DESIGN OF AN INTEGRATED PASSIVE AND ACTIVE DOUBLE FACADE SYSTEM FOR UK OFFICES

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ABSTRACT

The Egan Report, changes to Part L Building regulations, and the importance of office workers is challenging designers to improve the construction process, reduce operational carbon emissions, and enhance occupant comfort for office buildings in the United Kingdom. This thesis proposes a double skin facade system with integrated environmental systems to overcome these challenges.

The Facade deals with a number of conflicting requirements and a single-storey, naturally ventilated cavity, unitised Double Facade has been proposed to resolve them. The two key determinants for the Active Environmental System have been prefabrication and operational carbon emissions. To address these issues a decentralised system, comprising of a Reversible Air Source Heat Pump, Heat Exchanger, Active Beam and Active Trench is proposed, and integrated into the Double Facade. A key part of the design process has been working with industrial partners to develop the design and realise a full-scale prototype. This has been tested and evaluated in terms of key aspects of the comfort, weather and aesthetic performance. An appraisal of the product demonstrates that it achieves proof of concept; it is highly prefabricated and enhanced occupant comfort and carbon emissions targets can be met.

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INTRODUCTION

Background

The challenges in the design of offices in the United Kingdom are numerous and diverse. The preference for highly glazed facades, optimum comfort conditions, and improved value, quality and cost effectiveness of the construction process are all present, together with the challenge of achieving sustainability.

The preference for highly glazed facades in offices has a number of reasons; they include improved day lighting, view and visual connection with the outside, transparency as a corporate message and the ease of maintenance of glass whilst providing amenity to valuable workers. Highly glazed facades however come at the expense of increased heating and cooling loads. In winter, the high areas of glazing increase the heat loss from the building envelope when compared to an envelope with increased opacity combined with insulation. In summer, there is an increase in unwelcome solar gain, which can cause over-heating or necessitate air-conditioning.

To maintain large glazing proportions some architects and engineers have overcome the problem of overheating by the use of Double Skin Facades. This is a building envelope system comprising of two layers with a ventilated cavity in between. This serves as a protected zone for solar shading and has been shown to improve the overall thermal performance when compared to a single skin, all be it double glazed, fully glazed solution. It also provides benefits for occupant comfort through improved acoustic attenuation, radiant temperatures in winter and access to natural ventilation in difficult contexts (Heusler et al. 2001, pp.26–29). The design of a double skin facade is not straight forward as there are many permutations and many factors to consider including comfort.

Optimising comfort conditions in our places of work, has a considerable effect on occupant health, well-being and productivity. For office organisations, this is of utmost importance as the retention and performance of their workers are key to their success. This has been substantiated by various studies examining the indoor environment and its effect on comfort, productivity and recruitment (Derek Clements-Croome 2006)(YouGov Plc 2008). For organisations it therefore makes economic sense, to invest in a well designed internal environment that focuses on optimum occupant comfort conditions (Derek Clements-Croome

2006). It is thus of interest to establish the key variables related to occupant comfort and how they can be realised through the design of the facade and environmental systems.

The simultaneous improvement of value, quality and cost effectiveness of the construction process is long overdue. Many other industries such as the car industry have continued to provide customers with improved quality and scope, whilst reducing the time and cost required through the use of assembly line and concurrent engineering processes. The construction industry however, still follows a single craft model and has been challenged to improve its performance (Egan 1998). Prefabricated building components and off-site manufacture is considered as one of the ways in which its performance can be improved (Taylor 2009). The curtain wall facade has already embraced prefabrication with the development of unitised facades. Environmental systems however have a much reduced prefabrication level. However, the potential benefits of a prefabricated environmental system could be even greater than the facade as it affects the site issues considered the most advantageous for the use of prefabrication; minimisation of on-site operations, reduced congested work areas and multi-trade interfaces, and minimised on site duration (Blismas et al. 2006, p.123).

An example of the use of prefabricated environmental system coordinated with the facade in office buildings is the Deutsche Post Tower, Bonn, Helmut Jahn and Werner Sobek, 2001 (Franzke et al. 2003). The use of a decentralised heating, cooling and ventilation device not only improved the construction process, but also increased space efficiencies by allowing for reduced floor to floor heights, and reduced risers and plant room sizes for ventilation distribution. Centralised generation of heating and cooling was still provided. For further space, construction and in certain circumstances energy efficiencies, the heating and cooling source could be integrated into the facade on a cellular office zoned basis. This would completely eliminate the need for the central plant room, risers and distribution networks for room air conditioning and potential for even greater efficiencies and therefore value to clients.

Together with the improvements to comfort, construction and space efficiency, sustainability of the built environment is also a major design factor. There is a scientific consensus that global warming is being caused by increased anthropogenic carbon emissions (Pachauri & Reisinger 2007). The operation of office buildings make up a significant proportion of carbon emissions in the UK and in response building regulations are becoming more and more stringent in relation to the operational carbon emissions. Wider implications of office construction, use and disposal upon the environment are also being considered by some clients through schemes such as BREEAM [1] (Building Research Establishment Environmental Assessment Method) which go beyond simple compliance with Building Regulations. As the main influence for regulated carbon emissions and an impact on other aspects of the environment, the design of the facade and environmental system need to consider these regulations and schemes. The facade and the environmental system therefore have a key role to play in addressing all of these challenges.

Aim

The aim of this thesis is to develop a Double Skin Facade with Integrated Environmental Services that overcomes these challenges and specifically provides:

- A fully glazed facade;
- Enhanced occupant comfort for productivity;
- Deletion of the central HVAC system for improved space efficiency and value;
- A prefabricated environmental system;
- Exemplary operational carbon emissions and BREEAM performance.

The overall aim is to provide this functionality and attributes as a specifiable product to the construction industry to benefit occupants, clients and designers. This to be tested via a prototype Integrated Passive Active Double Facade System (IPADFS).

[1] For details of the impact of BREEAM on office design see Section 1.4.

Industrial Brief

The project was instigated by Anthony McLaughlin, Partner at Buro Happold Ltd, and the University of Nottingham who provided a brief and design criteria for the project. This is shown below with some minor alterations by the author relating to the comfort criteria. This was used as an initial brief and developed further during the course of the research.

'To develop an integrated façade component which 'globally' addresses the issues of enclosure, aesthetics, energy, light transfer, weather tightness, mixed-mode ventilation principles and renewable energy collection. The project should deal with a façade unit with dimensions equivalent to a double occupancy office. Room depth shall assume at 6m (i.e. that which can be effectively naturally ventilated and naturally lit). In terms of external influences the project will use Nottingham weather data and assume external air and noise quality to be suitable for natural ventilation.

The main drive for such an integrated façade would be to delete the central HVAC systems for a typical building thereby increasing greater area efficiencies as well as considerable reduction in plant space.

Apart from the goal of an energy-efficient façade or a great aesthetic, fundamental to the project is to ensure that we provide an enhanced working space within acceptable comfort criteria. In winter internal temperatures shall be a minimum of 20°c. In summer 25°c is the design temperature and 28°c not exceeded for more than 1% of the occupied hours per annum when calculated with the CIBSE design summer year data or adaptive comfort regime.[2]

The new façade component should be designed for off-site (factory) assembly and will incorporate/integrate the working components of the 'rooms' environmental systems i.e. heating/cooling/ventilation (ventilation being both mechanical and natural). For this it is foreseen that the module will contain electrical wiring systems, control wiring, compressor, evaporator, refrigerator pipe work, ventilation fans, natural ventilation flaps, solar control systems, glare control and maybe photovoltaic cells for power generation.' (University of Nottingham 2007, p.13)

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[2] The comfort criteria will be modified in Section 1.2 for enhanced occupant productivity in summer.

Methodology

The methodology comprises of a literature review and a product design process. The literature review is set out within Chapter 1 and Chapter 2 and includes:

- Best practice and future trends in UK commercial office architectural design, environmental system design and facade design
- Use of prefabrication in construction
- UK sustainability agenda related to the design of offices
- A review of precedent projects and products

The literature review will help develop the industrial brief from which a product design process can be formulated and followed.

Outline of Thesis

Chapter 1 reviews a number of pertinent issues related to UK offices. The first section provides a history of the modern office and the design and in particular, the importance of glass facades in office architecture. The second section examines the requirements for improved comfort in offices together with the economic case for improved comfort. This is followed by an introduction to carbon emission targets for UK offices and BREEAM. The chapter also looks at how the car industry has improved its performance and the ideas used which could equally be applied to the construction industry to improve performance.

Chapter 2 reviews the environmental systems and facades being used in UK offices buildings today and suggests strategies and technologies for further development. The review of the environmental system centres on alternatives to the centralised approach and the potential technologies suitable for a decentralised system. The facade is described in terms of the development of curtain walling technology and the dilemma being faced at the moment to maintain high levels of transparency yet improve overall energy performance. The next step in improving building performance is proposed and this is an Integrated Passive Active Double Facade System (IPADFS). It goes on to describe the design process to be used to reach the market, and the scope within this thesis.

Chapter 3 describes the facade design process from initial concept selection to detailed design. A number of different facade concepts are analysed for south-east and north-west orientations and a double skin facade is clearly the best solution. The southerly aspect, as the more challenging, is focussed upon and developed further. This includes the development of a comprehensive ventilation strategy, a consideration of building physics, energy generation and structural design.

Chapter 4 describes the development of an Active Environmental System from the basic options outlined in Chapter 2 into a detailed design and integration into the facade. The different methods of heating and cooling supply are analysed and an Air Source Reversible Heat Pump is selected and developed in detail. The fresh air supply and delivery options are also analysed and the solution for the supply concluded as a Heat Exchanger. The best option for the delivery of the heating, cooling and fresh air is concluded as an Active Beam together with an Active Trench for additional heating and cooling. Throughout the chapter integration into the facade is considered and in the final section different options for integration are considered and a single solution decided upon.

Chapter 5 describes the development of the design with industry and the realisation of a full scale prototype. The different organisation and the changes they suggest are documented and incorporated into final production information. This was then used to fabricate the different components. The assembly process carried out at the University to complete a full-scale 'proof of concept' prototype at the University is described in the final section.

Chapter 6 describes the testing and evaluation of the prototype. Testing was carried out on the Active Environmental System by taking temperature and velocity readings. The Double Facade was tested by hose water testing in the spandrel zone based on industrial standards. Feedback from architects and engineers was carried out by questionnaires. Feedback from other stakeholders such as maintenance personnel was carried out by discussion. Some of the design changes necessary as a result of the testing and evaluation are also set out.

Chapter 7 discusses the success of the prototype in relation to the brief requirements. It concludes with the benefits and drawbacks of the system, and key areas for design development as part of future work to progress from the prototype into a specifiable product.

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CHAPTER 1

OFFICE DESIGN IN THE UNITED KINGDOM: FORMS, CONSTRUCTION, COMFORT AND SUSTAINABILITY

During the twentieth century there has been a steady increase in the proportion of professionals engaged in office work and as of the year 2001, one in three people in the UK (United Kingdom) were classed as either professionals or managers whereas in 1911 it was under a fifth (Hicks & Allen 1999, p.5). This has been buoyed by the continued growth of the UKs banking, insurance, research, design and consulting services. To continue to grow and compete in the globalised economy, office buildings need to be designed and built to provide greater levels of productivity. At the same time we need to address the paradigm facing the construction industry of meeting the UK's challenging sustainability targets and improving build quality, yet remaining competitive on cost. This chapter examines the background to office design, the provision of healthy productive office spaces, the sustainability targets of UK offices and the methods used in design and construction.

The chapter begins with a brief history of the modern office leading to the key developer and client briefs, and the reasoning behind the predominant facade treatment. Since productivity is a key factor in the success of an organisation the main factors that improve productivity are examined, together with the potential economic benefits interventions may bring. The following section examines the sustainability agenda for UK offices, the current and future requirements and the ways in which improved energy sustainability can be provided. The final section contrasts the performance of the building industry with the car industry and the ways in which the former could be improved.

1.1. THE DEVELOPMENT OF THE MODERN OFFICE

Offices have been used for a number of centuries and continue to evolve. This section examines the development of the modern office from the early twentieth century, emerging working patterns and the use of all glass facades.

The proliferation of commerce in the industrial age of the 18th and 19th century led to the increase in construction of private banks, insurance groups and other commercial enterprises, which were based upon classical plans and facades. New ideas from notable modernists such as Mies van der Rohe in the twentieth century sought to break away from the use of classical designs and create an architecture based upon the modern industrial era, remove superfluous ornament and provide a 'skin and bones' architecture. Structural engineering technology allowed the external wall to become dissolved and more translucent than solid. The availability of steel beams and mechanical lifts allowed for deeper and taller buildings encouraged by developers and their funding mechanisms. Taller buildings and deeper floor plates were also made possible by developments in artificial lighting and air conditioning (Banham 1984, p.181). The limits in floor depth necessary to provide ventilation and daylight were no longer required. This allowed office buildings to become divorced from the external environment and highly glazed transparent facades to be used in different countries regardless of the climate. The main driver for the use of technology in developing these types of tall and deep buildings is economic, as developers look to make a return on an initial investment and the following design criteria become crucial:

- Maximum internal area on each floor
- Maximum net usable to gross building area
- Minimum external wall thickness
- Minimum horizontal support thickness
- Minimum floor to floor height

With the relaxation of height restrictions in London aimed at preserving views of St Paul's Cathedral and Westminster, this type of development arrived in London with notable buildings such as Centrepoint, London, Richard Seifert, 1967, and the more influential One Canada Square*,* London, Cesar Pelli Associates (CPA), 1991, (skyscrapernews.com 2011). The deep plan, hermetically sealed, highly glazed office designed by CPA, provides little contact with the external environment for occupants and requires large quantities of carbon intensive energy to support the artificial environment. Owner-occupied buildings, such as client Wessex Water Operations Centre, [1] in Bath by Bennetts Associates (2000) was designed with very different design considerations.

Wessex Water acknowledges the role of occupant comfort to increase productivity and the need to embed sustainability and energy usage into office buildings. The design is shallow plan and low rise which enables natural ventilation, high levels of natural daylight and contact with the external environment (Hascher et al. 2002, pp.160-163). The report from the post-occupational evaluation has shown the building to use less energy in heating and cooling than conventional offices and managers attribute increased staff motivation to the features of the design (CABE & Llewelyn Davies Yeang 2005, p.50). The task of a low energy and occupant comfort centred design was facilitated by the rural location. However, travelling to work in a rural location will usually mean the use of private transport and an increase in personal travel related emissions. This can be up to 50% of the energy consumption of UK office buildings (Edwards 2009, p.197); locating an office building within the city however would make public transport an option and provide lower travel related emissions per person. There are also economic and social benefits to inner city locations such as proximity to other businesses, shops and entertainment. We cannot simply turn our back on the city environment.

Instead we need to examine the ways in which urban office buildings can also provide high levels of occupant comfort yet, remain viable on inner city sites economically and address sustainability objectives.

Another interesting difference between One Canada Square and Wessex Water HQ is the difference in floor planning. One Canada Square being largely open plan and Wessex Water having a mix of spaces. This is part of a wider change in floor planning as noted by DEGW (1998) where four distinct categories were noted; open-plan, cellular, den and club. In this thesis a cellular layout will be concentrated upon as per the original design brief. However the floor plan used should still allow for future flexibility of the different layouts. As described by DEGW the minimum floor depth to enable each of the different floor layouts is 15 m. This will help ensure that the building can be adapted in future and reduce the likelihood of the building becoming unusable.

[1] Powergen, Coventry, 1995, also by Bennetts Associates is worthy of note as the first naturally ventilated major office building in the UK and a predecessor to Wessex Water (Stacey 2011)

Apart from the question of location and floor layout, an important factor and one of much debate is the predominant facade treatment used in office architecture, highly glazed facades.

1.1.1. Glass Architecture

"An architecture of high insulation values and small window areas, preferably on southerly walls only, is the logical response to the energy problem and the new thermal regulations. Yet our architectural concerns [are] with light and space, legibility, appropriateness, function, meaning and quality [which] will not be submerged in an acceptance of an architecture of insulated overcoats and minimal window areas whatever the price of energy." (M. Davies 1981, p.56)

One of the most debated topics concerning office architecture is the appropriateness of floor to ceiling glazing. The interest in the use of high glazed facades can be traced back to the industrial revolution and the *Crystal Palace* by Sir Joseph Paxton in cooperation with Fox, Henderson & Co. erected in London for the Great Exhibition in 1851. This was revolutionary in its design and construction. It used steel and glass in a way, which completely opened up the internal space to the outside and many designers were excited by the spatial dynamics created. Its construction also used prefabricated components and standardized as many components as possible (Schittich et al. 2007, pp.18-19). The potential for its use in office buildings began with the economic availability of iron and steel as a construction material. This meant the external wall could be dissolved and dematerialized as floor and roof loads could be carried within steel beams, columns and concrete structures, and the facade was relieved of its load bearing function. Early examples are the Flatiron Building, New York, 1902, D.H. Burnham & Co. The facade still however, remained largely opaque.

Ludwig Mies van der Rohe, in 1919[2] began to explore the potential for a non-load bearing facade with his sketches of a glass skyscraper (Figure 1.1). The initial sketch in 1919 shows a glass skyscraper, angular and crystal like, comprising of a small palette of materials, glass, concrete and steel. A later sketch in 1920 showed a more curved and multi-facetted glass skyscraper to provide a greater play of light reflections (Blake 1963, pp.24-27). This set in

[2] There is some disagreement in the literature on the actual years the sketches were produced, and likely to have been caused from confusion regarding the date they were produced and the date they were revealed to the public.

motion a number of ideas for other architects and Mies himself. The *Seagram Building* (1958) designed by Mies many years later realised a number of ideas in his initial sketches, was the first tall office building to use floor to ceiling glazing, and only had bronze mullions on the external facade to suggest a structure. It was admired by many of the distinguished architects of the day (Blake 1963, p.104) and did much to publicise the 'International Style'. The facade design was progressive, but in terms of low energy design and comfort conditions it performed poorly.

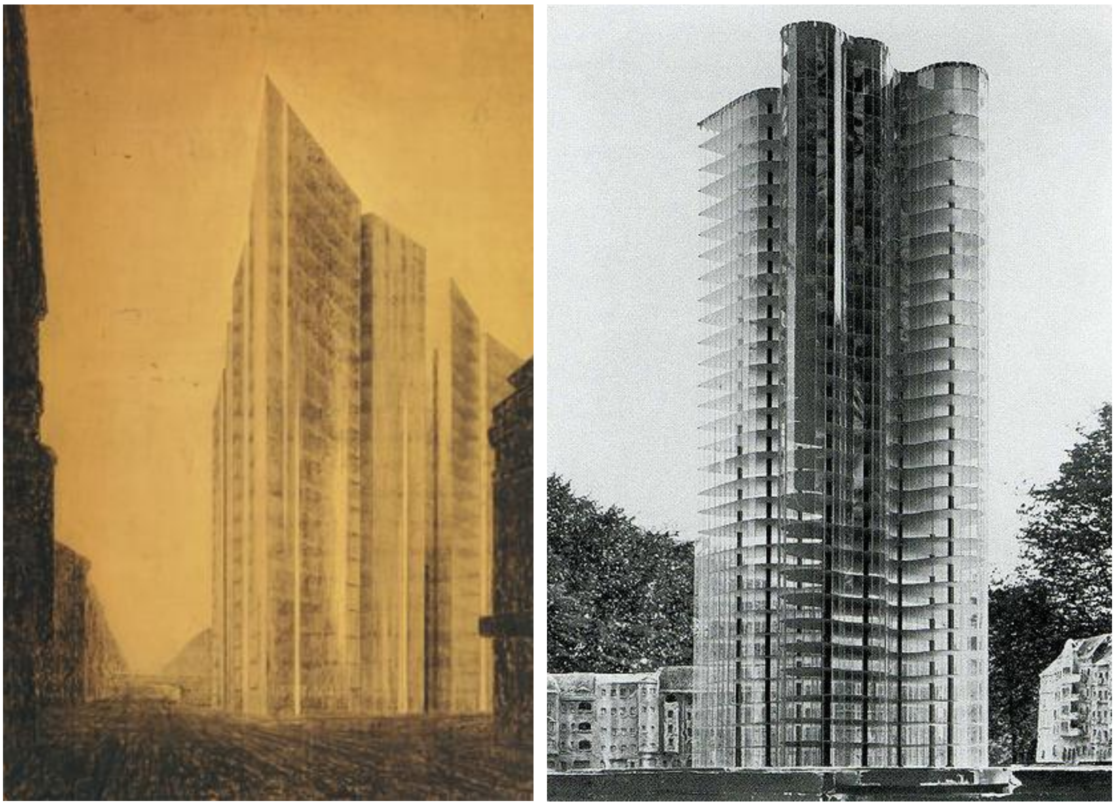


Figure 1.1 Ludwig Mies van der Rohe's sketches for a glass skyscraper in Berlin (1919 and 1920) http://www.moma.org/interactives/exhibitions/2001/mies/site/mies.html www.wikiarquitectura.org

Twenty years later in 1975 in the UK, Architect Sir Norman Foster's *Willis Faber Dumas* office (Figure 1.2) building showcased what new glazing technology and fixings could do to dematerialise the envelope further and fully embody the concepts of Mies early sketches. It also utilised a raised floor for services envisioning the growing service requirements of I.T. Since that time floor to ceiling glazing and raised floors have become common in office developments; however in recent years the relative merits and drawbacks of the extensive use of glass have been fiercely debated.

Figure 1.2 Willis Faber Dumas, Foster and Partners, 1973
http://www.fosterandpartners.com/Projects/0102/Default.aspx

Good day lighting is frequently given as a reason for floor to ceiling glazing. This does indeed provide high levels of natural daylight when compared to much more opaque construction and daylight is one of the key elements for office architecture in creating *'a space'*. It has also been proven to have a positive effect on occupant well being and reduces the need for artificial lighting and the associated energy use. However day lighting studies reveal that glazing below the level of the desk line contributes little to the daylight level of the internal space. Also glazing below the level of the desk is frequently fritted to mask the appearance of peripheral equipment and provide greater privacy to occupants (e.g. 55 Baker St, London). Closely related to day lighting is the visual connection to the outdoors that can be provided by a transparent façade. Occupants enjoy a view out of the office to stay connected with the environment, but it also allows eye muscles to relax.

Increased glazing area does however, come at the expense of increased heating and cooling loads. In winter the increased areas of glazing increase the heat loss from the building envelope when compared to an envelope with increased opacity and insulation. In summer there is an increase in unwelcome solar gain, which can cause overheating or necessitate air-conditioning. The response from industry has been more glass, in the form of double and triple glazing, and the use of low emissivity and solar control coatings. This has provided improvements in the overall U-value and solar transmission to an extent where the relative impact of heating and cooling compared to other end uses is comparable. Whether this is enough and whether more technological improvements can be achieved can only be established by reviewing the current and future regulations (Section 1.5) and comparing this to the energy performance of highly glazed facades (Chapter 3).

'"Lloyds chief promises 'greater transparency"
Lloyds Banking Group's outgoing chief executive, Eric Daniels, is to launch a major drive to improve the transparency of the lender's financial products in his last three months at the helm of Britain's largest retail bank.' (Ahmed & Wilson 2010)

The association of high glazing areas with transparent corporate culture is a frequently cited reason given by architects. Many companies and architects use transparency as a metaphor for openness and democracy to enhance their corporate image. To be considered a 'transparent' organisation at a time of distrust between large organisation and the general public is very much desired. There is also the association of highly glazed areas with urban renewal. The presence of buildings which are fully glazed has an association with areas of low crime levels and feelings of security. At night when a building is internally lit there is a feeling of safety in the urban environments as the barrier between the street and building is dematerialised creating a more open urban space (Elkadi 2006). Both corporate and public interests therefore favour glass architecture.

Finally there is the established position of glass and curtain walling in the construction industry. Curtain walling design, installation and maintenance is very familiar and responsive to the needs of architects, contractors and developers. Proprietary systems from curtain wall manufacturers minimise design time, testing time and production costs and bespoke systems offer architects greater freedom. Introducing other materials into the facade mix requires extra design work and testing to overcome uncertainties over interfaces, additional maintenance questions, additional suppliers, more complex supply chains and construction programming. Clients too are familiar with glass, its maintenance needs and it has proved itself as being very durable. All of the various stakeholders, designers, contractors and occupiers, have confidence in the use of curtain walling.

In summary there are number of reasons why fully glazed curtain wall facades will remain desirable as long as it is still possible and cost effective to meet building regulations on carbon emissions. If the performance of fully glazed facades can be made to meet more stringent regulations then it seems clear that demand for them will still remain, especially since financial institutions have never needed to be so transparent[3] and contractors and developers are under ever greater pressure to provide better quality buildings at reduced costs.

1.2. DESIGNING FOR IMPROVED PRODUCTIVITY, COMFORT AND HEALTH

The economic success of an organisation is strongly linked to the productivity of its staff. This was acknowledged over one hundred years ago in the design of the Larkin Building, 1906, by Architect Frank Lloyd Wright and the Larkin Soap Company (Quinan 1991) (Figure 1.3). Since that time productivity has been shown to be influenced by social, organisational, personal and environmental factors (Figure 1.4). From comfort studies (eg.Roelofsen 2002), as well as employee surveys (YouGov Plc 2008) the quality of the working space is frequently cited as the most important factor for occupant productivity and is within the sphere of influence of building designers. The principal factors influencing the internal environment such as thermal comfort, indoor air quality, lighting and acoustics along with good spatial design provides that quality. These factors will be examined in turn to provide design guidance on creating an improved environment for occupant productivity.

[3] The public trust of financial institutions since the financial crisis in 2008 has not recovered as of 2011

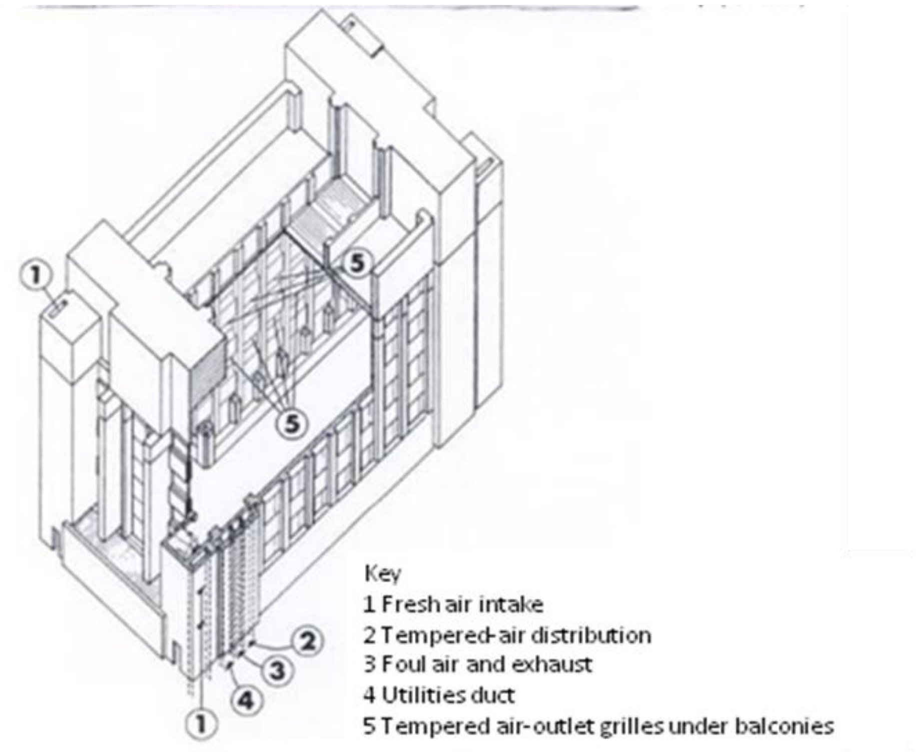


Figure 1.3 Ventilation system of the Larkin building, one of the first employee focussed and air-conditioned offices, Frank Lloyd Wright, 1906 (Banham 1969, p.69)

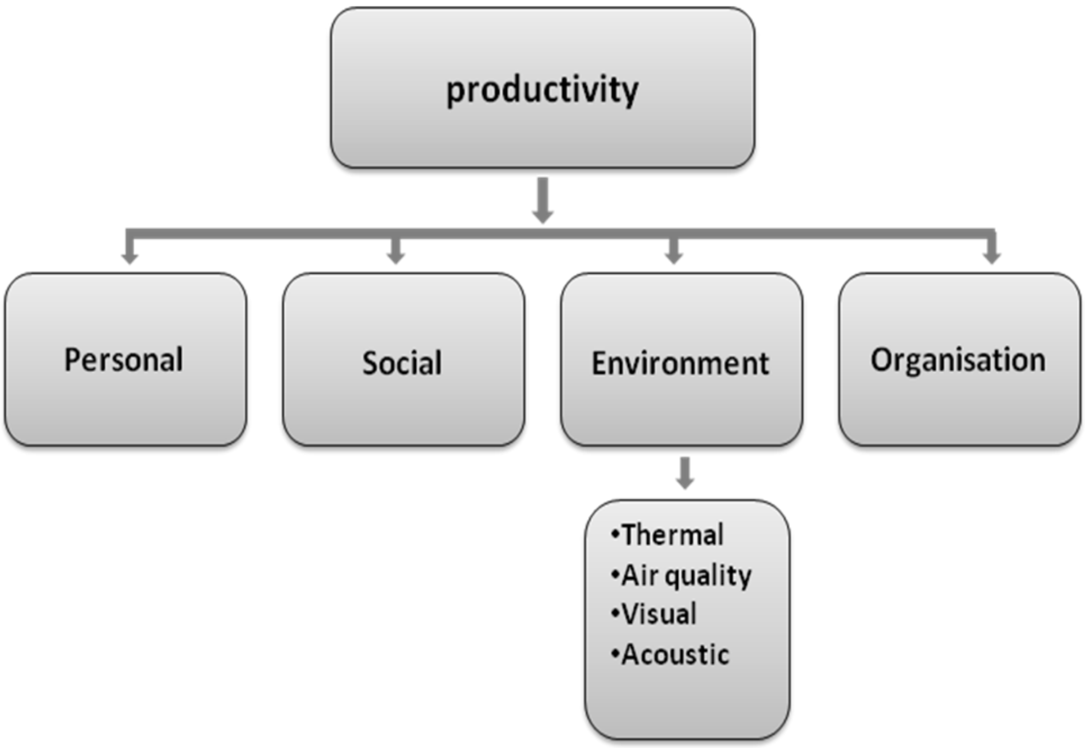


Figure 1.4 Factors affecting productivity (Clements-Croome 2000, p.11)

1.2.1. Thermal Comfort

Thermal comfort and indoor air quality are made up of the factors of temperature, humidity, air motion and contaminants. National and international standards exist for each of these factors however, there is much discussion and debate on their application. One of the reasons is that in many case studies, buildings conforming to the standards are still causing occupants to be dissatisfied with their environment (Abdou & Lorsch 1994). A critical review of standards and a clear position on thermal comfort requirements is needed.

Two methods are commonly used for establishing the temperature at which the body is comfortable. The first is the predicted mean vote (PMV) method first introduced by Fanger (Fanger 1970) and included within the international standard ISO 7730 (ISO 1994). The second is the 'adaptive comfort' model found within BS EN 15251 (ISO 2007), first introduced by Humphreys (Nicol 2010).

Table 1.1 Recommended comfort temperatures for air-conditioned buildings (CIBSE 2006, pp.1-6)

Building/ Room type	Winter operative temp.range for stated activity and clothing levels			Summer operative temp.range (air conditioned buildings) for stated activity and clothing levels		
	Temp °C	Activity Met	Clothing clo	Temp °C	Activity Met	Clothing clo
Offices:						
-executive	21-23	1.4	0.85	22-24	1.2	0.7
- general	21-23	1.4	0.85	22-24	1.2	0.7
- open-plan	21-23	1.4	0.85	22-24	1.2	0.7

The PMV method in ISO 7730 establishes the temperature at which the body has a zero net-energy heat balance by taking into account a number of environmental factors for example temperature and air speed, together with occupant factors such as clothing and activity level. CIBSE Guide A (CIBSE 2006, pp.1-9) provides recommended operative temperatures (a combination of the air and radiant temperature) for offices as shown in Table 1.1 which are derived from the PMV method.

These comfort bands are commonly used for air-conditioned buildings. It should be noted however, that within any group of subjects there is no single temperature at which they are all comfortable; there are always those who are either too cold or too hot on the seven point scale of thermal comfort (Table 1.2) as shown in Figure 1.5.

Table 1.2 Seven-point thermal sensation scale. (ISO 7730, 2005, p 2)

+ 3	Hot
+ 2	Warm
+ 1	Slightly warm
0	Neutral
- 1	Slightly cool
- 2	Cool
- 3	Cold

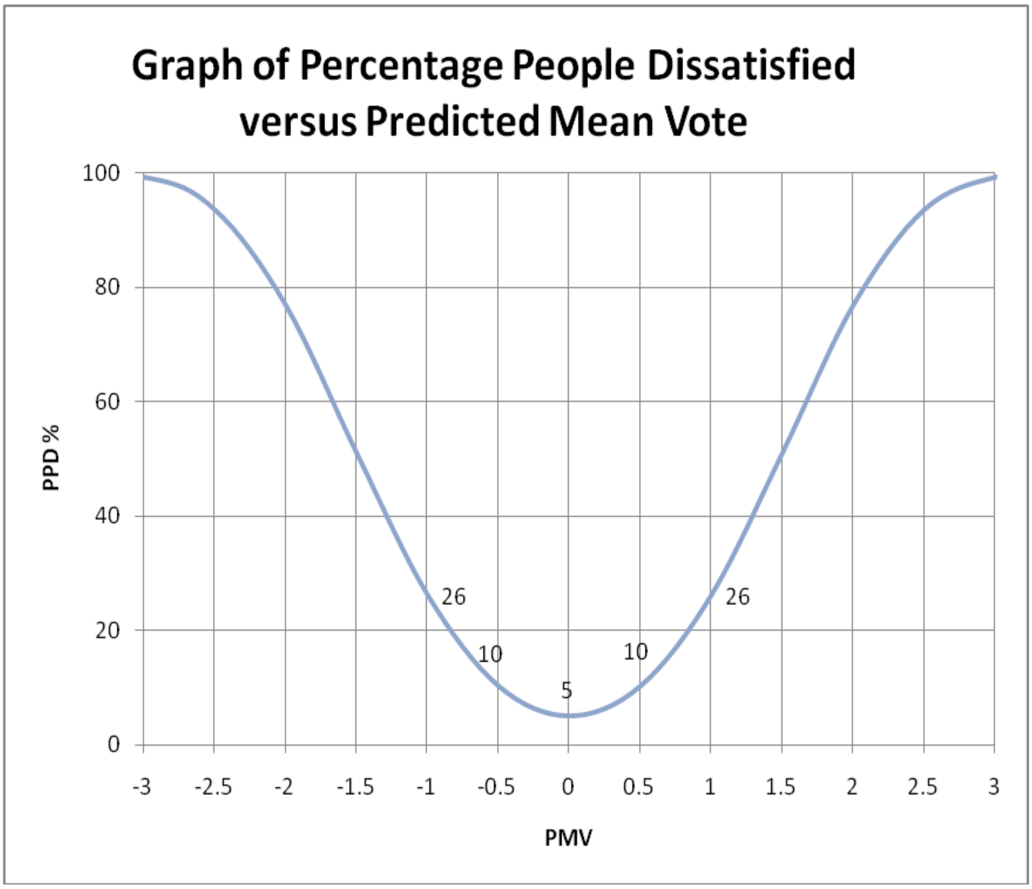
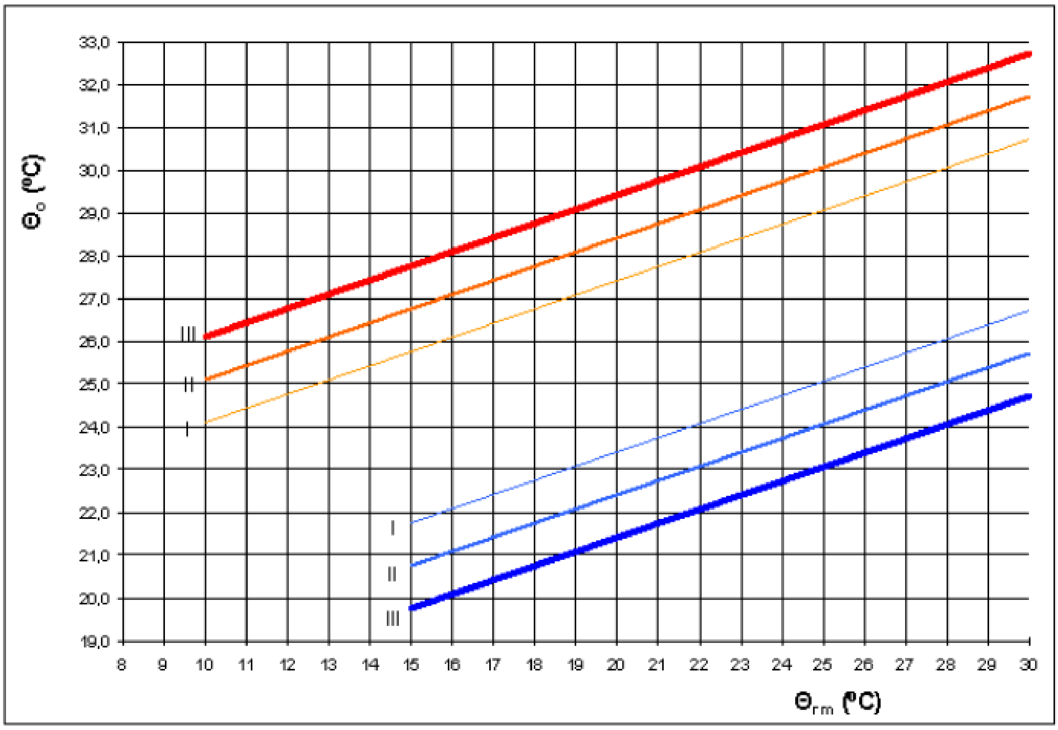


Figure 1.5 Distribution of percentage people dissatisfied with the thermal environment against the predicted mean vote calculated by using ISO 7730, 2005.

Comfortable conditions are generally considered as being in the -1 to +1 PMV sensation scale. This means that up to 26% of the occupants could be uncomfortable at a temperature deemed comfortable by the design parameters. This value can be reduced by adaptive approaches to clothing, but could also be reduced by allowing occupants to adjust the temperature based on their own preference. This could then take into account differing activity levels and clothing preferences or codes. This is reinforced by a study by Wyon (Wyon 2000) who showed that to achieve 99% people satisfied would mean a temperature range of 6°C, 95 per cent with 4.6°C and 90% with 3.9°C. The conclusion of the study was that individual control at each workplace had significant benefits in terms of productivity with an increase calculated at 7% for a temperature control of +/- 3°C. In an open-plan office situation, the solution could be to provide zonal control of the terminal devices. Providing individual control of the internal temperature is therefore a way of reducing the occupant dissatisfaction with temperature to 5% for a temperature range of 4.6°C based on the PMV method. An alternative to the PMV model is the adaptive comfort model.

The adaptive comfort model arose out of field studies of naturally ventilated buildings where it was found that occupants have a wider range of comfort criteria than that established by the PMV method. Naturally ventilated buildings were also found to provide comfort temperatures that correlate better with the outdoor air temperature (Nicol 2010) and the occupants were more accepting of higher temperatures. The reasons behind this are that natural ventilation gives users control to vary the internal temperature, keep pollutant levels low and link the indoor environment temperature with the external temperature. This has been incorporated into BS EN 15251 (ISO 2007) standard, which gives acceptable limits for naturally ventilated or free running buildings based on the outdoor air temperature as shown in Figure 1.6. In the UK, an overheating criteria of 1% allowance of working hours above 28°C in naturally ventilated buildings is commonly used in building design (CIBSE 2006, pp.1-12) instead, as a way of incorporating the adaptive comfort model in the design of naturally ventilated buildings.



Key

Θ_{rm} = Outdoor Running mean temperature °C.

Θ_0 = Operative temperature °C.

Figure 1.6 Design values for the indoor operative temperature for buildings without mechanical cooling systems. Note: New office environments are expected to lie within the bounds of class II. (ISO 2007, p.27)

Recent studies have shown however, that the optimum indoor temperature lies below these limits and is building related (Nicol 2010). It was also found that at temperatures above 25°C the environment was felt to be comfortable, but a significant proportion of occupants (44.2%) felt that their productivity was reduced. This suggests that cooling is still required in the hottest periods if high staff productivity is to be maintained.

A solution where both natural ventilation and air-conditioning are provided (mixed-mode) may be the best solution for occupants and other stakeholders. This is reinforced by the work of Rowe et al in Sydney (Leaman & Bordass 2000, p.188), where it is suggested that a mixed-mode system with user controls gives better thermal comfort, better perceived quality to perform work (i.e. productivity) and also better perceived air quality and overall satisfaction with the workplace. The conclusions drawn by Leaman and Bordass (2000, p 181) from a review of comfort studies are that '*occupants prefer natural ventilation as* *the default - in winter, spring and autumn- and air conditioning in the hot-humid parts of the summer.'* A mixed-mode approach is also more likely to be looked on favourably by developers, clients and investors since minimisation of risk and market flexibility is particular important. The option of air-conditioning allows flexibility in the type of use of the building (greater internal gains for instance) and future proofs the building against the impact of a warming climate, [4] urban heat island effects, greater pollution and changes in noise level around the building that may make natural ventilation problematic during certain periods. Risk can therefore be minimised by a mixed-mode approach as opposed to natural ventilation solution.

The mixed-mode solution, where natural ventilation is provided as well as air-conditioning with occupant control over the temperature, is therefore the solution which can provide optimum thermal comfort in the context of contemporary UK office buildings.

1.2.2. Radiant Comfort in Highly Glazed Offices

Thermal comfort is largely analysed through air temperature readings as the radiant temperature of the surfaces are generally in agreement with the air temperature. Where there is exposed thermal mass and a highly glazed facade, the surface temperatures can be quite different to the air temperature. This affects the overall temperature (an average of the air and radiant temperature) and can cause discomfort through temperature asymmetry if not addressed. Figure 1.7 illustrates the phenomenon.

[4] Naturally ventilated buildings will find it more difficult to prevent overheating based on future climate change scenario weather data (Jentsch et al. 2008)

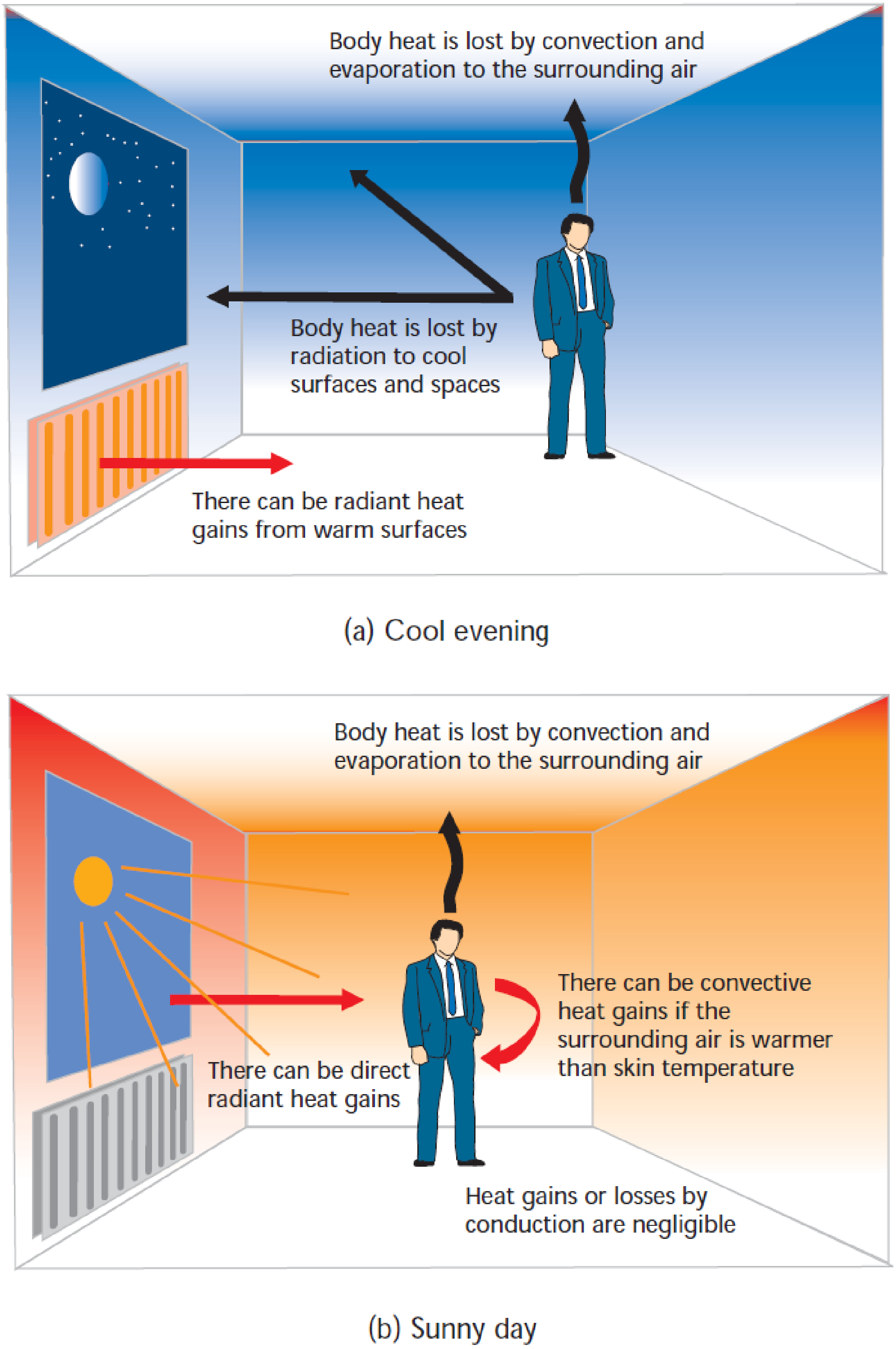


Figure 1.7 Body heat exchange with the environment (Race 2006, p.2)

Controlling the radiant temperature in the first instance allows comfort limits to be more easily achieved. In terms of temperature asymmetry, similar field experiments to those done on air temperature have been done using differing radiant temperatures of the different surfaces and their effect on occupant dissatisfaction. The results of the studies are shown in Figure 1.8.

