

The research question regarding the daylight performance of the double skin façade system with BIPV, defined in Chapter 1 was: '*Can the whole system be configured in such a way that there is no daylight penalty to the work-place environment?*' The daylight energy modelling presented here has shown that the single glass structure placed in front of an office room, 6.0m deep, with two, south oriented, double-glazed windows, does reduce daylight entering the room. It also tends to increase the need for artificial lighting to substitute for reduced daylight, and maintain an office environment with 500Lux illuminance intensity. However, careful design and specification, particularly with regard to the ceiling, can improve the distribution of light compared with the existing situation; and the potential savings on artificial light should not be compromised provided the room is used sensibly. Moreover, the double skin façade has two positive aspects. Firstly by filtering out the highest illuminance level directly near windows, the potential for glare is reduced. Secondly, the contrasts between areas with higher and lower daylight level are reduced, thus creating an internal environment with more uniform daylight and higher visual comfort. Finally, the double skin façade in this case incorporates photovoltaic cells, which not only generate clean electricity, but also are integrated into the outer skin so that they do not obstruct the daylight entering the office. In combination with measures for an energy-saving switching strategy and energy efficient light fittings, this should result in an office environment with a good quality and intensity of daylight, as well as being low energy consuming, and where the PV generated electricity makes a meaningful share of the office load.

Part of the hypothesis defined in Chapter 1 was that: 'The addition of the double skin façade with BIPV component reduces daylight entering the interior. However with careful room design, materials specification and positioning of PV cells, the reduction of daylight is not critical, and the distribution of daylight in rooms is improved compared to the pre-refurbishment situation'. This hypothesis has therefore been confirmed with the iterative daylight modelling presented in this chapter.

7.2 CHAPTER 7 REFERENCES

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CONCLUSIONS

8

CHAPTER 8

CONCLUSIONS ON THE OPPORTUNITIES FOR RETROFIT BIPV IN THE SCOTLAND, WITH PARTICULAR REFERENCE TO DOUBLE SKIN FACADES

8.1 OPPORTUNITIES FOR BIPV ON THE WHOLE OF GRAHAM HILLS BUILDING

The main case study building of this research known as the Graham Hills building, represents a typical 'workplace' category in Scottish cities, built between late 1950s and mid 1960s. The need for refurbishment [explored in Chapter 4] is evident after the building fabric and the building systems are more than four decades old and with many environmental problems. As previously explained, the Graham Hills Building roof has a redundant external appearance, lack of insulation and frequent leaking problems. A refurbishment option with additional insulation and freestanding, roof mounted photovoltaic modules, offers an opportunity for an improved roof condition, shading of the roof surface and providing useful electricity. PV arrays are proposed on roofs of the three office wings, perpendicular to the front office wing, facing south and at the optimum tilt for Glasgow equal to 36° from the horizontal. The areas of PV arrays could reasonably be: 100m^2 on the roof of the far west wing of offices, 130m^2 on the roof of the middle wing of offices, and 160m^2 on the wing of offices east of the main entrance, with a total PV area of all arrays of 390m^2.

The annual electrical contribution from the roof mounted PV system is predicted taking an average PV system efficiency of 8.1%. This is based on the monitoring results of the Northumberland building, Newcastle upon Tyne, England, described in Chapter 2, with opaque mono-crystalline, tilted PV panels, ventilated cavity and similar climatic conditions to Glasgow, as the closest example PV system proposed on the Graham Hills building. Since it suffered from significant shading, it is an estimate which errs on the safe side. Annual incident solar radiation for Glasgow, averaged over all weather conditions for south orientation and 30° tilt [Page and Lebens, 1986, p.171], amounts to

987kWh/m^2. The total PV roof system area proposed is 390m^2. Thus the total predicted annual electrical output from the proposed roof mounted PV system is 31,180kWh, or approximately 80kWh/m^2 PV system area.

A semi transparent PV roof system is proposed on a newly created atrium enclosing a large space between parts of the building [similar to the Brundtland Centre in Toftlund, Denmark, or the Jubilee Campus Building at the Nottingham University in Nottingham, UK, both described in Chapter 2]. It can provide shading, diffuse light for the atrium interior and produce electricity. The architectural proposal to glaze two of the three existing light wells on the Graham Hills building and create atria spaces is described in Chapter 3. The atria glass structure is a combination of clear glass on perimeters, above top floor offices to allow as much daylight, and semi transparent PV panels with mono-crystalline PV cells integrated between two sheets of toughened glass and cells density providing 40% transparency. A reasonable PV cell area on both atria is estimated to be 225m^2 each, resulting in total PV cells area of 450m^2 [similar to the total PV area installed on the Jubilee Campus building].

The average PV system efficiency is assumed to be 6.8%. This is based on the rather disappointing monitoring results of the Jubilee Campus building, Nottingham University, Nottingham, England, described in Chapter 2, with semi transparent mono-crystalline, atria roof integrated PV system, and similar climatic conditions to Glasgow. Therefore the estimate again errs on the safe side. Annual incident solar radiation for Glasgow, averaged over all weather conditions for south orientation and tilted surfaces [Page and Lebens, 1986, p.171], again amounts to 987kWh/m^2. The total atria PV roof system proposed of 450m^2 thus yields a total predicted annual electrical output of approximately 30,200kWh, or 67kWh/m^2 PV system area.

Another opportunity for integrating photovoltaic systems as a refurbishment and energy improvement strategy is on façade surfaces. The key to building envelopes becoming climate moderators and energy collectors is the multi-functionality of the façade integrated photovoltaic systems. The façade integration in refurbishment cases can be as an over-cladding option, as a sun shading lamella system, or PV cells integrated into a double skin façade component, the last being the main focus of this thesis. In the over-cladding option, the PV panels are used to replace cladding materials lowering the cost of the PV system, enhance the U-value of the external envelope, produce electricity to offset electrical loads, or in some cases, to utilise the heat from the channel behind the panels to pre-heat air for the ventilation system. Here it is proposed that integrated photovoltaic modules are installed as a ventilated rain-screen over-cladding system on the south facing solid wall to the east of the main entrance. Using mono-crystalline PV panels an area of 290m^2 is feasible. The average PV system efficiency is taken as 10%. This is based on the advantage that the mono-crystalline, ventilated vertical PV façade has a good heat transfer from the panels, and therefore lower temperatures which lead to higher efficiency. Since it is also a vertical façade, there is less solar radiation falling on the surface, and therefore it should be inherently cooler. With an annual incident solar radiation for Glasgow as above, but for south vertical surfaces [Page and Lebens, 1986, p.171], of 701kWh/m^2, and the total PV façade system of 290m^2, the total predicted annual electrical output from the PV rain-screen system is 20,330kWh, or 70kWh/m^2 PV system area.

A sun shading option, with integrated PV panels, is proposed for the south oriented glazed wall of the entrance atrium. The PV lamella system will shade the atrium space to limit the problem of overheating and also generate electricity. The proposed PV lamella system with polycrystalline PV modules run along the whole width of the south facing atrium wall above the main entrance, with four fixed lamellas per floor height and tilted to the optimum angle of 36° from the horizontal. This is similar to the PV lamella system of the ECN Building 31, Petten, the Netherlands, Chapter 2. Each lamella is 28.5m long and 0.4m wide, with an area of 11.4m^2. The total area of 19 lamellas is 216.6m^2. The average PV system efficiency is taken as 8.1%. This is again rather conservatively based on the monitoring results of the Northumberland building, Newcastle upon Tyne, England, described in Chapter 2]. Annual incident solar radiation for Glasgow as above, but for south orientation and 30° tilt [Page and Lebens, 1986, p.171], is 987kWh/m^2. With a total PV lamella system proposed of 216.6m^2, the total predicted annual electrical output from the PV rain-screen system is approximately 17,320kWh, or 80kWh/m^2 PV system area.

The above relatively sketchy proposals make use of areas where gaps in knowledge has been filled. Of course the thrust of this work concerns the gap which still exists with respect to the integration of a PV system in refurbishing window walls as a double skin façade. It is axiomatic that this acts as a noise barrier, thus allowing inner windows to open without the disturbance that presently exists. The modelling results of the double skin façade with BIPV

[Chapter 5 and Chapter 6], have shown that it also predictably reduces the conducted heat loss in winter. Most significantly, it can reduce the heat demand by re-circulating air from the buffer space, and with some refinements, the daylight in adjacent rooms can be optimised compensating for the presence of the extra glass skin. Finally, it generates electricity which can be directly used within the building. This multi-functionality of the integrated PV system offsets some construction costs and also contributes to the overall improved external appearance. All these aspects also have an influence on improved conditions for building users in their work place and their enhanced well-being. The added cost for PV, in case of a double skin façade option, is the cells themselves and their supporting system for collecting and transferring the generated electricity. However, the market in the previous years has shown a constant increase in systems production, and efficiency improvement of integrated PV systems, leading to reduced system costs.

The double skin, south façade with integrated semi transparent, mono-crystalline PV cells proposed on the Graham Hills building, has a PV area in front of one office of 6.62m^2, with a total PV area the entire south façade of 419.03 m^2. The average PV system efficiency has been calculated based on the summer critical week PV electrical network simulation results [the sum of the total weekly PV electrical output multiplied by 100, and divided by the total incident solar radiation falling on the vertical PV surface]. The results were an average PV system summer efficiency of 10.9% and a maximum PV system summer efficiency of 12.4%. The average PV system efficiency, based on the winter critical week PV electrical network simulation results was also calculated, as a sum of the total weekly PV electrical output multiplied by 100, and divided by the total incident solar radiation falling on the vertical PV surface. The results were an average PV system winter efficiency of 10.0% and a maximum PV system winter efficiency of 12.7%. The annual incident solar radiation for Glasgow is the same as for the ventilated rain-screen above, at 701kWh/m^2. For the total double skin façade PV system proposed, with 419.03m^2 PV area, and an average system efficiency [taken as a mean for the summer and winter] of 10.4%, the total predicted annual electrical output from the double skin façade PV system is approximately 30,550kWh, or 73kWh/m^2 PV system area.