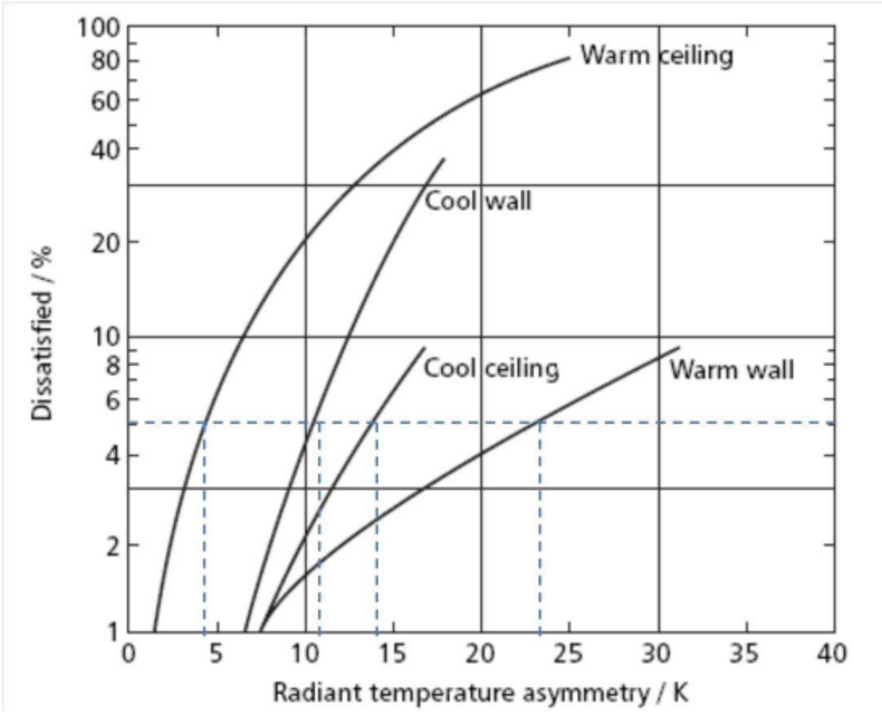


Figure 1.8 Percentage dissatisfied due to asymmetric radiation only, (CIBSE 2006, p.1.6). Note K (Kelvin) has the same magnitude as °C (degrees centigrade)

Guidelines for both warmer and cooler surfaces are considered in the study. For horizontal radiation temperature asymmetry, Figure 1.8 shows that occupants are more sensitive to cold walls than warm walls. To keep within a percentage dissatisfied of 5% a cooler wall should be kept within 10K and warm wall should be within 23K. The cool wall or winter condition can be kept within comfort limits by a local heat source such as trench heating or by improving the insulative value of the glazing through the use of insulated double glazing or double skin facades which provide a buffer space at an elevated temperature compared to the outside air. The warm wall scenario with a value of 23K may seem like a large enough tolerance, but in summer large amounts of heat can be absorbed by the glass from solar radiation and in the case of a double skin facade, the elevated air temperature in the cavity. Measures such as external shading or a well ventilated cavity are needed to ensure that the glass surface temperature stays below these limits.

The final consideration of radiant comfort is where direct solar radiation falls directly on an occupant, as it raises the mean radiant temperature considerably (see Appendix A). This will not be beneficial for occupants in summer and will require a large reduction in the air temperature in order to make the space comfortable. The solution is to provide some form of operable solar protection as direct solar radiation maybe enjoyed in the winter or at other times of the year.

Radiant comfort is important to consider in the design of a highly glazed office space as the temperature of the glass can vary considerably. In winter some form of heating the glass within 10°C and in summer a method of keeping the glass within 23°C of the rest of the surfaces is necessary to keep within comfort limits. It will also help to ensure that the air temperature does not have to be cooled or heated unnecessarily to provide a comfortable operative temperature.

1.2.3. Ensuring Indoor Air Quality for Health and Productivity

Indoor air quality comprises the factors of gaseous composition, humidity, contaminants and temperature (ASHRAE 1991). Typically for occupants it translates simply as a feeling of freshness, rather than stuffiness, and the avoidance of a build up of odours. A study by Dorgan and Dorgan revealed that improving the indoor air quality (IAQ) for problematic commercial buildings in the United States would have a payback period of only 1.4 years and over twenty years a net present value of $774 billion or $11, 227 per worker (Dorgan & Dorga 2000). This was purely as a result of improvements to the health and productivity of the occupants and the alleviation of detrimental effects of 'sick building syndrome' of which poor IAQ is implicated.

Ensuring a sufficient supply of fresh air to remove or dilute pollutants to an acceptable level has been the main method of achieving acceptable IAQ. Supplying enough oxygen only requires 0.2l/s/p, diluting carbon dioxide only 1.0l/s/p and diluting occupational contaminants 5l/s/p. However, the recommended fresh air delivery rate for a mechanical system is between 10l/s/p (CIBSE 2006, p.1.4) and 12l/s/p (BCO 2009, p.160) in a non-smoking office due to the high influence of air quality on productivity. The British Council for Offices (BCO) fresh air rate should be used since it is used in the specification for offices by developers. This rate of fresh air introduction however, assumes that the outside air is of sufficient quality for respiration.

Central parts of London, where a high concentration of commercial offices are and continue to be constructed has the worst air quality in the UK and is amongst the worst in Europe (GLA 2009, p.7). The main culprit is road traffic, particularly diesel engines and so the worst air quality is found along busy roads.

This situation is improving slowly with the ongoing improvements in car emissions, due to the very gradual renewal in the UK car fleet. [5] A mechanical system with particle filtration is a sensible response to this situation. At times where the outside air is of sufficient quality and to continue to provide occupants with personal control and connection to the environment natural ventilation should still be provided. Apart from the air quality the other factor affecting the use of natural ventilation is acoustic comfort.

1.2.4. Acoustic Control for Natural Ventilation

Inner city office sites are frequently faced with a high ambient noise level on one or more of their facade orientations. This creates a problem of providing natural ventilation as any openings in the facade deteriorate the noise level reduction. External noise can be from air, road and rail traffic, and industrial/commercial activities.

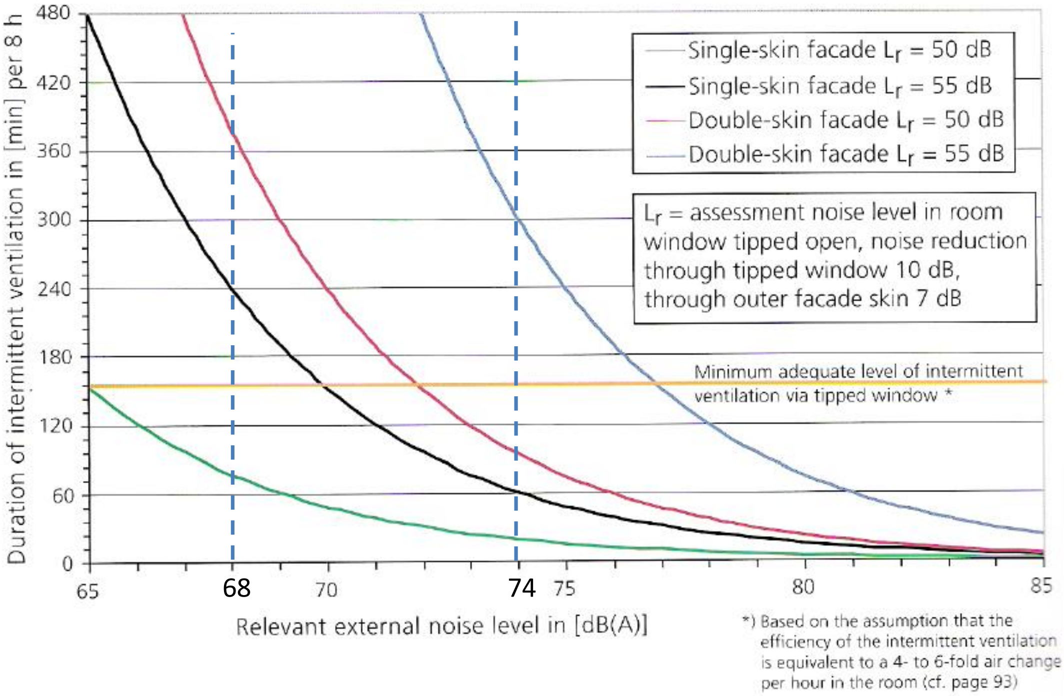


Figure 1.9 Nomogram for resultant noise assessment level in room in relation to duration of ventilation and relevant external noise level. (Heusler et al. 2001, p.40)

[5] The Greater London urban area is not expected to meet the NO_2 compliance by 2025 (even with the low emission zone introduction) and the majority of the urbanised areas will fail to meet compliance by 2015 (DEFRA 2011, p.9). Further initiatives may be implemented however to bring these dates forward especially since the EU could fine the UK for continuing to exceed agreed air quality standards.

The main ways of reducing airborne noise are by the use of mass to dampen the noise, absorbent materials and providing a more tortuous path for noise penetration. Curtain wall facades, even though thin, have significant sound absorbing potential due to the high density of glass. The challenge is however, how the facade performs when it is opened to permit natural ventilation. A detailed study is shown in Figure 1.9 where the amount of time for ventilation for different facade constructions is given. In an inner city environment the most common situation will be adjacent to a busy road, 68 dBA at 20m (BSI 1999, p.9). The graph shows that a well insulated single skin facade can provide some measure of ventilation at the lower road noise value. At the higher noise level only a double skin facade can provide sufficient ventilation. This provides a strong argument for a double skin facade or 'vented noise screen' to ensure that natural ventilation can be provided in the inner city environment where the majority of office buildings are subject to high levels of road noise.

1.2.5. Visual Comfort

Visual comfort has a relationship with both our physiological and psychological state. Occupants prefer naturally lit space with a view and there is also evidence that daylight has a strong effect on our health and wellbeing (Boyce & Hunter 2003, p.3). In the YouGov survey (YouGov Plc 2008) mentioned earlier, lighting ranked as the most important factor and therefore has an acknowledged value. The measures required to assure good comfort levels in terms of firstly providing a predominantly day lit environment and secondly a well designed artificially lit environment are worth exploring.

The guidance on providing a predominantly day lit environment throughout the year, is an average daylight factor of 5% and a minimum of 2% (SLL 2005). The daylight factor is related to the area of openings, the depth of the room and the reflectance of the surfaces within it. For the office space being designed for, a detailed calculation to provide this daylight factor is given in Chapter 3.

A view from within an office has both positive physiological and psychological effects. The physiological effect includes the ability for occupants to relax and exercise their eye muscles which are normally fixed upon single loci for long durations. The psychological positive effects include motivation and productivity (CIBSE 2004, p.8) and are likely related to the connection with being able to experience the passing of time and the external environment. Research by the National Research Council of Canada (Farley & Veitch 2001) has shown that a view of nature is the most important. CIBSE however (CIBSE 2004, p.10) suggests a view of the horizon is the most important and apply a cosine of importance immediately above and below the horizon level. Studies by Tregenza et al (Tuaycharoen & Tregenza 2007) have conducted a study which amalgamates both of these findings. It suggests that the horizon is preferred first of all, followed by a view of nature. Responding to this requirement without a specific building site would suggest firstly the eye level vista is provided followed by lower level transparency in the lower third to provide a view of nature (assuming there is some greenery at ground level).

In situations where daylight is insufficient, artificial lighting is needed to provide sufficient illuminance on the working plane. Table 1.3 provides the key criteria for providing a well lit task area. However as with thermal conditions, desirable illuminance levels between occupants vary considerably (Halonen and Lehtovaara cited in Veitch 2000, p.214) and individual control will provide greater satisfaction and increase productivity (Simpsons 1990 cited in Veitch 2000, p.215). An additional requirement for a well lit room is the distribution of lighting. The Society of Light and Lighting (SLL 2005, p.16) indicates that, '*To achieve a good luminance balance in a space, the average wall illuminance above the working plane, from both the direct and reflected components, should be at least 50% of the average horizontal illuminance on the working plane. (No one wall should be less than about 30 %.)'* To achieve this requires some form of up-lighting component either by suspended fittings or wall washers.

Table 1.3 Lighting criteria as given by the Society for Light and Lighting (SLL 2005)

Recommended maintained illuminance (lux)	300 for purely screen based work 500 for mainly paper based tasks
Limiting Glare Factor	19
Colour rendering	Ra 80 and above
Uniformity	0.8 over the task area split 400lux task, 100lux general

1.2.6. Comfort and Organisational Productivity

As mentioned through this section a comfortable internal environment is not only related to productivity, but also influences our health, feeling of well-being and comfort. For commercial offices the most compelling reason for providing improved internal environment is however the link with productivity. To provide additional controls and comfort conditions there will be an additional cost and this needs to provide a reasonable payback period for cost conscious clients and developers. The relative importance of rental and staff costs relating to commercial office organisations are shown in Figure 1.10. It can be clearly seen that staff costs make up the majority of occupier costs. The consequence of increased expenditure of initial costs (translated as higher rent/finance terms) and ongoing maintenance costs is therefore justified with only a slight increase in staff productivity. Work done by Rosenfeld (Rosenfeld 1989) for instance mentions that any additional investment in the climate systems of ten percent in a given office situation was justifiable if it produced a productivity increase of only 0.33%. This is derived from an example given where the capital cost of the air conditioning is $\$100/m^2$ per annum, average salary $\$3,000/m^2$ per annum and occupancy of 1 person per $10m^2$. Whilst salaries and rents vary on location and organisation this gives an indication of the relative magnitude of costs involved in office type organisations.

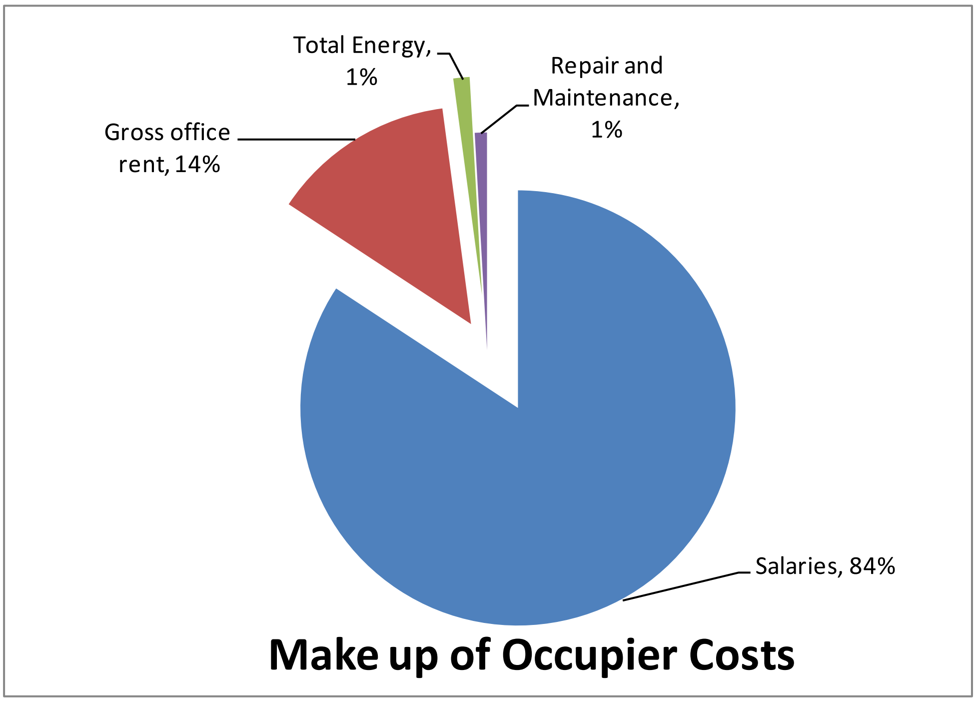


Figure 1.10 Relative importances of costs for a UK commercial office type organisation (Hawken et al in DCLG 2007, p.117)

The productivity loss which can manifest itself from poor indoor air quality and thermal conditions is generally higher than 0.33%. Raw *et al*. (see Mudarri 2000) examining self-reported productivity losses (absenteeism and reduced performance) in the UK collected data that showed about half of the workers in his study reported a loss of productivity of 7% on average due to symptoms related to indoor air quality which amounts to 3% overall when all the workers are considered. Greater productivity losses are given by Wyon (ibid) who shows that within the established comfort zone of 80% satisfied, there is still a reduction in key mental tasks such as arithmetic among the occupants of 5-15%. Existing buildings and buildings being designed today could have extra investment justified in their environmental systems as the productivity benefit is an order of magnitude greater than that required for cost neutrality within a year. The extra investment costs involved with improvements to occupant comfort and the corresponding increase in productivity is therefore worth implementing as it provides an effective and reliable economic advantage. Apart from the internal environment, organisational productivity and the way in which office design can facilitate this has been a topic for research.

A fundamental imperative to office design is to use space in a way that improves productivity. Research into work patterns by DEGW through their examination of office environments and their modes of working identify four principle types of layouts: the hive, cell, den and club (DEGW & BRE 1998). The two most common configurations in the late twentieth century years have been the '*hive'* (open plan) and cell (cellular) where as the 'den' and 'club' seek to provide a mix of spaces for individual and team work. Accommodating these layouts depends on the floor plate design.

DEGW categorise office floor plates into four distinct designs: *atrium, deep central core (15m to* core)*, medium plan* (15m) and *shallow plan (10.5m)*. These different office types suit different working patterns, but in terms of maximum flexibility to cater for each of the different working types the floor plates they identify most as flexible are *medium depth* and *atrium*. Together with the comfort requirements for natural ventilation and daylight penetration, both floor plates are also conducive.

This section has shown that worker productivity is mainly influenced by the internal environment and design guidelines to improving the environment have been provided by reviewing the literature. The influential factors of the internal environment are thermal comfort, air quality, visual comfort and acoustic comfort. Thermal comfort standards have changed over time and depend upon the type of building system: air conditioned or naturally ventilated. The latest research indicates that a mixed-mode solution where natural ventilation is the default and the provision for active cooling, together with personal control is the most beneficial for productivity. Radiant comfort has also been examined because the surface temperature of a highly glazed facade can be quite different to the air temperature and affect comfort. Providing a buffer space in winter and ensuring hot cavity air can escape in summer is one of the solutions and more appealing as it is a passive solution to ensuring radiant comfort.

Ensuring indoor air quality is achieved by providing sufficient outside fresh air and ensuring the air is of a sufficient quality. The rate to be provided has been set at 12l/s/p based on the BCO specification and the quality ensured by providing air filtration. As with thermal comfort, natural ventilation is still preferred, but this means as well as the air quality being satisfactory, a suitable acoustic environment needs to be maintained. The urban environment again creates a challenge for acoustic comfort and two scenarios have been examined, adjacent to a busy road and close to a railway line. A key factor is the design of the facade and the noise reduction provided. It has been shown that a double skin facade can provide much greater opportunities for natural ventilation, when compared to a single skin facade where the office is located adjacent to a busy road.

Providing visual comfort relates to maximising daylight, a controllable and well distributed artificial lighting scheme and a good view outside. The recommended daylight factor is 5%, which will require a calculation to establish the percentage of glazing need. Guidance on artificial lighting has also been provided and includes light levels, distribution and controls. The view out is an important element for visual comfort and a review of studies suggests that a view of the horizon is most preferable, followed by a view of nature.

Apart from the internal environment, productivity can be influenced by the organisational productivity which is influenced by the way in which the space is planned. To provide the flexibility to accommodate different office layouts, medium depth or atrium style floor plates are necessary.

As well as a comfortable environment, employees are also concerned with the 'green credentials' of their employers (YouGov Plc 2008). Employers themselves are also including sustainability as part of their corporate social responsibility agendas and put tremendous effort into making their credentials heard for the positive 'PR' it provides. This reinforces the need to examine sustainability issues related to UK offices.

1.3. SUSTAINABILITY AND UK OFFICES

There has been a growing consensus in recent years that our current model of development is unsustainable economically, socially and environmentally.[6] The development model has relied on cheap and plentiful fossil fuels, but the increased anthropogenic emissions of greenhouse gases associated with their use is changing the climate, providing more extreme weather conditions and raising sea levels across the globe. Without a stabilisation of greenhouse gas levels, the predicted increase in global temperature will cause a whole host of detrimental effects severely limiting the population that can be supported by the planet and reducing our living standards (Parry et al. 2007). The widely publicised Stern review predicted the loss in world GDP, if no action was taken on climate change to be at least 5% per year and that investment in more sustainable technologies now would be cost beneficial for the world, over the long term (Stern 2006).

Apart from the ethical basis for preventing climate change, the UK is no longer self-sufficient in energy needs and became a net energy importer in 2004 (Perry & Rosillo-Calle 2008). It is now exposed to the increasing global demand for energy and uncertainty on oil reserves. The UK government has responded with a raft of government legislation and planning documents to address both climate change and energy security. One of the most important has been the Climate Change Act 2008 (Great Britain 2008) which included legally binding targets for the UK of reductions in greenhouse gas emissions of 34% by 2020 and 80% by 2050 compared to 1990 levels (excluding aviation and shipping). This requires an increase in the supply of electricity generation from low carbon sources and a

[6] Though difficult to quantify, online trend tools indicate an increase in the use of the terms of sustainability from 0.05 to 045 from 1990 to 2010 and the use of corporate social responsibility has grown from close to zero in 2000 to 0.06 in 2006 - a marked increase.

reduction in energy demand. Buildings are responsible for approximately half of all emissions in the UK with commercial offices comprising 17% (Pérez-Lombard et al. 2008). As one of the easier sectors within which to reduce emissions, the UK government has and is progressively tightening Building Regulations Part L2A. How building regulations Part L2A 2006 and future revisions can be met is discussed in the first part of this section. Although wider considerations of sustainability are not legislated for as yet, the voluntary BREEAM (Building Research Establishment Environmental Assessment Methods) for Offices certification route is becoming more popular and will be discussed together in the latter part of this chapter. The first and foremost consideration is however reducing carbon emissions.

1.3.1. Meeting Part L2A 2006 and Future Revisions

Building regulations Part L2A, conservation of fuel and power regulates energy use in new office buildings with the aim of reducing carbon emissions. The fundamental criteria in Part L2A 2006 (DCLG 2006) is to achieve an acceptable building CO_2 emission rate. To show compliance the buildings emission rate cannot exceed the notional building emission rate plus a factor of reduction which will be altered in each successive revision as shown in Figure 1.11. The notional building is defined as a 40% glazed facade which is not representative of office facades, but does provide a challenging energy performance benchmark.

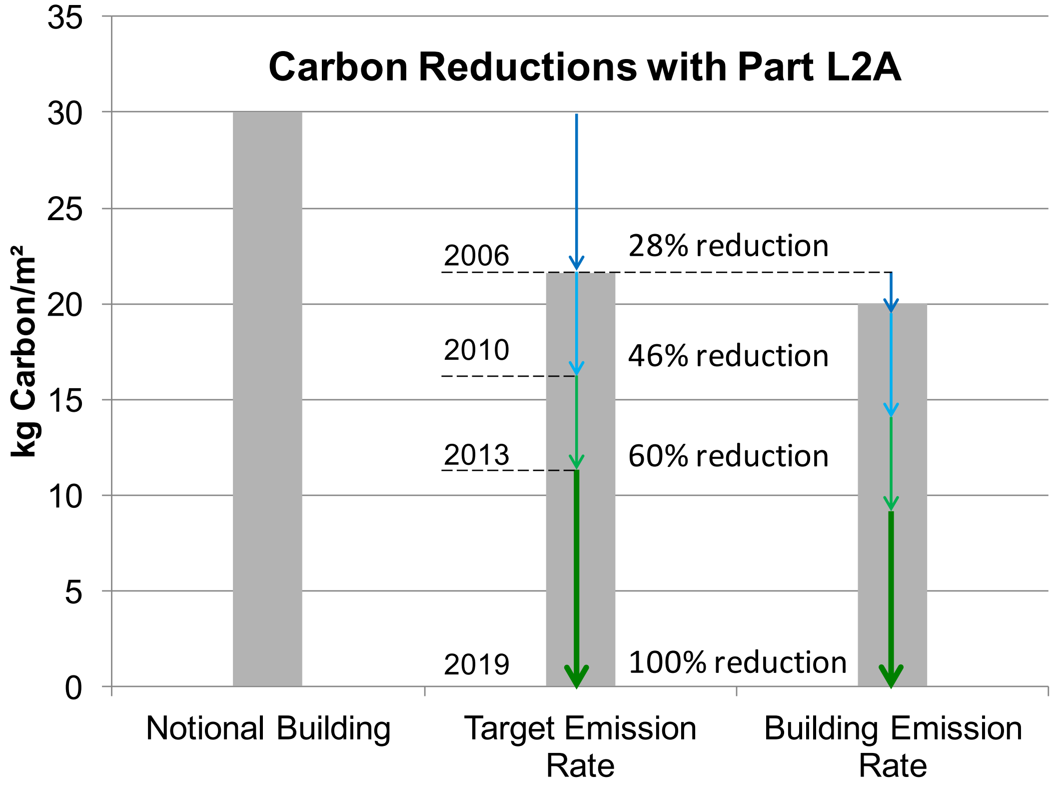


Figure 1.11 Carbon reduction targets for UK commercial buildings based on Part L2A

From Figure 1.11 we can see that the 2006 target emission rate is 25% below the 2002 notional building and in 2010 and 2016 envisaged as 25% and 44% below the 2006 building. The final target is for zero carbon regulated energy by 2018 and 2019 for public sector and commercial office buildings respectively (DCLG 2009a, p.19). The zero carbon target may be abandoned following feasibility studies (DCLG 2009b), but the interim targets remain a major challenge. Energy sustainability has to be embedded right at the start of the design process and followed through. A logical framework to follow through the design process is to begin firstly with the form of the building, then the facade, followed by the building services and then if necessary renewables. The building form will be established within this chapter.

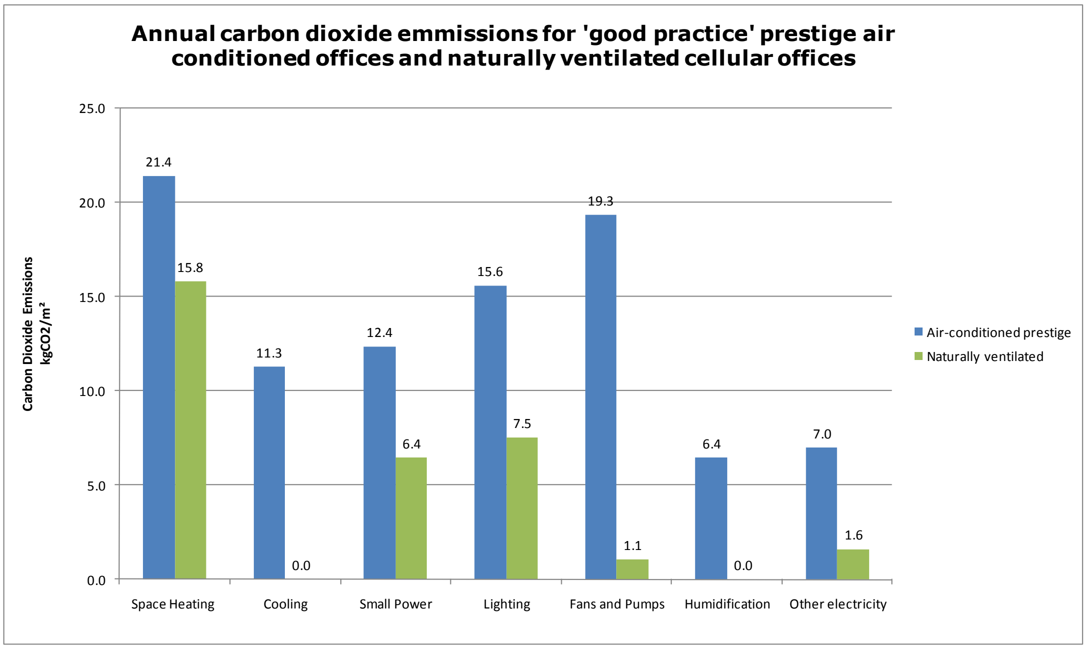


Figure 1.12 Annual carbon dioxide emissions for 'good practice' air conditioned and naturally ventilated cellular offices (Action Energy 1998, p.21)

Building form influences whether the office can be naturally ventilated and the day lighting performance. The energy use for an air-conditioned office and a naturally ventilated office building is shown in Figure 1.12 where we can see that a naturally ventilated building has much lower carbon emissions than an air-conditioned building. In addition lighting energy usage in both office types has high associated carbon emissions. It is therefore important to set the building form to enable natural ventilation and day lighting to dominate. The rule of thumb figure for single side natural ventilation is between 2 and 2.5 the height of the room as shown in Figure 1.13 (CIBSE 2005, p.15). For a 3 metre high room (a typical office ceiling height) the room depth is therefore limited to about 7.5m. This compares favourably to the medium depth office floor plate suggested in Section 1.2.6. Apart from the comfort benefits, providing natural ventilation will also assist in compliance as we can compare a mixed mode office to an air-conditioned office.

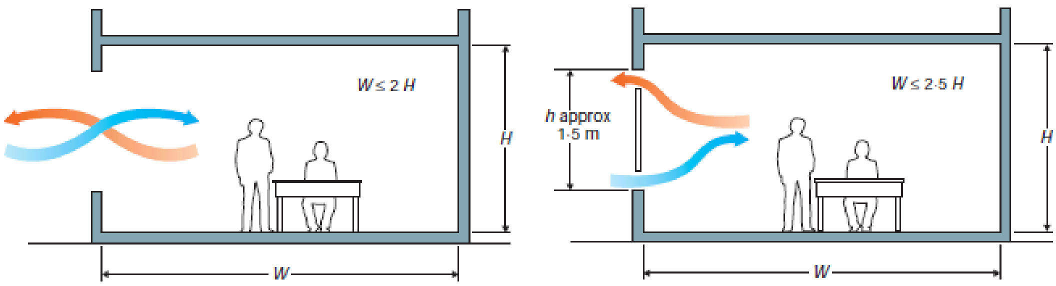


Figure 1.13 Natural ventilation limits (CIBSE 2005, p.15)

The proportion of area that can be day lit is related to the height of the transparent openings and the average reflectance within the room. The relationship is shown in Figure 1.14. For a room depth of 7.5 m (half the floor plate depth for medium plan office) the 3 metre high window needed for natural ventilation is sufficient to allow the room to be naturally day lit. However, further analysis is needed to ensure the 5% daylight factor and uniformity is achieved. This requires greater facade details and is presented in Chapter 3.

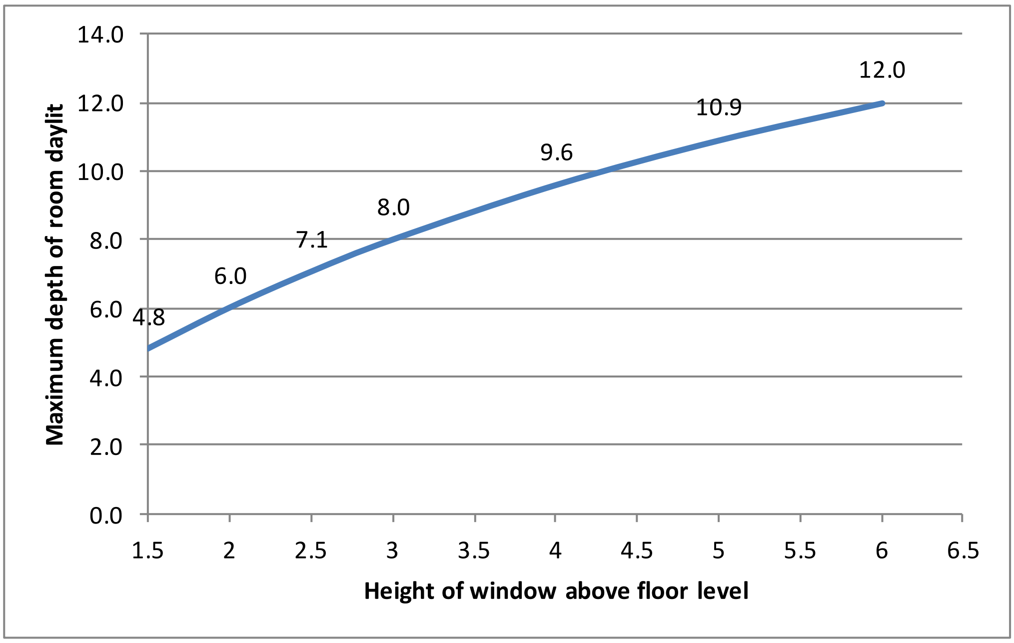


Figure 1.14 Relationship between depth of room and height of window for a daylit environment (CIBSE 1999, p.16)

With a low energy building form established, the facade then becomes the influential factor in reducing the three emission sources of heating, cooling and artificial lighting. The three are however, strongly linked and there is no simple formula for optimisation whilst including for comfort requirements. A more detailed and thorough analysis of facade technology and options for comfort and carbon performance is need and will be provided in Chapters 2 and 3. With the demand reduced as far as practical within the constraints of comfort and technology, the active environmental system then becomes the focus of attention.

An active environmental system can reduce carbon emissions by reducing the demand, reducing the carbon intensity of the heating and cooling sources and the energy used in the distribution and delivery. Office areas are normally conditioned regardless of whether they are occupied or not. Since offices are rarely fully occupied, a reduction of energy demand can be achieved by only servicing those areas which are occupied. This requires improved zoning and controls. The carbon intensity of the heating and cooling sources can be reduced by using alternative supply technologies such as biomass heating or ground source heating. Finally the distribution and delivery by fans and pumps for heating, cooling and fresh air delivery produces significant quantities of carbon emissions as shown in Figure 1.12. This is a consequence of the centralised generation strategy and overcoming the resistance of long service runs. Providing a more localised source for these services could reduce the energy needed and carbon expended. Improved zoning and controls, low carbon sources for heating and cooling and localised generation options are therefore discussed further in Chapter 2.

1.3.2. Embodied Energy Consideration

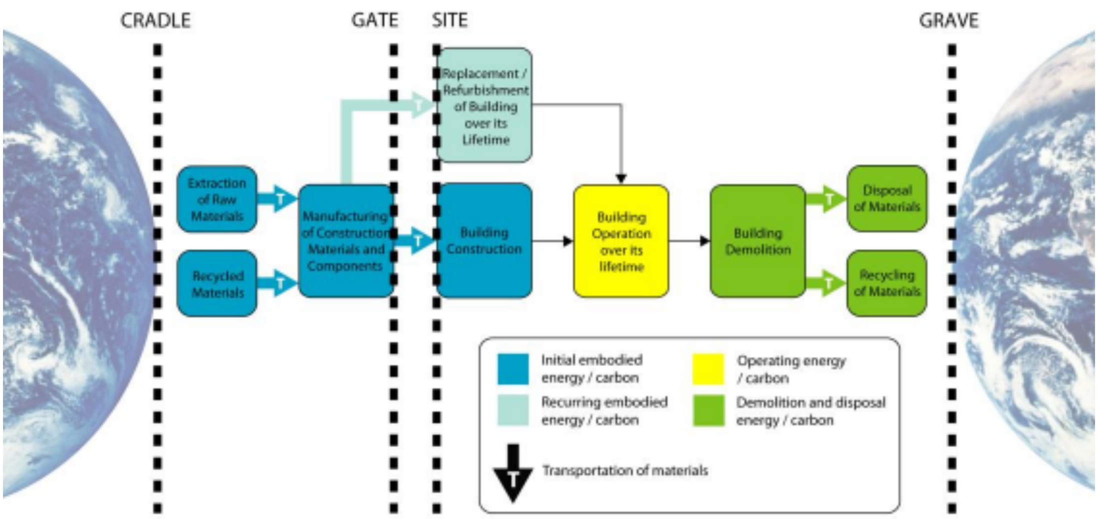


Figure 1.15 Distribution of embodied energy and carbon throughout a buildings lifecycle (Oldfield 2010)

Part L2A focuses only on reducing the energy / carbon of the building's operation over its lifetime, but energy is used and carbon emitted throughout the entire life of the building from the extraction of the raw materials, the processing of those materials into components, the construction of the building and the final demolition as shown in Figure 1.15 .

No legislation exists concerning regulation of any other stage of a building's lifetime. An estimate of the carbon footprint of UK construction in 2007 by the

UK Department for Business, Innovation and Skills has estimated the carbon footprint of UK construction and is shown in Figure 1.16.

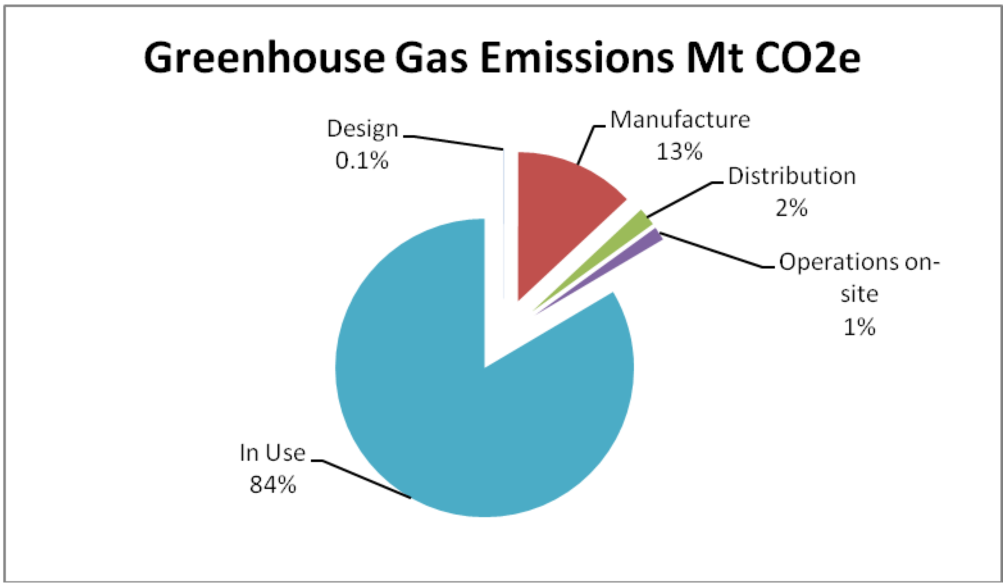


Figure 1.16 Carbon footprint of the UK construction industry by sector (BIS 2010, p.11)

This clearly puts the emphasis on reducing in-use emissions for current buildings, but as buildings approach zero carbon 'in use' the manufacture of materials and their embodied energy will need to be reduced if further meaningful progress is to be made on the reduction of carbon emissions and energy usage in the UK. The emphasis at present though is to reduce the in-use emissions. Where embodied energy is included is within more holistic assessment methods such as the Building Research Establishment Environmental Assessment Method (BREEAM) certification process.

1.3.3. BREEAM Assessment Method for Offices and Beyond

Organisations can demonstrate their commitment to sustainability via an environmental accreditation scheme such as BREEAM for Offices (BRE 2008), created by the Building Research Establishment (BRE). This is an environmental assessment method for buildings and has ten distinct categories in the 'BREEAM for Offices' version. The reasons for adopting BREEAM include easier approval of planning permission, a demonstration of corporate social responsibility and a commitment to quality. The ten categories are management, health and well-being, energy, water, materials, land use and ecology, transport, pollution and innovation. By addressing the various issues buildings are scored and given ratings from uncertified at the lowest end through to 'excellent' and in the 2008 version, 'outstanding' at the top end. Those issues of most relevance to the facade and environmental system are shown in Table 1.4 and will be kept in mind during the design process and revisited once the design has been progressed further.

Table 1.4 BREEAM categories and issues within the scope of the facade and environmental system (further information given in Appendix B)

MANAGEMENT	**WASTE**	**HEALTH AND WELLBEING**
Commissioning	Construction waste	Daylight Occupant thermal comfort Acoustics Indoor air and water quality Lighting
POLLUTION	**ENERGY**	**MATERIALS**
Refrigerant use and leakage NOx emissions	CO2 emissions Low or zero carbon technologies Energy sub metering Energy efficient buildings systems	Embodied life cycle impact of materials Material re-use Responsible sourcing Robustness

1.3.4. Economics of Sustainable Design

The separation of the building developer from the occupant in the developer model gives rise to a conflict of demands and requirements. Economic sustainability for an occupier relies upon the retention of employees, minimisation of churn, worker productivity and comfort, and having floor plans which enable new modes of working. They have been addressed in earlier sections and point towards medium depth floor plates and more sophisticated services and facade design. The extra investment cost would be quickly recouped from improved productivity, and owner-occupier offices can feel the direct benefits of increased expenditure through the attracting and retaining high calibre staff, reducing churn and subliminally transmitting a positive corporate social responsibility message. For commercial developers however, who are divorced from the operation and in use performance these benefits are not felt.

Developers are funded by venture capitalists and shareholders who are primarily concerned with the best return on their investment over the short term. This is usually achieved by maximising the total rentable area to plot area, net to gross floor area and floor area to facade area, together with low risk solutions to the overall construction system. This has meant deep plan offices that provide a greater floor area to facade area ratio, increased numbers of floors for greater net floor area to plot area ratio and a relatively simple facade treatment for a low risk form of construction. If we are to avoid ever greater levels of legislation to bring about improvements in comfort and sustainability, developers need to be provided with a financial incentive to build more comfortable and sustainable buildings.

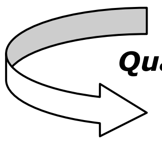
The key issue for developers is whether more comfortable and sustainable buildings are financially viable to support and build. There are some indicators showing that more sustainable and productive workspaces can attract higher rents and higher sale values in the U.S. (Miller et al. 2007). Evidence from the UK shows an emerging interest, but no hard evidence that it contributes to market value (Dixon et al. 2009). Just as sustainability performance and comfort requirements overlap in certain areas, e.g. daylight, a question worth exploring is whether capital cost of the increased cost per m^2 of floor area, with a shallower plan floor plate and risk, can be ameliorated in some way. This could be achieved through designing out superfluous components, improving floor area ratios whilst also addressing issues of sustainability and improved comfort conditions in the same way the adoption of double glazing improved comfort, reduced carbon emissions and reduced heating plant space and expenditure requirements.

There is an urgent need to reduce the carbon emissions of offices and this is being legislated through Part L2A. A key criterion is reducing the carbon emissions below the target emission rate which will be reduced over the next ten years to zero regulated energy. This is a major challenge and has to be embedded in all areas of the office design. A fundamental design decision is the room depth that can allow natural ventilation and be predominantly day lit which has been identified as 7.5m and provides a 15 m deep floor plate overall when lit and ventilated from both sides. This concurs with floor plate flexibility requirements identified in Section 1.2. Further improvements can now focus on the facade and environmental system which will be discussed in Chapter 2.

Carbon is emitted at all stages of a building's lifecycle, with operational energy being the major contributor followed by embodied energy. Although not a constraint yet, embodied energy will need to be considered once further reductions in carbon emissions are achieved as it will become a major contributor. Embodied energy is considered under BREEAM assessments. This widens the scope of sustainability performance and is increasingly being used to provide enhanced 'PR' for organisations. Once the design has been finalised it should be assessed to ensure that it allows a high score to be achieved.

To provide a sustainable office, there is the challenge of addressing the mindset of developers where reducing investment cost and ensuring low risk are the most important factors. This will need to be addressed by improving the design and construction process so that cost saving can be made elsewhere whilst providing improved comfort conditions and reduced carbon emissions.

1.4. DESIGN AND CONSTRUCTION CHALLENGES



Q x S = C x T

Quality Scope   Cost Time

Q x S > C x T

The new client mandate, more for less.

(Kieran & Timberlake 2004, p.10)

The production of Ford's 'Model T' in 1908 brought about a step change in the production of motor vehicles with the use of standardisation and assembly line production techniques, making it the most influential car ever built. One hundred years later the car industry has completely revolutionised its construction process from the original Ford single assembly line piece by piece approach, towards a modular approach. The car industry has also become much more supply side orientated in its product offering than the original Model T's 'any colour as long as it's black' choice. Customers can choose from different body styles, colours, engines, body trims and options; the VW Golf for instance is available in almost two million different variations (Pil & Holweg 2004, p.395).

Yet the industrial production methods used continue to deliver lower costs, reduced design and construction time, together with improved quality and performance. The old paradigm of having to sacrifice quality or scope for the sake of cost or time for manufacture has been overcome, but how?

In '*refabricating Architecture'* (Kieran & Timberlake 2004, pp.16-18) the architectural practice 'Kieran-Timberlake' examine the manufacturing process of cars and contrast this with building construction. The current design and delivery methods of the automobile manufacturer Daimler/Chrysler the *OEM* (original equipment manufacturer), in common with many other manufacturers, no longer use a linear process of additive parts along the assembly line, but modules and sub-assemblies which can be designed and produced concurrently. These modules or sub assemblies are drawn from outside manufacturers such as Delphi, who can concentrate on their particular assembly and ensure it is of sufficient quality and timely in its delivery. Other suppliers can also concurrently design and fabricate their own components instead of waiting for a preceding component to be ready. Direct links between the suppliers and OEM ensure coordination in spatial and temporal terms. Thus both the quality, scope and timeliness production of a car is improved and cost is reduced or maintained at a similar level by chunking the assembly process. This is common through the automobile industry and includes UK manufacturers such as Jaguar (see Figure 1.17). Building construction is still however, following the single craft model being used at the start of the twentieth century and trapped in the 'cost x quality = time x money' paradigm. The lagging performance of the building industry has not gone unchallenged or unnoticed.

Figure 1.17 Jaguar XF stats. Picture www.jaguar.com, data: (White 2010)

Jean Prouve (1901 – 1984) like many of the early modernists, observing the great progress during his early years not only in cars, but space rockets, air craft, motorcycles and trains sought to implement industrialised methods of manufacture into architecture. Through his integrated teams of engineers, architects and technicians he was able to unite the 'mind and hand' across an organisation, and designed prefabricated integrated buildings (Figure 1.18). Jean Prouve's thinking did not however, blossom through the industry because of in his opinion, a lack of understanding of industrialised methods of manufacture from businessmen (Prouvé 1971, p.20) which ultimately left him no choice, but to leave the running of his Maxeville factory to the financial backer, Aluminium Francais. For Prouve, the main obstacle preventing architecture from progressing in a similar way to industrial production in other fields was the fragmented nature of the building process and the separation of design from realisation. Towards the end of the twentieth century the situation in the UK was much the same.

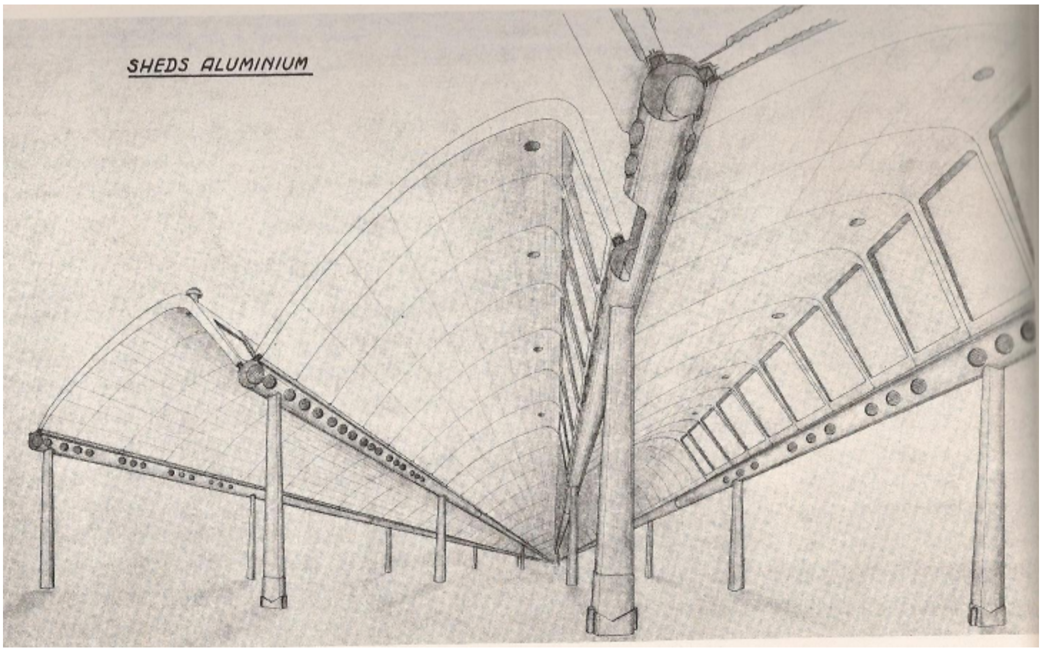


Figure 1.18 Sketch for entirely prefabricated factory with air-conditioning by Jean Prouve, n.d (Prouvé 1971, p.46)

The Latham report (Latham 1994) highlighted the poor levels of profitability and dissatisfaction amongst clients and consumers with the UK construction industry, namely over high levels of uncertainty over timely delivery, budget and to the standards of quality expected. Productivity and performance needed to be significantly improved. The Egan report, (1998) '*Rethinking Construction*', reiterated the poor performance of the construction industry and provided a number of recommendations to realise improvements which include:

- Partnering to provide longer term relationships
- Pre-assembly and standardisation and lean production techniques

Partnering may help reunite ‘the mind and hand’, but standardisation, along with the ideals regarding ‘authorship’ was noted by Colin Davies (C. Davies 2005) as two of the main reasons for the slow uptake of industrialised methods. Advances in technology stemming from lean production techniques, as mentioned earlier mean that standardisation has already given way to ‘mass customisation’. Software is available for instance which can rationalise a building envelope into sizes which are within manufacturable limits and it is then only a case of sending the appropriate CAD/CAM file to the machine for a different panel. The number of units necessary depends on the manufacturing process; that of precast concrete is shown in Figure 1.19, but in any case affords the designer much flexibility. The consequence of this as Michael Stacey notes is ‘*The architect, once a remote fabricator, can now directly control the manufacturing process. Digital design and delivery can transform the working relationships in the making of architecture, placing the architect at the centre of this creative process.’* (Stacey 2007, pp.212-213) Shared BIM (Building Information Model) is also part of the technological solution as different organisations can more easily collaborate and work from the same model facilitating the partnering process and lean production techniques. Current technology and manufacturing processes can therefore overcome the impediments to industrialised methods of manufacture encountered over the last century. Tackling the entire building however is too great in scope. To which parts of building construction is the application of prefabrication then most beneficial?

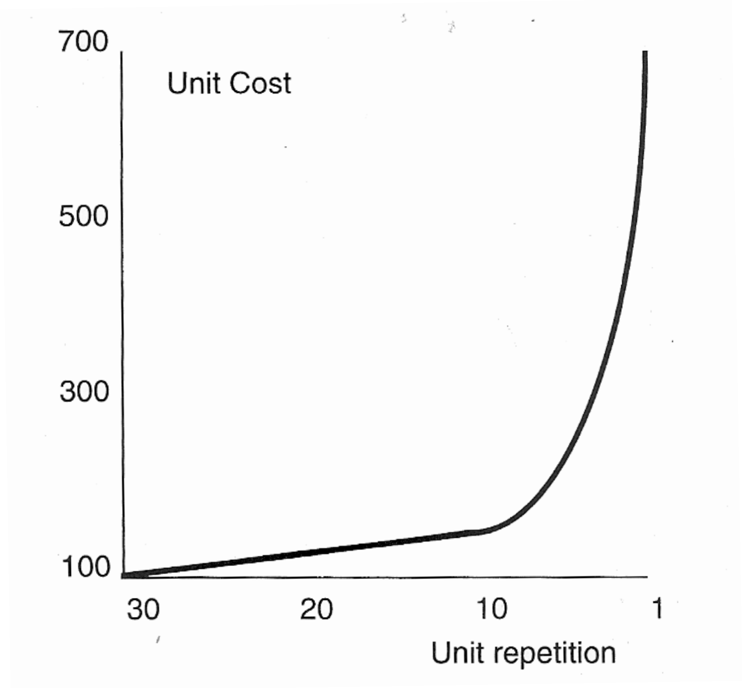


Figure 1.19 Relationship between unit cost and unit repetition for precast concrete cladding (Gibb 1999, p.1.1). After ten units, cost savings are only marginally improved.

An office building can be divided up into the following packages:

- Substructure (e.g. foundations)
- Frame (e.g. primary structure)
- Envelope (e.g. curtain wall facade)
- Services (e.g. HVAC, BMS, telecoms, IT)
- Internal Works (e.g. partitions, ceilings)
- Facilities (e.g. elevators, toilets)

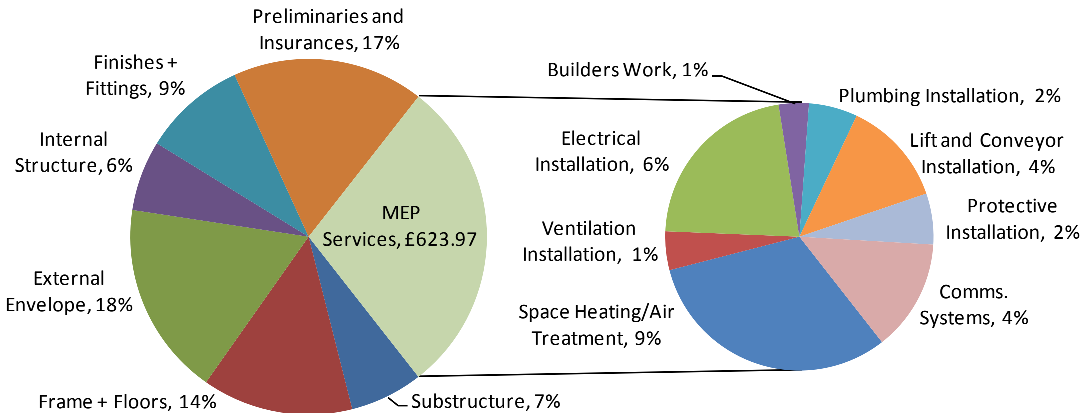


Figure 1.20 Cost model for the different packages in an office development (Parker & Jones 2011)

The building facade is already quite advanced in terms of its product offering with the wide availability of unitised and panellised systems. The advantages inherent in prefabrication are that the facade has a greater repetition in elements, is normally based on a common grid size and the supply chain is well integrated particularly with the larger curtain wall companies who can provide design services, manufacture, fabrication and installation as a complete package. The large volume of extruded profiles needed for a single project mean there is considerable flexibility to provide bespoke profiles and satisfy specific project costs, since the die only adds a small additional cost. The use of prefabricated unitised facades are generally only used on constricted inner city sites, or high rise buildings where time issues are critical. The obstacles to their wider application are connected with their longer lead time than the conventional stick systems and hence flexibility to changes in construction programme. They also attract a cost premium simply because of the increased quantities of material necessary for structural rigidity. Their application therefore depends on the circumstances; for the typology considered of inner city sites prefabricated facades are the best solution and a well established supply chain and technology already exists. Apart from the facade, a significant portion of the build cost as well as time duration is also related to the building services installation (Figures 1.20 and 1.21).

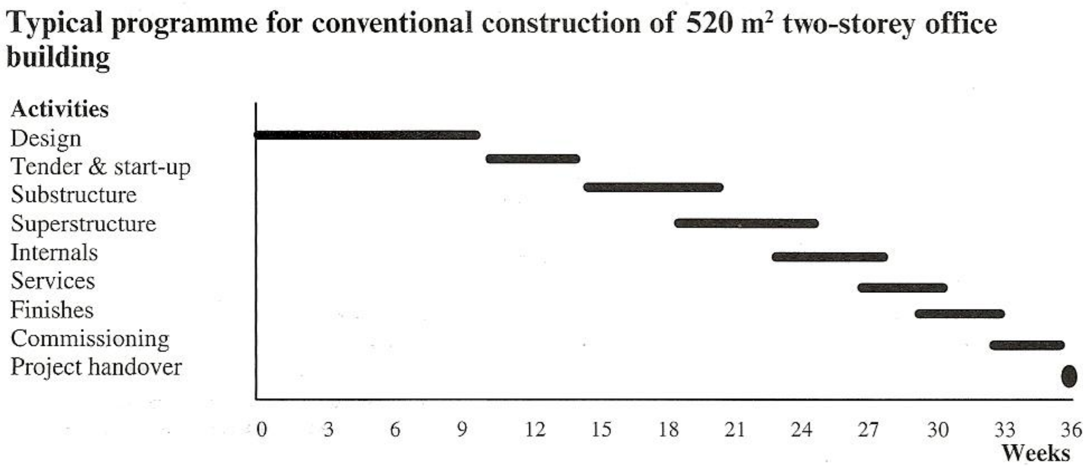


Figure 1.21 Construction programme – prefabricated services will shorten both the services, finishes and commissioning activities (Gibb 1999, p.2.2)

Prefabrication is most developed for the main structure and the facade as these are crucial in terms of the overall programme, have greater repetition and have traditionally been higher in cost. Building services however have grown and now comprise a large portion of the build costs and have a significant duration of the overall programme. In addition the second most important benefit considered by clients of prefabrication is the reduction of multi-trade interfaces (Blismas et al.

2006) and building services involve more trades than possibly any other package. As the least industrialised part of construction, significant cost and time saving potential together with improvements in quality have been identified with the introduction of prefabrication (Hawkins 2000). It may also assist in increasing usable space.

Usable space is as important in cars, as it is in buildings. Car manufacturers frequently use their boot capacity and leg room as one of their unique selling points. For developers as mentioned in Section 1.3 achieving certain gross to net floor area ratios and external wall to net floor area ratios are just as important for them for reasons of profitability rather than utility. The most space consuming portion of building services is the space conditioning. This can require 500mm of ceiling void and 8% of the gross internal floor area (Hawkins 2000, pp.30-31). Integrating this section of building services into prefabricated modules and providing space savings could therefore provide a significant cost benefit to clients. Cost savings, time saving, improved quality and space savings beg the question as to why building services are not more widely prefabricated?

The reasons behind the low level of prefabrication could be related to the historically low cost of building services, the design process, low repetition and a view that it is more expensive. The design process inhibits prefabrication of building services as they are usually fixed at a late stage and this does not provide the designers and the many different trades time to coordinate details and interfaces sufficiently to provide an integrated solution. This is further impeded by higher complexity and variety inherent in internal distribution where many different services compete for space and in different areas. The cost issue is one of some debate as like for like costs are not a fair assessment as they do not include the shortened construction duration. With the space saving potential of an integrated solution this could be used as a basis for the extra investment. Therefore providing a predesigned solution which can adapt to different building layouts easily has a degree of repetition and can achieve space savings, the barriers to implementation could be overcome.

The construction industry lags behind other industries such as the car industry in its manufacturing methodology and overall performance. The car industry provides ever greater quality and performance with reduced time and cost through lean manufacturing and concurrent engineering. The construction industry needs to achieve similar performance improvements and could do so by adopting similar methodologies. Building services could benefit greatly as it has a low level of industrialisation, comprises the lion’s share of cost, occupies a significant proportion of the construction schedule and takes up a significant amount of space. Exploring a prefabricated building services solution which includes the space conditioning, is a necessary step in addressing the cost and quality paradigm still being faced in building construction.

CONCLUSIONS

This chapter has provided the background to office development and an overview of the different challenges in the design and construction of UK offices. The modern office in the industrial era has developed mainly on the basis of improving economic efficiency for developers with the exception of owner occupier buildings. For developer led buildings where net to gross ratios are most important the results have been deep plan, high rise, fully sealed, air conditioned and artificially lit offices. Whilst being economic to build they do not achieve high occupant comfort standards nor are they suited to providing lower energy usage / carbon emissions required by forthcoming building regulations due to their over-reliance on energy consuming artificial environmental systems.

Instead, building form, the facade and the building services need to be designed on the basis of occupant comfort and lowering energy usage. This constrains the floor plan first of all to less than 15m wall to wall considering a 3m floor to floor height. The preference for a predominantly day lit environment and natural ventilation for comfort, together with the selection of an inner city high rise typology, requires a detailed examination of facade design as this is a difficult typology to provide comfort for, but is nevertheless an important one.

With the facade providing the internal environment for as wide a range of external environments as possible, artificial environmental systems then need to continue in the same vain; ensuring optimum comfort levels, lowered energy usage and carbon emissions. For improved comfort levels the system should be based on a mixed-mode system together with greater personal control. The link between improved comfort and improved productivity shows that if extra investment is needed there is still a net economic benefit to an organisation. As well as changes to the building form and facade, the environmental system also needs to be improved upon to achieve the reduction in carbon emissions necessary for compliance. Within the system each energy consuming and carbon emitting portion needs to be examined; the heating, the cooling, lighting and use of fans and pumps for the distribution of distribution of heating and cooling stands out.

Building services also stand out as being ripe for improvements to the way they are installed on site. The construction process has been accused of being lacking in terms of quality, performance, cost and timekeeping. Contrasts with the automobile industry have illustrated how backward construction still is and has shown there is great potential for improvement through greater levels of prefabrication, modularisation and integrated design. Although building services have both a significant cost and time duration they are not prefabricated widely. Adopting a prefabricated solution therefore has significant potential to reduce costs, improving quality and timeliness and could provide greater space efficiencies which would be very appealing to developers. Those which most influence comfort, sustainability and space requirements are those pertaining to the environmental system, heating, cooling, fresh air and artificial lighting. They should therefore be focussed upon initially.

Providing enhanced comfort, reducing energy usage/carbon emissions and utilising prefabrication methods is a challenging, but appealing design brief for a facade and building services component in many ways. Facade and building services technology now need to be reviewed to underpin the feasibility of such a component. A component which will defy current conventions in construction and satisfy the new client mandate; provide more for less.

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CHAPTER 2

ACTIVE ENVIRONMENTAL SYSTEMS AND FACADES: REVIEW AND FURTHER DEVELOPMENT

'A generation of double skin facades evolved that with its four main variants…was no longer merely a building envelope, but rather an integral part of the building's climate design by integrating climatic concepts … the next step - the integration of building services into the facade – seems logical, maybe even mandatory.' (Knaack, 2009)

There are a wide range of technologies for the building envelope and the active environmental system. To provide improved occupant comfort, greater prefabrication and lower carbon emissions, both areas need to be explored, and solutions or possible design routes proposed in order to synthesize the different requirements with technologies. Chapter 1 demonstrated the benefits of increasing the prefabrication level of the active environmental system. This chapter will explore the various strategies and technologies available to increase prefabrication as well as occupant comfort and low carbon emissions. The different technologies available for a highly glazed building facade will also be examined based on similar requirements. A suitable research and design methodology will then be developed to translate these requirements and technological solutions into a component.

2.1 STRATEGY AND TECHNOLOGY OPTIONS FOR A PREFABRICATED ACTIVE ENVIRONMENTAL SYSTEM

There are a number of different active environmental systems strategies available; what is needed in this thesis is a solution which facilitates greater levels of prefabrication, whilst providing space saving, ensuring comfort and reduced carbon emissions. The system could be considered to include heating, cooling, fresh air and lighting. Since artificial lighting requires little in the way of site work, the focus at this stage of development is on the air conditioning system.

A greater level of prefabrication is facilitated by repetition, manageable sizes and weight and controlled multi-trade interfaces. To make the prefabricated component applicable to more than one project, it should also be adaptable to different building layouts. This section will therefore explore strategies and technologies that can achieve the product requirements beginning with the distribution strategy.

2.1.1 Distribution Strategies for Environmental Systems

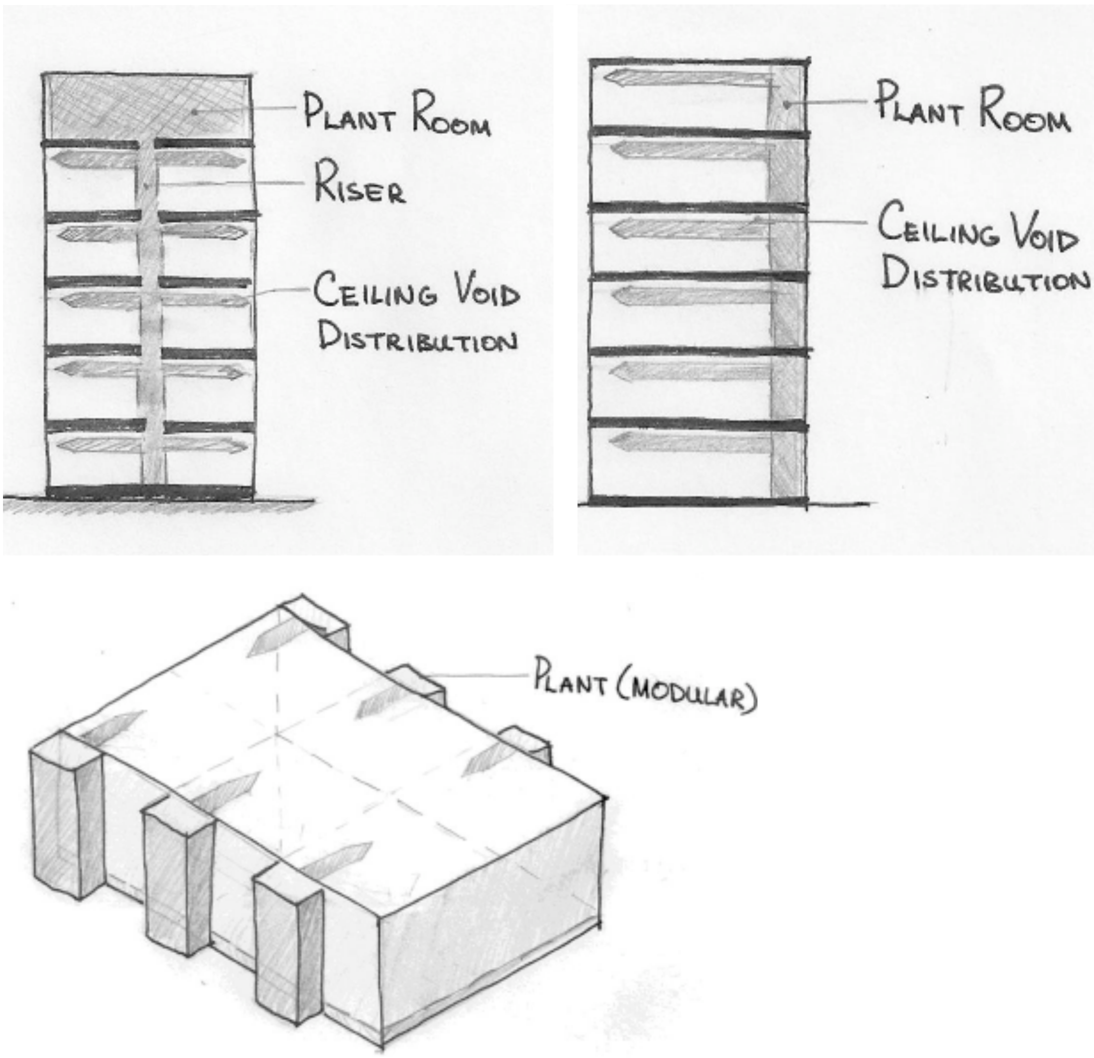


Figure 2.1 Distribution strategies for air-conditioning; centralised (top left), floor by floor (top right) and zone by zone (bottom left)

The environmental services supplied from a centralised location and distributed to each zone are typically heating, cooling and fresh air. However, there are alternatives which include floor by floor servicing and distributed zonal servicing (Figure 2.1). Each has a different potential for prefabrication, the level being dependent on a number of factors including design process implications, space saving, weight, assembly, size of components, accuracy of coordination information and repetition.

A centralised solution typically consists of a large plant room with gas boilers for heating, chillers for cooling and air handling units for fresh air, which is then distributed through risers and ceiling voids to be connected to fan coil units and radiators in the office space. In centralised systems the major components, air handling units, chillers and boilers are prefabricated and simply positioned into place on site. The connections and distributions however, are generally done on site due to the lengths and complexity of distribution routes navigating past down-stand beams, shear walls and being squeezed into risers and ceiling voids without bulging into view. Coordination issues frequently occur due the number of interfaces between different disciplines and late changes in the design which are not communicated through the design team. With large components, little repetition in distribution routes from building to building and late design 'fixity' a high level of prefabrication is difficult to provide with a centralised solution.

A floor by floor solution is where a small plant room is located on each floor to supply heating, cooling and fresh air. This no longer requires risers for vertical distribution, regaining space from risers. The plant room on each floor is smaller increasing the potential for prefabrication there and the distribution routes on each floor should be similar improving the scope for prefabrication. This still has the problem though of navigating through the ceiling void on each floor, avoiding structural beams, designing according to the floor plan and needing large components for distribution.

Zone by zone or a fully decentralised system avoids the need for a plantroom completely; instead a local independent unit for each zone with an individual supply of ventilation and heating and cooling is provided. This solution requires neither vertical nor horizontal distribution; space is therefore reclaimed from risers and ceiling voids as well as the plantroom. With no internal distribution needed the design then becomes independent from the floor plan and internal layout and only dependant on the facade. This omits the need to coordinate with the disciplines involved with the internal space layout (structural engineers, architects, other services) who normally fix the design quite late in the design process. The only coordination needed is with the facade which is fixed earlier in the design process, has a high repetition as well as having an established prefabrication technology and supply chains which could be utilised. Being out of the way of the competing internal trades also reduces the likelihood of remedial work.

From the perspective of space saving and prefabrication potential the most appealing option is the fully decentralised option. Changing to this strategy however has wider implications on other areas of the building design and need to be examined. Those of particular interest to this project include:

- aesthetics
- space savings
- capital cost
- comfort
- carbon emissions

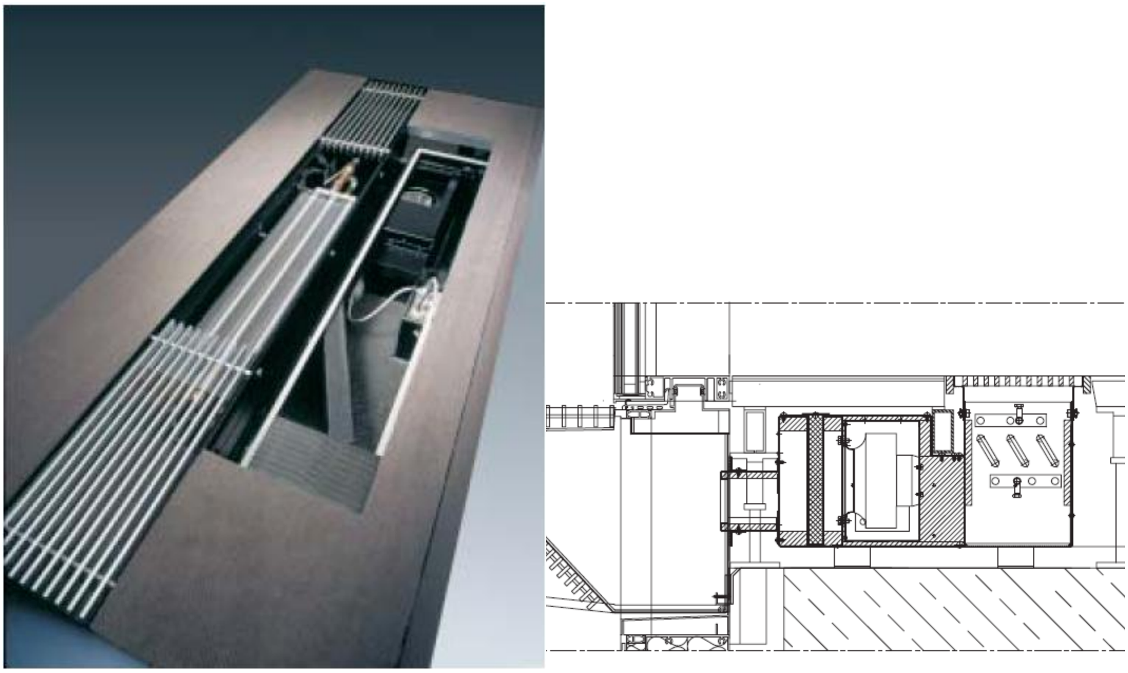


Figure 2.2 Trox FSL decentralised unit as used on the Deutsche Post Tower Bonn (FSL 2002, pp.2,4)

The aesthetic impact of a centralised system is already well accepted and developed. Louvre areas from different air handling units can be combined, the number of exhaust flues can be minimised and chillers and cooling towers be provided with some form of screen. A decentralised system will require a large number of individual louvres and free area over the entire facade and will therefore create a much different aesthetic. If the system can be restricted to use the spandrel zone only and detailed well, any negative impact on the facade could be avoided.

In terms of costs, the space requirement between a centralised and fully decentralised is significant. If we consider that a decentralised system utilises the surplus space within the spandrel zone and floor void, there are space savings to be made in a number of areas including the plant rooms, risers and the floor to ceiling heights. The space required in a centralised system plant room for the boilers and chillers together with risers for ducts and pipes has been calculated at 3.6%- 7.3% of the gross floor area (Pennycook 2003, pp.2-3) a large proportion of which can be converted to usable floor area, since servicing for other uses such as toilets and kitchens will still be required. The floor to ceiling height includes a suspended ceiling to hide the building services, but in a decentralised system this can be largely omitted. Table 2.1 illustrates the potential change in floor to floor height of 0.45m[1] without affecting the room height.

Table 2.1 Floor to floor make up comparison between centralised and decentralised system

	Centralised System	**Decentralised System**
Room Height	2.6m	2.6m
Ceiling Void	450mm	None
Slab Thickness	300mm	300mm
Floor Void	200mm	200mm
Slab to Slab Height	**3.55m**	**3.10m**

The changes in floor to floor height have significant space and therefore cost implications especially for high rises. The figures in Table 2.1 have been used to calculate the height of a thirty floor building as shown in Figure 2.3. Using a decentralised system for the same number of floors, the height can be reduced. Assuming build costs increase linearly with height and a thirty floor building would give a cost saving of 13% based on floor to floor height reduction alone. Alternatively a greater number of floors can be provided to increase the lettable floor area. There is therefore potential for a decentralised system to reduce costs through elimination of the suspended ceiling, but we need to also consider the additional costs.

[1] Areas such as bathrooms which would be every floor could accommodate services with a reduced floor to ceiling height and not affect the floor to floor height reduction. Kitchens may affect the floor to floor height due to larger air flow rates, but would not be on every floor.

The two additional costs would be the decentralised unit and the maintenance cost. In a centralised system a single unit is much more cost effective than multiple numbers of units. Minimising the complexity and installation costs of the decentralised unit is the main factor in reducing this disparity. The maintenance costs depending on the unit itself may be comparable. For the Trox FSL unit, a decentralised heating, cooling and fresh air delivery unit, the maintenance costs were shown to be similar to a centralised system (Franzke et al. 2003). This is due to the increased maintenance cost of the additional air filters and heat exchanger, being offset by the elimination of cleaning the distribution ductwork and annual fire damper inspections. If a heating and cooling source is part of the decentralised system, the maintenance cost may increase depending on the technology used. The cost is therefore strongly dependant on the technology and type of decentralised system used.

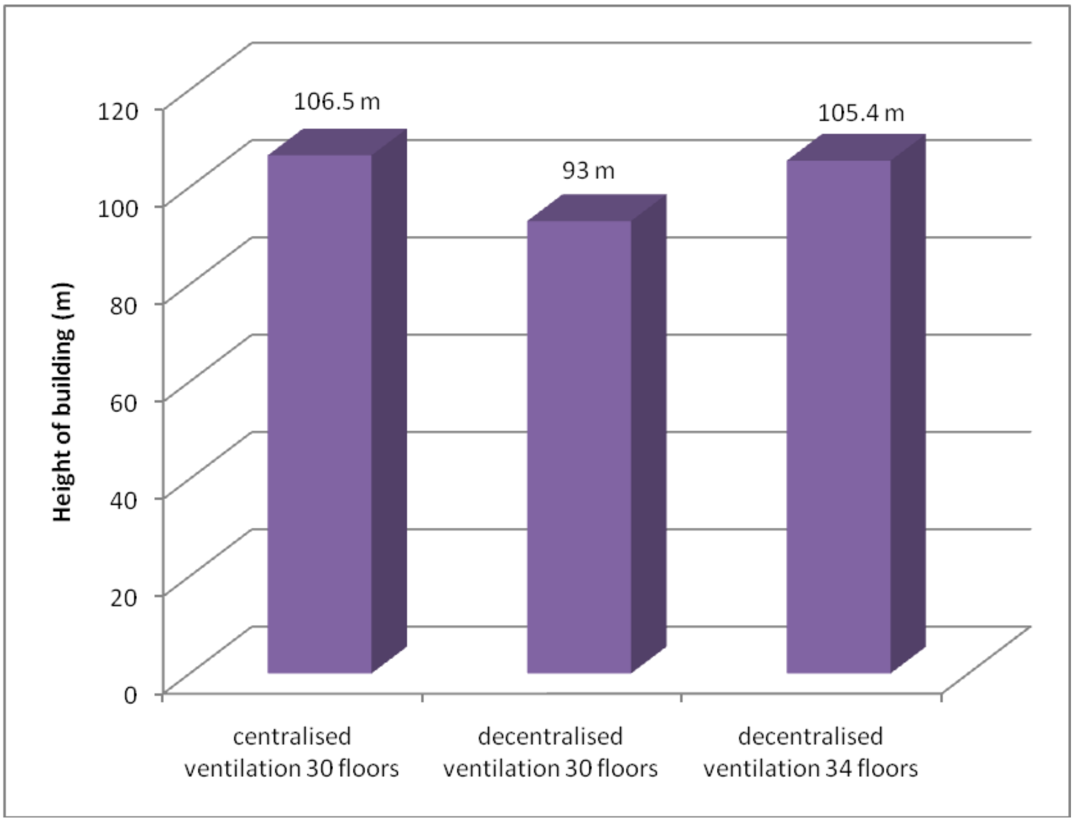


Figure 2.3 Height of a building with decentralised air conditioning compared with centralised air conditioning and distribution (Franzke et al. 2003)

The comfort requirements outlined in Chapter 1 included greater individual control of temperature and ensuring high indoor air quality. For both types of systems individual control of environmental conditions is possible. In regards to air quality, the decentralised system would benefit from being cleaned more easily, but in certain environments where one facade has polluted air, a centralised system would be a better choice as air could be drawn in from a 'cleaner' facade. The differences in energy usage between the two systems are more pronounced.

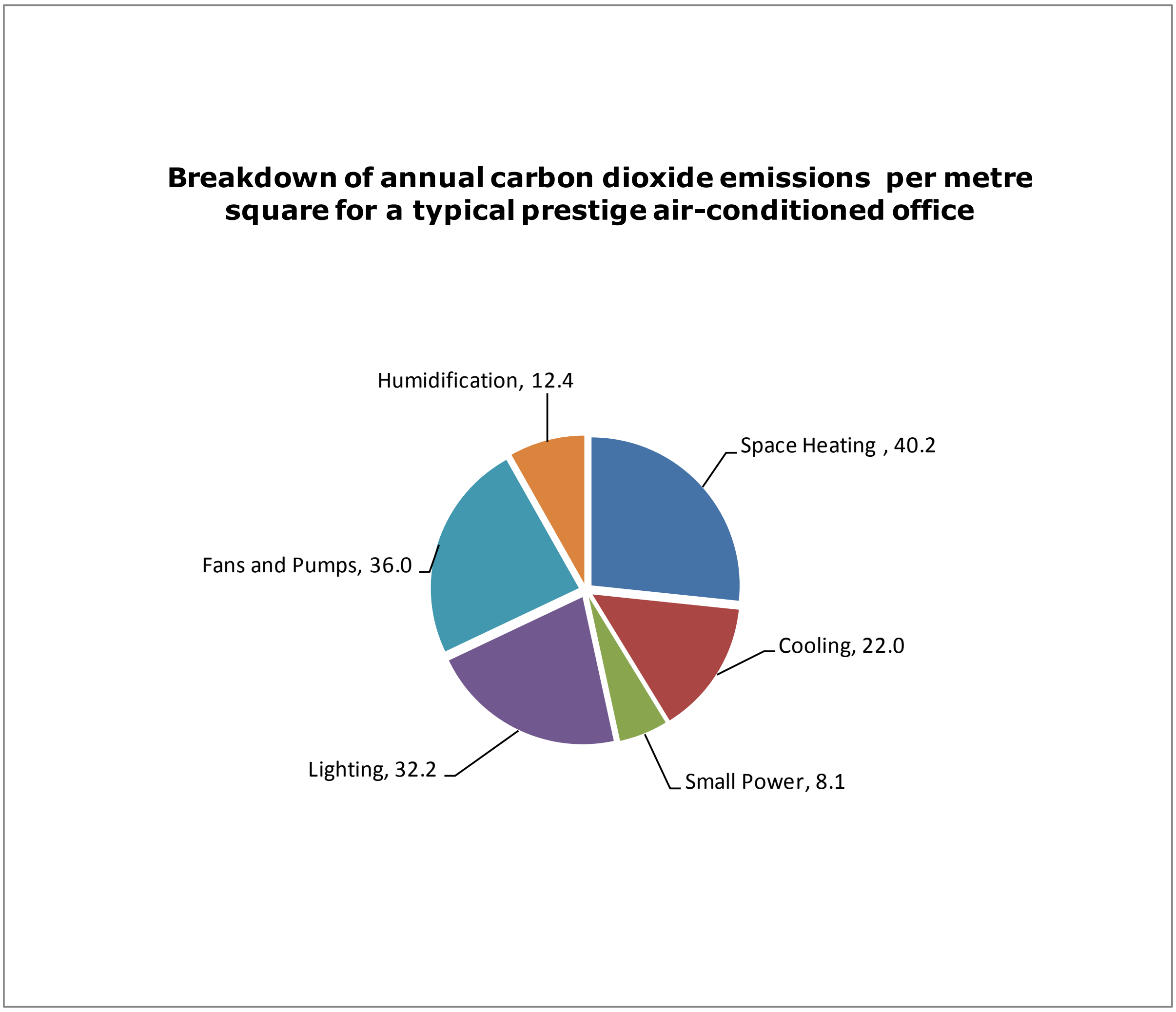


Figure 2.4 Carbon Dioxide emissions for a modelled low energy, shallow plan, low rise office (Action Energy 1998, p.21)

Carbon emissions are an important consideration due to the ever tightening Part L regulations (Section 1.3.1). There are opportunities to affect energy usage through the differences in zoning and distribution. Zoning of a building is where areas of a building are served independently from each other. Typically in a centralised system the whole building is conditioned based on a time schedule. However offices are rarely fully occupied and by only conditioning occupied areas, energy and carbon savings can be made. This is possible with a sophisticated, properly commissioned and maintained centralised system which has a number of modulating dampers and valves and inverter driven variable speed pumps and fans. In a decentralised system it is easier as each zone has its own system, which can be simply shut down when there is no demand. It is difficult to quantify the energy saved however, as it depends on the occupancy patterns of the particular building.

Distributing air, heating and cooling requires fans and pumps to overcome the resistance of the pipes and ducts. This is proportional to the distance travelled and the complexity of the route. Clearly a centralised system will have longer distances and greater complexity in the routing; the energy and carbon emissions used by the fans and pumps will be much greater than a decentralised system. The carbon emissions associated with the fans and pumps overall as shown in Figure 2.4 is significant. There is therefore a definite advantage in using a decentralised system for reduced fan and pump energy. The reduction of distribution also has a positive effect on the cooling load.

With a centralised system a suspended ceiling is normally installed to conceal the ductwork and pipe work distribution. In a facade or floor integrated decentralised system the suspended ceiling can be omitted as the ductwork and pipe work at high level can be omitted or reduced significantly. Removing the suspended ceiling allows the thermal mass of the slab to be exposed which has been proven to lower the day time temperatures significantly when a night cooling strategy is in place in UK office buildings (Kolokotroni et al. 1998). This increases the duration of natural ventilation periods and reduces or can even eliminate the requirement for active cooling depending on the natural ventilation rate. Carbon emissions can therefore be potentially reduced in decentralised systems through the distribution, improved zoning and exposed thermal mass.

There are however two instances where the carbon emissions could be increased. Firstly in a building with a mix of uses such as offices, retail and residential, heating from one area may be required in another. In a centralised system this can be transferred and overall energy and carbon can be saved. For these types of developments such systems have an excellent efficiency. In the UK however, the predominant development model is for uses to be separated out into different buildings (BCO 2009). The second instance is if the heating and cooling source itself is decentralised, the choice of technology as will be discussed in Section 2.12 is restricted and may lead to a higher carbon source. For example the Deutsche Post tower, Bonn, Murphy/Jahn, 2002, for instance uses a reversible ground source heat pump, which is one of the most efficient technologies available for generating heating and cooling. However it requires distributed pipe work, centralised plant and is therefore not applicable to a fully decentralised system. The deciding factor is the technology available for the heating and cooling source and its overall carbon performance. It is no use if carbon saved in reduced distribution losses is then incurred due to limitations on supply side technology.

There are a number of benefits to using decentralised systems including prefabrication, space usage however the aesthetics of the facade need to be detailed well, and critically the maintenance and carbon/energy performance of the heating and cooling technology needs to be comparable or better than a centralised system. A review of heating and cooling supply and delivery sources is therefore needed.

2.1.2 Supply of Heating, Cooling and Fresh Air

The current centralised solution of supplying heat by gas boilers and cooling from electrical vapour compression type chillers cannot be simply scaled down and this would ignore the alternatives being developed described in Table 2.2. For use in a decentralised system the requirements are primarily low carbon emissions. However ease of maintenance, spatial integration and cost effectiveness also need to be considered.

Heating supply sources include biomass, fuel cell combined heat and power (CHP), electric heating and heat pumps. In terms of carbon emissions biomass is considered to be low carbon, but is not suited to small scale operations due to its maintenance requirements and the difficulties of keeping exhaust flues away from openings and providing fuel to each unit. Fuel cell CHP utilises hydrogen to generate heat and electricity. However this is prohibitively expensive. The remaining sources of heating are direct electric heating and air source heat pumps. The influencing factor when deciding between electric heating and air source heat pumps is whether the supplied electricity is of low enough carbon intensity and the overall heating load. If they are both low enough then electric heating with its simpler construction and reduced maintenance would be preferable. Thermal analysis is required to make this decision and will presented in Chapter 4 once further information on the facade performance and loads can be calculated.

Table 2.2 Heating and cooling supply technologies for a decentralised system

Source	Use	CO^2 Emission	Comments
Biomass	Heating	Low	High maintenance required Only available at a large scale Exhaust flue constraints Fuel supply
Fuel Cell CHP	Heating and Electricity	Low-High	Carbon emissions depend on the fuel source - at presently prohibitively expensive.
Direct Electric	Heating	Low-High (see comments)	Depends on the carbon intensity of the electricity used and the overall heating requirement
Reversible Heat Pump	Heating and Cooling	Low-Medium	Ground source only suitable for centralised system Air source can be smaller scale, but has higher overall carbon emissions due to reduced COP (coefficient of performance)
Evaporative	Cooling	Low	Output is restricted and depends on low ambient humidity level.
Solar Absorption	Cooling	Low	Required consistent solar radiation and large spatial requirement.
Thermoelectric	Cooling	Low-High	Depends on the carbon intensity of the electricity used and the overall cooling requirement. With rising efficiencies could be a cost effective option.
Phase Change Materials	Cooling	Low-High	Restricted output and careful spatial integration requirement.

The options for cooling are also shown in Table 2.2. The most popular at present are vapour compression chillers due to their low capital cost, high efficiency, reliability and familiarity to the industry. The vapour compression cycle in cooling mode works by extracting heat from the room and disposing it into another medium which is usually either the ground or the external air. Using the ground is preferable as the ground temperature remains fairly constant through the year and does not rise as high as the air temperature in the summer. Using the ground is however dependent on the actual ground conditions and usually requires a ground investigation. Some centralised plant and distribution pipe work also has to be provided in this case. For medium rise to tall buildings which having a relatively small plot area to gross floor area, an aquifer or adjacent land to the site is needed to achieve the required heat sinks and generally only available on limited numbers of sites. Using external air as the heat sink on the other hand is suitable for locating around the facade of a building regardless of location. An added advantage is the vapour compression cycle can provide cooling, and when reversed, used as a heat pump to provide heating. An issue with the vapour compression cycle is the global warming potential of the refrigerant gases used and the phasing out of the main refrigerants being used today, hydrofluorocarbons (DEFRA 2011).

An alternative to vapour compression chillers are solar absorption chillers which use a heating source to drive the cycle rather than a compressor. They are however limited in application to the UK due to the reduced solar coincidence with cooling loads, high capital cost and additional component requirements.

Evaporative cooling is one of the oldest techniques used for cooling and uses the latent effect of water evaporation to cool the air. This form of cooling has very low carbon emissions, but can be limited in application in the summer as it relies on low humidity levels for the evaporative cooling to be effective and cannot be used to dehumidify supply air.

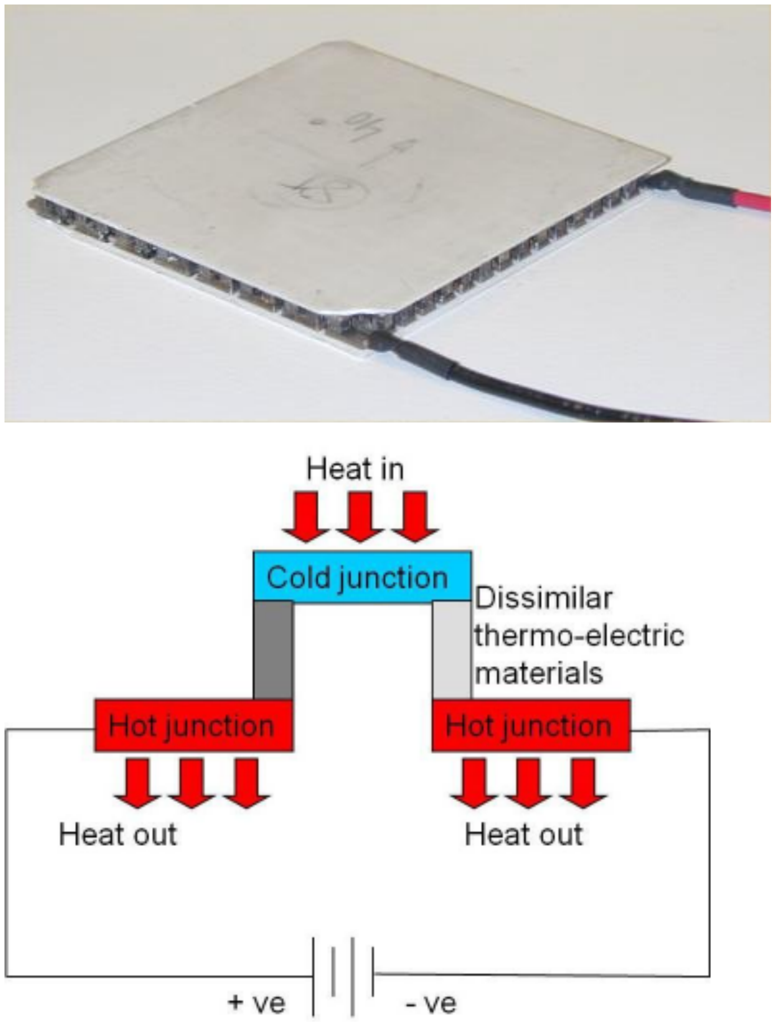


Figure 2.5 Principle of operation of thermoelectric device and picture of the device. Electrons take heat from the cold junction across to the hot junction.