BIPV Technique	Mono/Poly Cryst. Cells	Opaque/Semi-Transp. PV	Horizontal/Tilted /Vertical PV	PV [m2]	PV System Effic. [%]	Ann. Incident Solar Rad. [kWh/m2]	Ann. Elect. Output [kWh/m2]	Ann. Elect. Output [kWh/m2 PV]
Double Skin Façade	Mono	Semi-Transp.	Vertical	419	10.4	701	30,550.00	73
Roof Mounted	Mono	Opaque	36 Deg. from Horiz.	390	8.1	987	31,180	80
Atria Roof	Mono	Semi-Transp.	36 Deg. from Horiz.	450	6.8	987	30,200.00	67
PV Rainscreen	Mono	Opaque	Vertical	290	10	701	20,330.00	70
PV Lamella System	Poly	Opaque	36 Deg. from Horiz.	216	8.1	987	17,320.00	80
			TOTAL	1765			129,580.00	

Fig. 8.1 BIPV Systems on the Graham Hills Building

Fig. 8.1 summarises all the above results. The efficiency of double skin façade, based on modelling, and the similar value for the rain-screen may both be slightly optimistic. But, the remaining values, all based on measured results with specific problems, are conversely likely to be less than what is achievable. Therefore, overall, this estimate is considered to be realistic.

The Graham Hills building has a total floor area of 12,000m^2, and a total electricity demand for the whole 1991 year of 1,510,331kWh, or 125.86kWh/m^2 floor area, which also represents 55% of the total energy consumption of 224kWh/m^2 floor area [GA Group, University of Strathclyde, 1993, p.26-27]. As the Figure 8.1 shows, the total predicted annual electrical output from the PV systems proposed is 9,580kWh, which is 73.4kWh/m^2 of the total PV systems area, or 10.8kWh/m^2 of the total floor area. If one takes the 1991's total electrical consumption given above, the PV contribution accounts for less than 9%. However, an electrical load of nearly 126kWh/m^2 floor area is unacceptable in today's terms of energy consumption in buildings, where the good practice benchmark for electricity consumption in higher education type of buildings recommends 75kWh/m^2 floor area [CIBSE, 1998, p.12-4]. The renovation strategy of the Graham Hills building suggests measures for reducing the electrical load, such as a Building Management System controlling the switching system, new energy-efficient light fittings, computers with a stand-by saving energy mode, which should reduce the electrical load to a more reasonable level. If the electrical demand is assumed to be lowered to the best practice benchmark level, the PV electrical contribution will be more significant, i.e. 10.8kWh/m^2 of the 75kWh/m^2 total floor area is nearly 14.4%. In many cases the energy improvement strategy results is even better than the good practice level for electricity. For example, in the ECN 31 building in Petten, the Netherlands, described in Chapter 2, the renovation energy saving target for the annual electricity load was set to 50kWh/m^2]. If this were achieved in the Graham Hills Building, then the share of BIPV to balance the remaining electrical demand would exceed 20%.

8.2 ENERGY PERFORMANCE OF THE DOUBLE SKIN FAÇADE WITH HYBRID BIPV

The above rudimentary appraisal of whole-building potential for BIPV electricity generation constitutes the introduction to the detailed analysis of the performance of the double skin façade with BIPV. It is useful to know that a typical retrofit could yield more than 10kWh/m^2 of electricity per annum. However, the aims and objectives relative to research questions and hypothesis came about having identified an area of hybrid BIPV where a gap in knowledge existed. This then is the critical matter for formulating conclusions.

Before starting to discuss these, it is impractical to emphasise that the double skin façade is fundamentally only one component of the problem-led, whole building approach. This was the reason for providing tentative design proposals for the remainder of the building, all of these with reasonably well researched and monitored precedents [Chapter 2]. Indeed, to have investigated the double skin façade in the absence of such a context would have rendered the exercise much less meaningful, especially for an architect.

The January critical week thermal modelling results [Chapter 6] have shown a significant potential for an overall pre-heat contribution from the double skin façade, with heating loads of approximately one third of former values on a cold, overcast day, and one fifth on a cold and sunny day. Also, if one considers other, more common thermal performance improvement measures on the Graham Hills building, such as the improved insulation, and improved glazing, along with proposed glazed atria, the overall result on the Graham Hills building could expect very significant reduction in the thermal load.

The energy audit of the Graham Hills building [GA Group, University of Strathclyde, 1993, p.26] shows an annual space heating value of 1,117,680kWh, or 93.14kWh/m^2 floor area. If one takes 39 weeks [September to May] for a heating season, divided by the annual space heating load of 93.14kWh/m^2, it averages 2.4kWh/m^2 per week in a heating season. However, examination of typical space heating patterns over these months support that January could account for over 17% of the total. Therefore, a weekly figure of 3.6kWh/m^2 is realistic for the pre-retrofit condition. The winter critical week simulation results from the model that utilises the pre-heat air from the BIPV double skin façade has shown a heating load of 119.6kWh on a cold and sunny day and 178.9kWh on a cold but overcast day. When divided by 435m^2 total office floor area the results are: 0.27kWh/m^2 on a cold and sunny day and 0.41kWh/m^2 on a cold and overcast day. It is clear that the reduction in the building's heating load is very significant, from 3.6kWh/m^2 of the pre-renovation situation to 0.27kWh/m^2 and 0.41kWh/m^2 [cold and sunny and cold and overcast days respectively]. These are very impressive savings of 92.5% and 88.6% respectively, especially bearing in mind that the analysis indicates that a somewhat lower air supply temperature would have sufficed.

Compared to the potential for improvements of the electrical consumption, it is evident that thermal load is more significantly reduced. For the building-integrated photovoltaic systems it means that their integration as part of the building fabric must go hand in hand with an overall strategy to reduce the electrical load. Only then, BIPV systems can take more significant part of the overall electrical load. Returning to the space heating, what has to be acknowledged, amidst the emphasis of thermal savings in the order of 90%, is that the hybrid aspect of the BIPV, its thermal contribution in winter as a by-product of electrical generation is virtually irrelevant.

Chapters 5 to 7 presented the energy performance of the double skin façade component with BIPV, proposed for the Graham Hills building south façade as a refurbishment strategy to tackle the multiple environmental problems in rooms facing south orientation and a noisy road. The method of testing the architectural proposal of the double skin façade component was with computer based energy models consisting of a seven storey high segment of the case study building, taken from the middle of the south façade, with one office room facing one double skin façade component on each floor. This model was described in the ESP-r dynamic thermal modelling computer tool, capable of dynamically simulating complex thermal behaviours for critical summer and winter weeks. The ESP-r was also used to model the PV system integrated on to the double skin façade and to predict the amount of electricity that would be generated. The

ESP-r modelling results have demonstrated the capability of the programme for integrated thermal and electrical modelling, providing answers to research questions regarding the energy performance of a proposed architectural solution.

Another computer based modelling tool was used to investigate the effect of the double skin façade component on the office room internal daylight environment. The Radiance programme was selected for its high capability for predicting the distribution of visible radiation in illuminated spaces and ability to accurately simulate light behaviour in complicated environments. A one-room model of a Graham Hills building south facing office was developed, without the double skin façade as a starting point, and with five options of an office with a double skin façade component. The daylight modelling results have provided an insight to the daylight level distribution on the office work plane, and the potential for saving energy for artificial lighting for each model option. The underlining aspect of the two robust computer modelling tools, was to come as close as possible to the reality of the complex thermal, electrical and daylight processes in the building and to accurately predict its energy behaviour.

The findings of the ESP-r summer critical week modelling of the existing, non-refurbished Graham Hills building showed very high office temperatures. When the building was thermally upgraded with improved energy performing external wall and windows, it showed up to 10°C reduced office temperatures compared to the non-refurbished case. However, office temperatures were still high above the comfortable level and the noise problem in offices was not tackled. The energy modelling continued by introducing the double skin façade with BIPV component. Several options were tested. For example, model M3 had no windows open on the double skin façade and offices, representing a theoretical worst-case scenario of the building with very restricted ventilation. It was taken as a starting point for further exploration of the double skin façade thermal performance. The next model M4 explored an option of natural ventilation in the double skin façade, with office windows closed and double skin windows top and bottom opened. The simulation results showed reduced temperature in all double skin zones falling close to the ambient temperature, while temperatures in all office zones were still very high.

Model M5 explored an option with lower office windows closed, upper office windows opened, and double skin windows closed, showing the risk of a system where opening devices for the external skin were not functioning for some reason. The simulation results showed peak mid-day temperature in offices still high above the comfort level. Model M6 had office lower and upper windows opened, and bottom and top openings in the double skin space opened. In this case office temperatures were 10°C higher than in the case without the double skin façade component, showing that the presence of the double skin façade had increased temperature in offices and represented a serious factor for summer overheating in offices. One may argue that the Graham Hills building performs thermally better in summer without the double skin façade and could have had BIPV integrated as wall cladding. However, the advantage of the double skin façade component is in reducing the noise level in offices and hence encouraging users to open windows as part of the ventilation system. Also, as the winter energy modelling showed, very worthwhile overall potential for winter passive ventilation pre-heat has been demonstrated.

The results of the model M6 showed that only with means of natural ventilation, the peak day temperatures in offices would still be above comfortable level. Therefore, a mixed-mode ventilation strategy was developed, based on a naturally ventilated double skin façade, with upper office windows opened, and an additional supply of fresh air at 20°C from the corridor side. This option proved to be able to reduce temperature in offices during working hours to 25°C to 26°C., and in turn this was demonstrated to be reasonable relative to comfort parameters.

The hypothesis regarding the opportunities for retrofit building-integrated photovoltaics [BIPV] applied to a double skin façade construction is that in peak summer conditions, stack driven air movement within the double skin construction will keep the temperature behind the photovoltaic [PV] cells low enough to ensure that loss of PV cells' efficiency is not excessive. The investigation of PV panels' temperature in all skin zones has shown that for mono-crystalline PV cells efficiency is just below 14% for cells temperature of 45°C, followed by above 12% efficiency for cells temperature of 55°C, and efficiency of just below 12% for cells temperature of 65°C. As the theoretical loss in PV efficiency due to rise in PV temperature in this case is about 2%, one could conclude that stack driven air movement within the double skin construction does not cause excessive loss in their efficiency. However, by increasing air velocity in the solar chimney efficiency undoubtedly could be enhanced. The GSW case study building cited in Chapter 3, addressed this issue by means of a carefully designed roof spoiler. Although, the detailed profile of such a feature was deemed outside the scope of this work, it would appear to be worth pursuing. That said, the final model for the hot summer week did work, and the use of the same mixed mode system for both summer and winter condition provides major justification for the double skin proposition. Of course, in terms of the hybrid aspect of the BIPV, the heat given off the back of the cells in summer is not useful. Rather it is one contributing to the suggestion that accumulated air flow is advisable.