Peltier thermoelectric devices (Figure 2.5) are found in most computers to take heat away from the processor and use the flow of electricity through a peltier element to directly cool a surface. Their advantage is that they are small in size and have virtually no maintenance requirements. The efficiency from devices available on the market today is currently less than 1, but theoretically their Carnot efficiency could approach that of the vapour compression cycle. As with heating, their use is dependent on the carbon intensity of the electricity used and the quantity of cooling required.

For cooling the potential options are therefore vapour compression cycle, evaporative cooling and peltier thermoelectric although each has potential drawbacks. To make a firm decision on the choice of heating and cooling source further work is required to examine if and how the unit can be integrated into the facade whilst providing a desirable aesthetic.

The introduction of fresh air needs to be done with care to prevent discomfort from draughts. This can be avoided either by sufficient mixing with the room air before it reaches the occupant or preheating the supply air. The most energy efficient option is to preheat the supply air by use of a heat exchanger. This exchanges waste heat from the exhaust air to the supply air. The different heat exchangers available are:

- Plate heat exchangers
- Rotary heat exchangers
- Run around coil heat exchangers

Plate heat exchangers are the most economic choice and offer efficiencies of up to 80%. Rotary heat exchangers offer efficiencies up to 95%, but are more costly. They do require less space when a bypass control is required. Run around coils have efficiencies of around 60%. Their advantage is that the supply and extract streams do not have to be adjacent to each other, but additional piping and a pump are required. Their use is very much dependent on the benefit to be gained in terms of energy usage, comfort, spatial arrangements and cost considerations. A decision on their use will be left to later in the design process when greater information is available and a full analysis carried out (see section 4.1). After the heating, cooling and fresh air supply has been generated there is a choice of terminal devices for their delivery.

2.1.3 Delivery of Heating, Cooling, and Fresh Air

The terminal device used for delivering heating, cooling and fresh air also has an influence on the energy and carbon emissions and is the main factor in the comfort of the space. The most common options are:

- Fan coil units
- Variable air volume units
- Floor displacement systems
- Passive chilled beams
- Active chilled beams

Figure 2.6 Terminal Devices (left-right) cassette fan coil unit, VAV terminal, floor displacement grille

Fan coil units have been the most popular choice in office buildings due to their high heating and cooling outputs, provision for fresh air delivery, moisture removal and comparatively low capital costs. Their efficiency and maintenance requirements however are relatively high compared to other systems. Variable air volume units supply treated air to either heat or cool the space. The only devices in the office space are the damper units which are relatively maintenance free and provide a form of zonal control and modulation. This type of system however requires high space requirements; both in the plant room and on each office floor, but does achieve good comfort levels and reduced maintenance requirements when compared to fan coil units.

Floor displacement systems are also an all air system with the supply air coming from beneath the floor and air extracted at high level. This has the advantage of improving the indoor air quality as pollutant mixing is reduced, but does require distributed floor grilles which reduce space planning flexibility.

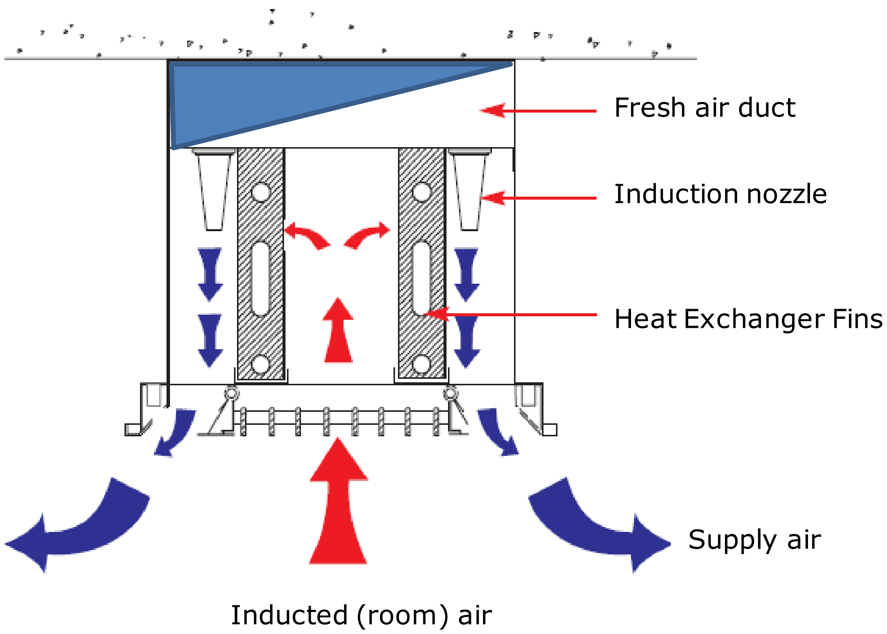


Figure 2.7 Principle of operation of Active Beam and picture of installation with integrated lighting at Hallward Library, University of Nottingham

Passive and active beams provide a quiet, energy efficient and comfortable delivery of cooling and heating into a space. Passive beams work by natural convection alone and are very energy efficient, but have low cooling outputs. Extra care also needs to be taken to avoid discomfort from downdraughts directly under the beams reducing their flexibility. Active beams work on the induction principle. The injection of a small quantity of fresh air though a specially designed nozzle induces five times the same quantity of room air through the heat exchanger and then back into the room with the fresh air as shown in Figure 2.7. They offer improved comfort conditions, higher outputs, can provide heating and fresh air provision when compared against passive beams. Active and passive beams are also available with additional services such as lighting, fire detection and personal announcements. The casing can also be custom designed. Active beams do still have a lower cooling output compared to other conventional system (approx 500W/m) and hence usually need to be used in conjunction with activated thermal mass or in a space with a low cooling requirement. For a design with low cooling and heating requirements active chilled beams achieve good comfort levels and have low maintenance requirements which has led to an increase in their popularity recently.

In conclusion, a decentralised system has a number of benefits worth exploring. The heating and cooling supply options for a decentralised system and lower carbon emissions have been identified as electric heating, air source heat pump for heating and vapour compression, evaporative and thermoelectric cooling.

Further work is required to examine how they can be integrated into the facade. The different options for terminal devices have been discussed with the best performing option for low energy, comfort and cost effectiveness being active beams. Even with low energy technologies for the environmental system, the minimisation of their use can only be achieved by the principal influencing factor; the design of the facade.

2.2 DEVELOPMENT OF THE CURTAIN WALL FACADE

Prefabrication and improving the energy performance are just as important design drivers for the facade as they are for the active environmental system. In addition high transparency though difficult to harmonise with energy performance is still desired. Before embarking on a design it is necessary to understand how these requirements have been met so far and build upon them to provide higher levels of performance. The technological developments to increase the transparency of the envelope will be discussed first, followed by prefabrication options. This will then be followed by the developments in technology that have improved the environmental performance of the curtain wall so far. The final section presents future requirements for the facade.

Providing a highly transparent curtain wall facade has triggered a number of innovations in the structural retention method of the glass units. The most common glazing retention methods for curtain wall facades (excluding sloped and roof glazing) (Vigener & Brown 2011) are currently:

- Pressure plate systems
- Structural silicone glazing
- Point fixed structural glazing

Pressure plate systems secure glass by clamping the edges with a continuous pressure plate via a gasket to avoid direct glass to metal contact. The gasket is compressed via a tightening of a screw in between the pressure plate and internal framing bar. The pressure plate is normally covered by a ‘snap-on’ mullion cover. This system is widely available, is cost effective and has high reliability as long as the gaskets are installed to cover the corners. Pressure plate systems utilising aluminium profiles require a thermal break to reduce the thermal transmission through the frame. If steel is used instead of aluminium the profile can reduce in size, but the finishes available are restricted. The appearance of the external cover using a pressure plate can detract from the overall transparency and glassy appearance, but is the most economic to construct.

Pressure Plate System (Schuco FW50+)	Point fixed (Pilkington Planar)	Structural silicon glazed (Schuco FW50+SG)

Figure 2.8 Images of the main types of glazing retention systems (www.schueco.com)

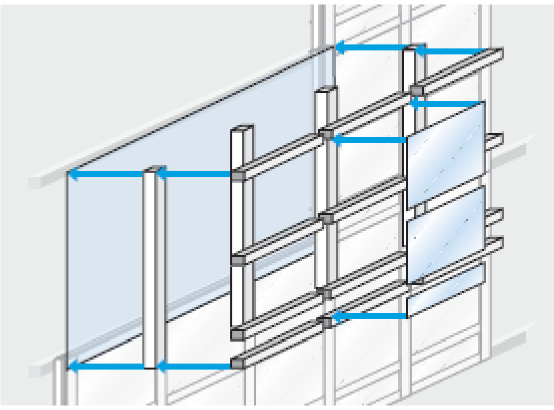
Structural silicone glazing (SSG) uses silicone adhesive to fix the glass to a retaining frame instead of a pressure plate and compressed gasket. This relies on a good chemical bond and factory controlled application procedure. Some local building codes stipulate the use of mechanical restraints as well. The advantage of SSG glazing is the smoother external appearance as frame profiles do not protrude from the glass surface and only gaskets or silicon bonds are visible between glass panels.

Point fixed systems can be considered an evolved form of patch plate systems and retain the glass through special fixings usually located near to the corners of the glass as shown in Figure 2.8. This method of fixing allows much greater transparency as the visibility of external framing components is almost eliminated. The internal framing can also be reduced further with the use of glass fins, steel framework or a cable net system instead of mullion and transom profiles. The glass has to be strengthened in order to withstand the increased localised stresses around the point fixings and greater complexity is involved during construction.

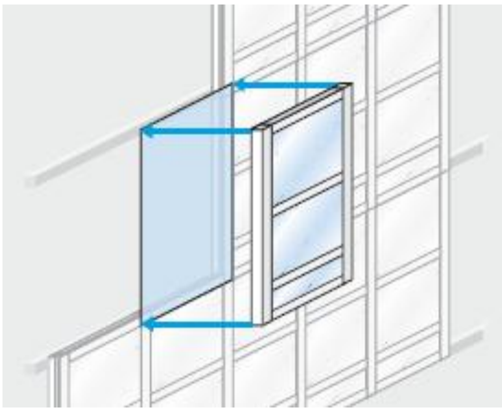
The choice of system overall is dependent on the desired aesthetic, economics, constructability and is decided on a project by project basis. The glazing retention method is the main influencing factor, but the transparency of the glass can also be influential.

The transparency of the glass itself is influenced by the glass thickness, number of layers, iron oxide content and any coatings or additives applied. Within the main raw material for glass silica, a small quantity of iron oxide is present which gives the glass a slight green tinge. When very thick or multiple glass sheets are used this becomes more apparent. By ensuring the raw materials contains a lower iron oxide content (<0.05%) low iron clear float glass can be produced which does not have the slight green tinge. This can be necessary where multiple layers of glass or increased thickness are used and high transparency is required. Glass coatings and additives can change the colour and radiation transmission. This allows glass to change the amount of heat entering or leaving, but is also accompanied by a fall in visible light transmission; the lower the g-value (solar heat transmission), the lower the visible light transmission. Solar control coatings whilst reducing the cooling load, can therefore increase the heating and lighting load and need to be used with care. In situations where many panes of glass are used low iron glass should be specified and very low g-values avoided, allowing a predominantly day lit interior.

The assembly and logistics of curtain walling is crucial to the timely progress of a construction project as it allows the internal trades to begin work. In response the industry has developed elemental 'stick' systems and a more prefabricated form of construction called 'unitised systems'. Stick systems arrive on site as a kit of pieces and are installed on site, component by component after being prepared in a factory. The mullions are usually attached first followed by the transoms and glass. Their advantage lies in their flexibility to suit the construction program, ability to be adjusted on site and reliability. They are however slow to construct and normally require significant scaffolding or access machinery.



Stick system construction – individual mullions and transoms fixed on site



Unitised system construction –complete frame and glass installed on site

Figure 2.9 Stick and unitised construction methods

Unitised systems use profiles which are split with a gasket and male female union piece between. They can then be installed on site as completed units of framing and glass, normally a single storey high reducing site work considerably. For inner city sites, where space is very constricted, and on medium to high rise projects where scaffolding is difficult, unitised curtain walling systems are preferable. The units are produced in a factory fully glazed and so offer improved quality, and reliability. For SSG units a unitised system is essential as the glass has to be bonded flat under controlled conditions and normally within a specialised factory. Carefully designed connection brackets are needed in a unitised system assembly to allow both horizontal and vertical adjustment on site to allow for structural tolerances. Disadvantages to unitised systems are the higher facade cost because of the increased aluminium quantity in the profiles and transportation costs. There is also the requirement for improved on-site handling equipment such as cranes to position the units into place. If the extra costs are offset by greater speed of installation, reduced on-site labour, health and safety risks and reduction in remedial work, then unitised systems are preferable. A compromise between the two systems is ladder or the semi-unitised system which have part of the facade pre-fabricated. There are a number of options available therefore - 'stick', 'unitised' or something in between - which can suit different site conditions, glazing retention method and whether the building is high rise or low rise. For the typology being considered, inner city, medium to high rise, a unitised system is needed. There have also been a number of developments in facade technology for improved energy performance.

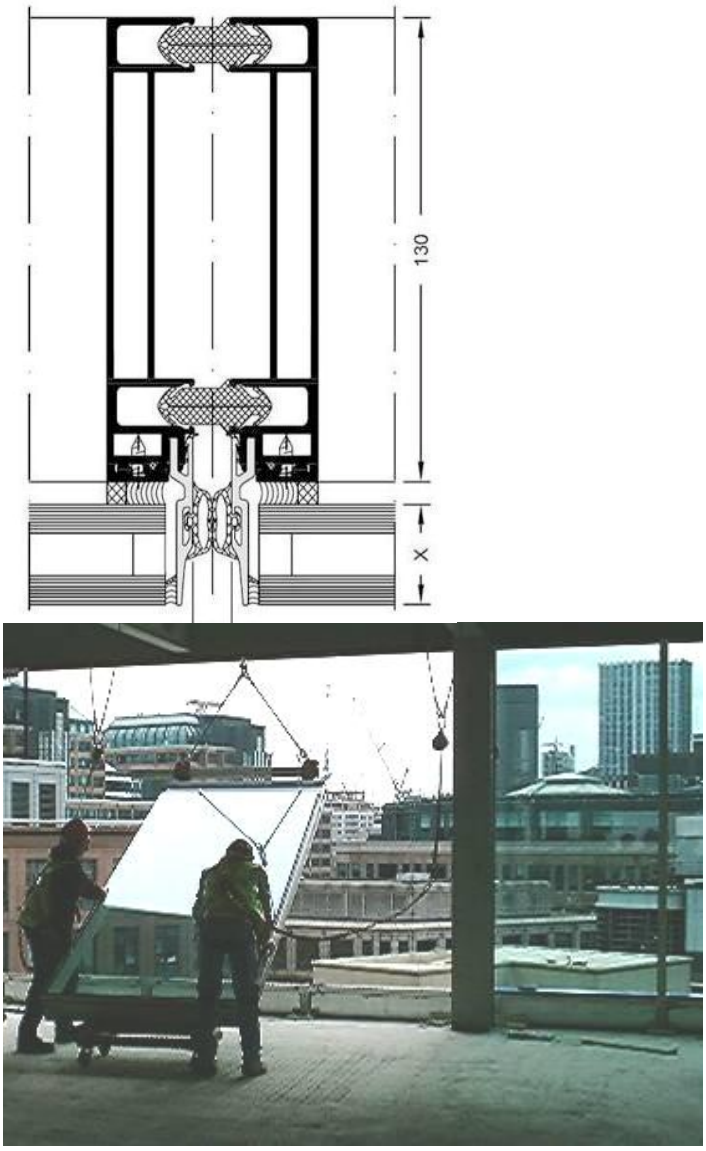


Figure 2.10 Example of a unitised profile (Schueco USC 65 SG) and installation (More Seven, London, Fosters and Partners, 2010)

Although carbon emissions are produced by the active environmental system, the amount of cooling, heating and lighting used is related to the performance of the facade. The tightening energy regulations for curtain wall facades have so far been met by reducing heat loss and heat gain from the building envelope through a number of technologies as shown in Figure 2.11. Facade profiles have been modified to include thermal breaks; glass has also developed in parallel to offer low-emissivity coatings to reduce radiative heat loss and solar control coatings to reduce the admission of unwanted solar gain and lower thermal conductivity spacers.

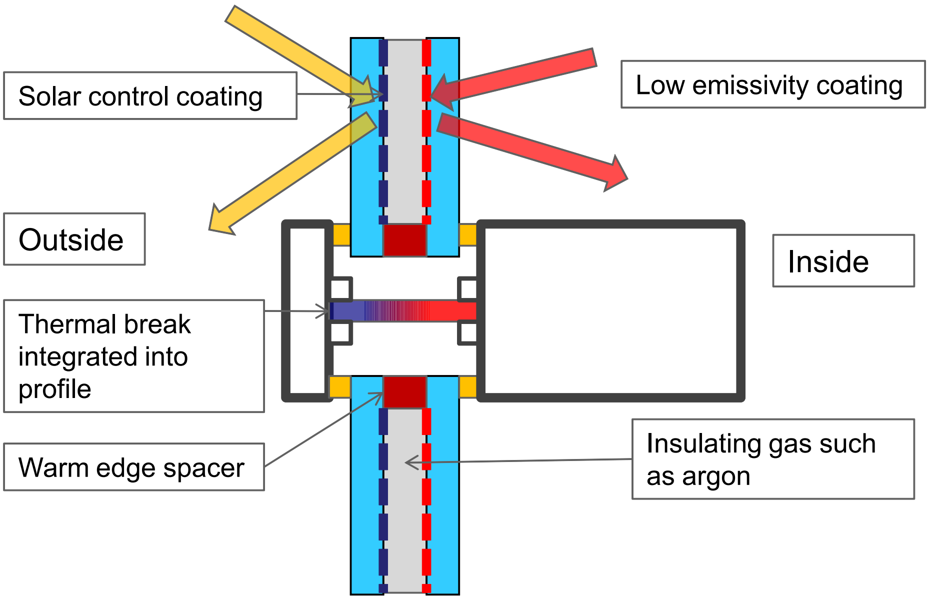


Figure 2.11 Advances in curtain walling for improved energy performance

These developments have allowed highly glazed facades to meet building regulations in the past as Part L specified minimum U-values to try and limit carbon emissions. Since 2006 however building regulations began to regulate the overall building energy performance and carbon emissions which has meant a greater focus upon the facades role in building energy performance as it influences all of the regulated energy uses; heating, cooling, lighting and fan and pump energy as well as occupant comfort. The facade has to be truly multi-functional to offer reduced energy usage and improved comfort by offering the functionality described in Table 2.3.

Table 2.3 Functional aspects of future facades

LIGHTING	Daylighting Maximisation of daylight Glare protection Artificial lighting
INDOOR TEMPERATURE	Insulation Collection of solar gain Protection from solar gain Heat rejection
AIR QUALITY	Natural ventilation Air filtration
ACOUSTICS	Attenuation of sound
ENERGY GENERATION	Electrical

Simply reducing the U-value or providing an improved solar control coating can no longer be implemented to achieve the required performance. In the northern European climate the winter and summer requirements in terms of thermal control are very different. Solar gain is beneficial in winter, but unwelcome in summer, maximisation of daylight is required in winter, but this can lead to excessive solar gain in summer. This is one of a number of design paradigms the facade has to resolve as shown in Table 2.4.

Table 2.4 Design paradigms for the future development of facades and curtain walling

Thermal Control	vs.	Transparency
Daylight	vs.	Glare/Solar Control
Ventilation	vs.	Noise
Openings	vs.	Pollution/Security/Weather
View Through/Transparency	vs.	Air Tightness
Sustainability	vs.	Weather Tightness/Insulation
High Quality	vs.	Capability
New Technology	vs.	Manufacturability
Complexity	vs.	Structural Behaviour/ Cost/ Risk
		Fast Installation

The requirement for transparency and preassembly are already well progressed in curtain wall facades. The main challenge today is reconciling transparency with energy performance and overcoming the design paradigms outlined. This can only be solved by providing a dynamic, intelligent facade which can change in response to the external or internal climate conditions.

2.3 THE FACADE AS A CLIMATE SKIN

A building envelope which can manipulate the passage of energy flows in the form of heat, light, air and sound with manipulating functions similar to those described in Table 2.4 has been termed by Professor Wiggington as buildings with 'intelligent skins' (Wigginton & Harris 2002). Technologies such as thermo chromic and photo chromic glass exist, but have lifetimes below that acceptable for building facades. A solution which has been commonly used is the double skin facade and features in many of the case studies presented in the book 'Intelligent Skins' (Wigginton & Harris 2002) as it combines many of the manipulating factors. With its potential for dynamic properties and flexibility it has the potential to overcome a number of the design paradigms outlined earlier.

2.3.1 Double Skin Facades

Figure 2.12 Paimio Sanitarium, Finland, Architect Alvar Aalto, 1933.
Photo credit: Stygoweb

Double skin facades were originally another means of creating unheated buffer spaces to improve the thermal comfort of a room such as that used by the Finnish Architect in his design for the Paimio Sanitarium (Figure 2.12). Their popularity for commercial offices began in the late 1990's with their use on high profile buildings such as RWE Essen, Ingenhoven Overdiek, 1997 and the Commerzbank, Frankfurt, Foster and Partners, 1997 which provided improved comfort and energy performance figures over standard high rise buildings. This was due to a greater interest in energy efficient buildings and the optimisation of internal comfort conditions.

A number of definitions for double skin facades exist (see www.bestfacade.com), the definition below is taken from the Belgian Building Research Institute (2004).

'A ventilated double facade can be defined as a traditional single facade doubled inside or outside by a second, essentially glazed facade. Each of these two facades is commonly called a skin (hence the widely-used name *"ventilated double-skin facade").* A ventilated cavity - having a width which can range from several centimetres at the narrowest to several metres for the widest accessible cavities - is located between these two skins. There exist facade concepts where the ventilation of the cavity is controllable, by fans and/or openings, and other facade concepts where this ventilation is not controllable (the ventilation is produced in this case via fixed permanent ventilation openings)... Automated equipment, such as shading devices, motorised openings or fans, are most often integrated into the facade. '

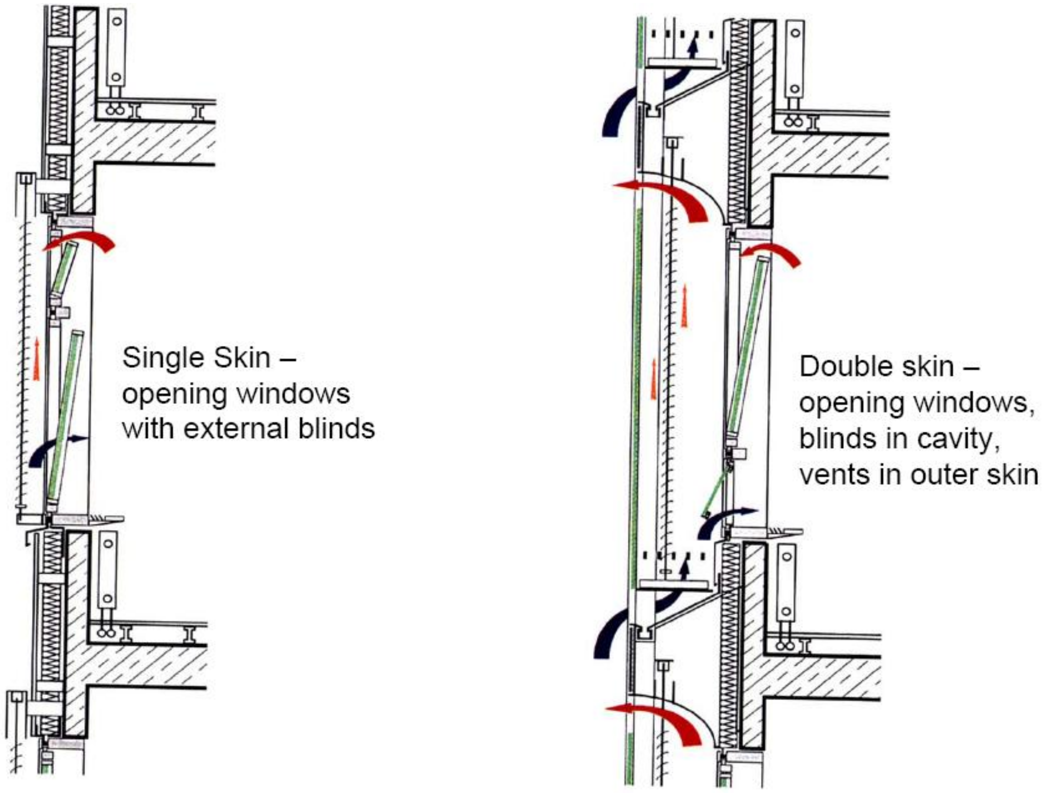


Figure 2.13 Single skin and double skin concept. The double skin facade has an inner skin which is double glazed, a narrow ventilated cavity with venetian blinds and an outer skin which is single glazed (Heusler et al. 2001, p12).

Double skin facades have a number of established benefits. They include:

- Dynamic control of solar heat gain for optimum seasonal performance
- Protection of shading devices
- High levels of natural day lighting without high solar gain
- Provision of natural ventilation in difficult contexts
- Reduction and reliance on mechanical environmental systems
- Attenuation of external noise sources

Control of solar heat gain is achieved by solar shading located within the cavity between the two skins. This captures the majority of the solar gain which can be exhausted from the building or introduced into the internal space. This allows for a highly glazed facade without the corresponding high solar gains in summer when they are unwelcome or admission of solar gain in winter when it can contribute to the heating requirements.

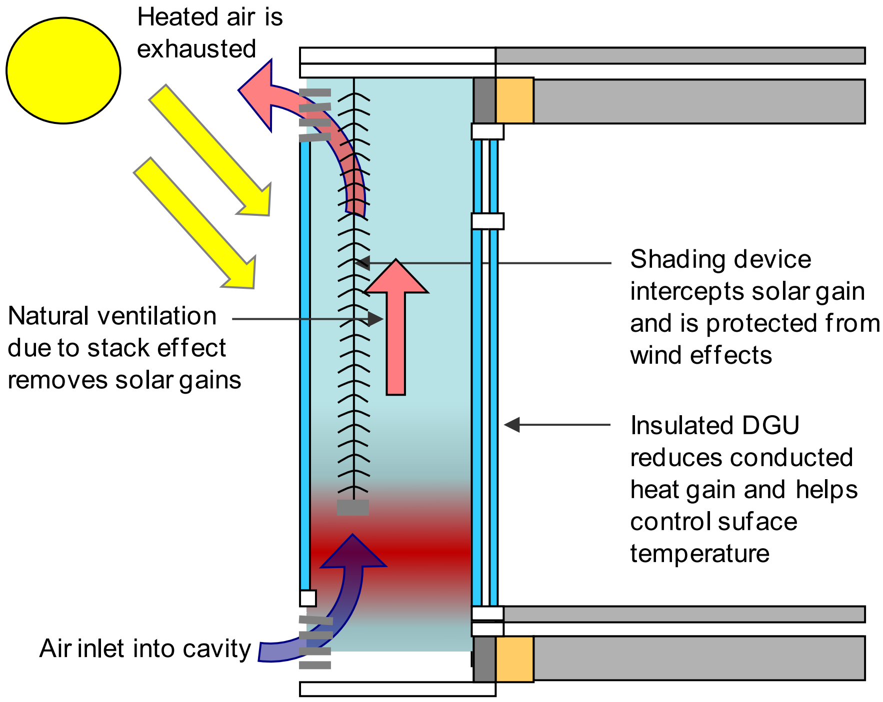


Figure 2.14 Principle of solar heat protection in a naturally ventilated double skin facade during the summer

External shading could be used on a fully glazed facade and achieve a similar reduction in solar heat gain, but this has a number of consequences. Wind effects, particularly for high buildings, mean the shading device needs to be particularly robust, and makes dynamic control difficult. If the device is fixed, the overall daylight transmission and the overall transparency to allow occupant connection with the external environment is permanently reduced, increasing the lighting and heating loads and reducing occupant psychological comfort. It can also make external glass cleaning and replacement difficult. The interstitial shading in a double skin facade however is protected from the wind and hence can be of a simpler construction, more easily include the functionality of being raised up or down to allow views and transparency in winter when solar shading is not always required. With a decrease in solar heat gains and corresponding cooling loads, environmental systems can be minimised and less energy intensive devices such as chilled beams used. In winter the cavity space captures solar heat gain, and this in turn increases the radiant temperature of the internal glass, and heats up the air in the cavity which can facilitate natural ventilation. This provides a more comfortable environment for the occupants and allows a reduction in the heating load.

One of the main advantages of double skin facades is the provision of natural ventilation in difficult contexts such as noisy or medium to high rise buildings. As mentioned in Chapter 1, having an additional skin increases the attenuation of external noise and permits greater periods of natural ventilation in noisy sites. For medium and high rise buildings high wind effects dominate and in this case attenuation of the wind pressure and speed is provided by the additional skin. If natural ventilation is required in these types of sites, a double skin facade is worth exploring. There are some negative aspects to consider at the same time though.

The disadvantages of double skin facades include:

- Cost
- Access and maintenance
- Complexity

The additional glass skin has an additional cost and the many permutations and aspects to consider increase the design complexity. An additional glass skin increases the maintenance as two additional surfaces have to be cleaned. Access also has to be provided to the cavity to allow for cleaning which means suitable openings which increases the cost further. Design complexity increases as there are many additional aspects to consider with a double skin facade such as fire and smoke compartmentation, acoustic flanking noise and construction logistics. They can be overcome however, and the additional cost is worth the extra expenditure so long as improved comfort is achieved as demonstrated in Section 1.2.

The double skin facade as a form of dynamic facade already meets many of the requirements for a modern facade and has taken on some of the role of conditioning the internal space back from the active environmental systems. This thesis proposes that the double skin facade concept should be developed further, so that full control of the internal environment is established by firstly optimising the design of the double skin facade and then integrating a decentralised environmental system to achieve the advantages outlined in Section 2.1. By using the double skin facade, installation of the environmental systems can be facilitated by using the facade as the carrier and the spatial requirements could be provide by using the cavity space within the spandrel zone. Before devising a suitable design methodology and beginning design, a market review of projects and products that have already taken steps toward this goal will be reviewed.

2.3.2 Precedent Projects

Precedent projects providing integrated environmental systems as part of the facade provide ideas and sources of knowledge for further development. One of the first built projects using facade integrated environmental systems is the Lafayette Park Apartments, Detroit by none other than Mies van der Rohe (Banham 1984, p.188). More recent projects include the Deutsche Post Tower, Bonn, (one of the inspirations for the PhD proposal) and Capricorn House, Dusseldorf which will be discussed in detail.

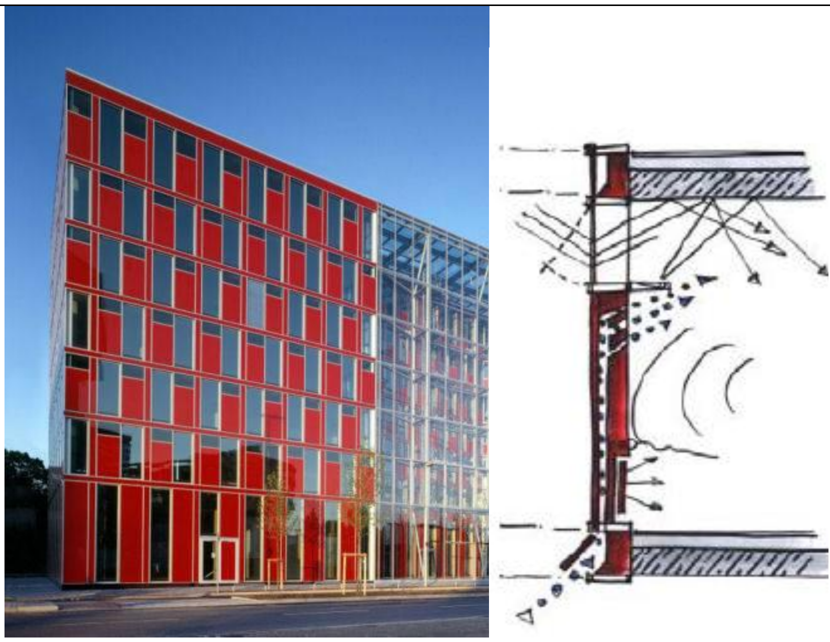
The Deutsche Post Tower (Table 2.5) is credited with being one of the most ecological skyscrapers built so far. This is a result of the integration between engineering and architectural design. The form of the building accentuates the ventilation concept and the facade design makes natural ventilation of the internal offices possible. The facade is a deep cavity corridor and multi-storey type with openings located to accentuate wind driven ventilation. This enables natural ventilation of the internal spaces. It is also one of the first projects to use a decentralised heat recovery intake device with integrated heating and fresh air supply. These are situated around the perimeter to serve each office space. This enabled a reduction of plant room, riser and ceiling void space. Each user can also control the unit and regulate the conditions according to their own comfort preferences. As the internal gains are greatly reduced by the double skin facade design, a low energy cooling system utilising water from the adjacent river could be used in a chilled ceiling system.

Table 2.5 Project data for Deutsche Post Tower

Client	Deutsche Post AG (now DHL)	
Architect	Murphy/Jahn	
Occupancy	Commercial Offices	
Height	163m	
Completion	2002	
Cost	-	
Facade	Multi-storey naturally ventilated double skin facade	

Structure	Concrete core, concrete-steel composite columns with steel bracing between columns and concrete outriggers	View of Post Tower Photo credit: Thomas Wolf http://en.wikipedia.org/wiki/

Table 2.6 Project data for Capricorn House

Client	E.ON Energy Trading	
Architect	Gaterman + Schossig	
Occupancy	Commercial Offices	
Height	Seven storeys	
Completed	2008	
Cost	-	
Facade	Integrated double skin	
		External view and environmental system concept Photo credit: Rainer Rehfeld (Gatermann + Schossig 2008)

A more recent project utilising a decentralised system is the Capricorn House (2008) in Düsseldorf, Germany. This project uses a similar decentralised system as used on the Deutsche Post Tower and manufactured by Trox GmBh. It is situated behind an opaque red panel in a slimmed down version with the functions of air filter, heating, cooling, heat recovery and dampers; a very sophisticated unit. The effect of the opaque red panel reducing daylight levels and increasing diversity was reduced by the incorporation of a light shelf with high level glazing above the panel.

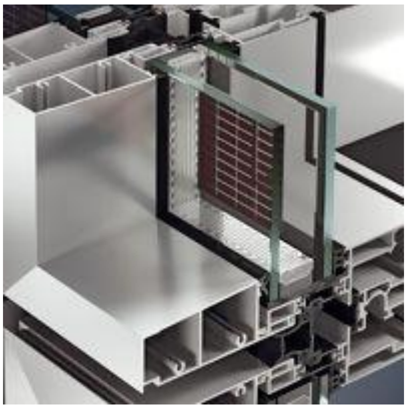
Both projects utilise the Trox FSL ventilation unit (Figure 2.2) which provides heating, cooling and fresh air individually, but still relies upon central generation of heating and cooling, thus not fully decentralising plant and making maximum floor space gains. As well as precedent projects some system products are available that combine a number of certain facade functions.

2.3.3 System Products

System products include 'TE Motion' by Wicona and the Schueco 'E^2' and '2°' systems. Wicona building systems have developed a pre-fabricated facade system which has arguably gone the furthest in the way of intelligence and functionality. Ventilation, heating, cooling, day lighting steering, solar protection and energy generation are combined into a unitised system. The environmental system is decentralised as per the previous examples, but there is also the option of manual window opening to provide a mixed mode of operation. The heating and cooling system is also decentralised, but relies on central generation of the heating and cooling. The lighting system uses a steering system on the shading device to reflect daylight deeper into the space. Additional LEDs on the inner profiles of the facade provide some artificial background lighting. The solar protection uses standard metal coated venetian blinds. The energy generation is via photovoltaic cells which are arranged on pivoted slats in the opaque area. Wicona's data indicates an energy reduction of 50% over a standard single skin and centralised environmental solution. The unit does have opaque elements used for ventilation which reduces the transparency of the unit and creates a quite bespoke aesthetic. As yet no realised projects using the system have been found.

Figure 2.15 TE motion unit as installed at the Hydro test centre and spatial arrangement (Wicona 2010)

Schueco, a multi-national curtain wall system provider has developed two types of multi-functional facade systems, the E^2 and 2°. The Schueco E² system combines building enclosure with opening units, decentralised ventilation, solar shading and photovoltaic modules available as a single skin solution. Novel aspects of the system include external operable shading device which can operate at wind speeds up to 30m/s and photovoltaic modules complete with inverter and wiring. The ventilation system uses the same Trox FSL unit as used in the Deutsche Post Tower. The photovoltaics are arranged to have a degree of transparency. The features not addressed by this system are natural ventilation in difficult contexts (e.g. high rise) and issues of maintenance with the external shading device due to its external location.



Semi-transparent thin film PV

Roller blind able to withstand high wind speeds

Figure 2.16 Schueco E² system showing PV integration and spandrel zone (Schueco 2010)

A product more focussed on the domestic market is the 2° concept. This seeks to address the thermal issue of the relatively high U-value glasses compared to a well insulated wall and allow users to determine the degree of transparency and heat insulation they require. This is achieved by a sliding layer system of panels. An insulated panel and thin film PV panel are hidden behind a highly insulated opaque panel and can be automated or manually adjusted. This creates a quite specific aesthetic, reduced transparency at all times and no possibility for natural ventilation in difficult circumstances.

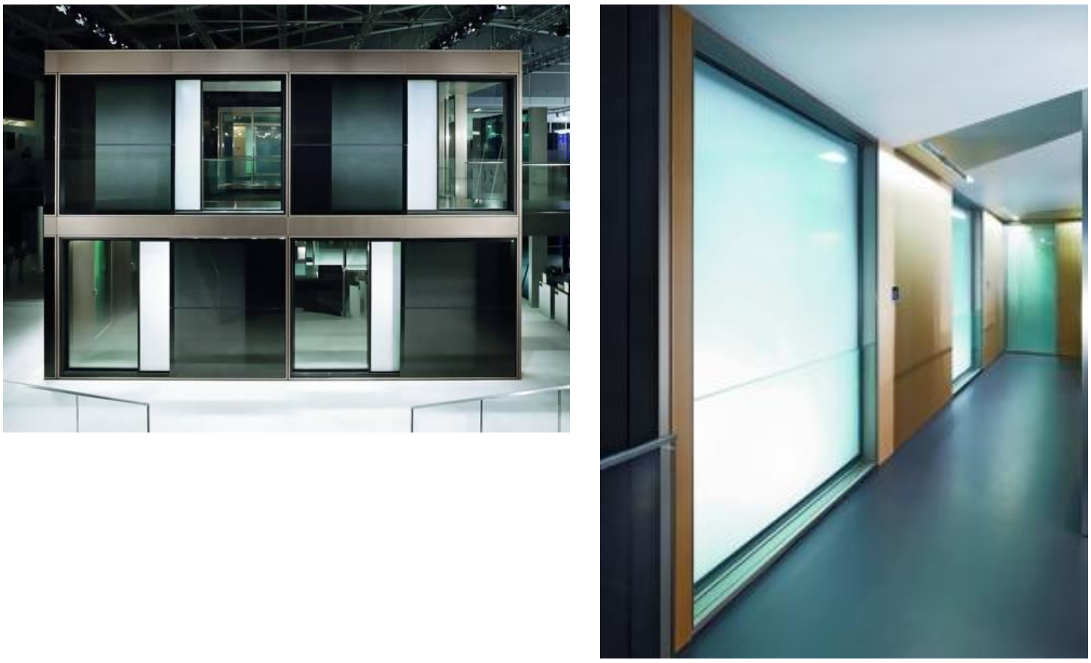


Figure 2.17 External view and internal views of the Schueco 2° System (Schueco 2009)

All of the projects and products reviewed here still rely on a centralised supply of heating and cooling and/or have opaque areas of facade in the visible area. Scope for a product that is fully decentralised for even greater space and assembly efficiency and yet offering the option of a fully glazed aesthetic exists.

2.4 PRODUCT DESIGN METHODOLOGY

In architecture, designing a product for use across different projects, challenges the view that industrialised methods cannot be used because of the uniqueness of each project. By opening up to this possibility, a different form of design process can be implemented in architecture. These two themes will be explored in this section culminating in a product design process to be used in this thesis.

Product design in architecture is constrained on one hand, to the bespoke, since individuality, design philosophy and architectural intent differ from project to project, but on the other hand, is facilitated by many projects sharing certain characteristics and design challenges which can be universally addressed. System providers using industrial methods for instance, provide a range of profiles based on some commonality, which can be successfully applied in a range of circumstances. Certain characteristics or a typology can therefore be addressed so long as the product can be systemised to provide flexibility and market appeal, without resorting to standardisation. This also assists in the design process as constraints are necessary to reduce design, testing, fabrication and assembly time spent on excessive product variations. In this thesis the chosen typology and design brief has been established in the preceding sections and includes:

- inner city urban location, medium to high rise (Section 1.1)
- medium plan (<15m) depth building (Sections 1.2 and 1.3)
- highly transparent envelope (Section 1.1)

This provided a reasonable amount of constraints to the design, however, as the design process proceeded, further design decisions could only be made by using a specific site. For this reason a search was conducted to find a site that matched the typology and the University of Nottingham Tower Building, was found to be a suitable exemplar (Figure 2.18). Further information on the building is included in Appendix C. This building provides the site, basic geometry and further design guidelines where necessary for the facade component.

Figure 2.18 View from the west side of the Tower Building

The most common design and administration process used within the construction industry is The RIBA Outline Plan of Work (RIBA 2007). It breaks the design and construction process into 13 different stages denoted by letters A through to M. This is the norm in the UK as a framework within which stages are sometimes consolidated on smaller projects. The thirteen different stages (A - M) are:

- A Inception
- B Feasibility
- C Outline Proposals
- D Scheme Design
- E Detail Design
- F Production Information
- G Bills of Quantities
- H Tender Action
- J Project Planning
- K Operations on Site
- L Completion
- M Feedback

This however allows for little optimisation of the design for construction or performance in use and the development of a systemised component which can be used from project to project. The industrial product design typically goes through the following stages (Ullman 2010):

1. Define project and its planning;
2. Identify customers and their needs;
3. Evaluate existing similar products;
4. Generate engineering specifications and target values;
5. Perform conceptual design;
6. Perform conceptual evaluations;
7. Develop product/prototype;
8. Evaluate product for performance and cost.

It is common for car manufacturers through the design process to consider the whole life cycle of the product especially the production stage to ensure that waste in time and materials is minimised as discussed in Section 1.4. Stages seven and eight would also go through a number of iterations until the product meets the required performance and intended cost.

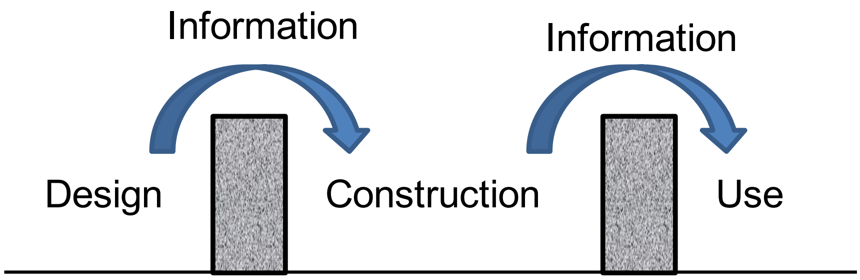


Figure 2.19 Over the wall design approach and one way information flow

This contrasts with the traditional design process in the construction industry where there is much more of an 'over the wall', sequential, design approach (Figure 2.19). Designers produce detailed design tender drawings and performance specifications which are passed on to the contractor. The contractor's team of sub-contractors then produce the actual production and installation drawings and construct the building. Once finished, it is handed over to the client who may occupy the building or rent/sell it to another organisation. This fragmentation and sequential one-way flow of information promotes little scope for improvement for constructability or performance in use. Many aspects of the building are the initial prototype and it is not surprising that coordination issues, timeliness, cost increases and defects arise during construction and that the needs of occupiers are not fully addressed. Using elements of a product design process in architecture would therefore be advantageous in improving the construction and 'in-use' performance. An indicative design process to be used is shown in Figure 2.20.

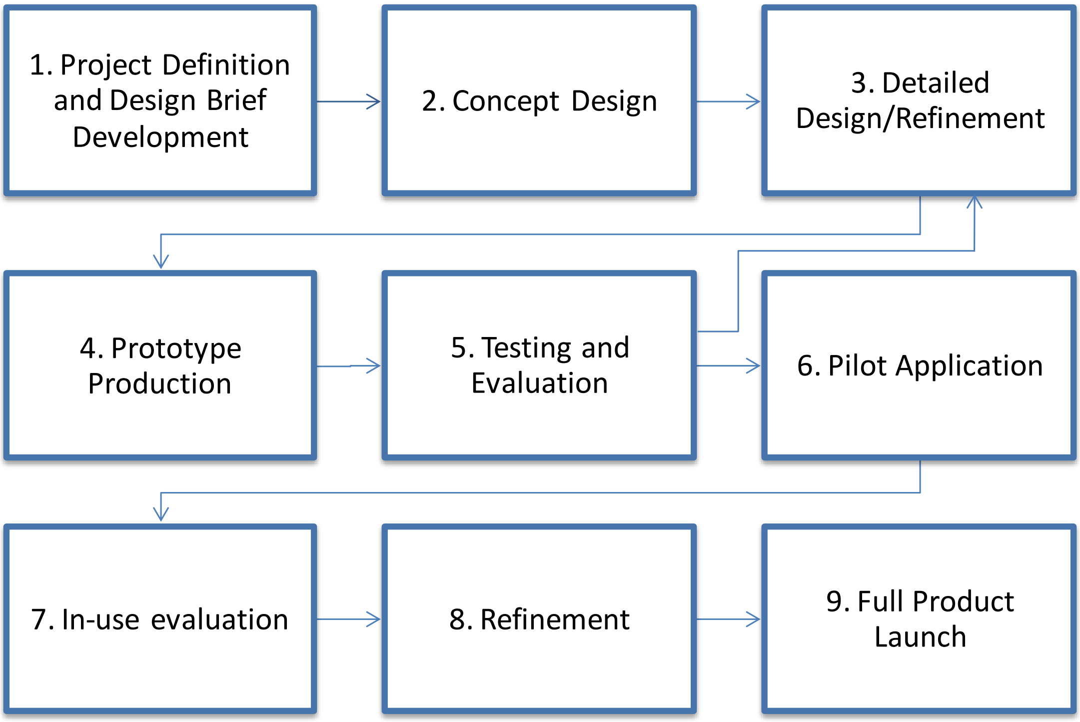


Figure 2.20 Intended design process for component

As the number of iterations between stages 3 and 5 increases, the prototype will demonstrate more aspects and resemblance to the pilot application and go through the following stages:

- Proof of Concept – demonstrate the key concepts;
- User Experience – capture user interaction;
- Visual - capture the intended design aesthetic;
- Functional or Beta Level – Represent to the greatest extent practical the final design including aesthetics, materials and functionality.