In addition to the thermal improvements, the PV panels integrated in to the double skin façade have provided an electrical output with an average efficiency of 10.9%, and a maximum efficiency of 12.4%. Although, one has to have in mind that these are predictions based on computer modelling and monitoring results of other European buildings with BIPV [presented in Chapter 2] have shown lower PV system efficiency is usually lower than predicted. The amount of PV generated electricity in summer by a fairly small area of the façade is sufficient to cover up to 33% of the electricity for offices artificial lighting and computers, or to run fans for mechanical air supply and the remainder used to reduce the offices' electrical load. The PV electricity can be directly used in offices due to the good match of PV generating electricity and offices working hours. In this way, the performance of the BIPV has reduced the non-renewable electrical load.

The results of the winter critical week modelling of the existing, non-refurbished Graham Hills building [model M8] showed poor thermal performance in all offices and Office_7 with lowest temperature as a result of the poor thermal properties of the roof. The energy modelling of the improved Graham Hills building, but without the double skin façade with BIPV [model M9], showed thermal improvement in all offices with higher office temperature throughout the whole winter week, but still needing space heating to achieve comfortable temperatures.

The results of the model M10 showed that the addition of the double skin façade had a positive effect on the thermal performance of offices in winter, with higher office temperatures than in case with no double skin façade [as in model M9]. The modelling also showed temperature in all skin zones constantly above ambient air temperature, suggesting that the glazed cavity with southern exposure traps solar radiation, along with energy from the offices, with a possibility for this energy to be used for pre-heating supply air to offices. The modelling showed a substantial overall benefit of the pre-heat contribution from the insulated double skin façade, ranging from 70% saving on an overcast cold day to 80% on a sunny winter day. The mixed-mode ventilation strategy, which proved successful for avoiding overheating in offices during summer, could be successfully modified to achieve the winter thermal internal comfort. The office air supply temperature was modelled at 23°C, as extracted from the top of the double skin façade and additionally heated in the roof air-handling unit. The one-day thermal modelling has shown that on a particularly sunny winter day it would be possible to extract pre-heat air from the buffer space at a temperature close to 23°C and deliver directly to offices without a need for additional heating. The modelling also indicated that a lower supply temperature would have provided thermal comfort during a cold week in winter.

However, relating to the statement made above regarding the irrelevance of the hybrid PV contribution, the winter modelling has also revealed that a double skin façade without BIPV would perform marginally better than with the BIPV. This is due to the PV cells blocking more of the direct solar gain than they thermally contribute. The principal thermal contribution to the buffer space is the heat lost from the adjacent office rooms, and the thermal contribution of the PV cells as they generate electricity only partially makes up for the thermal loss due to the presence of the PV cells. Compared to the overall pre-heat savings attributed to the double skin façade acting as a buffer space, the thermal output of cells was found to be very small, i.e. ranging from 0.75% to 1.25% on overcast and sunny days respectively [described in 6.2]. Therefore it is fairly deemed irrelevant. It is the system as a whole which works well, with or without the PV. On the other hand, the additional benefit of PV generated electricity in winter is enough to run all fans for pre-heat extract from the buffer space and air delivery to offices. Also, the temperature of PV panels showed that the theoretical PV cells efficiency would be about 13% for cells temperature of 50°C, 15% for cells temperature of 25°C, resulting in overall PV efficiency loss of 2% during very occasional peaks in exceptionally sunny winter weather.

With all this, the double skin façade with BIPV as a refurbishment package is very suitability to tackle the environmental problems of the case study building in winter conditions. Also, the hypothesis stated in Chapter 1 regarding the winter performance of the retrofit double skin façade with BIPV, is confirmed, i.e. in cold winter conditions, although the thermal input of the photovoltaics is insignificant, the PV electrical contribution is useful relative to the power for fans operating a mechanical warm air supply with passive ventilation pre-heat and heat recovery.

The big question remains for the applicability of BIPV in double skin facades is simply one of economics. The PV can perform a useful task even in winter, but can it economically justify itself? This of course, was a question which was consciously set to one side at the onset. However, it must be acknowledged that the irrelevance of the hybrid PV aspect does not help its case, even though the performance of the double skin façade is so impressive. On the other hand, it must also be acknowledged that in terms of the hierarchy of environmental improvements, the outer skin as acoustic shield and enabler of natural ventilation was the first priority. Hence it effectively provides a free support structure for the PV. The very essence of what the term 'building integrated' signifies.

The next big dilemma for the double skin façade was whether its impact on daylight could be countered. The daylighting modelling results showed an existing office without the double skin façade component has a glare problem in the front office zone, sufficient daylight in the middle zone and a fair daylight contribution at the back zone. Once the double skin façade was added to the existing external wall, a series of refinements to the model [maintenance grill at sill level and white, reflective, suspended and tilted ceiling as the best option] resulted in a daylight performance with reduced potential for glare in the front zone, more evenly distributed daylight throughout the office work plane, and the 1.5%DF threshold fractionally moved further back into the room compared with the base case without the double skin. The daylight level was reduced throughout the whole office work plane and consequently, the potential for saving energy was also reduced. Despite this, the double skin façade reduced the problem of glare by reducing the daylight at the front of the room and reduced the contrast between area with strong and low illuminance level, resulting in an office environment with more uniform daylight level and better visual comfort._Part of the hypothesis defined in Chapter 1 stated that: 'The addition of the double skin façade with BIPV component reduces daylight entering the interior. However with careful room design, materials specification and positioning of PV cells, the reduction of daylight is not critical, and the distribution of daylight in rooms is improved compared to the pre-refurbishment situation'. The hypothesis has therefore been confirmed with the daylight modelling.

In terms of potential for saving energy, results suggest that the integration of the double skin façade should go hand in hand with refurbishment measures for energy efficient light fittings and energy saving lighting strategy [occupancy-sensed lighting, automatically dimmed lights and provision for occupants control]. An office environment with good lighting comfort and efficient use of electricity, where the PV generated electricity can make a significant contribution to the remaining electrical load, has been shown to be achievable.

Thus, the overall results of this detailed investigation have provided original and useful new insights. Previous research findings published with regard to hybrid BIPV have been shown to be somewhat misleading. The systems into which the PV is integrated may work well in reducing winter heating loads, but the PV itself plays a minor thermal role. It is certainly insignificant for the particular application of a double skin façade. In terms of pre heating, the PV is simply a 'passenger' on a good thermal system, its only serious role generating enough electricity to move the air which is part of that system. In summer, their shading effect may help to keep the solar chimney cooler than it would have been without the PV, but the openings at the bottom and top are more powerful influences in this regard. Returning to pre heating in winter, PV might contribute relatively more thermally in an opaque cladding system, but even then the other inputs to the cavity are likely to be dominant. Having come to such a conclusion, the multiple functionality of BIPV is likely to feed on increasing interest for architects not forgetting that PV's prime purpose is to displace fossil fuel generated electricity.

8.3 RECOMMENDATION FOR FUTURE WORK

A possibility for further investigation is the life-cycle analysis of multifunctional BIPV systems on demonstration projects. If, for example, the building which has been investigated here were upgraded, this could then be tested. An important aspect would be identifying add-on PV cost relative to alternative non-PV equivalent options, such as all-clear glass double skin façade, or opaque lamella shading system without integrated PV panels. Also, an investigation of the air-flow in offices and double skin façade buffer space with a computer fluid dynamics [CFD], would provide a more detailed analysis of the air movement in the double skin façade buffer space and also in offices. This in turn could be augmented as suggested above, by the incorporation of a 'spoiler' at roof level to enhance mass air flow in the 'solar chimney'. Another possible aspect would be to quantify the energy and CO_2 emissions saved over a year for BIPV as built, compared to energy and CO_2 emissions saved over a year for non-BIPV equivalent retrofit. Finally, the social well-being survey of building users and its effect on their productivity might offer valuable opportunities for further research with this thesis as a starting point.

What this work has achieved is an original step along the research path to such future work. It has firstly provided contextual insight regarding the viability for building-integrated photovoltaic systems as part of an overall strategy for significant improvement of typical 'workplace' buildings in a Scottish built environment context, from an energy, environmental and internal comfort point of view. Secondly, and more significantly, it has also provided new knowledge of the overall thermal, electrical and daylight performance of a double skin BIPV glazed façade component, as one of the least explored BIPV techniques in Northern Europe.

8.4 CHAPTER 8 REFERENCES

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APPENDIX
OTHER BIPV PROPOSALS ON THE GRAHAM HILLS BUILDING

A

A1.1 ATRIA

The Graham Hills Building has three large light-wells or courtyards. There is a three sided court open to the west, which is a threshold to the car park, a completely enclosed court in the centre and another three sided court marking, but at present not celebrating, the main entrance from George St. Their appearance is dismal and rundown, providing an unpleasant sight to the offices that overlook them. It is proposed to cover the second and third of these light wells with glass constructions and create attractive atria. These spaces will provide weather protection, improve thermal performance of offices in a similar way to the twin-skin south façade, this time with the opportunity for planting to oxygenate and freshen the air, and provide much needed amenities for staff and students. These amenities will be in a form of a space for social interaction, including a cafe, planting and water features. The atrium floor will preserve the existing concrete material acting as a thermal mass with the addition of new hard finishes as appropriate.

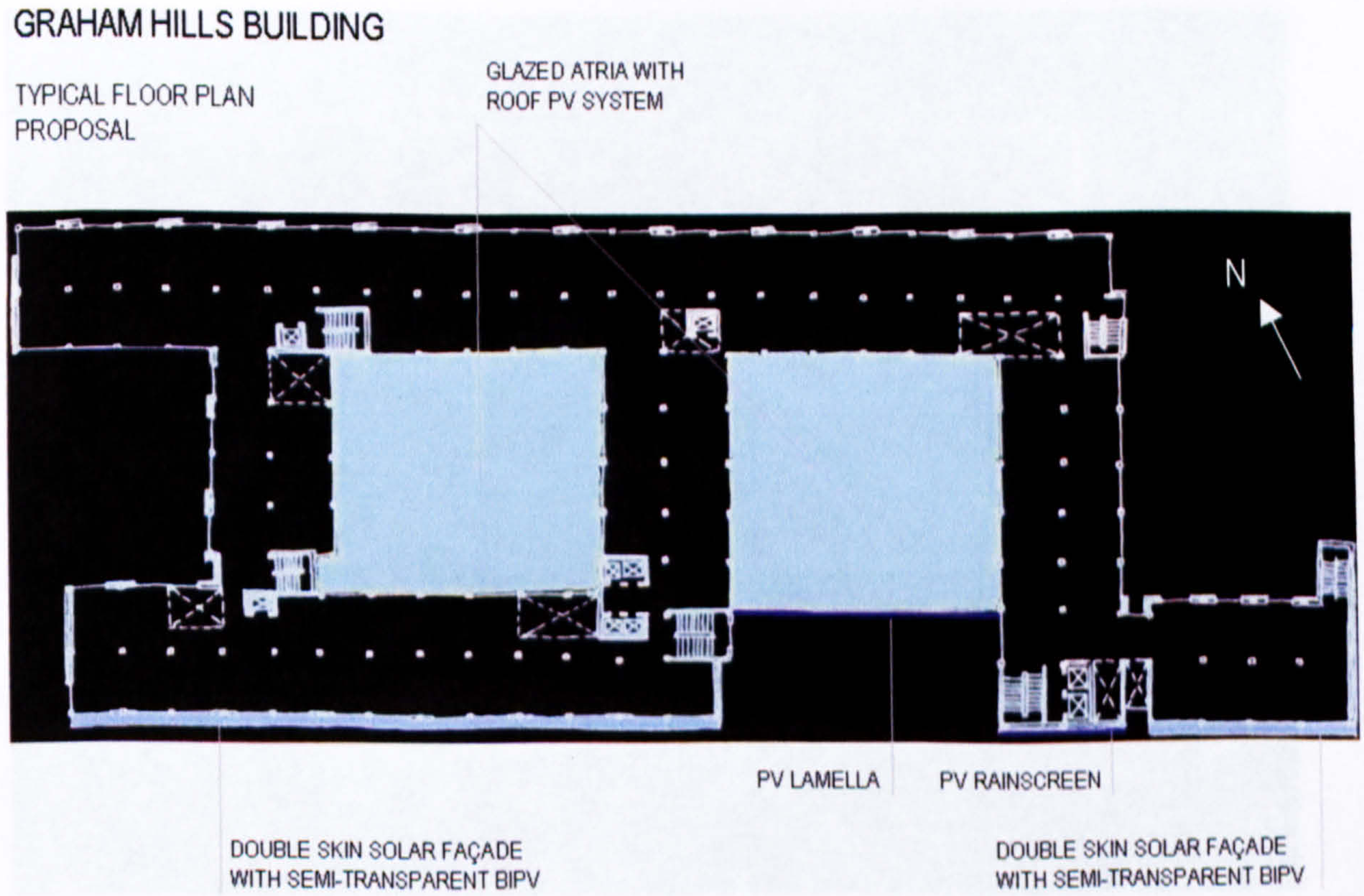

Fig. A 1.1 Graham Hills building typical floor plan proposal

The entrance atrium roof glazing will be constructed as a saw-tooth structure with vents for atrium ventilation, and it will be covered with a combination of clear glass and transparent PV-glass modules with mono-crystalline solar cells to provide 40% transparency. This will provide a degree of shade inside the atrium in summer, as well as an interesting play of light. The glazing on perimeters, above top floor offices will be clear glass without PV cells, as in the Jubilee Campus Building at the Nottingham University atria [Riffat *et al*, 2001], to allow as much daylight in top offices facing the atrium. PVs will also generate electricity required mechanisms to open glazing for ventilation and any excess electricity will be used for appliances and lighting. To further limit any potential problem of radiant overheating/discomfort, the atrium's south oriented glazed wall will have a system of horizontal PV sun shading lamellas [similar to the ECN building 31, Petten, the Netherlands case study building in chapter 2]. The proposed PV lamella system will shade the atria space and also generate electricity. The remodeled entrance area will have a positive impact on clarity of expression and position of the entrance. A part of two garage levels next to the main entrance will be converted into offices and/or cafe with galleries providing a view over the main entrance foyer. Reducing the car-park space is seen as an environmental measure to reduce the number of cars used in urban areas [Local Agenda 21].

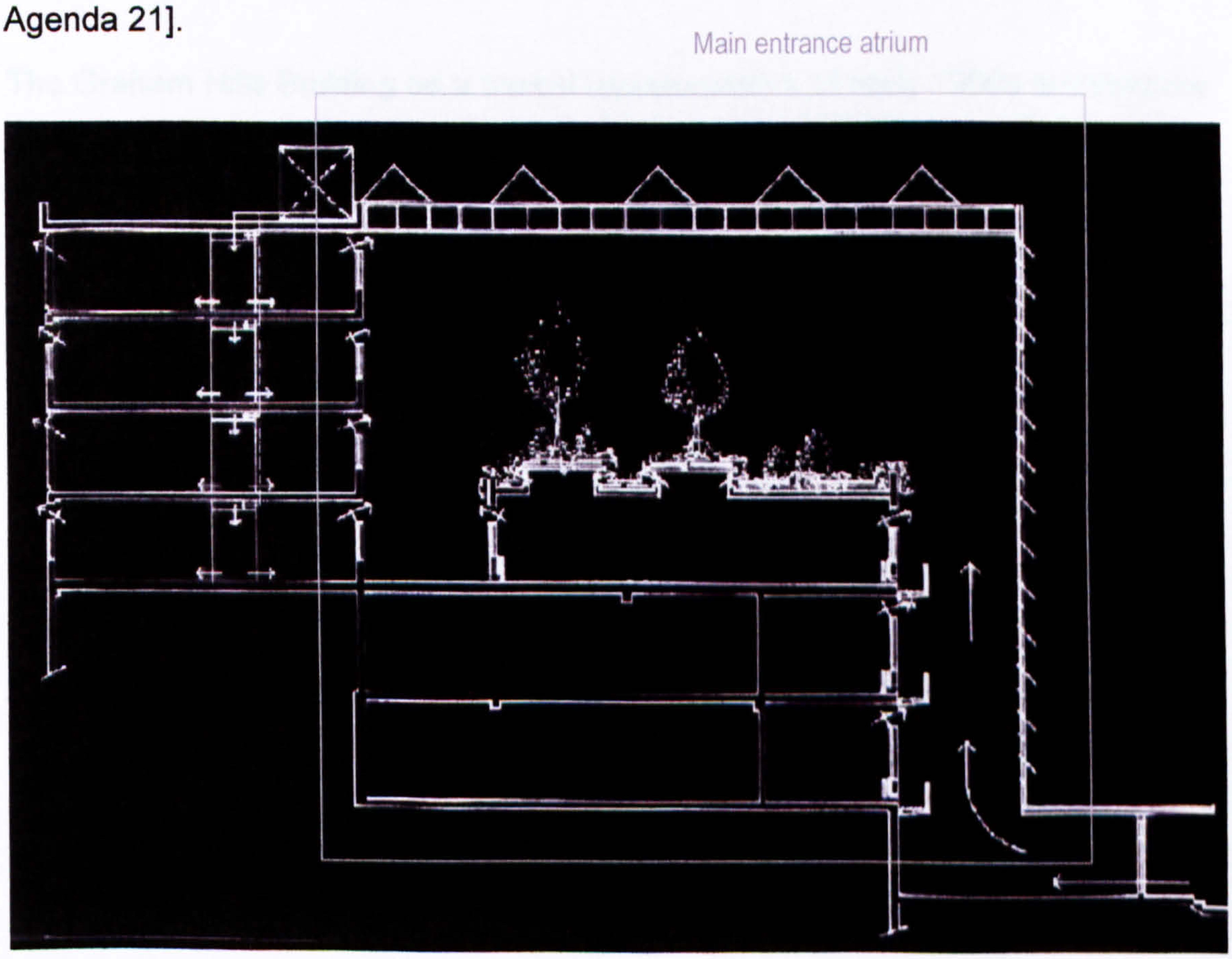

Fig. A 1.2 Graham Hills building summer energy diagram

The second courtyard will again be covered with a glass structure with semi transparent PV panels concentrated in the central part, serving as a weather protection and creating a 'micro-climate' for surrounding offices. What is important to note is that the entrance and the central atrium are linked by a wing of offices that will now overlook both atria. These offices will not then be exposed to outdoor weather and temperature conditions, and therefore, their heating requirements are expected to fall. In winter, warm fresh air supplied to offices via the system of corridor ducts will leave via the host atrium, and convect upwards to the roof, with its temperature boosted by the sun in good weather, where it will be ducted to the plant 'pods' as previously described. The third floor pool offices below the floor of the atrium constitute special cases. Again, they will now receive a mechanical air supply, and their existing roof-lights will be remodelled to serve as 'daylighting-chimneys' passing their vitiated air into the atrium. To avoid the potential for summer overheating during heat waves, glazed atria roofs will have generous opening sections [controlled by the Building Management System] to exhaust warm air in summer, effectively enabling breezes inside the atria.

A 1.2 ROOF MOUNTED PV MODULES

The Graham Hills Building as a typical representative of early 1960s architecture has a large flat roof area. This is suitable for installation of freestanding, tilted roof mounted photvoltaic arrays. It is not necessary to penetrate the surface of the roof to attach the support structure, but the roof will require additional insulation. Arrays of opaque, mono-crystalline PV modules will be mounted on roof areas of three office wings perpendicular to the front office wing, facing south at the optimum tilt from the horizontal for Glasgow equal to 36°. The location is chosen because of existing outside stairs access [mounting and maintenance] and position of air-handling 'pods' that exclude other two flat roofs areas. Here, the BIPV is at its most basic, producing electricity only, with the only other positive environmental spin-off perhaps being the shading of the roof surface.