How far this thesis can progress through the intended design process and prototype development stage is limited by the financial and time constraints of a Ph.D. The allowance for a curtain walling mock-up and performance test in a City of London office for instance is estimated at £250,000 (Parker & Jones 2011). A realistic aim for this thesis is the completion of stages 1 through 5, which includes the production of a 'Proof of Concept' prototype. This will outline the design approach without exactly replicating the intended aesthetic, production process or functionality and used to identify key areas where further design development and testing is necessary. The specific elements which should be proven relate to the potential for enhanced occupant comfort and energy sustainability as well as an improved construction process through industrial involvement and prefabrication. An expanded design process to be completed in this thesis is shown in Figure 2.21.

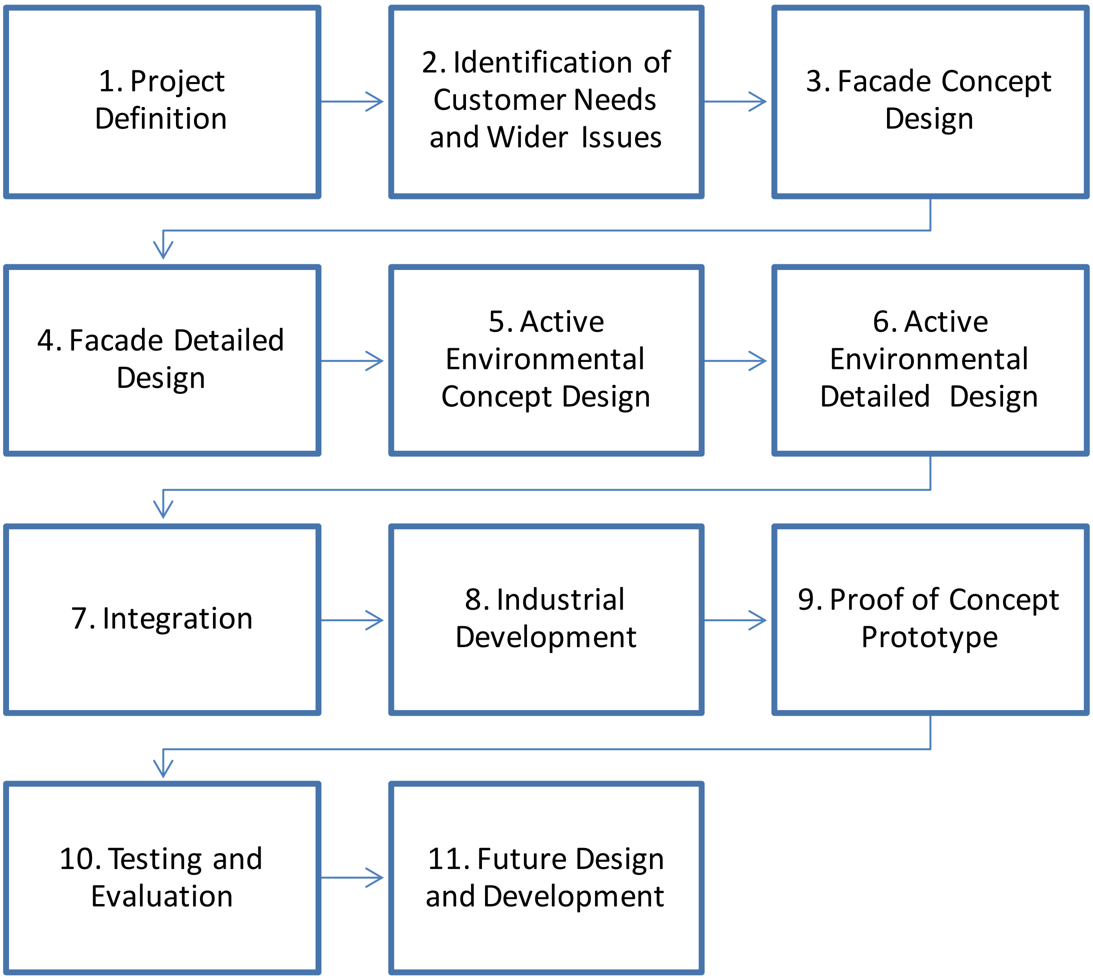


Figure 2.21 Design stages to be completed within the thesis

Stages 1 and 2 have been completed in the preceding chapters, but as the project goes on further insight into the needs of the customer (architects, facade engineers, clients) will be added. The design of the facade will precede that of an active environmental system (stage 5), as the facade will influence the heating and cooling loads and provide the ‘chassis’ for integration in Stage 7. Stage 8 will develop the design with industry suppliers and fabricators for production optimisation and to produce a proof of concept prototype. The testing and evaluation stage will consist of basic tests on the technical features and obtain the reaction of relevant stakeholders and prospective customers. Finally, responding to the evaluation stage and the insight gained during the whole design process, future design and development changes are to be provided in stage 11.

CONCLUSIONS

This chapter has described the different active environmental systems and facade technologies, which could be utilised to provide an Integrated Facade. The requirement for an environmental system, which lends itself better to prefabrication was established in Chapter 1. In this chapter, alternative strategies to the centralised solution were discussed and concluded with the use of a fully decentralised system for individual servicing of office zones, as it has the greatest potential for prefabrication. This has been compared with a centralised solution and shown to have a number of benefits in other areas including space utilisation and energy performance. The success of this system depends on whether a decentralised system can be integrated into the facade, whilst retaining high transparency levels and energy performance. Chapter 4 will begin the process of design and integration of the environmental system into the facade system.

The development of the building envelope to provide high levels of transparency, prefabrication, improved energy performance and comfort has also been discussed. The main area in which further progress is needed is the energy performance, as highly transparent envelopes provide a number of design paradigms. They can only be solved by a dynamic facade, and a double skin facade is one such facade. This thesis proposes that the double skin facade could take on full responsibility for the internal environment by integrating the environmental system. This would provide a suitable carrier for the components and possibly the entire spatial requirements by using the cavity in the spandrel zone. A review of projects and products has revealed that there is a market niche for a product based on the design brief. To take the design process forward an inner city, urban, medium to high-rise typology has been established, together with a case study building on which the component is based around. The design methodology to be used has also been established. The next design stage is the conceptual design of the facade, and environmental systems. The facade will be designed first in Chapter 3 to optimise the design as much as possible to reduce the size and energy requirements of the active environment system, which will be developed in Chapter 4.

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CHAPTER 3

FACADE DESIGN: CONCEPT TO DETAIL

Facade design is often considered the highest risk element in building and interweaves aesthetics, environmental performance and structural design tighter than any other building element. The starting point for the design varies from project to project, from enabling an architect's creative vision to a performance driven design. For this project a performance driven approach is taken based on the brief and the requirements in Chapter 1, and centred on the building typology and external conditions outlined in Section 2.4.

The design brief requirements discussed in Chapter 1 do not directly translate into a detailed double facade as proposed in Chapter 2. A number of design paradigms still exist, certain characteristics are project specific and a number of different permutations and types of double skin facade are available. The starting point for the facade design at this stage is to first ensure that the energy performance is an improvement over the Part L notional building and then determine which double skin concepts can provide an acceptable ventilation concept. The concept chosen will then need to be developed to address day lighting, solar control, thermal insulation and renewable energy collection for holistic performance. This is not solely related to reduced carbon emissions, but also maintenance and occupant comfort conditions. The final aspect to consider is the structural design and space planning necessary to enable prefabricated components, which also meet occupier requirements and reflect realistic loading conditions and deflection schemes. The starting point for this process is to first select an appropriate double skin facade typology to fulfil the natural ventilation and glazing fraction requirements.

3.1. FACADE TYPE SELECTION

The starting point for the facade selection here begins from the constraining requirement to provide natural ventilation for a medium rise office building in a noisy, exposed location. This restricts the choices to certain types of layered facades which can attenuate wind affects and noise. The facade decision diagram in Figure 3.1 outlines the options available.

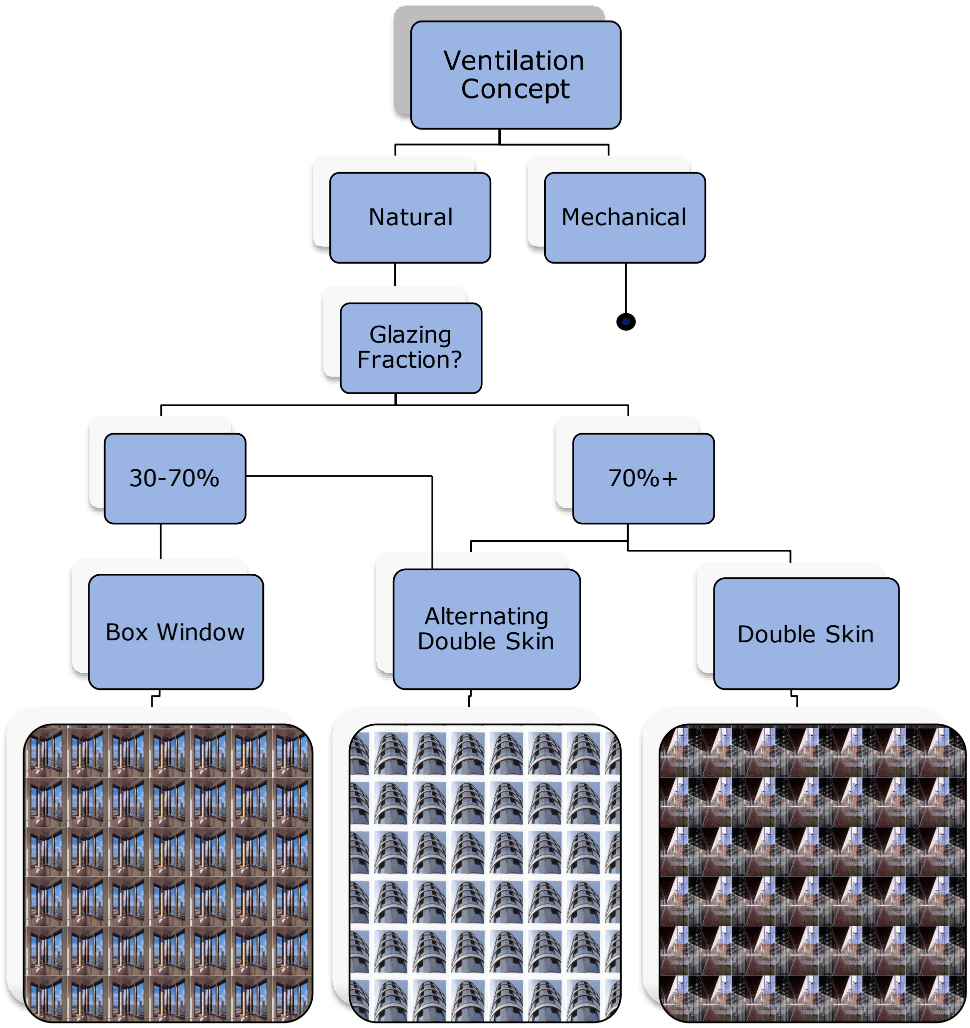


Figure 3.1 Facade decision diagram for natural ventilation in high rises (Images: Potsdamer Platz 1, RPBW, (Heusler et al. 2001, p.15), unknown, (Hausladen 2007, p.105), Glaxo Wellcome House West, RMJM, (CABE 2007))

The three facade options each have their own benefits, drawbacks and glazing proportions. The box window comprises of a standard window opening with a second glass placed a short distance in front to provide a ventilated cavity. Its use goes back to central European farmhouses pre 1900's (Heusler et al. 2001, p.8). It has been updated since then and a modern version was used by Renzo Piano in Potsdamer Platz, Berlin, 2000 (Heusler et al. 2001, p.15). The advantages of the box window are weather protection of solar shading, noise reduction and comfortable supply of air in winter and transition months. The disadvantages are restricted views, ventilation rate and overheating in the cavity. Box windows are used where largely opaque facades are desired. They are generally suitable in situations requiring natural ventilation, low ventilation requirements in summer and in terms of an aesthetic where higher levels of opacity are preferred.

The alternating double skin facade comprises of both double and single skins which alternate between each bay. The double skin in winter can preheat and provide fresh air even during windy conditions. In summer the double skin can also provide fresh air and air for cooling even in windy conditions provided it has not overheated. If it has overheated, the single skin can then provide fresh air and air for cooling, provided the wind conditions are acceptable. This allows for a greater portion of the year to be naturally ventilated, even during peak summer conditions. There is also a cost saving compared to a double skin facade. The disadvantages of this arrangement are firstly the consequences of providing solar protection for the single skin portion. A solar control coating would create an uneven day lit environment and if no coating is added the solar protection afforded would produce high solar gain in the space. Secondly the improved radiant surface temperature would be lost in the single skin portion. The impact is dependent on the relative proportions of double and single skin, and orientation. Finally the surface of the facade would be uneven, which is considered to be an unpopular aesthetic choice. Overall this type of construction is a good option where natural ventilation is the only means of controlling the indoor temperature in summer.

The double skin facade was introduced in Section 2.3. When compared to the box window, it has the benefit of providing higher levels of transparency and compared to the alternating double skin facade, a more homogenous facade appearance and an improved lighting/solar gain balance. The double skin facade therefore is the preferred solution so long as natural ventilation can be provided for significant periods of the year. This will be returned to in Section 3.3.

With the facade concept established for providing natural ventilation, before examining the energy performance, it is useful to examine the solar geometry and views important for the case study building. Ecotect (Marsh 2010) was used to visualise the solar path around the building as shown Figure 3.2 and a site visit was conducted to examine the views available from the two main facades. We can observe that the south-east facade receives low angle radiation in winter and high angle radiation in the summer. The solar radiation in winter can be best exploited by a highly glazed facade, which will serve to reduce the heating load.

In summer, the high quantity of solar radiation which enters at a low angle needs to be prevented from entering the space. This facade also has the main views over the immediate Engineering Faculty right through to the south of Nottingham which can only be fully exploited by a highly glazed facade. Considering the views, the dynamic response needed to respond to the incident solar radiation, the double skin facade best meets these needs for the south east facade and will be progressed further.

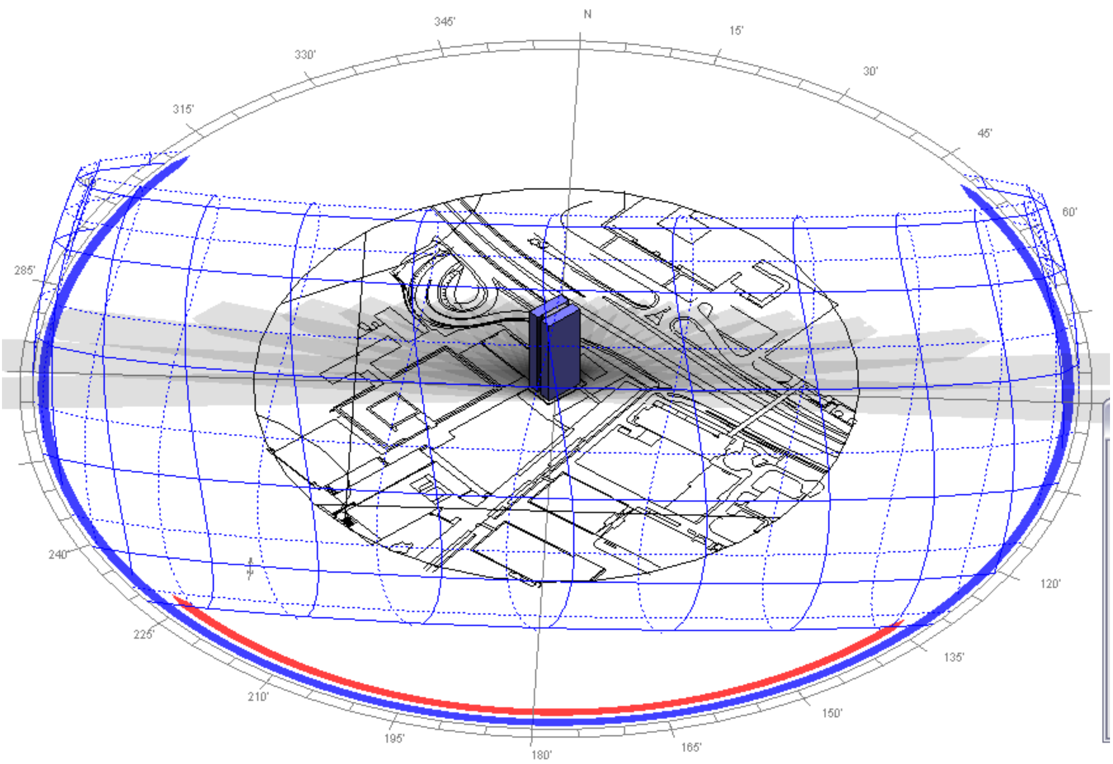


Figure 3.2 Sun path diagram for the Tower Building produced using Ecotect (Marsh 2010)

Examining the solar geometry for the north-east facade we can observe that it will only receive direct solar radiation in the summer at a low angle. In winter with the small quantity of incident solar radiation there will be little reduction in heating load and an envelope with a reduced U-value rather than high solar transmittance would be much more beneficial. In summer the low angle radiation could be intercepted by horizontal blinds, vertical fins or recessed detailing if necessary. The views from this facade are quite restricted since this facade faces a steep incline and the immediate buildings are not noteworthy. Either an alternating facade with a high insulative property or box window would be suitable since there are no significant views or solar radiation in winter to exploit. To further ratify the interpretive performance of the different facades an energy performance simulation is a useful way of accumulating the interrelated effects of changes in facade type on the heating, cooling and lighting requirements.

3.2. COMPARITIVE ENERGY PERFORMANCE ANALYSIS

There are a number of computational tools available for calculating the energy performance on a building. However, double skin facades require a great deal of work to model accurately and using sophisticated tools such as IES and TAS, it is time consuming to compare different facade concepts. To assist in the selection of the facade by way of quantitative data, a web based design tool, MIT design advisor (MIT 2009) can be used instead. This has been programmed to allow comparisons between different facade constructions, including double skin facades, to be carried out quickly and easily. In this case, it is required to compare different constructions and their associated energy needs against the Part L2 2002 notional building (DCLG 2006). The input geometry of the room analysed in the program is a 5 m x 5 m x 3.5 m high, in order to represent a cellular office with the London weather file. The facade constructions are a highly glazed single skin and a highly glazed double skin facade. The model also contains a 40% glazed facade with values for thermal, solar and daylight transmission similar to those specified for the notional wall in the NCM Modelling Guide (DCLG 2008) to provide an appropriate benchmark. For the ventilation system all of the simulations consider full air-conditioning with the exception of the double skin facade. It is considered that the double skin model can also provide mixed-mode ventilation, since natural ventilation is an option. The double skin model also considered an exposed soffit as it is based on a decentralised system, where a suspended ceiling is not needed to conceal ductwork. Further information on the program and model inputs is provided in Appendix D.

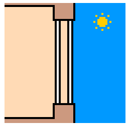
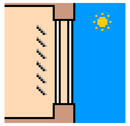
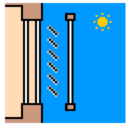
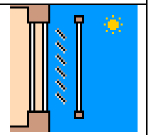
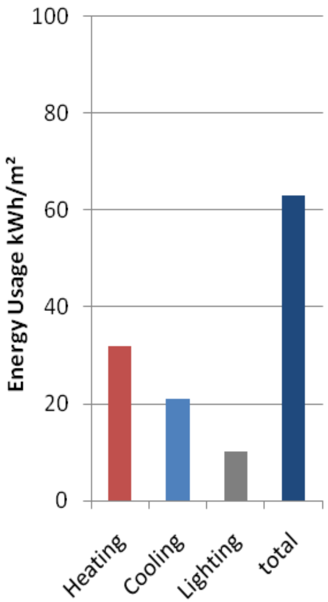
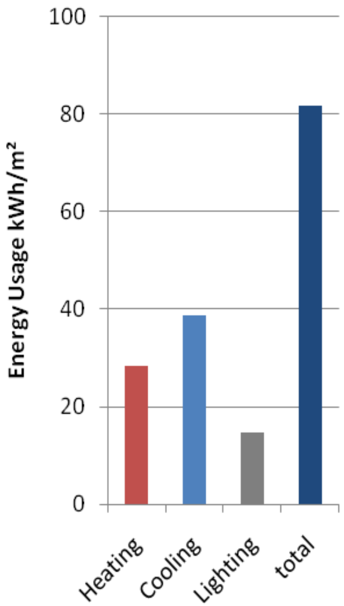
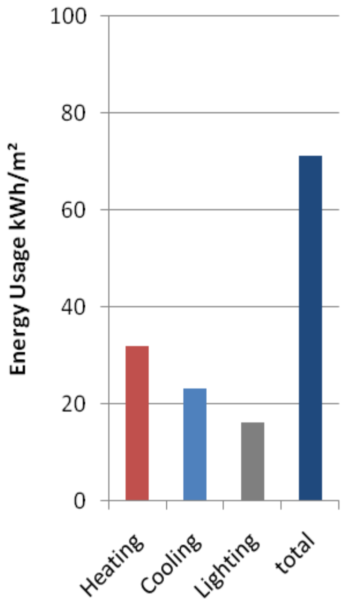
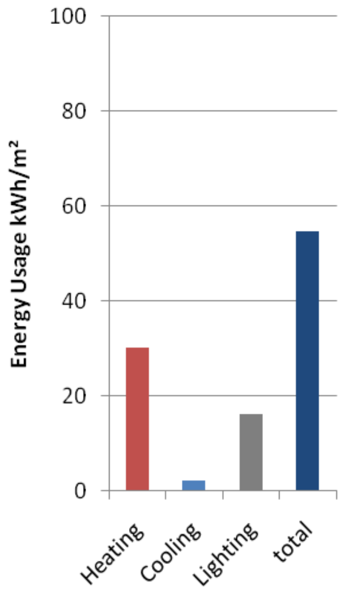
System	Reference (40% glazed)	HP Single Skin	DSF+Full Air Con	DSF+Mixed Mode
	40% glazed Blue coating 	85% glazed HP coating 	85% glazed HP coating 	85% glazed HP coating 
Winter Min (°C)	16	18	18	18
Summer Max(°C)	28	31	29	29
				

Figure 3.3 Energy Analysis Chart for Different Facade Systems (South East Orientation)

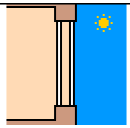
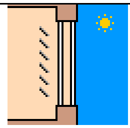
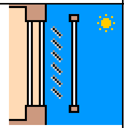
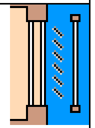
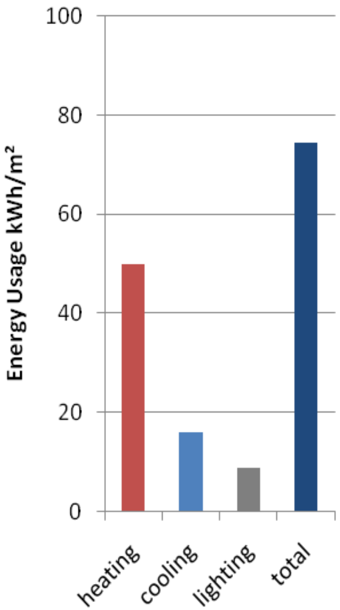
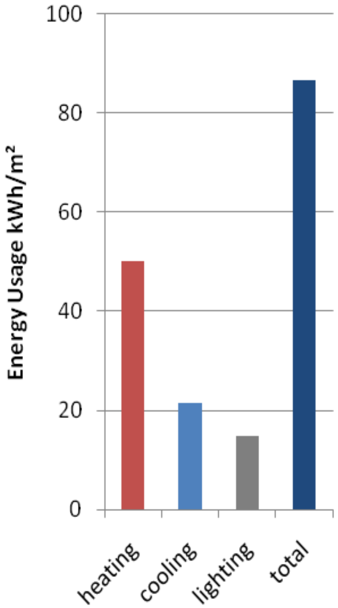
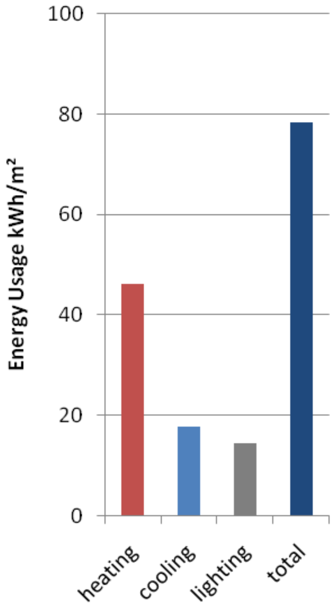
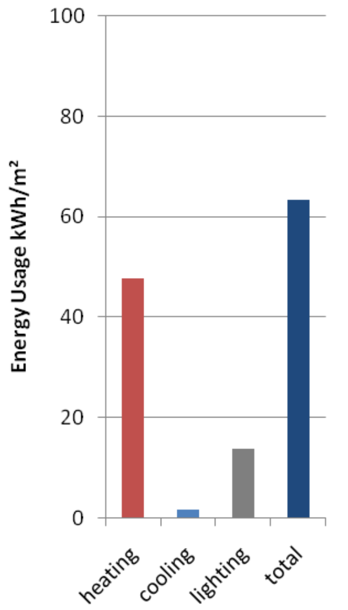
System	Reference	Single Skin + Int Blinds	DSF+Full Air Con	DSF+Mixed Mode
	40% glazed Blue coating 	85% glazed HP coating 	85% glazed low e coating 	85% glazed low-e coating 
Winter Min (°C)	18	18	18	18
Summer Max(°C)	29	28	26	27
Energy usage				

Figure 3.4 Energy Analysis Chart for Different Facade Systems (North West Orientation)

The results for the south-east facade in Figure 3.3 give an indication of how the facade is likely to perform against the 40% glazed notional wall. We can observe that the high performance single skin with internal blinds, has an increase in energy usage overall due to the marked increase in cooling load. The double skin solution fully air-conditioned model, which would afford greater solar protection reduces the cooling load, but increases the lighting energy due to the reduced light transmission created by the extra distance, layers, and coatings. The double skin facade mixed mode strategy however, has a lower overall energy usage as the cooling energy requirement is reduced by a greater amount than the additional lighting energy. The reduction in cooling can be explained by the availability of natural ventilation and an exposed slab which passive cooling. The overall reduction in carbon dioxide emissions compared to the notional wall in this case is 13%; a significant step towards the 2006 requirement of a 28% reduction overall of Carbon Dioxide emissions (the remainder would be taken up by building services improvements and possibly renewable energy provision). This demonstrates that a highly glazed facade for this orientation can have a reduced energy usage, compared to one with only a small proportion of glazed area, if the potential for the double skin facade to provide natural ventilation is fully realised.

The orientation in the simulations was then changed to north-west and initially used exactly the same facade parameters. The initial results for the north-west showed a much higher figure for heating energy for each of the different cases studied. In response, the high performance coating for the double skin facades was changed to a low-e coating to improve the heating and lighting energy figures (the high performance coating has a reduced solar and light transmittance). The single skin was changed to a low emissivity coating, however the cooling energy increased dramatically and the least energy usage arrived from the high performance coating. The results with the amended coating are shown in Figure 3.4. It may seem surprising that the heating load is similar for all the cases even though there is an increase in glazing area against the 40% glazed notional wall. This is attributed to the increase in area being offset by the lower U-value used in the HP single skin and double skin models. As with the south-east facade the mixed mode double skin facade has the lowest energy usage and provides a reduction in CO_2 emissions of 15% against the notional wall. This is again achieved by natural ventilation and an exposed slab providing passive cooling. The relatively high proportion of heating energy indicates that a reduction in U-value would be very beneficial by some of the options and will be explored further in Section 3.4.

Both facades are therefore suitable for applying a form of double skin facade. Only one facade can continue to be developed within the confines of the time and resources available at this stage. The south-east facade will continue to be developed as it has the more difficult task of avoiding overheating in the summer and has to adapt to much more diverse range of solar radiation conditions. Adaptations necessary to enable its use on the north-west can be developed once the south-east facade is fully developed using the same underlying system to reduce complexity and costs. An example of the design rationale are production cars which are designed on the same chassis and as much as possible similar parts, but can provide a wide range of performance from high speed performance to more frugal economic types.

3.3. DOUBLE SKIN VENTILATION AND OPENING STRATEGY

The complexity and breadth of design options of double skin facades is very high and has to satisfy a number of demands. The initial step in double skin design is to establish a successful cavity ventilation strategy to avoid overheating in summer. The ventilation strategy also has to be further developed to naturally ventilate the internal room to reduce energy usage and provide occupant amenity. With a suitable strategy in place, the actual dimensions of the units are to be decided upon carefully in coordination with the space planning of the room and construction logistics. The final consideration will be the access and maintenance arrangement to clean and service to keep the facade fully functional and to avoid falling foul of Construction, Design and Management (CDM) regulations (HSC 2007).

3.3.1. Cavity Ventilation

The importance of avoiding overheating in double skin facades has generated a wide range of concepts which can be categorised into types of partitioning, ventilation and cavity width implemented. The partitioning types commonly used are**:**

1. Multi-storey facade
2. Shaft-box facade
3. Single storey corridor facade
4. Louvered outer facade
5. Facade partitioned per storey with juxtaposed modules (cascade type)

(Intelligent Energy Europe 2007, p.Typology)

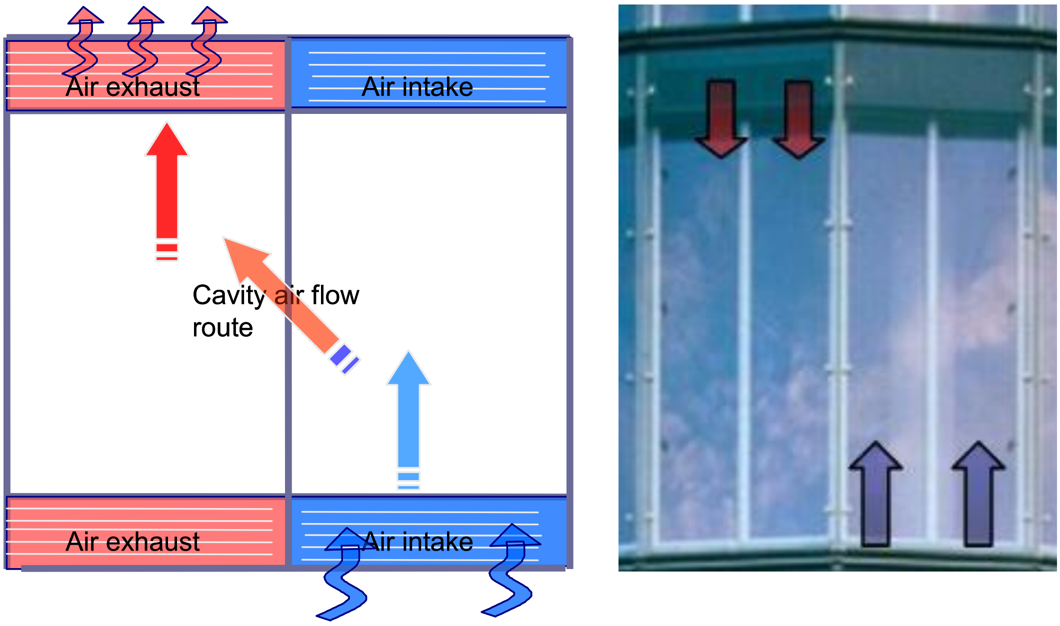
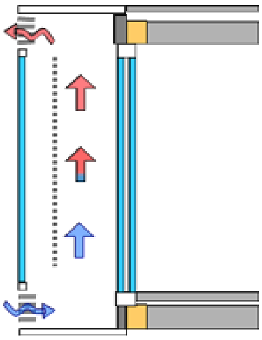
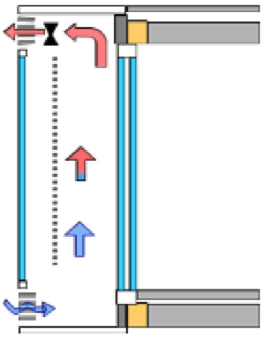
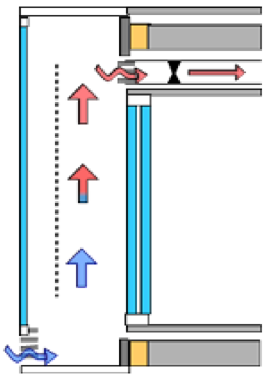
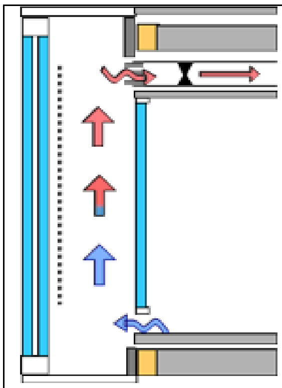


Figure 3.5 Cascade type double skin facade working principle and illustration, RWE Essen, Germany, Ingenhoven Overdiek and Partners, www.glassonweb.com

The first three options are suited to a building level design as they rely on the geometry and microclimate of the building. Implementing one of these options would create a high level of design development for each project. Options 4 and 5, the louvered and cascade type could be used on a cellular basis and work more independently from the building geometry and microclimate of the building. The high cost and reduced transparency of the louvered facade however make it undesirable. The cascade type facade is shown in Figure 3.5 and has the advantage of a reduced cost compared to the louvred facade, but ensuring a sufficient ventilation rate to avoid overheating needs greater attention.

Table 3.1 Ventilation concepts to avoid overheating and analysis for double skin facades

Type	Benefits	Drawbacks
 1. Natural Outside to outside	Least complex out of all the options Natural ventilation of the room available	Possible overheating of the cavity
 2. Mechanical Outside to outside	Overheating of the cavity avoided Natural ventilation of the room available	Cost and complexity increased with extract fan for each module
 3. Mechanical Outside to inside	Guaranteed extract rate Preheating of fresh air Good acoustic attenuation	Cost of ductwork and extra fan Suspended ceiling if exposed ductwork undesirable

 4. Mechanical Inside to inside	Guaranteed extract rate and stable cavity temperature Heated air can be recovered centrally Maximum acoustic attenuation through glazing	Cost of ductwork and extra fan Suspended ceiling if exposed ductwork undesirable

The ventilation mechanism to avoid overheating can be either mechanical or naturally driven. The different options available are depicted in Table 3.1 together with their benefits and drawbacks. The mechanical options draw air up through the cavity though an inlet louvre which can be internal or external and either back to the central air handling plant or straight out through the facade. The benefit of this type of system is that the air flow through the cavity is guaranteed, the risk of overheating eliminated and in the centralised version the heated extract air may be of some use. It also can avoid external openings in the outer skin to provide greater noise reduction. Both options however have an extra energy usage for the fans and an additional cost, in the case of the centralised system for the ductwork and extra fan, and in the localised option a number of additional fans. The centralised system also goes against the overall objective of eliminating the central plant. In terms of acoustics for the case study building, without carrying a full acoustic site investigation, the naturally ventilated outside to outside option could be considered to provide acceptable acoustic conditions based on other buildings in similar locations and the literature (e.g. Figure 1.11). To reduce energy usage and plant costs therefore, a naturally ventilated cavity should be investigated before adopting a mechanically ventilated solution to the issue of overheating.

Double skin facades generally fall into two cavity depth categories, *narrow* double skins which are less than 500mm and *wide* double skins which are between 500mm and 1500mm. Wider double skin facades can more easily avoid overheating and provide usable space for occupants to use and enjoy. However there are two major disadvantages from a commercial perspective to wide double skin facades. The first is the reduced transportation and construction efficiency. Since the wide units are mainly air it becomes uneconomic to transport a single unit and better to split the units into an inner and outer skin. They then need to be fully assembled on site before being lifted into place. The use of the site tower crane which is normally an issue on any congested site is also increased since a smaller number of units can be lifted and placed onto the floor before being installed onto the facade by the Facade Subcontractors own mini crane. The alternative is for exclusive use of the tower crane which will also attract a direct cost premium rather than an indirect cost associated with increased time and man hours for installation. The additional floor area within the cavity and cost premium is not reflected in the key performance parameter of net to gross floor area ratio, since the net floor area is taken up to the inside facade of the inner skin mullion. Minimising the depth of the double skin facade is therefore economically advantageous as there are material and construction efficiencies.

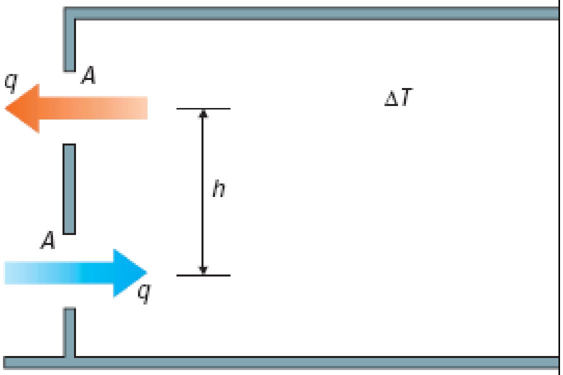
The advice given in the literature (Oesterle, Poirazis, Cook) and from the industrial sponsor, is that a double skin facade of minimum depth 300 mm and solar shading located closer to the external skin should avoid overheating. For greater confidence a calculation using the specific dimensions is needed.

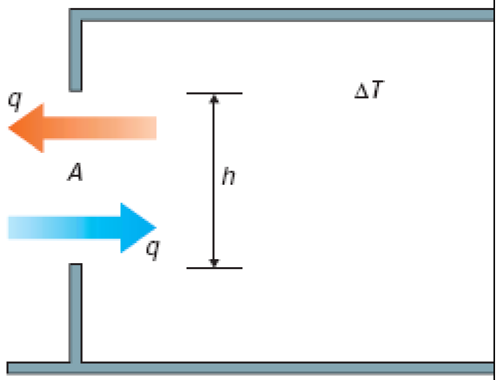
The calculation of openings required to each achieve certain air flows and avoid overheating in double skin facades is very complex and normally needs to be carried out with computational fluid dynamic software. With the use of Window Information Software (WIS) (WinDat Thematic Network 2004) however, an overheating check and the external openings sizes required can be calculated much more quickly and with sufficient accuracy. The model considered peak summer conditions in the UK, single storey cavity ventilation and a limit on the maximum surface temperatures of the inner glass of 30°C. The free area required was calculated at 20 mm high by 1100 mm within each bay which can be provided within the spatial limits of the spandrel zone. Therefore overheating in the cavity can be avoided by a single storey, cascade type naturally ventilated double skin facade, with the opening areas calculated and provides a solution which is not building specific. However, the double skin facade is not only meant to provide sufficient air flow in the cavity to avoid overheating, but also to provide natural ventilation for fresh air and free cooling for the office space which will be examined in the next section.

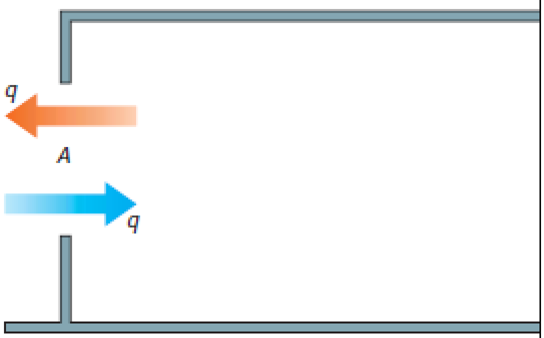
3.3.2. Room Ventilation

In the UK and Northern European environment, the outdoor conditions can be categorised into three periods; the colder winter months (-5 to 10°C), the mid-season temperate conditions (10-25°C) and the peak summer conditions (25°C+). Using a double skin facade there is also the additional condition of a sunny winter's day that should be considered. The ventilation strategy in each period will be examined in turn and a solution which meets the requirements of the different periods developed.

In the colder winter months, adequate levels of indoor air quality are required whilst trying to reduce the heating load which, with the low outside air temperatures means reducing the fresh air rate to a minimum. This can be achieved in a naturally ventilated system by providing trickle vents, or in a mechanical system by either providing twelve litres per second per person or ensuring the carbon dioxide concentration in the air is maintained below 1000ppm. Trickle vents are a more economical solution, but they will not ensure that the flow rate is achieved at all times, will increase the heating load since they will be introducing outside air at all times and could cause discomfort draughts. A mechanical system based on carbon dioxide levels or a set flow rate is therefore preferable in winter. During the peak summer conditions the outside air temperature is greater than the indoor comfort air temperature. Therefore the greater the introduction of outside air, the greater the cooling load. It is therefore a similar case to winter whereby guaranteeing the fresh air rate by the use of a mechanical system provides an improved energy performance and comfort conditions.

<table>
<tr>
<td>Dual vents – buoyancy driven


$A = q/Cd. \sqrt{(Ti+273/ \Delta T.g.h)}$
where Cd= 0.6</td>
<td>Single vent – buoyancy driven


$A = q/Cd. \sqrt{Ti+273/ \Delta T.g.h}$
where Cd= 0.25 (buoyancy)</td>
</tr>
<tr>
<td>Single vent wind driven


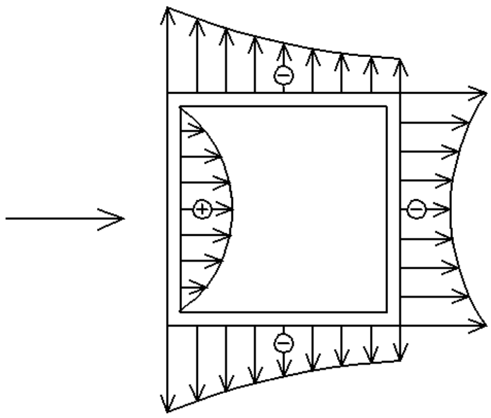
$A=q.C.U$
Where C is the wind pressure coefficient dependant on flow field, wind speed and opening geometry</td>
<td>Wind pressure coefficient distribution plan view

$C_p = (p_w - p_o) / (½ \rho V^2)$
Where p_w = static pressure at some point on the building (Pa)
p_o = free stream static pressure (Pa)
ρ = free stream density of (kg/m^3)
V = free stream velocity normally calculated at building height or other reference height (m/s)</td>
</tr>
</table>

Figure 3.6 Calculation of opening sizes for single sided ventilation in buoyancy and wind conditions (CIBSE 2005, p.46)

The mid-season condition is concerned primarily with ensuring there is sufficient ventilation to offset the internal and external gains in order to reduce the need for air-conditioning. This is greater by an order of magnitude than the fresh air requirement and can therefore be used as the required flow rate. The factors under the designers control for natural ventilation are the size of external and internal openings, their configuration and their opening effectiveness. Calculations to establish opening sizes can be found in CIBSE AM 10 (CIBSE 2005) with ventilation strategies based on stack or wind effects (see Figure 3.6). For low rise buildings calculations can be based on the stack effect solely as this is the dominant form and used for high rise buildings to provide a worst case scenario. For the outer skin we need to provide sufficient area not only to avoid overheating in the cavity, but also provide the necessary opening area required to provide ventilation for the internal room to remove the internal gains (see Figure 3.7).The recommendation in the UK for overheating analysis in the UK, is to consider the stack effect with a temperature difference of three degrees between inside and out, since buoyancy driven flows are reliable and for low building heights wind effects are small. The opening area required using this data is 2.26 m² and the area provided by a top-hung, bottom hung configuration is only 0.99 m² (see Appendix E). This analysis however ignores the effect of the outside air coming via the cavity and wind effects which may have an effect when considering a double skin facade and a medium or high rise typology.

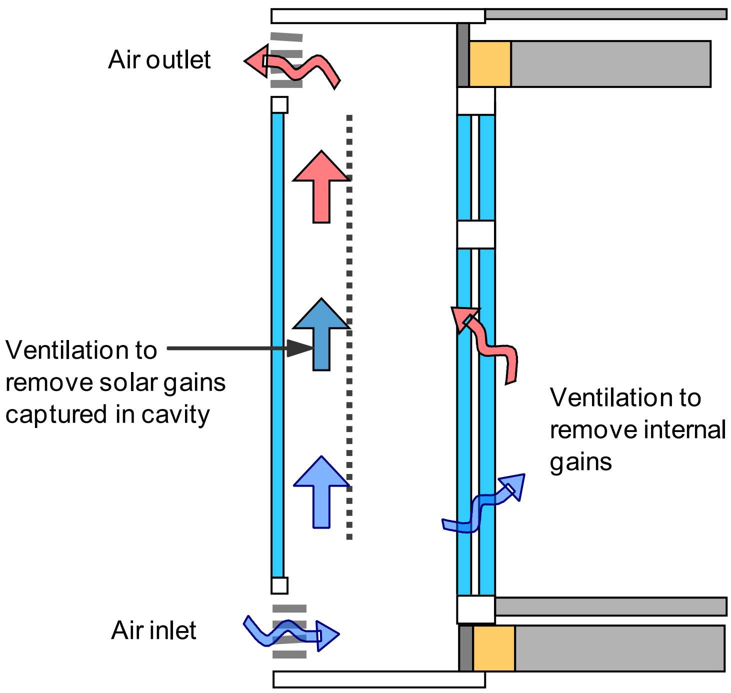


Figure 3.7 Flow requirements for naturally cooled double skin office

As described in Chapter 2, the double skin facade in summer intercepts solar gains when the cavity blinds are lowered very effectively. This raises the cavity air temperature above the ambient and in the absence of wind effects drives the solar heated air out and brings cool outside air. To provide the maximum amount of free cooling to the room, the ventilation flow path into, and out of the room should avoid the transfer of solar heat gain captured in the cavity, nor upset the advantageous flow pattern set up in the cavity itself. A detailed examination of the cavity air flow and temperatures is therefore necessary.