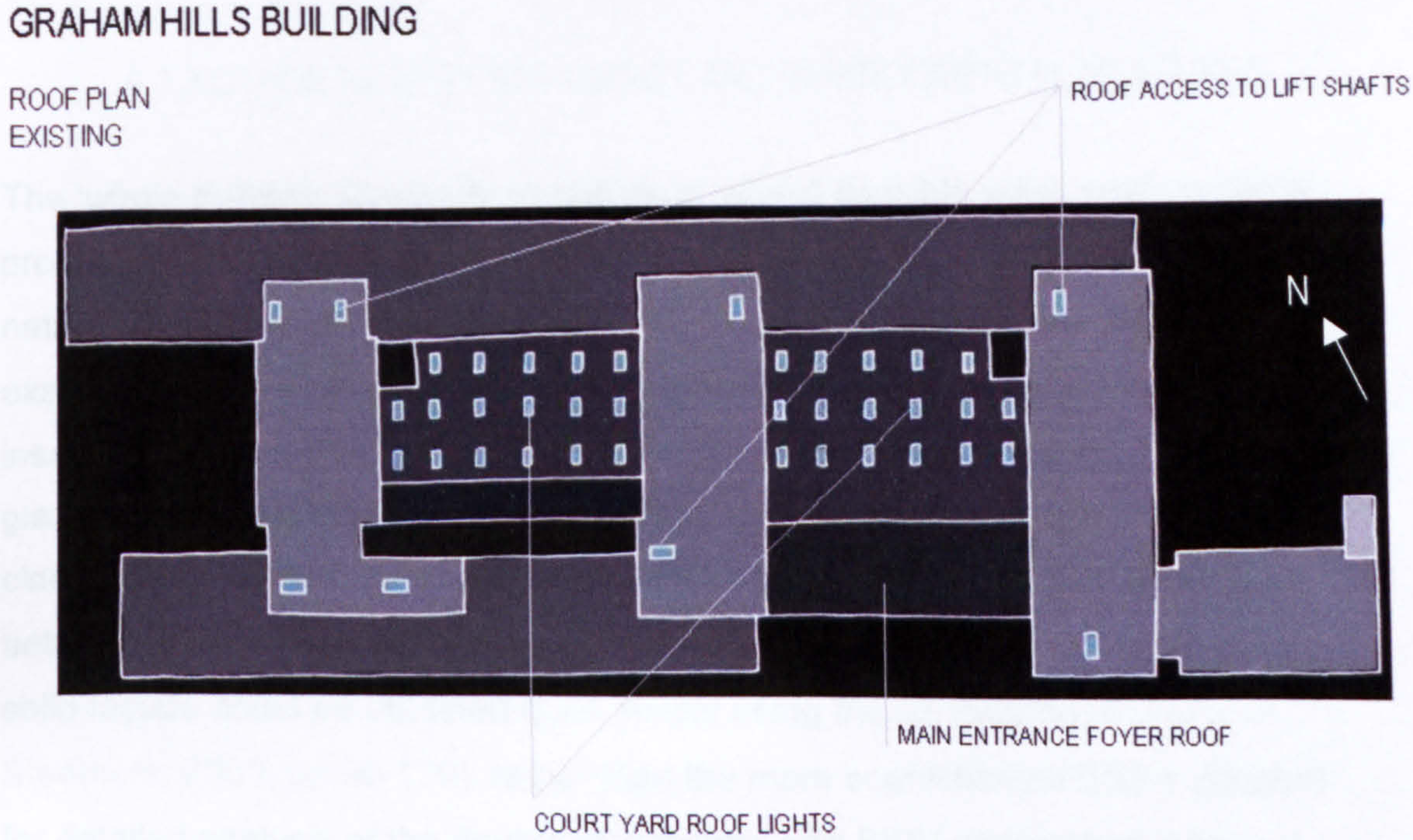

Fig. A 1.3 Graham Hills building roof plan as existing

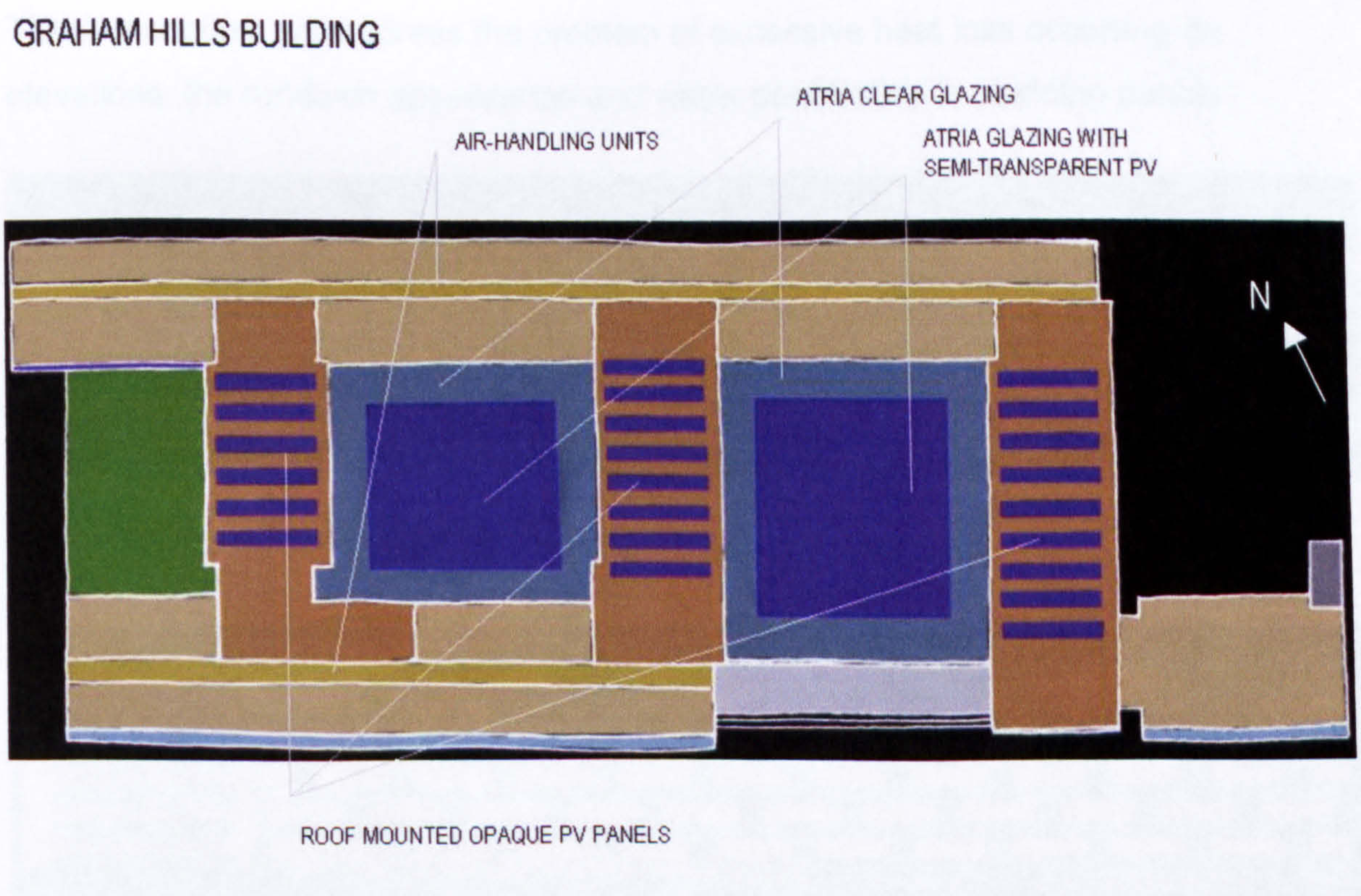

Fig. A 1.4 Graham Hills building roof plan proposal

A 1.3 OTHER ENERGY EFFICIENCY AND ENVIRONMENTAL MEASURES

The 'whole building approach' to reduce or where possible solve environmental problems, apart from emphasis on BIPV systems as an integral part of this, naturally embraces other traditional energy conservation measures. For example, improvements on the north, east and west elevations will include over-insulating and over-cladding concrete panels and high-performance double glazed window replacement of the existing, single glazed windows. The over-cladding on the north elevation could reduce the area of glazing in favour of better thermally performing spandrel panels. The optimum ratio of windows to solid façade could be obtained quite simply using the LT method [Baker and Steemers, 2000, pp.96-179], rather than the more sophisticated ESP-r adopted for detailed analysis of the double skin façade with BIPV component, where a gap in knowledge has been identified. However, the proposal here is simply one of principle. It is not the intention to subject all aspects of the intended improvements to detailed analysis, since this would not constitute a new insight. These measures will address the problem of excessive heat loss occurring on elevations, the rundown appearance and water penetration in cladding panels.