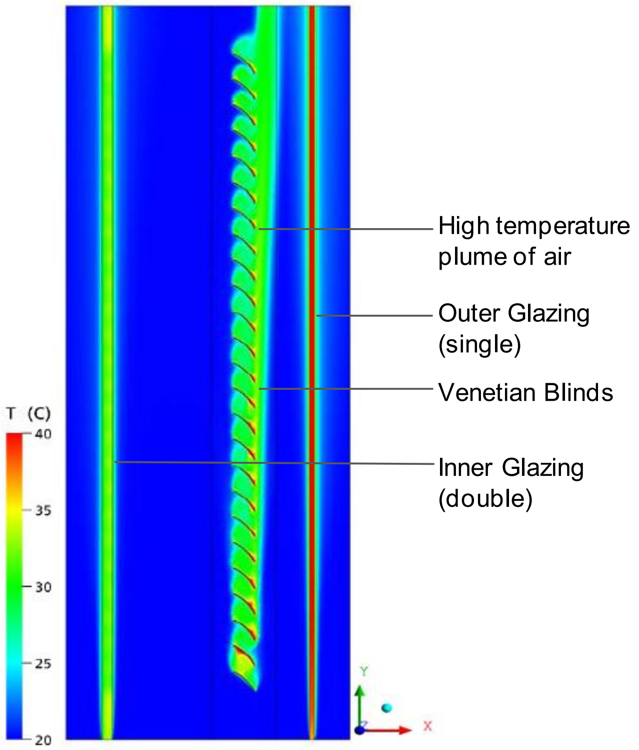


Figure 3.8 Temperature distribution in a double skin facade cavity (Ji et al. 2007)

A literature review of studies examining the cavity air temperatures and flow patterns has shown a horizontal as well as vertical stratification within the cavity (Ji et al. 2007). The hottest air in the horizontal is located between the venetian blinds and external skin (see Figure 3.8), with the air adjacent to the internal skin remaining much cooler and close to ambient conditions initially. The openings in the inner skin therefore need to maintain this horizontal stratification to prevent heated air from entering the room and maintain the vertical temperature distribution so as not to disturb the stack effect of the cavity. An opening configuration as shown in Figure 3.9 could be suitable, where a low level room air entry opening is located in the cavity inlet bay, as this can bring in cavity air which has not had a chance to heat up. The room exhaust air opening is located at the top of the outlet bay and opens into the cavity. This should prevent hot cavity air from entering and instead capitalise on the suction effect of the cavity and exhaust room air only. This opening configuration would work in a similar way during summer nights to provide night cooling of the thermal mass.

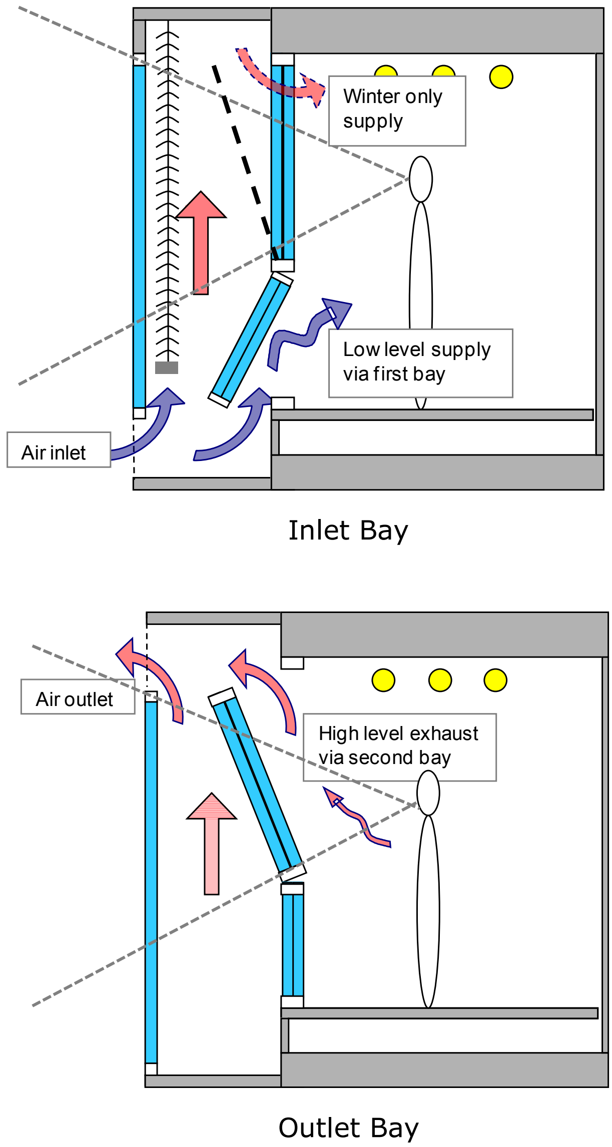


Figure 3.9 Scheme for opening configuration to ensure entry of cool outside air and prevent ingress of cavity hot air and enable an unobstructed view

On a sunny winter's day there is also potential for fresh air preheating since the cavity within the double skin facade collects solar radiation and warms the air within it. This can be warm enough to be comfortably introduced without causing draughts and save on heating energy and fan energy for fresh air. In this scenario the most beneficial opening strategy would be for only the top window in the inlet bay to be open as shown in Figure 3.9 (inlet bay). This should ensure that the fresh air has preheated in the cavity before entering the room. The opening configuration is therefore adaptable to the mid-season and sunny winter day conditions. Other aspects apart from the ventilation flow rate also need to be considered in the design of the openings.

Together with the air flow requirements we need to simultaneously consider the ergonomics of the window opening controls and the location of intermediate transoms. To provide controls in an accessible position, reduce the required opening force for manual operation and the stiffness requirements of the frame, it is advantageous to reduce the size of the opening by way of introducing a transom somewhere along the height of the glass to divide it into a fixed portion and openable portion. The metric handbook (Littlefield 2011, pp.2-6) gives a recommendation of between 500 mm and 1900 mm for the minimum and maximum heights of controls. To avoid disrupting views a clear area between 1.0m and 2.5m for able bodied persons and 0.9 and 1.2m for wheelchair users is recommended. The transom should therefore be located either at 0.9 m or above 2.5 m. A transom at 2.5 m would be beyond an accessible height and therefore a continuous transom at 0.9m high is to be implemented. Both openings still open into the cavity so the impact on the floor space will be minimal. The overall opening strategy is shown in Figure 3.9.

To verify the effectiveness of the opening configuration, computational tools were utilised due to their low cost, reliable results and reduced time requirements. No single tool could effectively model the double skin facade performance and so a dynamic thermal modelling tool VE IES (IES 2010) was used to gather data on the summertime energy performance, together with a commercial CFD package (Fluent Inc 2003) for the ventilation flow rates and WIS (WinDat Thematic Network 2004) for the double skin facade construction performance data. An additional Further information on the analysis can be found in Kilaire and Khan (2010) included in Appendix F. The results from the analysis are given in Table 3.2 and show that the natural ventilation strategy developed can be used for a significant duration of the year and reduce the energy required for cooling significantly.

Table 3.2 Number of hours and cooling load reduction for the mixed mode and fully air-conditioned cases (Kilaire & Khan 2010)

Model	Nat. vent only hours	Mech. Cooled hours	Cooling Load kWh/m²	Reduction %
Mixed mode buoyancy	1035	265	8.73	62%
Mixed mode wind	1209	91	3.35	86%
Fully air conditioned	-	1300	23.21	-

3.3.3. Ergonomics, access and maintenance consideration

An often neglected aspect of facade design is the access and maintenance strategy. A facade may look and function well once constructed, but if it cannot be accessed and maintained, it will rapidly lose its aesthetic appeal, functional capability and have a shortened lifetime. It is also the designer's duty under the CDM regulations (HSC 2007) to consider how hazards can be reduced or eliminated by those who clean and maintain their design. With the additional Active Environmental System components in the spandrel cavity, the access and maintenance arrangement has to be even more rigorous.

The access and maintenance requirements typical for curtain walls (CWCT 2005) are:

- Cleaning of the glass surfaces and louvers;
- Replacement of any damaged glass panels;
- Periodic inspection of joints and components.

A narrow cavity double skin façade is particularly problematic, as twice the number of surfaces needs to be cleaned, the presence of an additional skin makes internal or external only access difficult and a narrow cavity restricts access between bays inside the cavity[1]. In addition mechanical components within the spandrel area may need to be serviced or replaced.

The strategy for any given building is dependent on the availability of access. For instance buildings located adjacent to railways or busy interchanges may prefer internal access only. On the other hand some other occupiers may have security concerns and prefer external access to be provided instead. In

[1] A wide cavity allows movement and access between the bays which would reduce the cost of openings, but affects the acoustic attenuation. For a cellular office it would not provide sufficient acoustic privacy.

conversation with Buro Happold Facade Engineers the preference is for an externally accessed cavity to avoid disturbance to the office space. This complements the design of a facade focussed on providing an improved internal environment and one desirable for occupiers. However the basis for an internally accessed cavity should also be described in concept so as not to exclude a significant proportion of buildings.

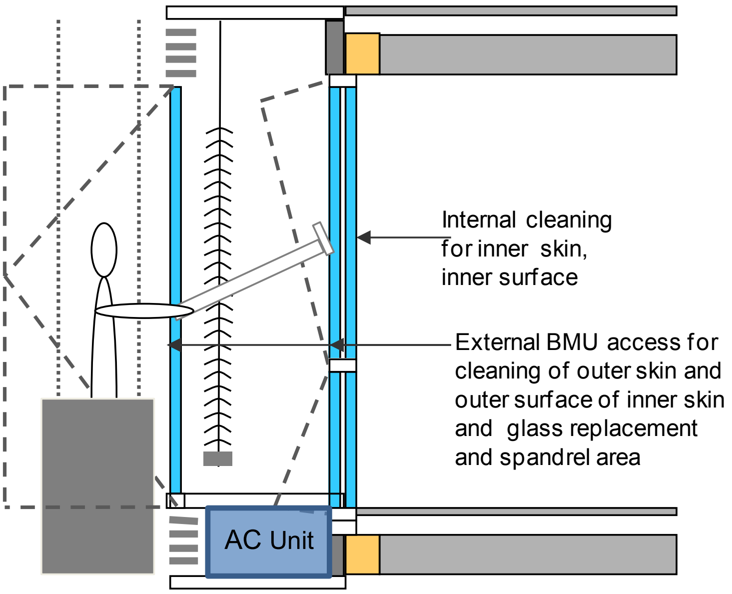


Figure 3.10 Externally accessed cavity concept

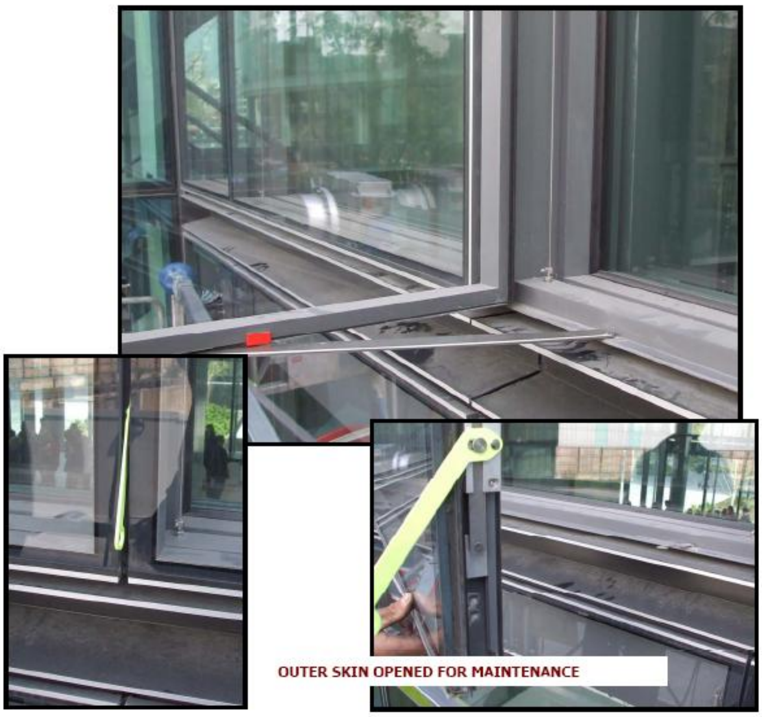


Figure 3.11 Externally access double skin cavity, 7 More London, Foster and Partners, pictures by Lindner Schmidlin (Buro Happold Intranet)

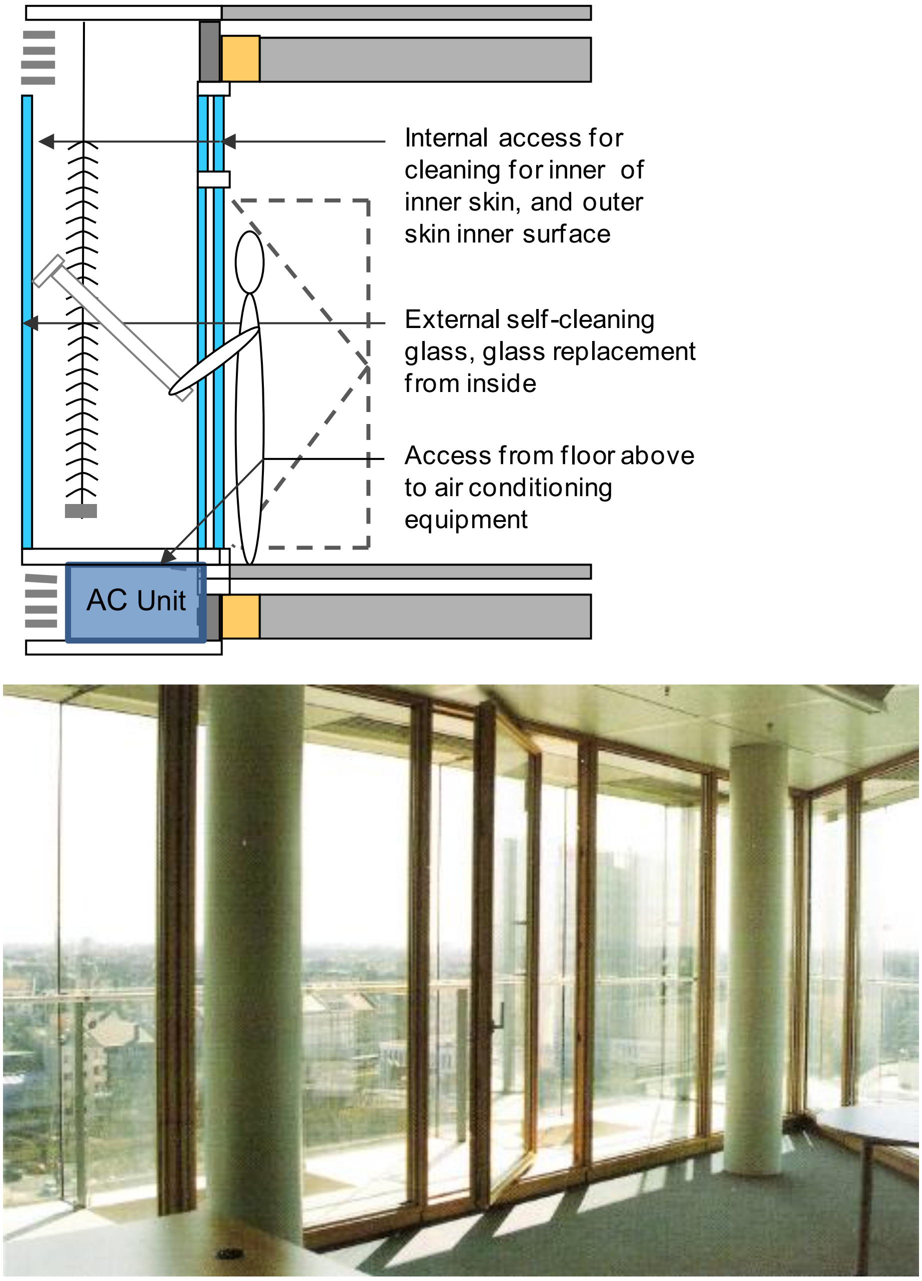


Figure 3.12 Internally accessed cavity concept and illustration, Stadttor, Dusseldorf, Germany, Petzinka Pink & Partner, (Heusler et al. 2001, p.176)

The access arrangement for an externally accessed cavity would maintain the top hung, bottom hung configuration for the inner skin. The external skin would then be openable with a side-hung window in each bay as shown in Figure 3.10. An example of this system is shown in Figure 3.11 and has a concealed opening mechanism for visual appeal when not in use. The strategy for an internally accessed cavity is shown in Figure 3.12 and requires a change to the internal opening design. To enable access a door height opening is required and so the transom location must be changed to high level. To still provide an advantageous air flow pattern as analysed earlier, the openings can be of the tilt-turn type to allow low level air entry and high level exhaust as with the externally accessed configuration. With the ventilation strategy and opening design established the next step is to address the other major performative aspects of day lighting, solar protection and thermal insulation.

3.4. DAYLIGHTING, SOLAR PROTECTION AND THERMAL INSULATION DESIGN

The three physical properties of light transmission, solar transmission and thermal insulation are interlinked. A good facade design seeks to optimise each, whilst keeping in mind their affect on each other as well as aspects related to cost, constructability and aesthetics. With the quantitative information gained from the ventilation and double skin performance analysis a more detailed holistic energy performance analysis could be carried out and is further detailed in Appendix G.

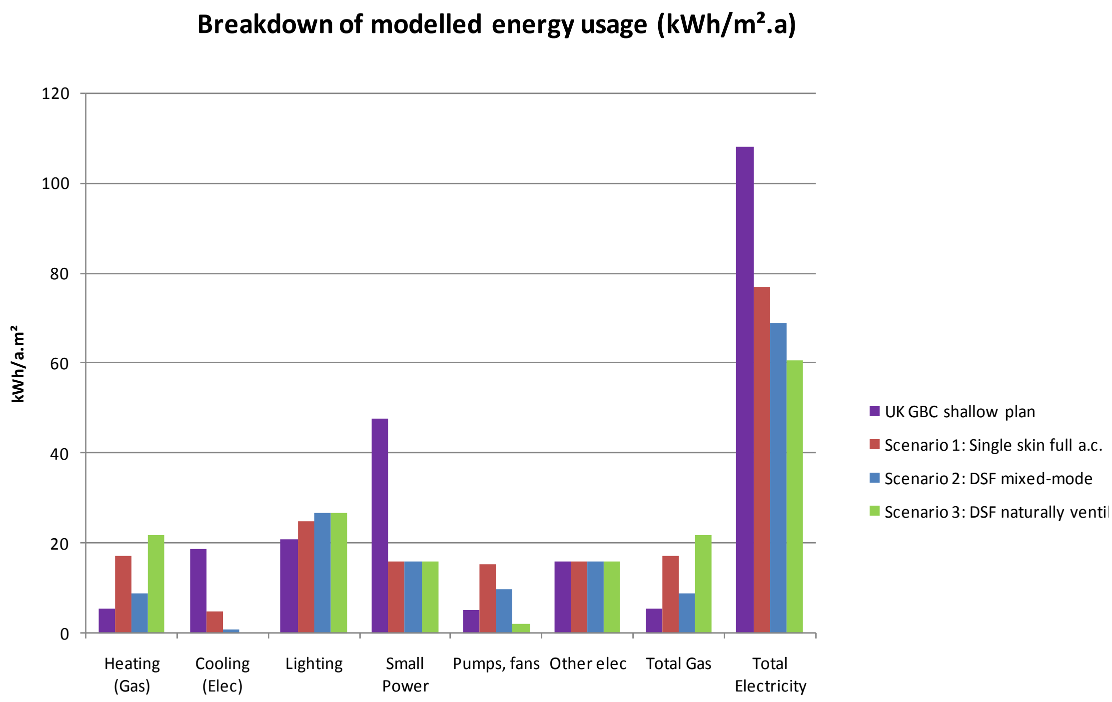


Figure 3.13 Breakdown of energy usage for a mixed-mode, naturally ventilated double skin facade, south facing (Kilaire & Oldfield 2010, fig.4)

The results of the energy usage for the double skin facade are shown in Figure 3.13 and compared to a published low energy office model for comparison (DCLG 2007, p.32). The lighting load consumes the most energy and therefore the potential for day lighting of the internal space needs to be maximised. The other major component of the energy usage under the facade designers control is the heating load which can be examined further. The first step due to the relative magnitudes is to examine the day lighting and then address the issues of glare protection, solar protection and thermal insulation.

A good day lighting design will promote occupant well-being, productivity and reduce the artificial lighting energy (see Chapter 1). At the same time it can be the cause of overheating and increase energy usage of cooling. The double skin facade as discussed previously is a way of alleviating this paradigm, but the day lighting strategy still needs to be detailed further. The major influences are light transmission, solar transmission, depth of the room, average internal surface reflectance and solar geometry. If the depth of the room that needs to be daylit is considered to be limited to six metres and the internal surface reflectance's to be beyond the scope of the design, the main design focus is on providing sufficient daylight entry through the facade and to ensure that this can be controlled through the different seasons and weather conditions to prevent overheating and glare. To enable a largely day lit space throughout the year an average daylight factor of 5% and minimum 2% is required (SLL 2005). The equation for the daylight factor is given below and shows that the factors under the designers control are the area of glazing and transmission factor (a high glazing obstruction coefficient is promoted by a good access strategy to clean it regularly).

$$\text{Daylighting Factor} = \frac{M.W.\theta.T}{A\,(1-R^2)}\ \%$$

where:

M = Glazing obstruction coefficient (dirt or barriers to light transmission)

W = Area of glazing

θ = Angle of visible sky

T = Glazing transmission factor

A = Area of internal surfaces

r = Area weighted average reflectance of room surfaces

(Littlefair 1988)

To assess the impact of different proportions of glazed areas and light transmissions, a daylight study was carried out in VE IES and is shown in Appendix H. Figure 3.14 illustrate the different proportions of glazed areas and Figure 3.15 the day light factor distribution. The analysis reveals that a 5% daylight factor can be achieved by both a fully glazed and two thirds glazed facade for the room size considered. In terms of uniformity, the two-thirds glazed facade performs better. There is however, a benefit of increased view through providing a fully glazed facade and should therefore be the primary option with a two thirds option as a viable alternative for reduced heat loss. For southerly orientated facades it should be noted that the issue of highly glazed areas is not as detrimental to the heating loads as northerly orientations, since solar radiation is available in winter to reduce the heating load as shown in Figure 3.3 and Figure 3.4 previously. An aspect that should also be considered in respect to daylight is the lower solar altitude during winter and the prevention of discomfort glare.

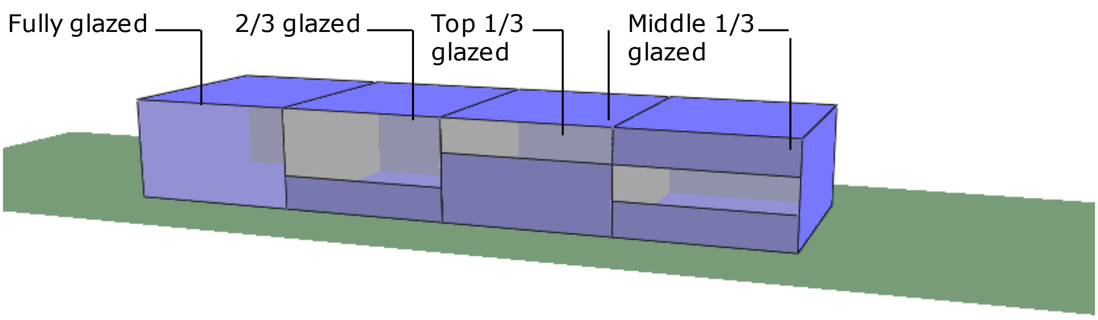


Figure 3.14 Model representation showing varying glazing sizes and positions

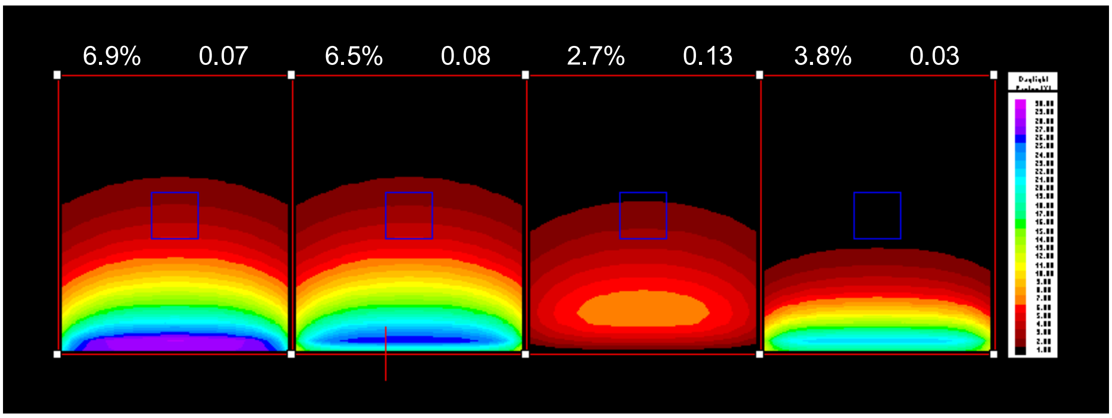


Figure 3.15 Contour diagram of daylight factors with average daylight factor (%) and uniformity (minimum/average) values indicated

Glare can be caused by direct sunlight shining into the eyes of occupants or the sunlight reflecting off surfaces in an occupants view field. The control of glare in winter and summer due to solar geometry and the energy balance is quite different. In winter, the sun is at a low altitude, which could cause direct glare and the entry of solar gain into the room is beneficial. Using the interstitial blinds to control glare would reduce the solar radiation entering the room, so internal roller blinds are preferable. To maintain admittance of daylight level, they should ideally be located in the lower two-thirds and the upper third used to reflect daylight deep into the room. The reflection could either be by a light shelf or as part of the interstitial blinds with the profiles in the upper third shaped to redirect light. Since a light shelf would be quite obstructive to the facade aesthetic, the redirecting blinds are the preferred option. In winter, the internal roller blind would be under occupant control, as they may enjoy the feeling of direct radiation or it may cause discomfort. This configuration is shown in Figure 3.16.

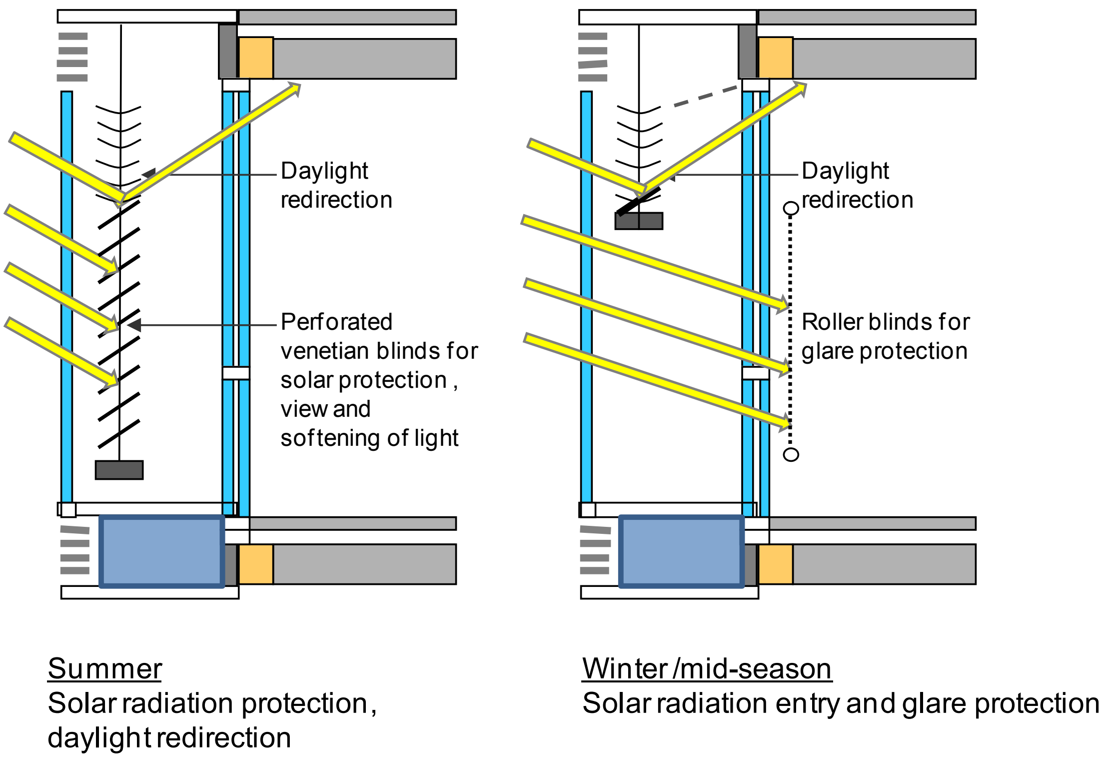


Figure 3.16 Solar control in winter and summer

In summer, the solar gain associated with direct solar radiation is unwanted so the interstitial blinds can be used. This would avoid also glare provided the blinds do not reflect light onto surfaces in the view field. To maintain some view and prevent a harsh shading effect, perforated blinds are proposed to allow the view to be maintained and some daylight to filter through. The lowering of the interstitial blinds in summer would be based upon the room air temperature exceeding 23°C to ensure the double skin facade reduces solar gain when required in summer. The configuration is shown in Figure 3.16.

The principle heat loss routes for a typical building are infiltration, ventilation and transmission. The typical breakdown for a design winter day[2] is shown in Figure 3.17. The relatively small infiltration loss assumes a value of 0.2 air changes per hour (ACH) as suggested by CIBSE. In a proprietary curtain wall system infiltration can be relied upon to comply with 0.2 ACH as the system has been through validation procedures to ensure the design and actual product is compliant. The most critical area for any envelope system in achieving air tightness is the interface between different systems and the penetrations for mechanical and electrical services. In a fully prefabricated system this can be resolved to some extent by the quality and precision in the factory environment, but would also need to be considered in the environmental system design in Chapter 4.

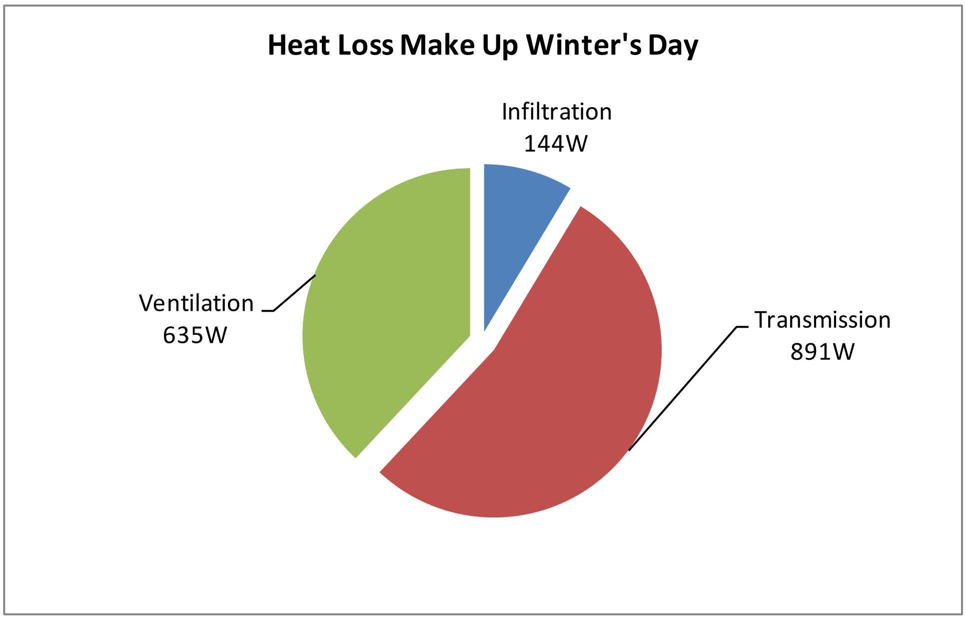


Figure 3.17 Pie chart of heat loss make up for design winter condition for the proposed facade concept

The ventilation heat loss is governed by two components the temperature of the outside/incoming air and the air flow quantity. It is normally reduced by utilising a mechanical heat recovery system which will be discussed in Chapter 4. The

[2] Outside temperature -4 °C, Internal temperature 21 °C, Infiltration 0.2 ACH, Fresh Air Rate 24 l/s, Glazing 1.4 W/m²K, Wall 0.3W/m²K, Glazed Area 4.8 m x 3 m, room size 4.8 m x 6 m.

double facade and opening design can also contribute to the reduction during sunny winter conditions as discussed in Section 3.3.2.

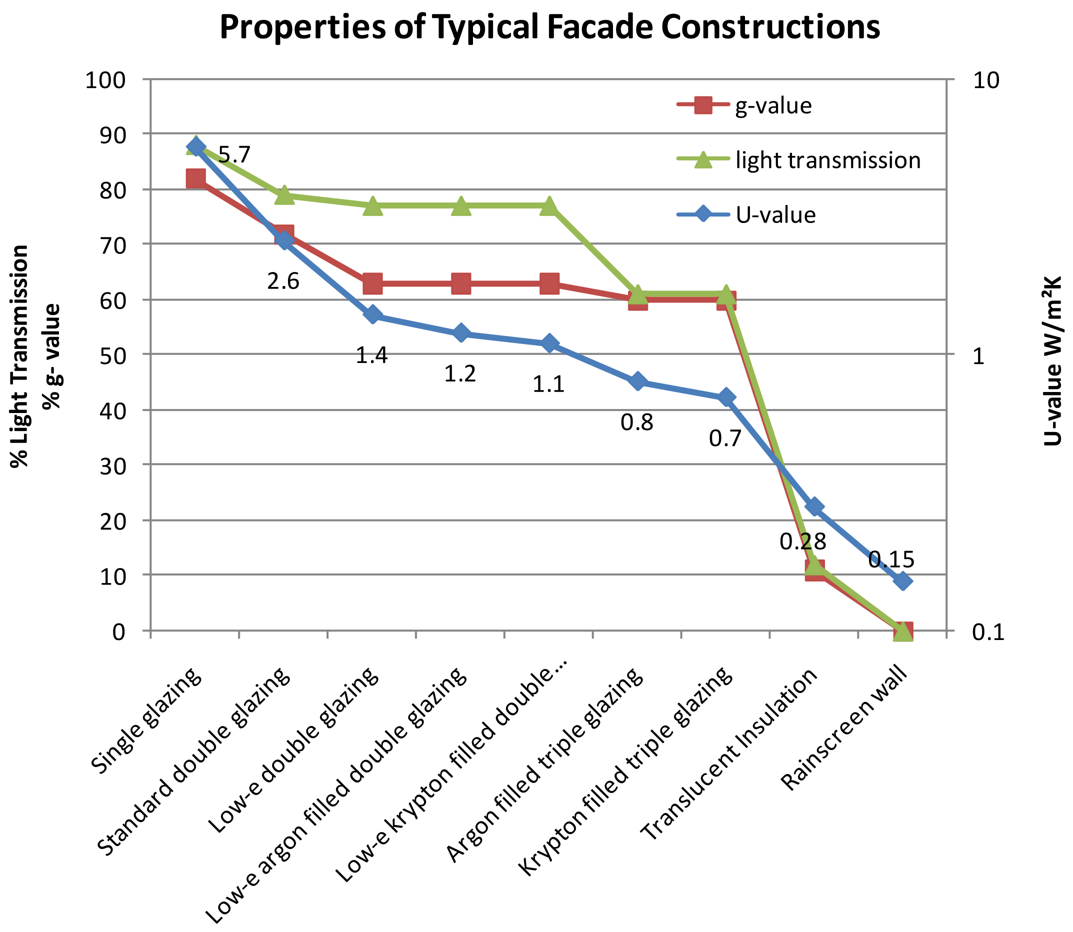


Figure 3.18 Properties of glazing and opaque constructions. Glazing values refer to centre pane U-values.

The transmission loss through the facade is related to the overall U-value and the temperature gradients set up. Reducing either of these will be beneficial in reducing the heating load. For a highly glazed facade the most dominant influence on the overall U-value are the glazing units and the frame. The different glazing unit U-values that can be achieved through different constructions, coatings and cavity fillings are shown in Figure 3.18 together with solar transmission (g-value) and light transmission values. The most common configuration used today is a 6mm outer pane, 16mm cavity argon filled cavity and 6mm inner pane with low-e coating, as modelled in the previous energy performance analysis. Further reductions in the centre pane U-value, can be achieved either by a krypton filled cavity instead of argon, or an additional pane of glass; both however are problematic. Krypton is approximately 200 times more expensive than argon which makes it hard to justify based on the modest reduction in U-value unless a narrow glass unit is advantageous.[3] An extra pane of glass to create a triple glazing unit increases the weight and depth of the unit, making openings and framing more bulky as well as reducing the light transmission quite significantly and hence increase the lighting load reducing the day light working potential for occupants. In terms of U-value, both options still compare poorly with a well insulated wall (U-value 0.15W/m²K) and for this reason the low-emissivity 6-16-6 double glazed unit will be specified. In future permutations to meet more stringent criteria, the use of translucent insulation could be considered, as it can provide a significantly lower U-value of 0.28W/m²K does not have as great an effect on the transparency as opaque insulation and allows some day light through.

Table 3.3 Comparison of different materials suitable for glass framing

Frame Type	Young's Modulus	Thermal Conductivity	Typical Frame U-values
	G.Pa	W/ K.m	W/m^2K
Softwood	7	0.13	0.9
Al Alloy	72	160	1.8
Steel	210	50	-
PVC	3	0.17	0.9
GFRP	23	0.32	0.8

The frame U-value can be a major factor in the overall U-value if it occupies a significant proportion of window area. With the high number of openings in the current design, the frame occupies 24% of the facade area. It is therefore worth examining ways in which this can be reduced by selection of a material with a low thermal conductivity. The main material choices for framing and curtain walls are shown in Table 3.4. Apart from thermal conductivity, an important parameter where large glazing units are required is the Young's Modulus in order to keep the profile dimensions small. From this perspective Steel, Aluminium and GFRP are the most suitable. For unitised construction methods the integration of interlocking gaskets and screw holes to enable ease of assembly is an important consideration. In this respect steel is a difficult material to work with as its high Young's Modulus and high extrusion temperature make it

[3] In period properties for example narrow glass units can replace the existing single glass panes without replacing the frame

expensive to extrude into complex shapes. Aluminium and GFRP on the other hand can be made into complex shapes by the extrusion or pultrusion processes respectively. The extrudability of Aluminium also allows the incorporation of thermal breaks into the profile overcoming its high thermal conductivity and surpassing steel. Plastic thermal isolators integrated into the profile as shown in Figure 3.19 can provide frame U-values of 1.2W/m²K matching the glass units specified earlier. To reach lower levels of frame U-value substantial further development work is required beyond the scope of this thesis and should be considered in the next development stage. A potential solution currently adopted on stick systems would be to use GFRP for the pressure plate which has achieved a frame U-value of 0.8W/m²K.

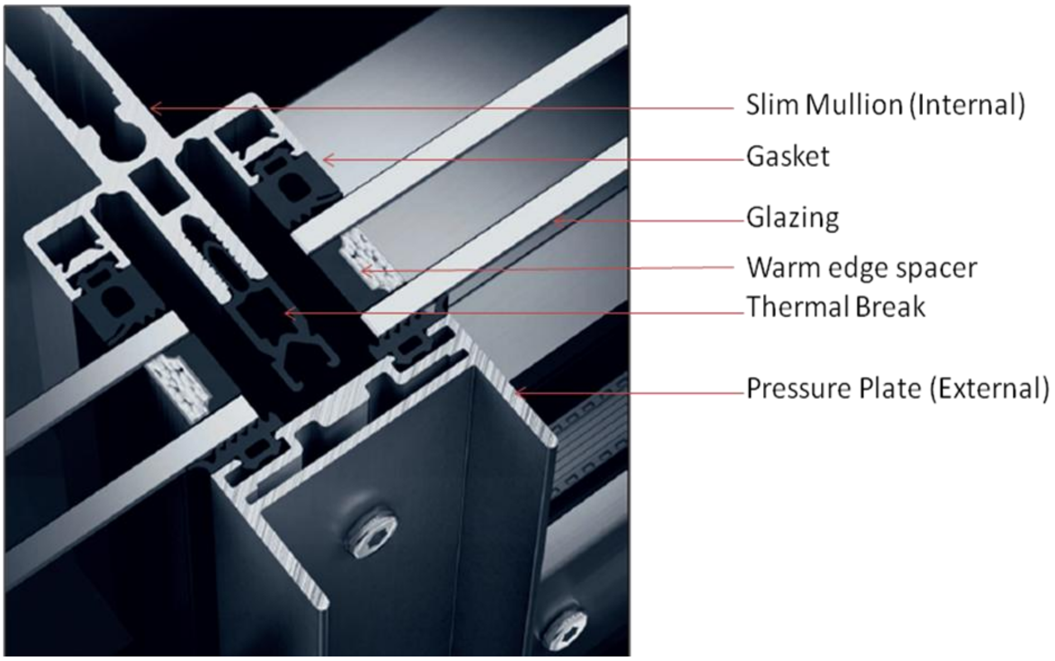


Figure 3.19 Thermal break integration into aluminium pressure plate (www.schueco.com)

In contrast to the inner skin the main performance requirement of the outer skin is to maximise as much visible light and solar heat radiation entering the cavity to reduce the use of artificial lighting and winter heat loss. The radiation transmission properties for a single glass unit are affected by the thickness, glass properties and any coatings. For strength an 8mm glass unit is required, which when appeared through the other units would give a green tinge to the glass which may not be required. This can be reduced by specifying low-iron glass. Uncoated glass can be used as any coatings will degrade the radiation properties and are not necessary.

During the winter, the heating load could be minimised by reducing the air flow through the cavity to a minimum. The effect of restricting the air flow through the cavity by completely reducing the opening area in the external skin was analysed in WIS. This was found to have only a small effect on the winter night time U-value, which is when the majority of the heat loss occurs. The use of dampers to achieve this is costly and introduces extra complexity for a small benefit and will therefore not be implemented.

In the UK climate, thermal insulation primarily affects the heat loss, but the high cavity temperatures in a double skin facade could lead to unwelcome transmission gain in summer. To examine the affect WIS was used to check on the surface temperatures of the glass. This revealed that the temperatures were not significantly higher than a single skin comprised of a double glazing unit with internal blinds. If the cavity depth was reduced, a case for using triple glazing would be strengthened, but in this case the present '6-16-6' configuration is acceptable.

They type of glass treatments required are influenced by the location of use and the environment. As the internal glazing is full height, BS 6206 requires that the glass is safety glass which can either be toughened glass or laminated glass on the inside pane. Since the cavity is accessible similar requirements apply to the outer pane. To keep the thickness of the glass lower toughened glass is preferable. The external skin is also full height, but since it is a barrier it needs to provide some post breakage containment and must therefore be laminated. With the high temperatures occurring between the blinds and the external glass, thermal stress could be an issue and therefore both laminates in the external skin should be heat strengthened.

The section has examined and developed the day lighting, solar protection and thermal insulation properties of the double facade. The day lighting design through the use of internal and external blinds has enabled a high daylight factor whilst controlling the solar gain and glare. In terms of thermal insulation, the transmission loss has been difficult to reduce without having consequences on other areas of the design. The most suitable area for further work is the framing which currently needs to be based upon aluminium alloy, but other materials or combination of materials should be looked at in the next development stage. The make up of the glass units has also been specified to satisfy both thermal and glass safety requirements. With energy usage now minimised, improvements to the overall energy performance can be made through its energy generating potential.

3.5. INTEGRATED ENERGY GENERATION

Two forms of input energy are normally needed in offices; electrical and thermal. In the proposed Active Environmental System the thermal requirements are to be met by either an air source heat pump or electrical heating; both require electrical input energy.

Table 3.4 Capital costs of different renewable options (DCLG 2007, p.48)

Type	Cost per kg of CO2 saved each year
Solar PV	£14.78
Small scale wind	£12.50
Biomass CHP	£1.15
Large Scale Wind	£1.02

Generating electricity through renewables is particularly beneficial since electricity in the UK is derived mainly from the burning of fossil fuels of gas and carbon, (DECC 2009, p.table 3) which are rising in cost and have a high carbon dioxide intensity. Even without the damaging consequence of using grid supplied electricity by 2019 all UK offices will need to be self-sufficient in their regulated energy needs and with the use of an air source heat pump electricity will be the only energy source used. At a site and building scale, the choice of technology is very much dependant on the available resources, economics and local politics. For the case study at the University of Nottingham, it should be commented that very few of the new buildings have integrated renewable energy generation, yet the University has aspirations to move towards carbon neutral performance (Estate Office 2010, p.18). The reason is the University has the land and wind resources for providing large scale wind turbines which are the more cost effective renewable energy generation option as shown in Table 3.4. Current plans include for three 125m tall wind turbines located along the River Trent (Utton 2011) which will provide 40% of the Universities target reductions required for 2015. The majority of urban office developers do not however have the opportunity to install large scale wind turbines and building integrated technologies are the only option.