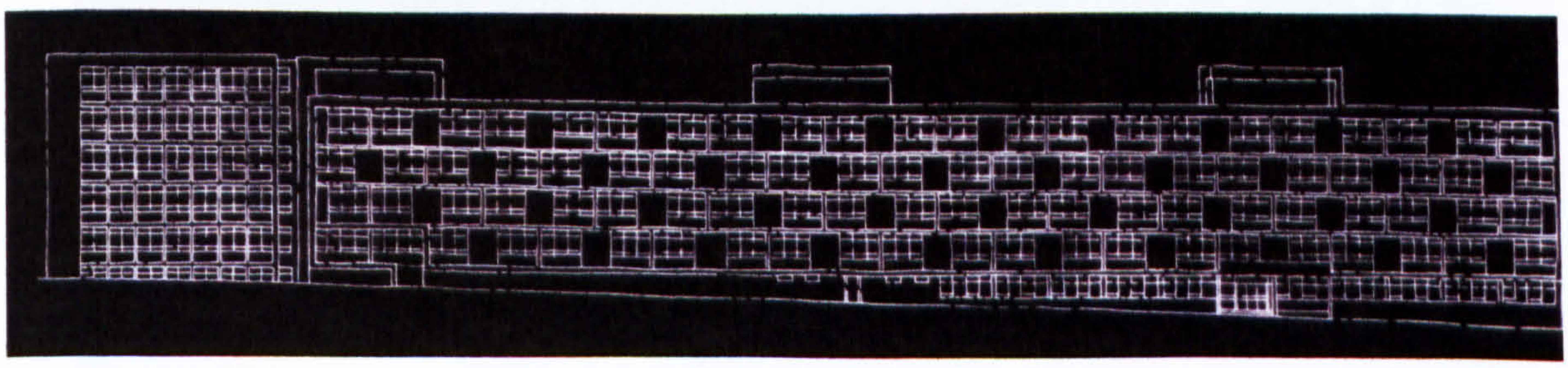

Fig. A 1.5 Graham Hills building north elevation as existing

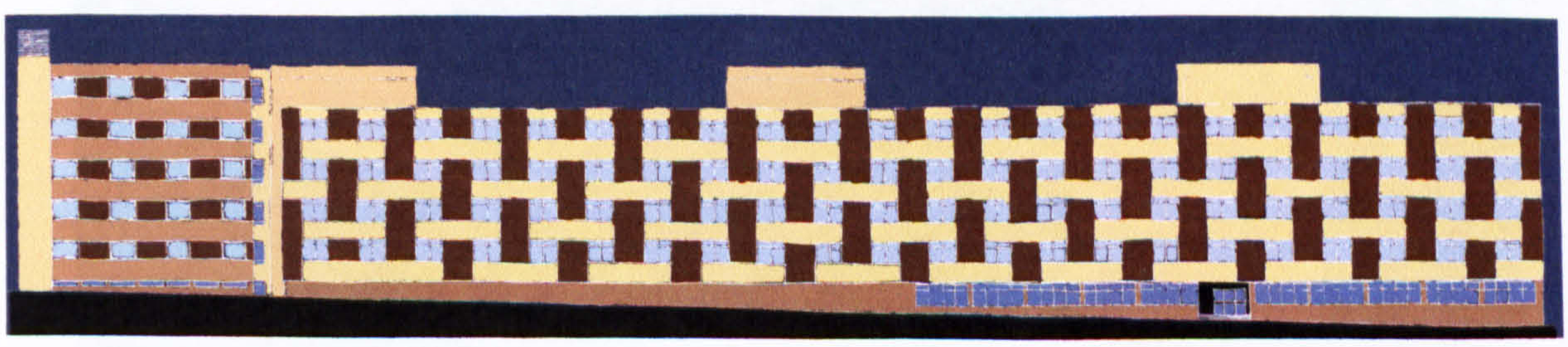

Fig. A 1.6 Graham Hills building north elevation proposal

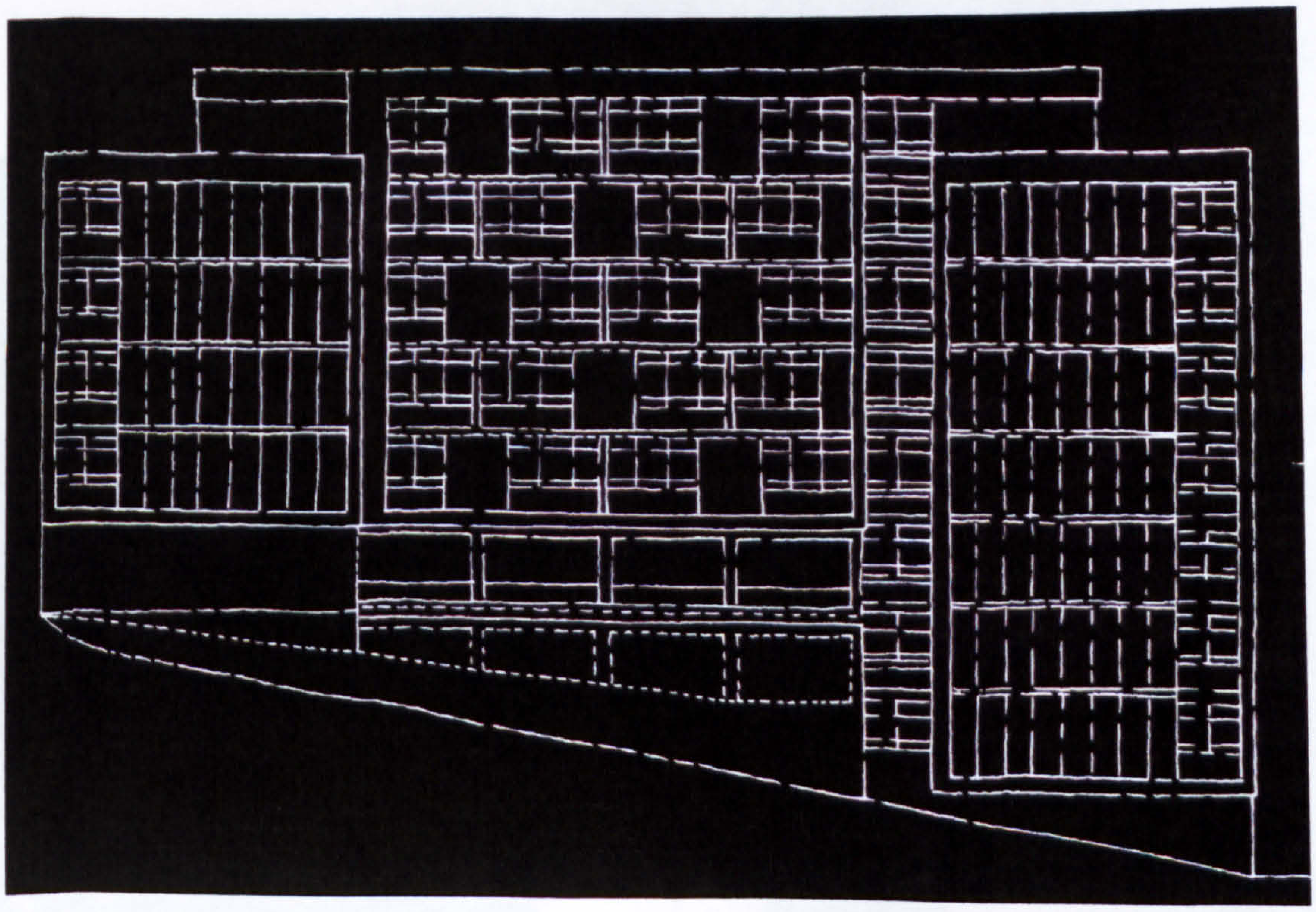

Fig. A 1.7 Graham Hills building west elevation as existing

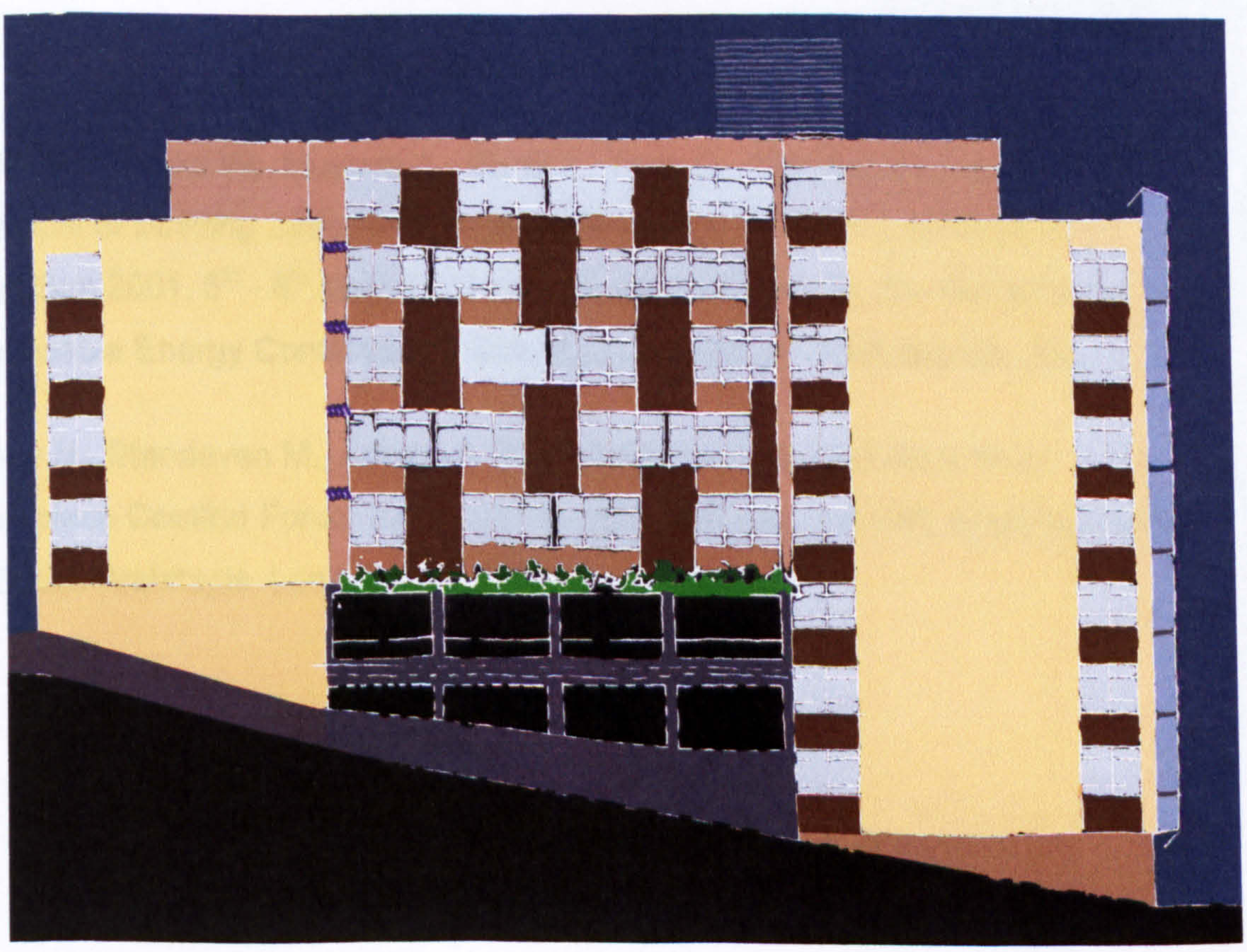

Fig. A 1.8 Graham Hills building west elevation proposal

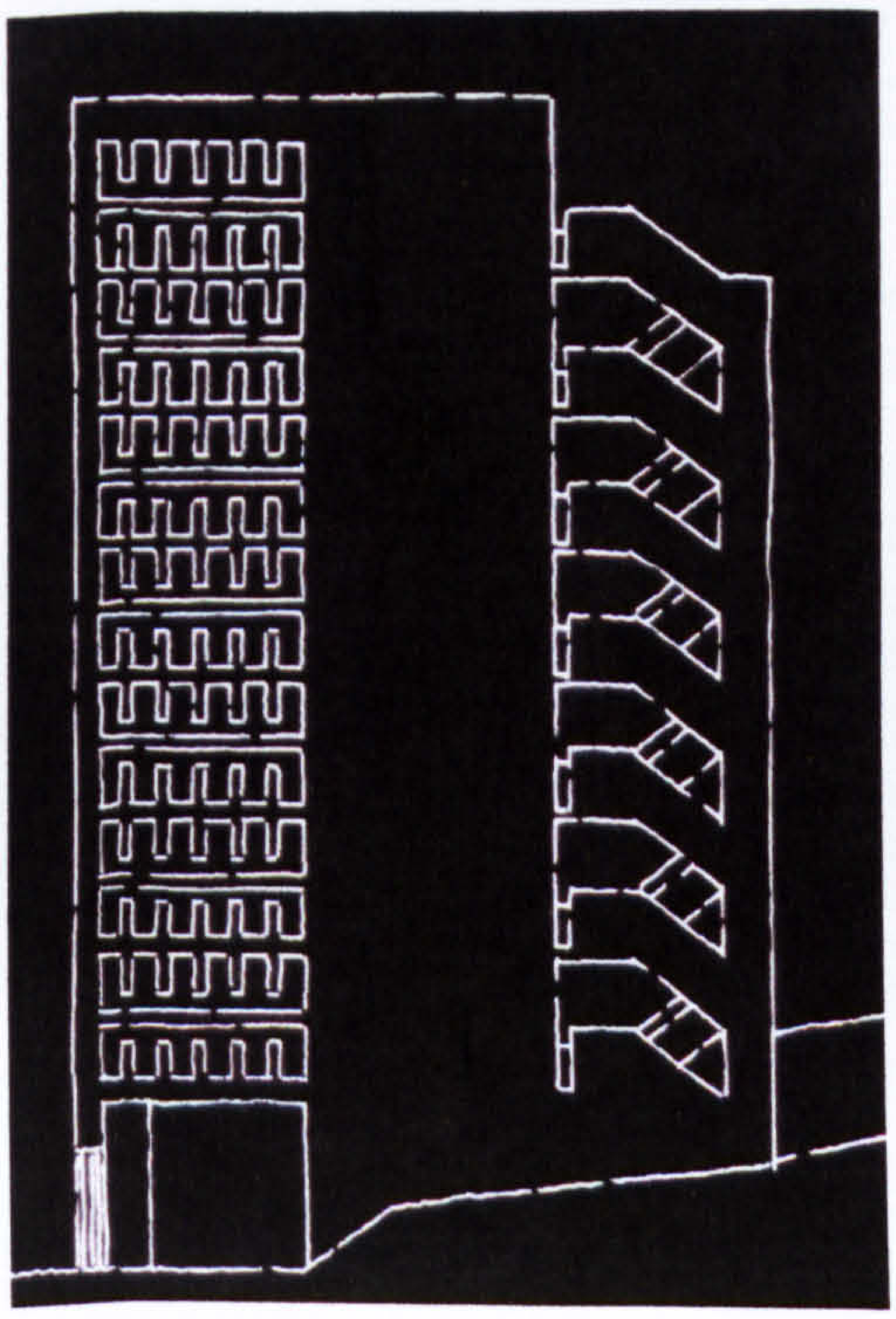

Fig. A 1.9Graham Hills building east elevation as existing

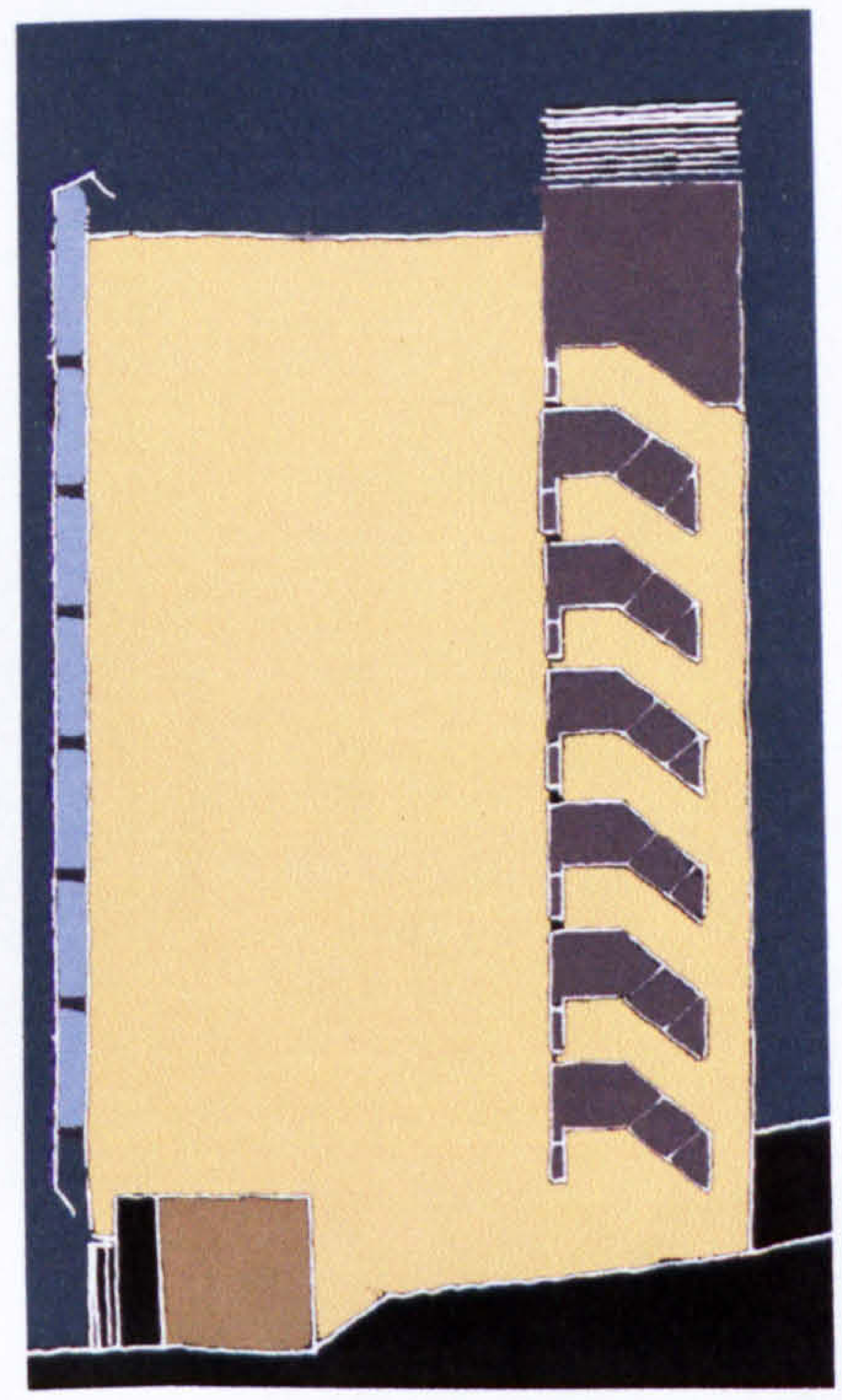

Fig. A 1.10 Graham Hills building east elevation proposal

A 1.4 APPENDIX A References