Table 3.5 Module efficiency, temperature coefficient and expected life for different PV technologies (Agrawal & Tiwari 2010)

PV technology	Module efficiency η_{ref} (%)	Efficiency correction coefficient ϕ_{ref} (/°C)	Expected life years
Mono-crystalline Silicon (c-Si)	16	0.0045	30
Poly-crystalline Silicon (p-Si)	14	0.0045	30
Amorphous Silicon (a-Si)	6	0.0020	20
Cadmium Telluride (CdTe)	8	0.0025	15

The three main options for onsite generation are photovoltaics (PV), micro-wind turbines and combined heat and power (CHP) plant (DCLG 2009, p.88). For integration into a facade the most suitable option is photovoltaic technology. Photovoltaic cells generate electricity with zero emissions of CO2, SOx, NOx or any other gases associated with global warming and atmospheric pollution. Their working principle is based upon the conversion of solar radiation into electrical radiation through the use of semi-conductor technology. There are number of different PV technologies being developed, those that have reached market maturity are shown in Table 3.5, together with their performance characteristics. However, a decision on which type to use and how they are to be integrated also needs to consider their visual and light transmission properties.

Monocrystalline

Polycrystalline

Amorphous thin film

Cadmium Telluride

Figure 3.20 Appearance of different photovoltaic types

The different photovoltaic types have different colours and geometry as shown in Figure 3.20. Polycrystalline silicon in particular has a visible crystalline structure in various shades of blue whereas the others are uniform in appearance. To provide transparency to the modules the cells can be spaced apart to allow some light penetration. The different options for integration of the solar cells into the building facade could be either as part of external shading, the external skin or the cavity blinds as shown in Figure 3.21.

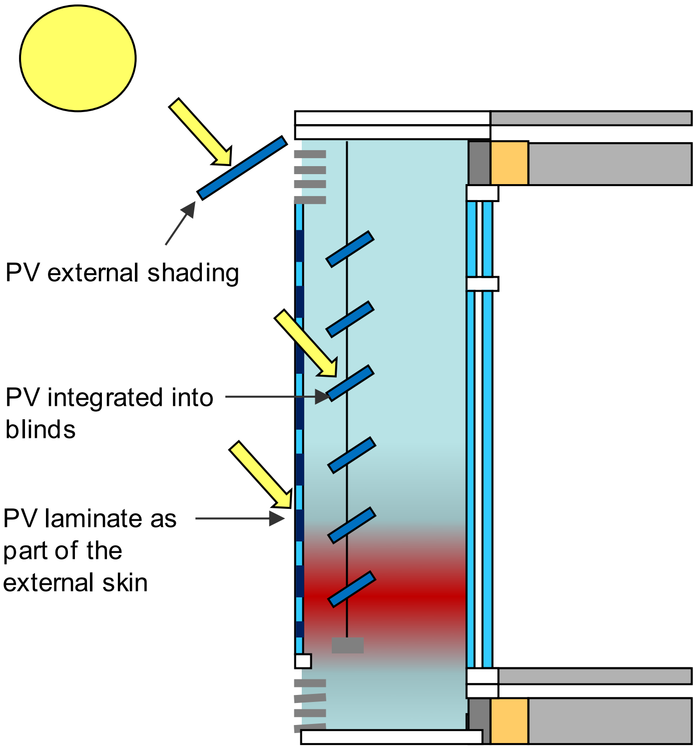


Figure 3.21 Options for photovoltaic integration into the facade

The external shading option would achieve the highest radiation levels as it could be tilted at an angle, but would disrupt the smooth aesthetic of the facade. The integration into the blinds would provide the least disruption to the facade and could be at an angle, but the high temperatures towards the top of the cavity and the light transmission loss through the outer skin would reduce the efficiency of the solar cells. Integration into the external skin would maintain the smooth external appearance. To provide transparency and not affect the daylight factor the photovoltaic modules should be limited to the lower third of the glass and spaced apart. Being located in the lower third, the cavity air temperature would also be close to outside air temperatures and provide a favourable cooling affect to prevent degradation of the performance at high temperatures. With the operating temperature close to outside air temperatures the PV type could be any of the options outlined depending on the quantity of renewable energy generation and transparency desired – an additional benefit of a double skin facade. At the back of the PV modules the glass should be either screen printed or fritted to provide a more desirable aesthetic from the inside.

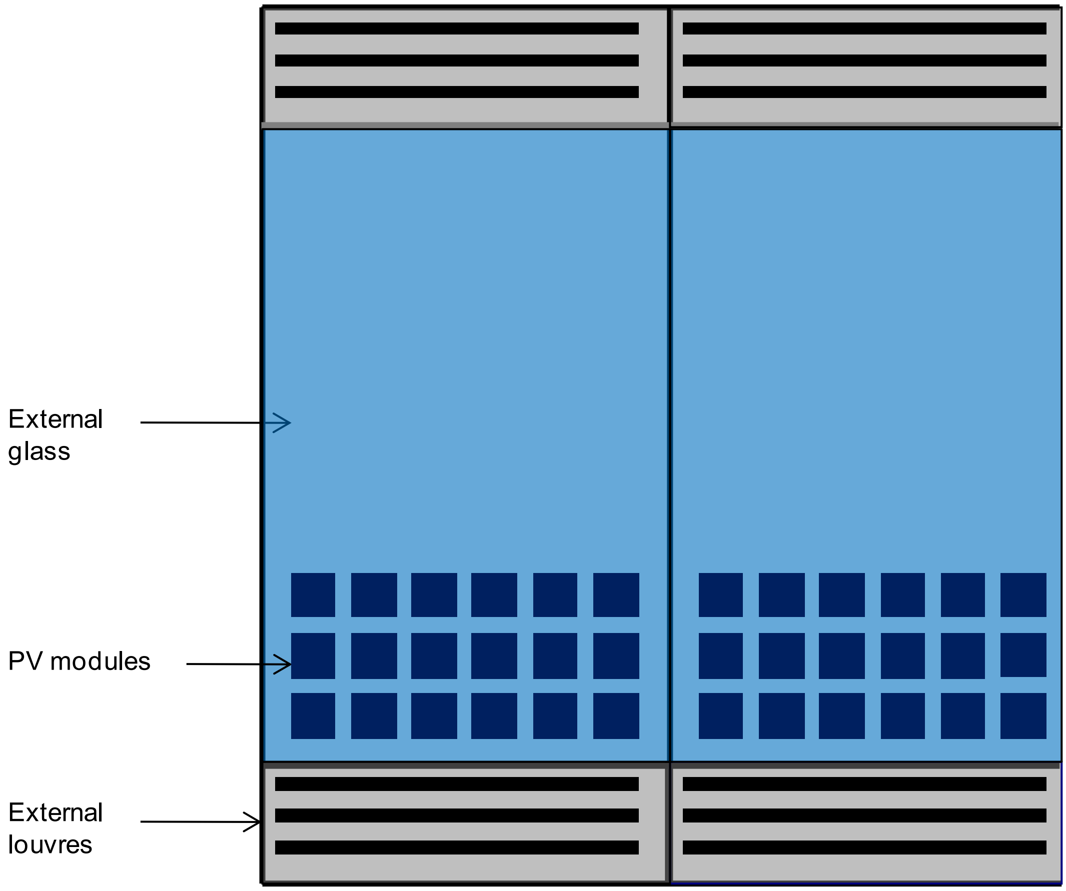


Figure 3.22 Photovoltaic integration into the external skin concept

The main barrier to the inclusion of PV modules is the integration into the well established supply chain of curtain walling and the interface required between the facade element and integrated services element. The curtain wall profiles will need to allow for the wiring and ideally wired during fabrication to electrical isolators ready for the simple connections to an inverter and the electricity network on-site.

Building integrated energy generation for the case study building is not required since the University has much more economical means of renewable energy generation. However the option to integrate renewable energy generation has been examined and the conclusion is that photovoltaic's integrated into the lower third of the outer skin provides a solution which balances energy performance with visual performance.

3.6. SIZING OF UNITS

The size of the prototype facade unit is a balance between maximising the size for reduced number of installation operations and reducing the size for ease of manoeuvring (through weight as well as a reduction in size). The starting point is the dimensional coordination followed by transportation and lifting considerations.

The width and height of the unit together with intermediate glazing bars is influenced by the planning configuration of the office and construction logistics. The width of the unit should tie in with the partition spacing to avoid unsightly partitions interfacing with glass instead of a mullion. The British Council for Offices (BCO 2009) recommended mullion spacing is 1.5 m. It is stated that this 'has proved economic' and can produce a 3 m office, which is divisible into 0.6 m modules for standard ceiling and carpet tiles. The generic recommendation is not a strong argument however, as almost all suppliers and fabricators of curtain wall profiles can provide considerable flexibility in the dimensions and profile sizes, and in many existing projects this spacing is not adhered to. For the office spaces being considered, (a mix of spaces to allow den and club configurations, see Section 1.2.1) the smallest partition spacing is for a two person cellular office approximately 4.8 m wide using dimensional coordination. It can also be advantageous to keep to a 0.6 m divisor to accept standard tiles. The space availability and efficiency during transportation is also a major consideration. A standard articulated truck has a spatial dimension for carrying of goods of 2.5 m wide, by 3.2 m high and 12.0 m long. A unit therefore of overall width of 2.4 m, with each bay 1.2 m would utilise the space effectively, is divisible into 0.6 m and two units would give 4.8 m an acceptable width for a two person offices.

The height of a prefabricated facade unit is dependent on the floor to floor height and is normally kept at a single storey for ease of installation and deflection purposes (see Section 2.7). The storey to storey height comprises of the floor make up and the finished floor to underside of ceiling/slab. To provide a high daylight factor for a 6 m deep office, a glazing height of approximately 2.4 m is needed, for indirect artificial lighting a minimum of 2.5 m is required. The British Council for Offices (BCO 2009) recommended height is slightly higher, between 2.6 m for shallow plan offices and 3.0 m for deeper plan offices. A ceiling height of 2.6 m will be used to reduce costs at this stage. A more generous height should be considered in future as it does improve the quality of space. To allow for a floor make up of a 200 mm raised floor zone and a 300 mm thick slab, a floor to floor height of 3.1 m is derived. The unit weight as a result of these dimensions was estimated and is below the limit for cranes and glass manipulating units for external or internal installation. Using a conservative crane limit of 500 kg, (lorry mounted telescopic crane (Chudley & Greeno n.d., p.188)) and considering the glass weight only with dimensions of 2.4 m (wide) x 2.6 m (high) for the inner and outer skin, the weight of the unit is estimated at 432kg; below the 500 kg limit with excess to allow for the HVAC equipment (the glass size is overestimated to take into account the aluminium). Once more precise dimensions and weights are known for the aluminium profiles, glass and HVAC are known this can be reviewed (see Chapter 7). Based on the information available at this stage, the size of the prototype is set at 2.4 m wide, 3.1 m high and from Section 3.3.1 a cavity depth of 0.3 m. With the overall size established the next stage is to develop the design of the profiles and frame itself to ensure the component meets structural performance criteria.

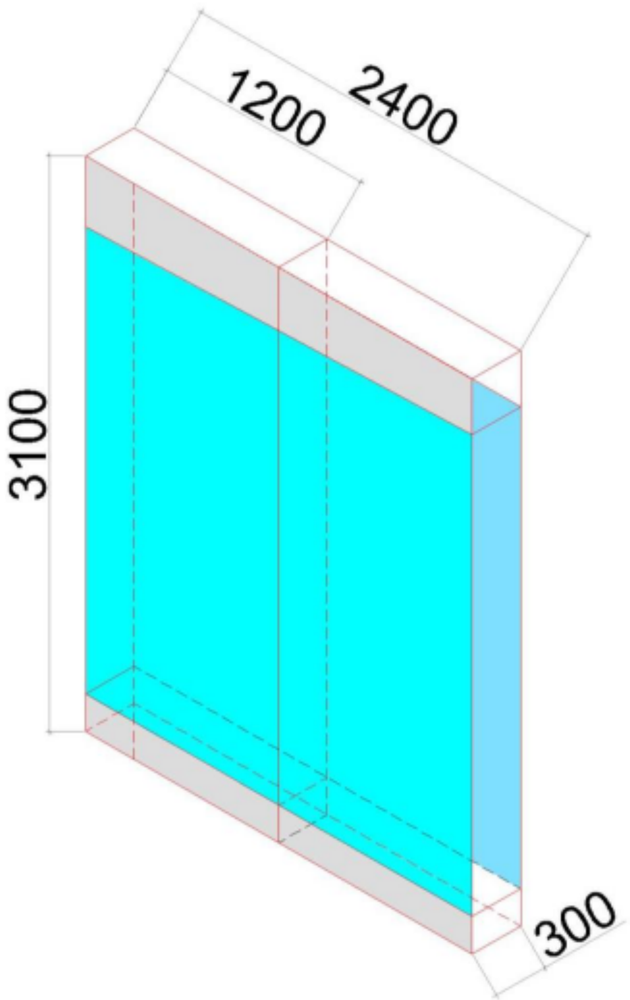


Figure 3.23 Overall size of typical unit

3.7. STRUCTURAL, FIRE AND ACOUSTIC DESIGN

The structural design of a curtain wall facade is a complex interplay between spatial requirements, and material properties of the facade components, such as weight and deflection behaviour resulting from wind loads which is dependant on location, exposure and height. The starting point for the structural design is an understanding of the issues encountered with facades. Following on the stiffness of the assembly and the tolerances that need to be allowed for has to be examined to take into account not only the self-weight, but the realities of floor slab deflection under live loads and wind loads. Other primary structure movement regimes such as settlement and heave will be excluded at this stage and dealt with on a project by project basis as they are project specific. The issues that will be addressed here are:

- Responding to the live load and wind loads and deflection criteria
- Fixing to the primary structure and tolerances
- Fixing of the outer skin
- Glass fixing
- Profile sizing

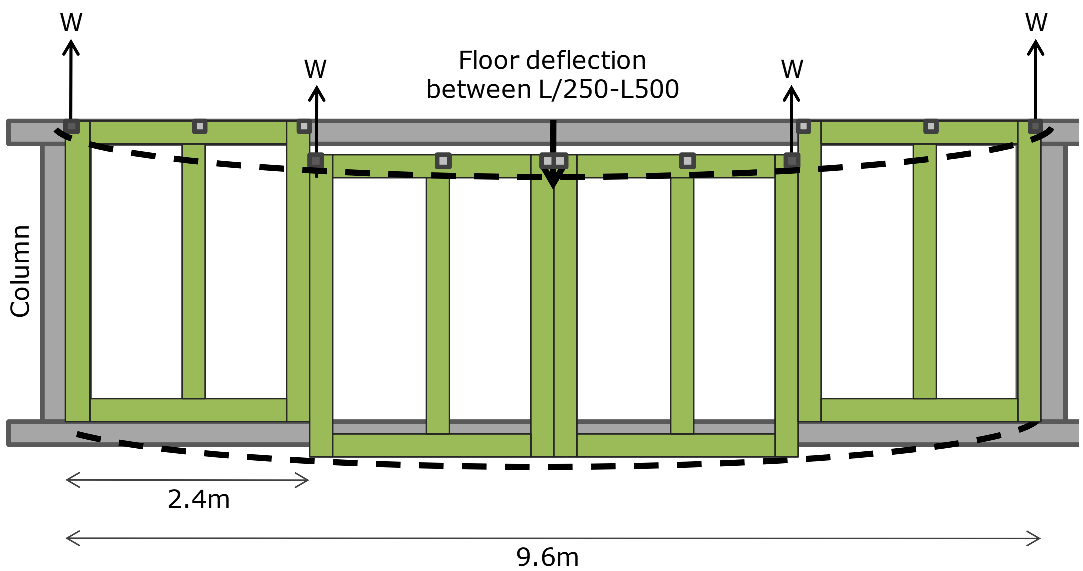


Figure 3.24 Elevation of deflection scheme under slab live load

The two primary deflection schemes considered here are live load slab deflection and wind sway deflection. The live load deflection limits for slabs are between length over span of 250 to 500 (L/250 to L/500) or 20mm whichever is the lesser (as given in BS EN 8110 Part 3). The slab span considered optimal for the 2.4 m units is 9.6 m centres as this places this column along the partition line when considering two cellular offices of 4.8 m wide each. The maximum deflection at the centre would then be between 20 mm (L/250 is 38mm so limited to 20mm) and 19.2 mm (L/500). Figure 3.24 illustrates this deflection scheme and shows firstly, the deflection for the middle two units would be half the maximum deflection since they are supported on the side closest to the column and secondly, single bracket for each unit would need to support the full weight of each unit. The maximum *unit* deflection would therefore be between 10 mm and 9.6 mm. The unitised profiles specified need to therefore absorb this amount of deflection to prevent air and water penetration, and forces being exerted across adjacent vertical units

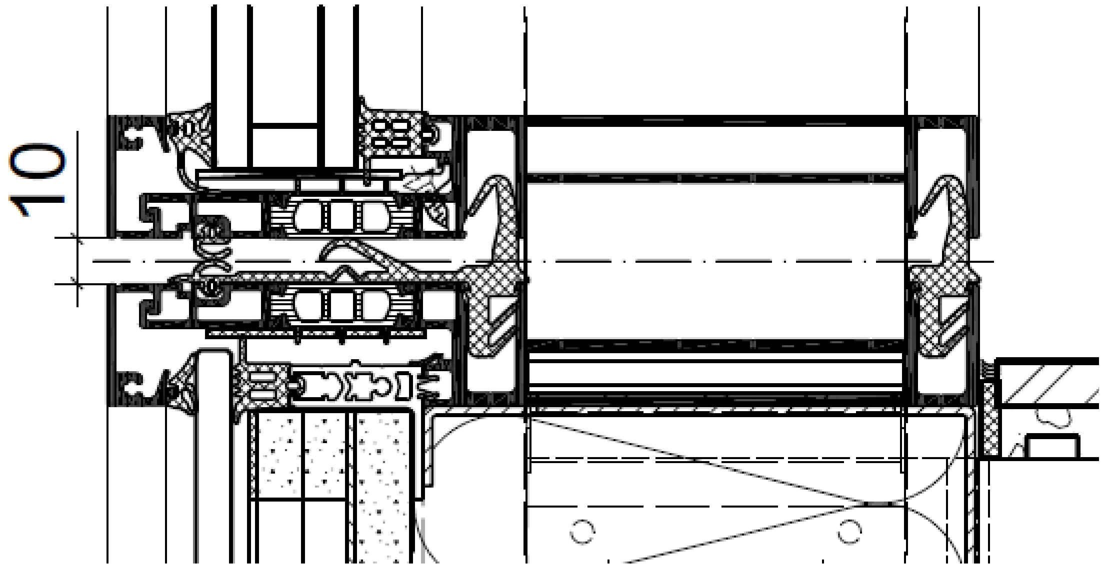


Figure 3.25 An example of a unitised transom profile to allow for +/- 5 mm deflection

Under the building wind sway condition the deflection scheme is as shown in Figure 3.26. This reveals that the rotation of the units again concentrates the load of each unit onto a single bracket and so as in the live load deflection case the bracket needs to be stiff and strong enough to accept this load. Further analysis of wind loads would need to be carried out by a specialist to examine the effects of vortices, separation and funnelling around the building due to its height.

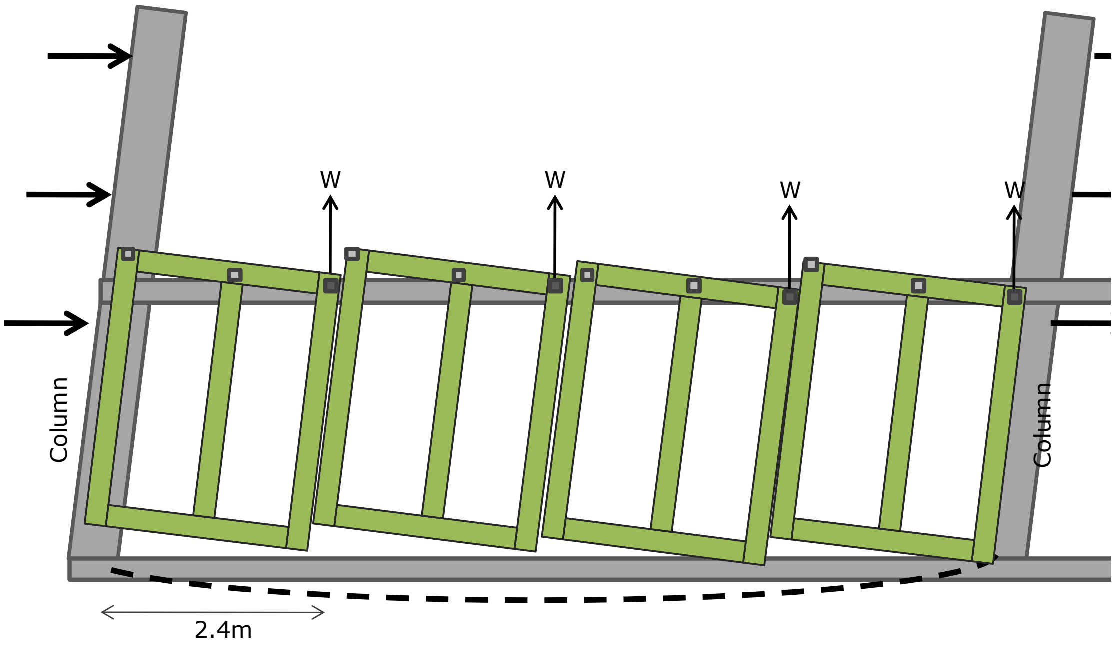


Figure 3.26 Elevation of deflection scheme under wind sway condition

Apart from having to carry the full weight of the units, the brackets used to attach the double skin facade to the primary structure need to facilitate installation and provide for tolerances. Under CDM regulations it is a designer's responsibility to provide safer ways of working so far as reasonable (HSC 2007). In terms of brackets the options available are the slab edge, the underside or on top. The safest location is on the top of the slab and will be implemented unless forced to change otherwise. If we also consider that the structural columns are usually inset from the edge of the slab, the force of the bracket is moved closer to the counteracting force reducing bending moment so there is an advantage with this location. The restriction with this location is that unit separation (between one unit and the other) needs to be above the bracket to allow the curtain wall to be hung as shown in Figure 3.27. The unitised transom profile would therefore need to be located at the finished floor edge and all of the components in the spandrel zone relate to the office below.

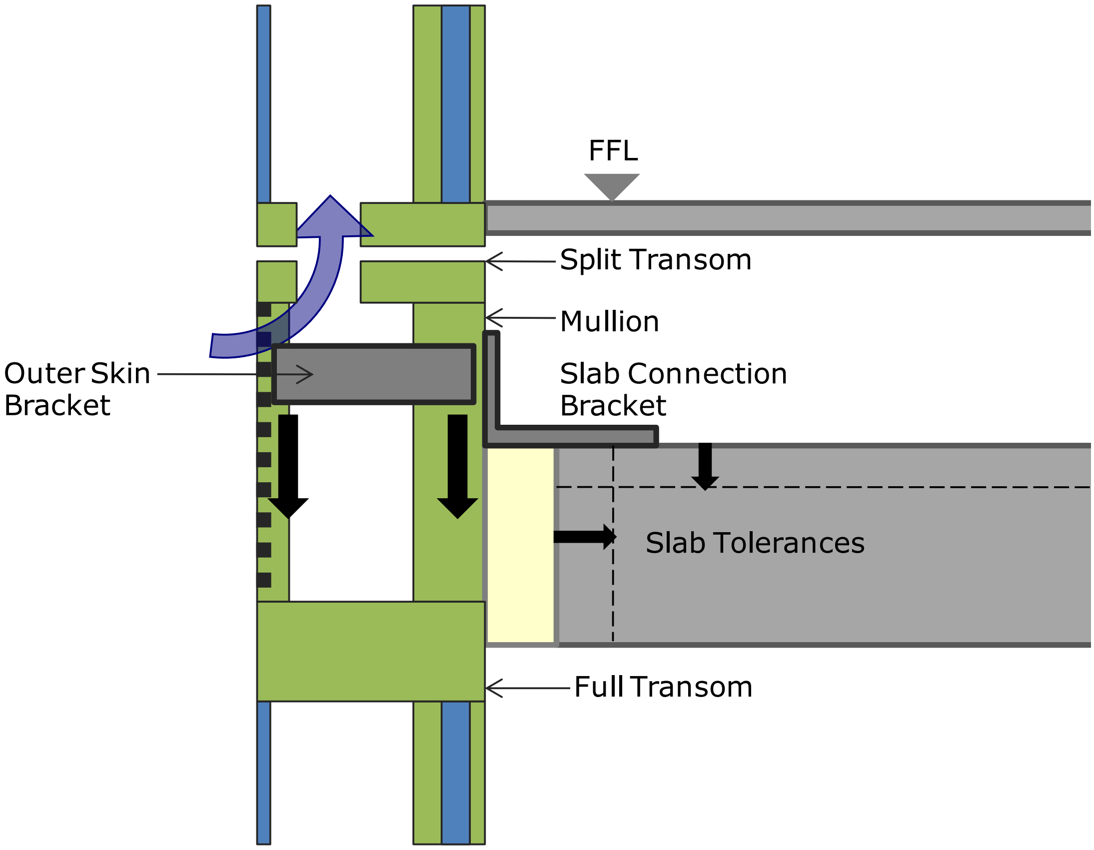


Figure 3.27 Section of unitised layout and connection to the slab

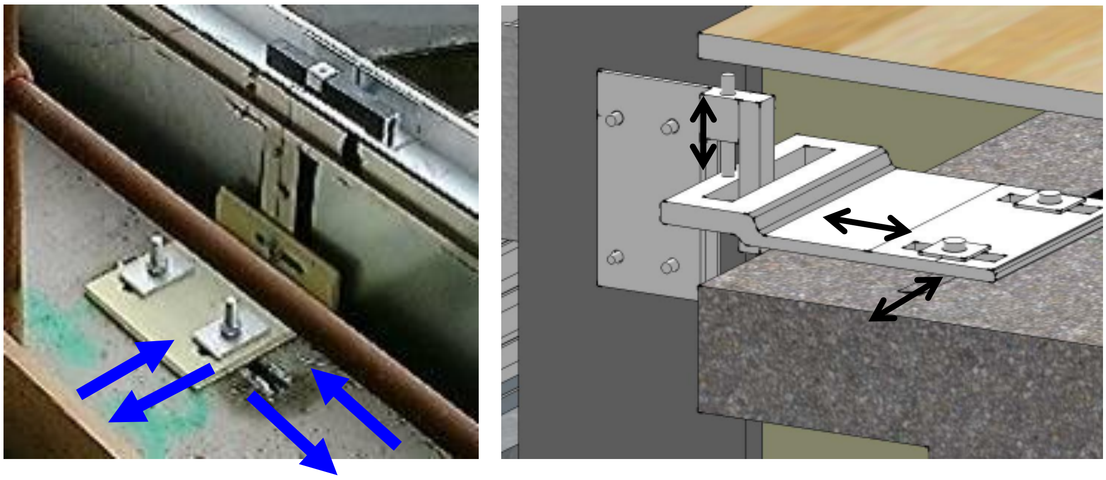


Figure 3.28 Floor brackets for top of slab connection (shims needed for vertical adjustment) and edge of slab connection with three direction adjustment (Buro Happold Intranet)

To allow for construction tolerances the slab connection bracket needs to have a means of adjustment in all three dimensions. As shown in Figure 3.28, proprietary cast brackets have a means of adjustment in the horizontal 'x' and 'y' dimensions only by slots and the vertical 'z' direction being adjustable by the use of shims underneath the bracket. This can create extra work during site installation due to level differences whilst shims are inserted and removed, and plastic shims are susceptible to creep. A bracket with the ability to adjust in all three dimensions by the use of a set screw is therefore proposed, an example of which is illustrated in the second bracket in Figure 3.28 and has been used since the 1970's. At the bottom of the mullion to allow for thermal expansion, yet provide a restraint in the horizontal plane, each unit is connected to the unit above by a spigot (see Figure 3.29). This is to be used in both the inner and outer skin.

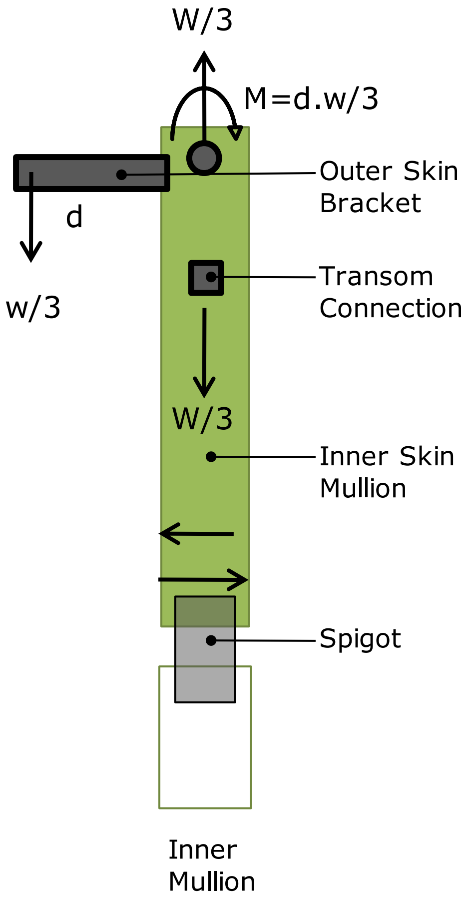


Figure 3.29 Section showing principles of load transfer in the mullion of the double skin prototype – W relates to the weight of glass in an entire bay

To support the outer skin dead load a connection bracket is needed back to the inner skin and will act as a cantilever as shown in Figure 3.29. By calculating the turning moment, the stiffness and size for an aluminium plate can be calculated. This will be developed further in Chapter 5 with industry. For the wind load, a series of cast aluminium brackets extending out from the inner skin as shown in Figure 3.30 have been introduced to slim down the outer skin profiles. The brackets can be altered in spacing or design in response to the wind load conditions and client preferences.

Also of note is the mullion configuration for the inner skin. The conventional method of curtain walling is to locate the main mullion internally and the Pressure Plate on the external side. To reduce material usage, provide greater usable internal floor area and less interruption to the internal view of the facade, there is an advantage in locating the main structural part within the cavity and moving the Pressure Plate inside. There is also a structural advantage in doing this since the external skin is supported by the inner skin and moving the inner profile closer to the external will reduce the cantilever. The final aspects to consider are the glass support and profile sizes.

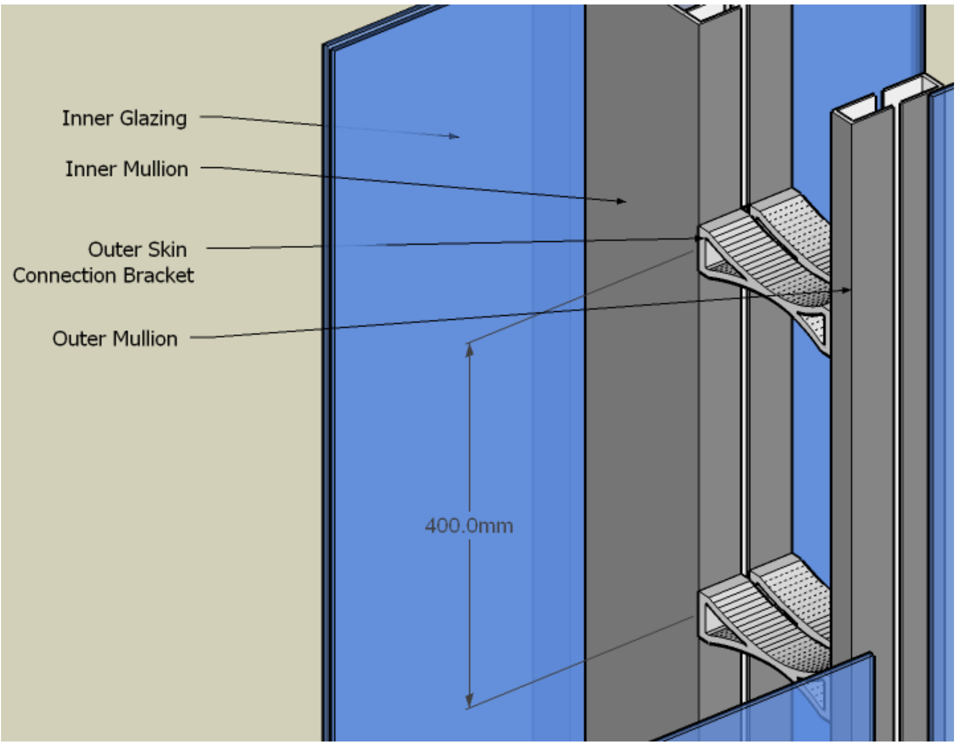


Figure 3.30 Double Skin Facade Structure with the main mullion in the cavity[4]

A key factor in the appearance of curtain walling is the technique chosen for support of the glass units with the different options presented previously in Section 2.2. To achieve a smooth external aesthetic, a Structural Silicone Glazed outer profile is chosen. Further visual lightness could be provided by the use of a point fixed system. For the inner skin a Pressure Plate Profile is needed to allow for opening hardware (the Pressure Plate unconventionally is in the room).

[4] A precedent for this type of support can be found on London Bridge Place (in construction) by Renzo Piano Building Workshop

Regardless of the orientation, there would be little benefit in terms of the external visual transparency in using Structural Silicone.

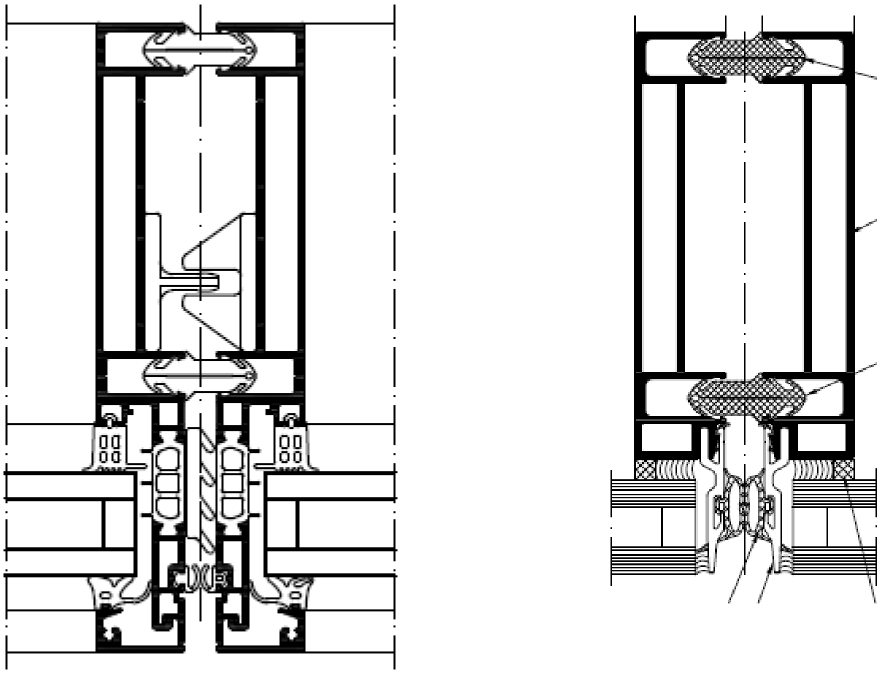


Figure 3.31 Typical unitised mullion layout with pressure plate system and structural silicone – note the split section to enable the curtain walling to be delivered in units (Schueco International KG 2009, p.USC 65)

With an estimation of the loads, the mullions and transoms sizes can be estimated according to wind speed data and referring to manufacturer's guidance tables or software. In this case a profile sizing program, Schueco Statics (Schueco International KG 2005) was used to give an approximate idea of the size of profiles required. This allows for the input of height above the ground, spans, wind speeds and then lists the profiles that would be suitable in the Pressure Plate and Structural Silicone ranges as required.

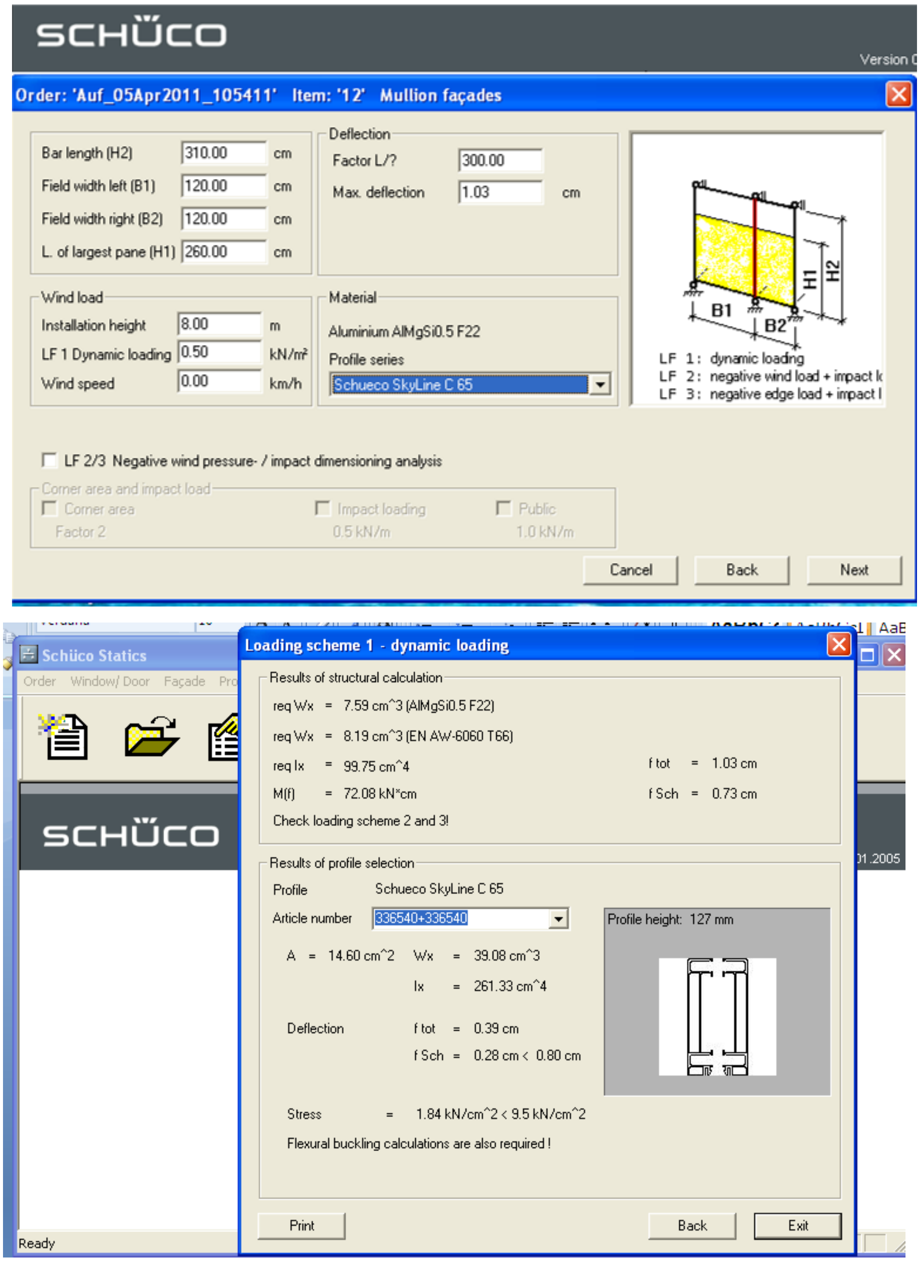


Figure 3.32 Screenshots of Schueco Statics Program (Schueco International KG 2005)

The fire performance for the facade is dependent on the height. For the type of offices being considered in this thesis where the height is greater than 30m fire stopping within the cavity is generally not required since it is mandatory for the office space to have a fire suppression system of sprinklers and smoke extract(Table A2, Approved Document B). This has been accepted on a number of double skin facade projects in the UK such as London Bridge Place and the Shard. Advice from Buro Happold Facade Engineers is however that a level of fire resistance may be required if there is a staged evacuation to reduce vertical transportation requirements. A sensible approach if there are no acoustic requirements is to either extend the sprinklers into the cavity zone or ensure that the evacuation procedure is based on the fire floor and the floors above and below evacuated simultaneously as a minimum in terms of staging. Where there are acoustic separation requirements to reduce flanking noise when internal windows are opened then 160 mm of rockwool to provide a rated time of two hours could be provided below and around the unit transom and unit mullion.

Structural design of the double skin prototype has examined the live loads, wind loads and deflection criteria, together with the support of the different components. The live load analysis has shown that a single bracket will need to take the entire weight of the unit in certain conditions and the units accommodate a vertical movement of 10 mm. Fixing to the primary structure is to be via a bracket at the top of the unit which will allow three dimensional movement to accommodate tolerances. Support of the outer skin is to be via an aluminium plate and cast brackets between the inner and outer skin. For each project further analysis and tuning will need to be carried out as structural design is site and project specific. The glass is to be structurally silicone glazed on the outer skin and pressure plate fixed on the inner skin. The profiles themselves have been sized in accordance with a system provider’s selection program.

CONCLUSIONS

Facade design, like many aspects of architecture is tasked with interweaving a number of competing demands. In this chapter, the design brief outlined in the Introduction and Chapter 1, and following on from the review of technology in Chapter 2, has been translated into a detailed facade design.

The most onerous requirement to achieve was natural ventilation due to the building typology considered. This has been overcome by the use of a double skin facade. Further analysis on the different types of double skin facade, have revealed that a cascade type, naturally ventilated, narrow cavity facade is the most advantageous for the component. Through computational analysis using a number of different software packages, it has successfully demonstrated that it provides a significant duration of natural ventilation, as well as being an improvement over the notional building in Part L. The natural ventilation strategy importantly, has also been coordinated with view, access and maintenance considerations.

Other aspects have also been considered and developed. The day lighting performance of the facade has been shown to provide a good daylight factor, whilst solar control has been provided by the use of interstitial blinds and internal roller blinds depending on the season and occupant preference. The improvement of thermal insulation performance has been explored and the most promising measure available without compromising the transparency is an improvement to the profiles. For energy generation the use of integrated photovoltaic modules in the lower third in a staggered configuration, allows a balance between aesthetics and performance. The unit size has been established as 2.4 m wide by 3.1 m high based on dimensional coordination and transportation. A preliminary structural design for the unit has been undertaken and established the deflection criteria, connection brackets to be used (inner and outer skins) together with the glass support types and profile sizes. In Chapter 5, the design of the facade will be further developed with a curtain wall system provide and fabricator to incorporate their knowledge and expertise.

The passive performance of the component is now considered to be sufficiently developed to progress the Active Environmental System further. The facade performance values can be used to derive the performance requirements of the Active Environmental System and the spatial constraints within the facade used for integration of the Active Environmental System.

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CHAPTER 4

DESIGN OF THE ACTIVE ENVIRONMENTAL SYSTEM: CONCEPT TO DETAIL TO INTEGRATION

With the facade providing the internal environment for a much of the year as possible, it is now left to the Active Environmental System to ensure comfort conditions when passive measures are insufficient. The design has to consider the components used for delivery and supply of services, together with their impact and integration into the facade. The system should provide a combined prefabricated solution to harness the benefits described in Chapters 1 and 2, which ensures occupant comfort and low carbon emissions.

Already, a number of suitable options for an integrated, decentralised environmental system have been established in Chapter 2. In this chapter, these options have to be further refined from concepts to design details. This selection of components has to consider the carbon performance of the different solutions, together with other issues such as comfort, cost and prefabrication for the supply, and delivery, of heating, cooling and fresh air. A key final aspect of the environmental system design, is the challenge of integrating the components into the facade and reaching a solution through the tension that can exist between a desirable aesthetic, mechanical components and prefabrication. For the fully decentralised system recommended in Chapter 2, the initial task is to establish the heating and cooling supply source.

4.1. HEATING AND COOLING SUPPLY OPTIONS: ANALYSIS AND SELECTION

The choice of heating and cooling supply is influenced by the ease of integration, cost and carbon emissions. Options for both heating and cooling will be discussed and analysed separately based on these requirements. This section will then conclude with the optimum supply system for this application.
In Chapter 2, the choice of heating supply suitable for a decentralised system was limited to:

a) Electrical Resistance Heating

b) Reversible Air Source Heat Pump (RSHP)

Their benefits and drawbacks should be explored base on ease of integration, complexity, cost and carbon emissions.

a) Electric resistance heating works on the principle that as electrons flow through a circuit, some of the energy is dissipated as heat. The integration of electrical heating is straight-forward since the number and size of components is very small. The capital and maintenance cost is comparatively very low for the same reasons and due to the market maturity of this type of technology. The main drawback to electrical heating is the associated carbon emissions per kWh since the carbon intensity of the UK grid is high.