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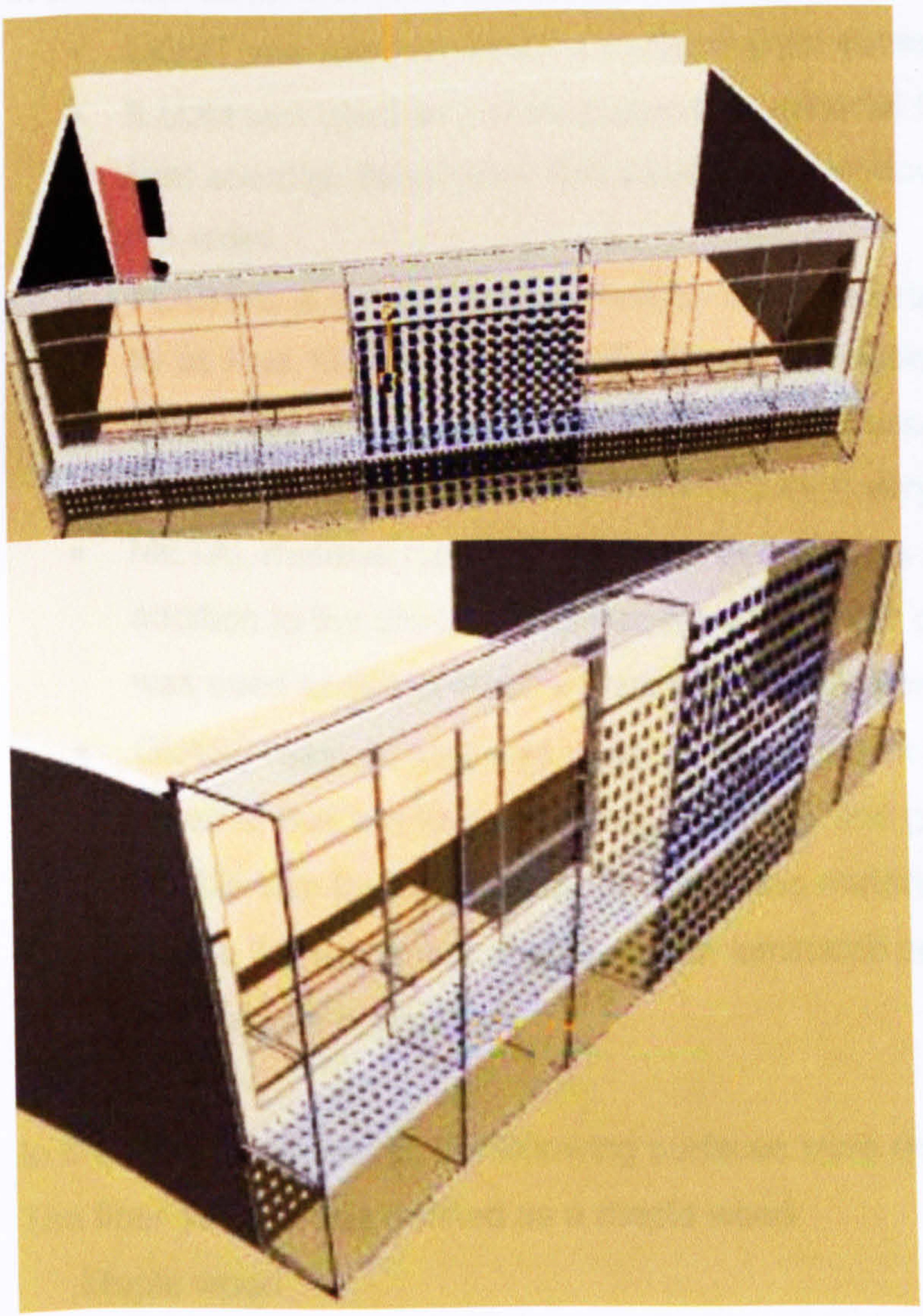
APPENDIX DAYLIGHT MODEL IN RADIANCE

B

APPENDIX B

B 1.1 SOLAR OFFICE MODEL



B 1.1 Solar Office Radiance model

The geometry of the solar office model was created by basic surfaces defined as polygons. Polygons orientation was determined by vertex ordering, read counter clockwise from the front. Surfaces' shape, size, location and composition represents the geometry of the solar office and the double skin façade component. Each surface is defined by a modifier, most commonly defined as 'void', a type of material used, and an identifier, which can be any name given for a particular surface.

B 1.1.1 SURFACE MATERIALS

Radiance has in total a capability to create 25 material types and 12 modifiers. In the solar office model the following material types were used:

- LIGHT was used for emitting surfaces [light sources], i.e. the sky.
- ILLUM was used as a special light type material for defining secondary light sources. Secondary light sources are windows where skylight enters the room.
- PLASTIC is a material type in which most materials falls into. It is defined by its Red, Green and Blue reflectance, its fraction of specularity and its roughness values, where a value of zero corresponds to a perfectly smooth surface, and a value of 1 would be a very rough surface.
- METAL material type has the same definition as the plastic material in addition to the specular component, usually 0.9 or greater. Metal material was used to define window frame and maintenance grill platforms.
- GLASS material type was used to define glass surfaces in existing external wall windows [as double glazing], and glass panels of the double skin [as single glazing]. The glass material was also used to define the two layers of glass of the laminated solar cells in the double skin façade component.

In the solar office model, the following surfaces were defined:

The floor surface was defined as a maple wood

```
Maple wood
Void        plastic        maple_wood_floor
0
0
5   0.4   0.4   0.4   0.2   0.2
```

The ceiling was defined as a white paint

```
Void        plastic   white_paint_ceiling
0
0
5   0.8   0.8   0.8   0   0
```

Wall surfaces in the office and corridor were defined as light crème paint

```
Void        plastic   creme_paint
0
0
```

5 0.7 0.7 0.7 0 0

Office door was defined as a wood material

Void plastic wood_office_door

0

0

5 0.329 0.199 0.1 0.1 0.1

Window frame was defined as a metal material

Void metal oxidised_aluminium

0

0

5 0.5 0.5 0.5 0.9 0.1

The maintenance grill platform was defined as a new galvanised metal material

Void metal new_galvanised_metal_grill

0

0

5 0.6 0.6 0.6 0.9 0.1

Office external wall windows were defined as a double glazed, clear glass material with 0.69 transmissivity and 62% light transmittance.

Void glass clear_glass

0

0

3 0.69 0.69 0.69

The glass panels of the double skin façade were defined as a single glazed, clear glass material with 0.87 transmissivity and 82% light transmittance.

Void glass clear_glass

0

0

3 0.87 0.87 0.87

The PV cells on the double skin component were defined as opaque dark-bleu plastic material, size 12.5cm x 12.5cm, and 5cm spacing between cells

Void plastic pv_cells_dark_blue

0

0

4 0.008 0.022 0.081 0 0

- LIGHT material was used to define the direct light source, i.e. the sky. For the day lighting analysis, the sky was defined as a CIE standard overcast sky [10,000Lux]. The CIE overcast sky is produced with the gensky program. The gensky is a program that generates the sky dome and direct sunlight component for day-lighted scenes. To illuminate the scene with the sky component, gensky produces the *skyfunc* modifier, which is used to create a sky component light source. The skyfunc is used to modify the luminance of *sky_glow.* In turn, sky_glow modifies a source whose geometry is a huge hemisphere centred about the +z axis. The source is the direction and an angular diameter representing the sun with 180° source providing an infinitely distant dome [Larson *et al*, 1998, p. 358].

The CIE overcast model does not include the sun, therefore the global horizontal illuminance is the same as the diffuse horizontal illuminance. The CIE overcast sky is measured by the horizontal illuminance, given in Lux. A horizontal illuminance for an overcast sky is 10,000Lux. The gensky program generates a 10,000Lux CIE overcast sky by specifying the diffuse horizontal irradiance [-B option]. To produce a 10,000Lux sky the irradiance that corresponds to this illuminance is 10,000/179 = 55.866W/m^2, where the conversion factor is the Radiance own value for luminous efficacy and is fixed at K_R = 179 lumens/Watt [lm/W] [Larson *et al,* 1998, p. 357].

```
!gensky      -ang  45  0  –c  –B 55.866
skyfunc      glow  sky_glow
0
0
4     1.0  1.0  1.0  0
sky_glow     source       sky
0
0
4     0  0  1.0  180
```

To define the ground plane, an upside down sky was used to represent a luminous ground by applying the skyfunc modifyer to a 180° glow source, where the direction vector is pointing downward. The glowing ground was defined in the sky scene as:

```
Skyfunc      glow  ground_glow
```

```
0
0
4       1.0  1.0  1.0  0
ground_glow   source          ground
0
0
4       0  0  –1   180
```

A glowing ground behaves differently from a glowing sky. Although the same modifier was used for both, Radiance distinguishes between the two by testing the z component of any day's direction vector. Above the horizon, the sky model brightness distribution is applied, but below the horizon, a constant brightness value is used. Defining a constant brightness value is based on two factors: the sky's [diffuse] horizontal irradiance and the average ground reflectivity. The horizontal irradiance is evaluated from the zenith radiance and the average ground reflectivity default value is 0.2, or 20 % typical for ground plane reflectance.

Gensky is also used when the luminance of the sky needs to be accurately distributed through windows to illuminate as interior environment. The ILLUM material is applied to all glass surfaces to define them as secondary light sources where sky light enters the room. The process begins by creating surfaces across these interior openings. An invisible light emitting material [illum] is used to modify this surface. *Skyfunc* was then converted into a modifier that conveys the day lighting distribution to the *illum* surface, so that it invisibly radiates light into the room as though it were coming from the distant sky. For each window to distribute daylight from the appropriate sector of the sky, the invisible illum light sources must be created [Larson *et al,* 1998, p. 151-153].

Mapping the sky lumin to glass surfaces:

```
Skyfunc         brightfunc      window_bright
    2       winxmit winxmit.cal
    0
    0
    window_bright      illum    window_office
    0
    0
    3        0.88   0.88   0.98
```

B 1.2 LIGHTING SIMULATION AND RENDERING

Radiance employs a light backwards ray-tracing method. Light is followed along geometric rays from the point of measurement [the view point] into the scene and back to the light sources. The result is mathematically equivalent to following light forward. Radiance use two main rendering programs:

- RVIEW, an interactive tool for scene viewing allowing a quick preview of a scene, checking the model, and selecting views for final, high-quality renderings, and
- RPICT, a rendering tool that produces high quality pictures which are a 2D collection of real colour radiance values. Both tools were used to generate images of the solar office model.

B 1.3 IMAGE MANIPULATION AND ANALYSIS

The pictures produced with Radiance have pixel values that are real numbers corresponding to the physical quantity of radiance [recorded in Watts/steradian/m^2]. The most essential Radiance image manipulation tool is PFILT. It adjusts the picture exposure and performs anitialising by filtering the original image down to a lower resolution.

B 1.4 INTEGRATION

Radiance has executive programs to simplify the rendering process. In the solar office model the RAD program tool was used. Rad is a program that set up rendering procedure and optimises the rendering process based on provided parameters. It requires a list of all scene description, lighting, material and view files, and several other parameters including entering a low, medium, or high value for the rendered image quality. It is a very important program that controls scene compilation, rendering, and filtering.

B 1.5 DAYLIGHT FACTOR

DAYFACT is the lighting analysis tool in Radiance. It is an interactive script to compute illuminance values and create contour plots of daylight factors and percentage of saving energy on a specified work plane. The Dayfact script requires input values for the origin of the work plane [x, y, z coordinates], the work plane width and length, and input values for the ambient parameters. The origin of the work plane in the solar office model was defined as 0 0 0.8, i.e. the work plane starts from the front left hand side corner of the office room and it is 0.8m above the floor level. The work plane was defined with 10.35m width and 6.0m length, corresponding to the office floor plan dimensions. The input values for the ambient parameters included:

- ab ambient bounces
- ad ambient divisions
- ar ambient resolution
- av ambient value
- aa ambient accuracy
- as ambient sampling

The -ab parameter sets the number of ambient bounces, i.e. the number of inter-reflections that will be calculated. The –av parameter sets the ambient value approximation to the given RGB radiance [red, green and blue]. This corresponds to the average radiance in all directions in the visible scene, in Watts/steradian/m^2. The –ad parameter sets the number of ambient divisions, which is how many initial samples will be sent out over the divided hemisphere. The –as parameter sets the number of ambient super samples. This is the number of rays that will be used to sample areas in the divided hemisphere that appear to have high variance. Super sampling improves accuracy significantly in scenes with large bright and dark regions by carefully sampling the shadow boundaries. The –aa parameter sets the ambient accuracy to the specified fraction. This is the maximum error permitted in the indirect irradiance interpolation, and it is generally less than 0.3. The –ar parameter sets the ambient resolution. The accuracy of the indirect interpolation will start to relax at distances less than the maximum scene size divided by this number [Larson *et al*, 1998, p. 363]. The DAYFACT script also requires input for the produced pictures file names, specified file containing the sky description, and the work plane design level defined in Lux. In the daylight factor analysis for the solar office ambient parameters are defined as: -ab 3; -ad 1024; -as 512; -aa 0.1; -av 0 0 0; -ar 128. The sky is defined as 10,000lux CIE overcast sky, and the work plane design level is defined as 500lux.

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