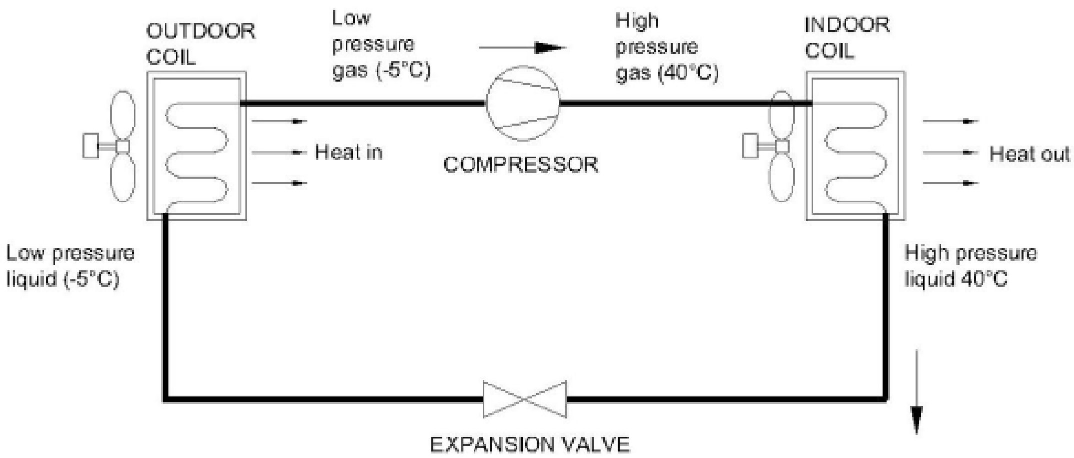


Figure 4.1 RSHP operation in heating mode showing the flow of refrigerant

b) RSHP's also use electricity, but instead move thermal energy from a source which is at a lower temperature, to another location termed the heat sink which is at a higher temperature, by the application of work by a compressor (see Figure 4.1). The integration of RSHP's is much more complex than electrical heating, as a number of components are required and the process has to be closely controlled. The capital and maintenance cost is also much higher than electrical heating. The main benefit of RSHP's is their ability to provide 2-3kW of useful heat for every 1kW of electrical heat supplied even in winter conditions and therefore have comparatively lower carbon emissions per kWh to other sources. In comparison to electrical heating they have much lower carbon emissions per kWh, but much higher capital and maintenance costs.

Before a decision can be made the cooling source needs to be identified, and followed by an assessment of the carbon emissions.

The choice of cooling supply is based upon the carbon dioxide emissions, cost and ease of integration, as with the heating method. The options outlined in Chapter 2 for cooling were:

a) RSHP (cooling mode)

b) evaporative cooling

c) phase change materials

d) thermoelectric cooling

a) RSHP's in cooling mode are a well established cooling mechanism and is the most common method of providing cooling today. The benefits and drawbacks are similar in heating mode as discussed in the previous section. Additional advantages are the cooling temperature can be adjusted to provide dehumidification, and an efficient use of components when used for heating and cooling.

b) Evaporative cooling has been used for centuries in the Middle East and India, (Ford et al. 2010, p.15) and uses the latent heat of evaporation to cool the air. This is most suitable for hot and dry climates as it relies on an increase in the moisture content of the air and where a sustainable and reliable water supply is available. To assess its potential application in the UK, the climate was analysed on a psychrometric chart (Figure 4.2). During the summer season (April to September), the chart shows how many hours the coincident dry bulb temperature and wet bulb temperature is low enough for evaporative cooling. The chart reveals that there is a significant number of summer hours (estimated at twenty three) where occupant comfort temperatures will be exceeded. It will therefore not be implemented and would only be an option if adaptive comfort criteria models were introduced.

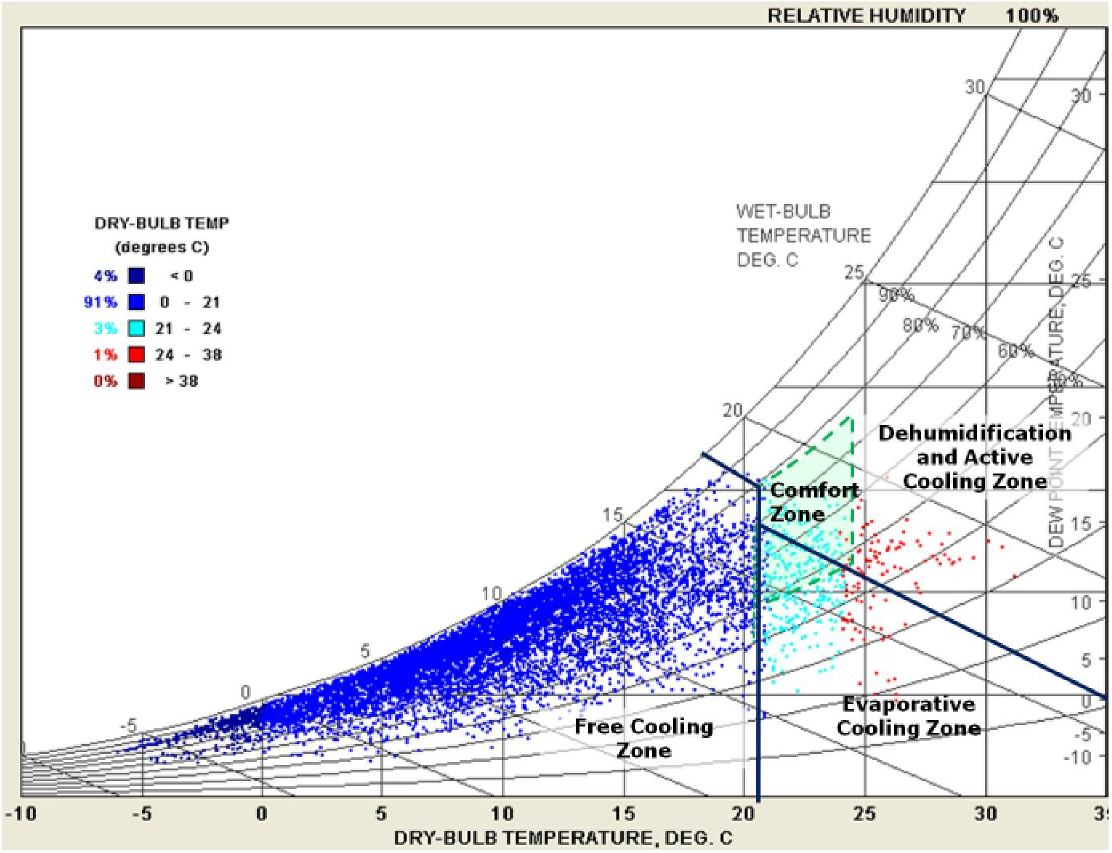


Figure 4.2 Evaporative cooling assessment for London using the CIBSE design summer year weather file. Partly produced using Climate Consultant 4 (Milne & Liggett 2008)

c) Phase change materials have been a popular research topic for cooling provision recently (Zalba et al. 2003) because of their comparatively low energy usage and low maintenance requirement. They work by absorbing and releasing latent heat during the process of melting and freezing, and can be incorporated into a cooling regime in summer as depicted in Figure 4.3. Phase change materials have been integrated into buildings in a number of ways recently; these include plasterboards, floors, insulation and windows. The market ready applications are predominantly passive in nature and rely on natural convective air flows to cool which only provide limited cooling capacities. Active methods where a fan is used to encourage the air flow to provide greater capacities, are still at an early stage of development (Turnpenny et al. 2001) and further development work is needed. The benefits of PCM, encourages further work. The design stages needed are selecting a suitable phase change material, sizing a system and integration into the design.

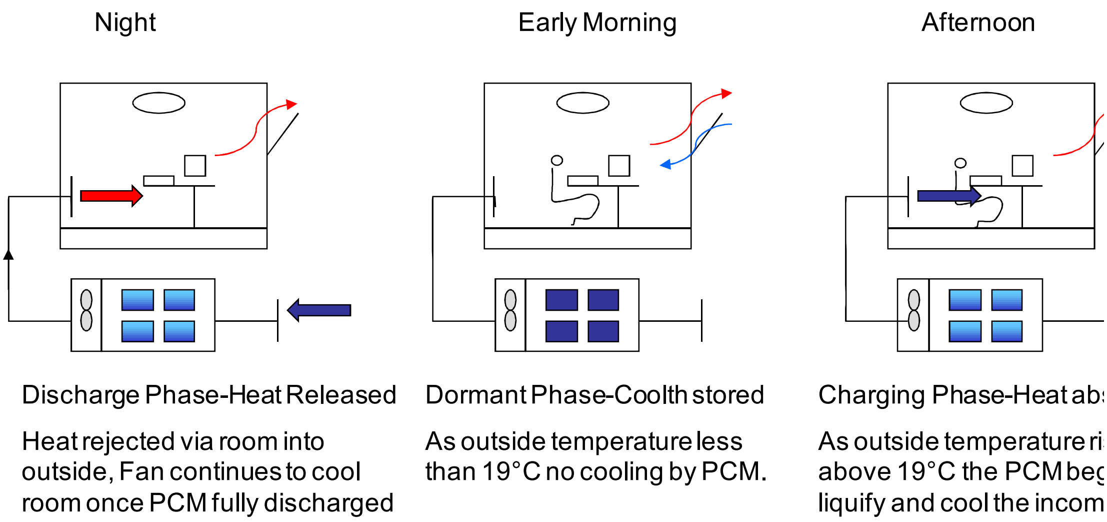


Figure 4.3 Principle of phase change material cooling

Every material can undergo a change of phase at a certain temperature and pressure, what gives certain materials a greater popularity is a suitable phase change temperature and a high latent heat. In this design the specific requirements for the phase change material are:

- a melting point above 20°C so as not to increase the heating load and below 25°C to provide a cooling effect;
- physical properties of high specific latent heat capacity, high conductivity, low spatial requirements and long term chemical stability;
- commercially available at a reasonable cost in a form suitable for use.

By reviewing the literature and contacting industrial suppliers, a selection of the most suitable phase change materials to provide a suitable melting point of around 21°C were found and are shown in Table 4.1. Of those the organic paraffin's are the best performing, due to their long term stability and chemical inertness. They are also commercially available in containers from PCM Products Ltd (www.pcmproducts.net) under the trade name 'PlusICE A22'. How they can be integrated into the design and their overall carbon performance needs to be developed however.

Table 4.1 Properties of suitable phase change materials (PCM Products Ltd 2009), (Nagano et al. 2006).

Material	Tm Melting Point °C	Ts Solidifying °C	Latent Heat kJ/kg	Quantity Rqd kg	Density kg/m³
Organic Paraffins					
Hexadecane C16H38	13.9	13.2	201	149	
Octadecane C18H38	28.2	24.7	202	148	
Mix 3:7 of above	18.5	20.2	121	247	645
PlusICE A22	22		172	174	785
Organic Non-Paraffins					
Polyethylene Glycol 600	20-25	20-25	146	205	
Salt Hydrates					
FeBr3.6H20	21		105	285	

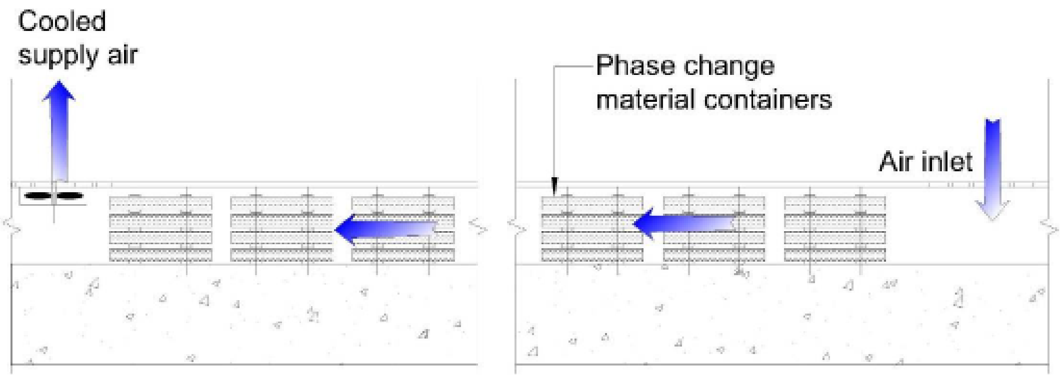


Figure 4.4 Indicative phase change material cooling system within the floor void

A concept design shown in Figure 4.4 was developed based upon detailed calculations shown in Appendix I. This revealed that thirty six containers are required which requires a significant volume. The most suitable location was the floor void adjacent to the facade. In this design air is mechanically driven across the phase change material to increase the cooling output. From the calculations it is shown that whilst the cooling requirement for a day could be stored, the cooling output would not be able to satisfy the peak demand and overheating of the room could occur during peak conditions. This is primarily due to the low conductance of the plastic HDPE phase change material containers (chosen because of their chemical inertness) and the small temperature difference between the air and the phase change temperature. An alternative strategy would be to custom make the containers to increase the surface area, lower the phase change temperatures and relax the comfort requirements. In addition the surface temperature on the containers needed to dehumidify the air, would necessitate a phase change material transition temperature close or lower than that of the typical summer night time regenerating temperature. It is apparent that a phase change cooling system requires a great deal of developmental work outside the scope of the project and has performance drawbacks in terms of humidity control in summer.

d) Thermoelectric cooling is a solid state type of heat pump and uses the peltier effect - whereby electrons transfer heat from a cold junction to a hot junction in a diode - to provide cooling. This is a virtually maintenance free cooling method and well established through its use in the computer industry. However, the efficiencies attainable by thermoelectric cooling are currently only 5 - 8% and cannot compete with RSHP efficiency alone (vapour compression cycle efficiency is 45% Carnot). Theoretically the efficiency could be increased even beyond the vapour compression cycle (Riffat & Ma 2004) and could be an option in the future given a breakthrough in materials.

To reach a final decision, a combined heating and cooling emission assessment is needed. The heating and cooling systems could be logically combined as the following:

- Reversible air source heat pump for both (RSHP)
- Heat pump and phase change material cooling (HP + PCM)
- Electric heating and phase change material cooling (E + PCM)
- Electric heating and thermoelectric cooling (All electric)

The first option, the reversible heat pump can provide both heating and cooling as mentioned earlier by the use of a reversing valve. Alternatively the heat pump could be used only in heating mode to take advantage of its high COP and use PCM for low energy cooling. To reduce space requirements and complexity the heat pump could be replaced with electric heating. For even less space usage and complexity the thermoelectric cooling could be used instead of PCM. Table 4.2 provides the carbon dioxide emissions for each of the different systems, based on the heating and cooling loads calculated in Chapter 3 and using typical values for coefficient of performance (COP).

Table 4.2 Annual carbon dioxide emissions for different heating and cooling options

		South RSHP	South HP + PCM	South E + PCM	South All Electric
Annual Cooling Load	kWh	125.1	125.1	125.1	125.1
COP		3	6.1	6.1	0.6
Electricity	kWh	41.70	20.51	20.51	208.50
CO2 @ 0.48 kg/kWh	kgCO2	20.02	9.84	9.84	100.08
Annual Heating Load	kWh	86.2	86.2	86.2	86.2
COP		3.5	3.5	1	1
Electricity	kWh	24.6	24.6	86	86
CO2 @ 0.48 kg/kWh	kgCO2	11.8	11.8	41.4	41.4
H & C CO2 emissions	kgCO2	31.84	21.67	51.22	141.46

		North RSHP	North HP + PCM	North E + PCM	North All Electric
Annual Cooling Load	kWh	64.6	64.6	64.6	64.6
COP		3	6.1	6.1	0.6
Electricity	kWh	21.53	10.59	10.59	107.67
CO2 @ 0.48 kg/kWh	kgCO2	10.34	5.08	5.08	51.68
Annual Heating Load	kWh	341.2	341.2	341.2	341.2
COP		3.5	3.5	1	1
Electricity	kWh	97.5	97.5	341	341
CO2 @ 0.48 kg/kWh	kgCO2	46.8	46.8	163.8	163.8
H & C CO2 emissions	kgCO2	57.13	51.88	168.86	215.46

Note: Maximum heating and cooling loads calculated as part of the thermal modelling presented in the section 3.4 and are shown in Table 4.2 for the worst case orientation. File Ref: 2010 Energy Analysis

We can see from Table 4.2 that the 'all electric' system comparatively has an extremely high carbon dioxide emission value, which is unfortunate since it would be the easiest to integrate. Even with a doubling of COP for thermoelectric cooling, the COP would still remain well below the other options. Results for the east and west show a similar pattern to the south. For a north facing facade, as expected the carbon emissions are more sensitive to the heating source and therefore favoured a heat pump for heating; the cooling source makes little overall impact due to the low cooling load. The best performing option overall is a heat pump coupled with phase change material for cooling. However, as mentioned previously the PCM system will not be able to dehumidify the air in summer; a combined RSHP and PCM system would be required to guarantee comfort conditions. At this stage for manageable developmental work, ease of integration and reduced complexity a RSHP is to be progressed further.

From Table 4.2 large differences in heating and cooling load suggest some form of linking between the two systems. However on closer inspection of the data the heating loads and cooling loads do not occur at the same time. Large heating loads occur generally during the morning for both sides, but the solar gain on the south reduces the requirement. Cooling loads generally occur in the afternoon, but there is limited cooling available that can be transferred from north to south due to the small temperature difference between the two zones. It may however be worth investigating at a later stage is if a heat pump located on the south where the solar gains in the exhaust cavity can be made use of, and heat pump in cooling mode only in the north facade which remains relatively cool in summer is overall more efficient. This would require a very detailed dynamic model where the temperatures in the cavity are accurate throughout the year which is outside the scope of this thesis.

4.2. DETAILED DESIGN OF THE REVERSIBLE HEAT PUMP SYSTEM

A small number of RSHP systems are available on the market from mainstream manufacturers such as Mitsubishi Electric (Mitsubishi Electric 2010), but there are a number of issues in utilising existing products. Firstly, these systems use refrigerant gases which have a high global warming potential and are likely to be banned from use in the near future. Secondly, are also manufactured as single blocks which present a problem in configuring them to fit into the facade. Thirdly they are set up for use with fan coil units not Active Beams which require different temperatures. A RSHP design is therefore needed which is future proofed against possible legislation on refrigerant gases, can be configured to fit into the facade and finally can provide the correct temperatures for application with an Active Beam.

4.2.1. Refrigerant Selection

The Montreal Protocol (UNEP 1987) first initiated a series of legislations to regulate the use of refrigerant gases that were damaging the ozone layer and is widely regarded as one of the most successful environmental protection legislations (Grabiel 2007). The replacement to the damaging chlorofluorocarbons (CFCs) have mainly been hydrofluorocarbons (HFC's) which do not damage the ozone layer, but are powerful greenhouse gases and have a high global warming potential if released into the atmosphere. The current UK government position is for a 'phase-down' of HFCs at some point and to allow their use only for 'important products or where there is no suitable alternative'

(DEFRA 2011). To future proof the design it is worth exploring alternatives which have low ozone depleting potential and low global warming potential.

There are many thermodynamic and chemical properties which influence the choice of refrigerant. Important properties include operating pressure, critical pressure, critical temperature, freezing point, normal boiling point, specific volume, coefficient of performance, specific power consumption and specific heat ratio. These values are shown for a number of different refrigerants in Table 4.3.

Table 4.3 Properties of phased out, transition and future refrigerants (BSI 2008b, pp.49-51)

Refrigerant Name	Designation Number	Chemical Formula	ODP	GWP (100yr ITH)	Critical Point °C	Pressure at 50°C Bar	Practical Limit kg/m³	Flammability LFL kg/m³	Ignition Temperature °C	Safety Group	Vapour Density @25°C, 1Bar kg/m³
Phased Out Refrigerant											
Chlorodifluoromethane	R22	CHCIF2	0.05	1500	96	2	0.3	n/a	635	A1	3587
Transition Refrigerants											
Tetrafluoroethane	R134A	CH2FCF3	0	1300	101	1.4	0.25	n/a	743	A1	4258
Zeotropic	R407C	Blend of HFCs	0	1520	86	2	0.31	n/a	704	A1	3582
Zeotropic	R410A	Blend of HFCs	0	1720	72	3	0.44	n/a	-	A1	3007
Future Refrigerants											
Propane	R290	CH3CH2CH3	0	3	97	1.8	0.008	0.038	470	A3	1832
Isobutane	R600A	CH(CH3)3	0	3	135	0.7	0.0086	0.043	460	A3	2440
Ammonia	R717	NH3	0	0	132	1.5	0.00035	0.104	630	B2	0.704
Carbon Dioxide	R744	CO2	0	1	31	-	0.036	n/a	-	A1	44

Table 4.3 provides the properties for the most common phased out refrigerant, R22, which has a ozone depleting potential (ODP) and the transition refrigerants being used today with a low ODP which were introduced following the Montreal Protocol (UNEP 1987). The most promising future refrigerants are also included in the Table which have no ozone depleting potential a low global warming potential and beneficial thermodynamic and chemical properties (James M. 2008). They include:

a) Hydrocarbons (e.g. Propane and Isobutane)

b) Ammonia

c) Carbon Dioxide

Each of the potential refrigerants will be discussed in turn to ascertain their suitability.

a) Hydrocarbons such as Propane have seen use in domestic refrigerators (Danfoss GmbH 2009) due to their similarity in performance to HFCs. Similar sized compressors and components can be used making the system cost comparable to HFCs. It has zero ozone depleting potential and a global warming potential of only three. The major drawbacks however are its flammability and explosiveness. This risk has to be negated by restricting the quantity of gas in a room referred to in Table 4.3 as the practical limit. A calculation of the gas within the room was performed and showed that the quantity of gas needed is 0.5 kg, below the room limit of 0.6 kg. The use of propane therefore is well suited to this size of system and application.

b) Ammonia has become popular in large capacity chillers and is widely available. It has zero ozone depleting and zero global warming potential as well as good thermodynamic properties. Ammonia is however highly toxic and corrosive. The provision of enhanced safety procedures and high material specification due to its toxicity and corrosiveness make it unsuitable for an application within an occupied space.

c) Carbon Dioxide is finding application in heat pumps particularly in the domestic application where hot water is required since it is easier to provide both higher temperatures and heat transfer coefficients. Other benefits are its zero ozone depletion potential and a global warming potential of one; much lower than conventional refrigerants. The gas is also cheap and non-toxic. The major drawback however is the high pressure it works at, up to 100 Bar compared to 25 to 30 Bar for HFC heat pump systems. This substantially increases the cost of the pipe work and components substantially.

The most suitable option is therefore Propane as it is safe to use and more economic than the two alternatives provided that the room limit is not exceeded due to any design changes later on. The system can now be further developed based on the thermodynamic and chemical properties of propane.

4.2.2. Performance Requirements and Provision

The primary functions of the RSHP are:

- To provide heating or cooling;
- To provide suitable temperatures and outputs in heating and cooling mode.

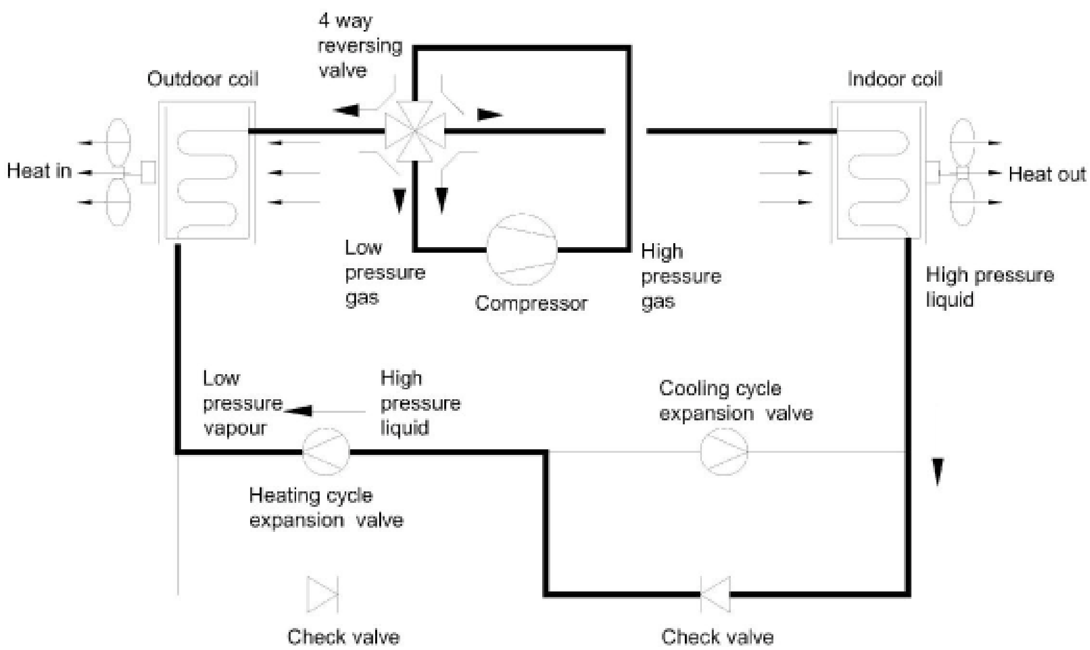


Figure 4.5 Basic components for a reversible heat pump system (heating mode shown)

A RSHP system can operate in either cooling or heating mode simply by the inclusion of a 4-way reversing valve and through the use of check valves as shown in Figure 4.5. The 4-way valve is operated by a solenoid switch that switches the flow path so the condenser becomes the evaporator and vice a versa. To ensure that the flow passes through the correct expansion valves, check valves are required.

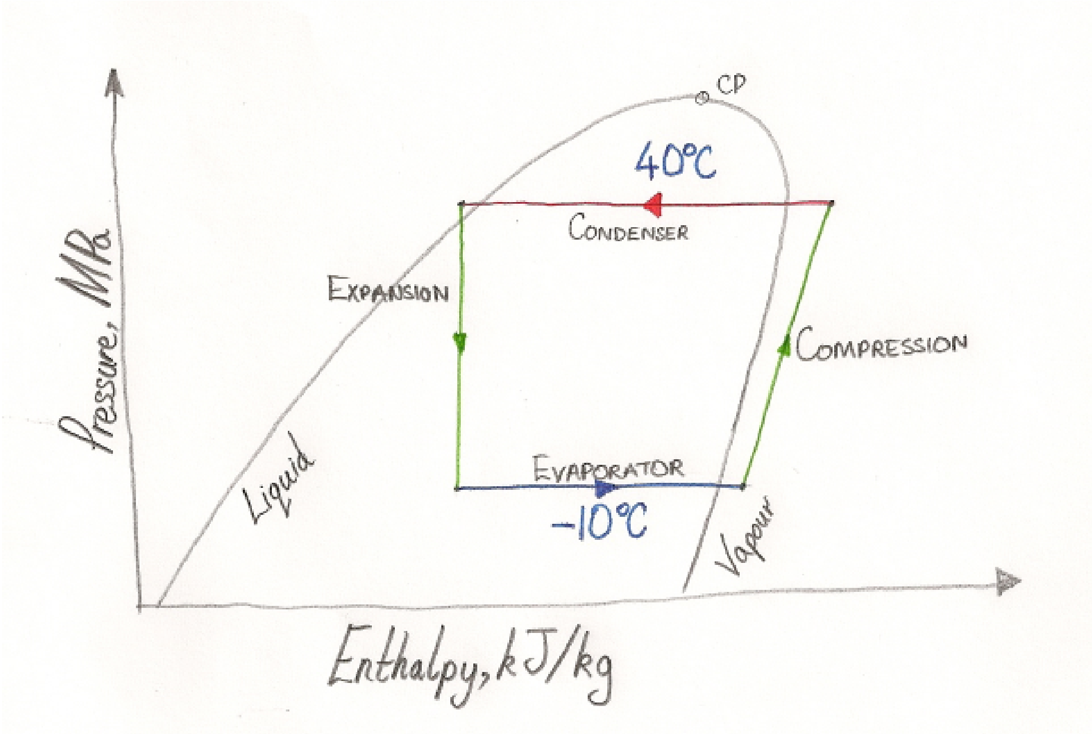


Figure 4.6 Indicative pressure-enthalpy cycle in winter

The refrigerant temperatures are based upon both the heat source and heat sink and achieving sufficient heat exchange. In winter, the outdoor coil needs to absorb heat from the outside air and evaporate the refrigerant, and then transfer this into the room (the heat sink) by condensing the refrigerant. To absorb heat from the outside, the outdoor coil (evaporator) needs to be at a lower temperature than the ambient air to drive the heat transfer. A coil temperature of -10°C was calculated as sufficient, to ensure that heat can be absorbed even during the peak Nottingham winter condition of -4°C from the condenser (see Appendix J). To then discharge heat into the room, the refrigerant temperature needs to be above 21°C. Typically, a temperature of 60°C - 80°C is used in hot water pipe work however, a lower temperature of 40°C reduces the work carried out by the compressor and thereby improving the efficiency. It will also be useful to use the same temperature in the cooling cycle as will be shown. Using a temperature of 40°C will depend on the heat delivered by the Active Beam to ensure there is sufficient heat transfer into the room, which will be checked with the supplier in Chapter 5. The ideal pressure-enthalpy process using these temperatures is shown in Figure 4.6.

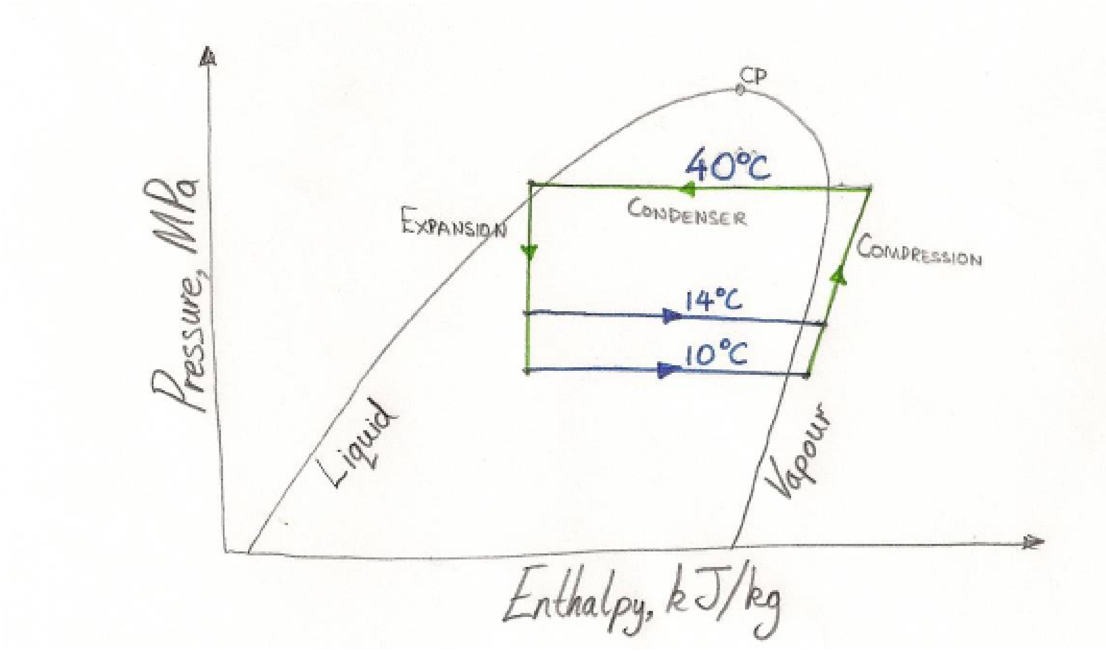


Figure 4.7 Indicative pressure enthalpy cycle in summer

In summer, the heat exchange cycle is reversed. Heat is discharged to the outside by condensing refrigerant and absorbed from the inside by evaporating refrigerant. A condensing temperature of 40°C is common practice in the UK, as it is higher than the summer design temperature of 26.3°C. A heat discharge calculation shown in Appendix J verified that this allows for sufficient heat discharge. The internal evaporating process (absorbing heat) is more complicated as it has to balance the latent (moisture) load and the sensible load. An examination of the psychrometry of the cooling process reveals that a degree of dehumidification in summer is required, due to the latent load of the introduction of humid fresh air and the latent load of occupants. To dehumidify the air, a coil temperature below the air dew point is required. As Active Beams do not have the facility of moisture removal, an additional cooling coil will be required and is discussed further in Section 4.4. Therefore two different evaporating temperatures and cooling cycle expansion valves are required in the cooling cycle, with the indicative pressure-enthalpy process shown in Figure 4.7. The temperature for the Active Beam coil is to be set at 14°C and the additional coil 10°C (lower than the dew point).

The full chart for both processes is shown in Figure 4.8 which has been used for calculation of the flow rates, compressor size, pipe sizes and the majority of the components as given in Appendix K. The schematic developed before contacting industry for the production of the prototype is given in Figure 4.9.

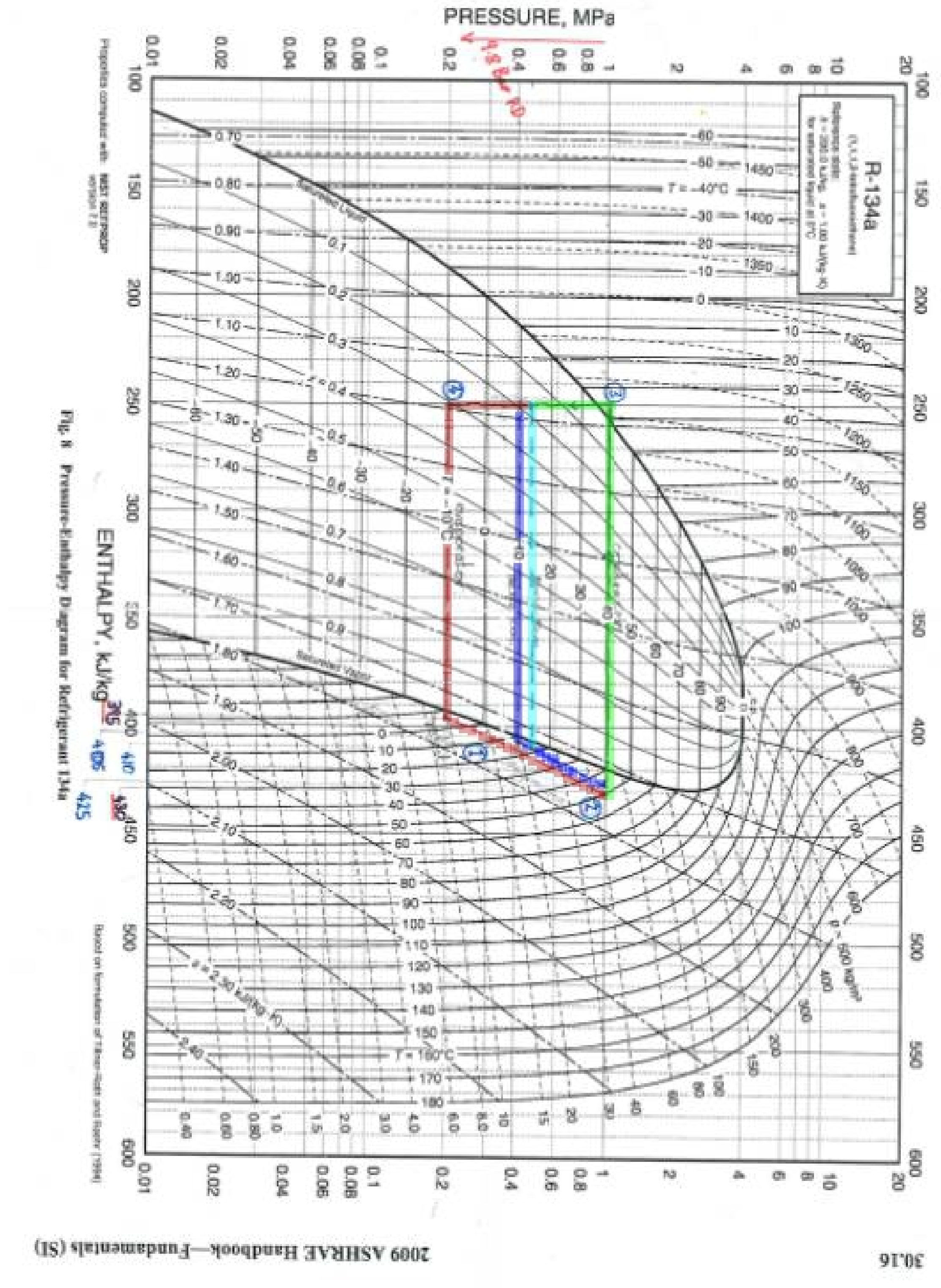


Figure 4.8 Pressure-enthalpy chart of cooling and heating processes

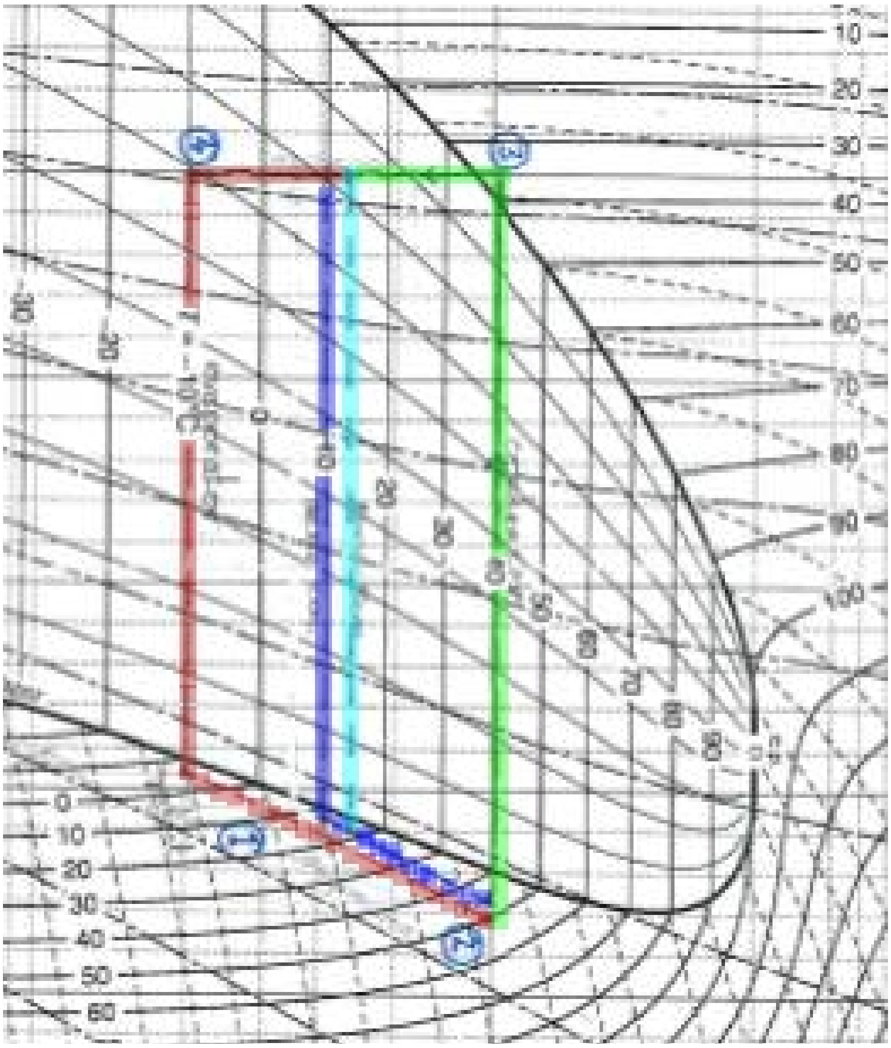
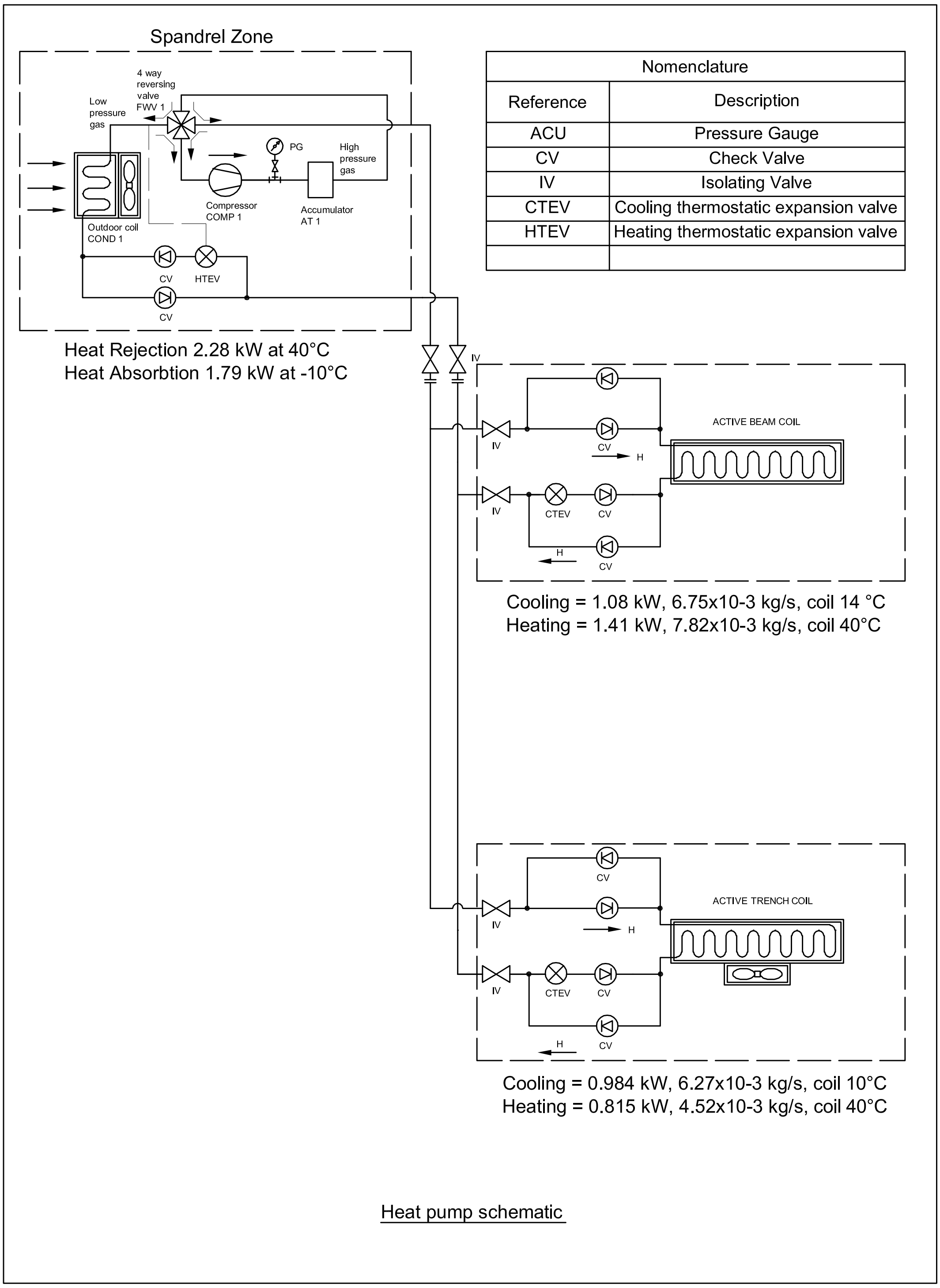


Figure 4.8 Pressure-enthalpy chart of cooling and heating processes (enlarged view



Nomenclature	
Reference	Description
ACU	Pressure Gauge
CV	Check Valve
IV	Isolating Valve
CTEV	Cooling thermostatic expansion valve
HTEV	Heating thermostatic expansion valve

Figure 4.9 Schematic of reversible heat pump system

4.3. FRESH AIR SUPPLY: OPTIONS AND ANALYSIS

The mechanical fresh air supply system has a number of components that are needed to provide the necessary fresh air quantity for comfort and productivity, as well as drive the induction effect of the Active Beam. The inclusion of a Heat Exchanger was established in Section 2.1 to reduce the winter heating load. The fresh air quantity and comfort conditions were established in Section 1.2. The fresh air system now needs to be developed to detail all of the necessary components to provide these conditions and provide sufficiently detailed information to find suitable manufacturers and suppliers. The fresh air supply system comprises of louvres, ductwork and the Heat Exchanger as shown in Figure 4.10. The design process for each component will be documented in turn.

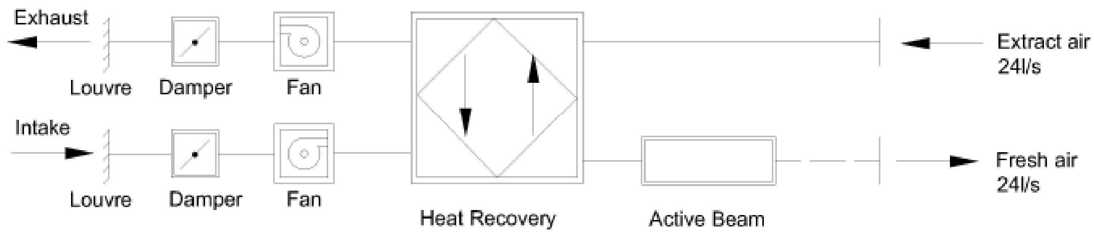


Figure 4.10 Overview of mechanical fresh air system

The louvres are the means of entry and exhaust of air between the outside and the interior. They are designed to provide sufficient area for fresh air entry, whilst preventing rain entering and located to avoid recirculation. The louvre size and type will be selected from manufacturer's data, as it will depend on the particular model used. Guidance on the sighting of the intake and exhaust is found in CIBSE Guide B (CIBSE 2005, p.2.5.2) and BSI which recommends a minimum distance of 2 m when openings are on the same facade (BSI 2008a, p.35). This will add extra complexity to the duct work. To verify that there will be no short-circuiting a numerical method of analysis could be carried out, but this is complex as well as site specific due to wind effects. What can be considered is a form of tracer gas test into the air flow path once a realised prototype has been completed, to determine the level of cross-contamination between intake and exhaust (see Chapter 6).

The dampers are an additional weather protection device and prevent air infiltration from occurring outside operational hours. The two types of damper that could be considered are backdraught dampers and motorised dampers. However, backdraught dampers only work in one direction and would be unsuitable for the supply, where air flow during operational hours is from outside to inside. Motorised dampers that work on the basis of an electronic signal can be used by opening and closing whenever the system is switched on. The ductwork between the damper and other components is specified in terms of size, shape and material. The size is related to the flow rate, velocity and pressure drop. For a low velocity system, the velocity is kept between 3-6 m/s and the recommended pressure drop no greater than 1.0 Pa/m (Hawkins 2011, p.43). The corresponding duct size would be a 125 mm circular with a velocity of 2.0 m/s and 0.5 Pa/m however this will also depend on the connection sizes of the other components.

Table 4.4 Air to Air heat exchanger types and performance (ASHRAE 2008, pp.2-68)

Heat Exchanger Type	Sensible Eff.	Latent Eff.	Pros	Cons
Plate (sensible only)	50 to 80	0	No moving parts Easy to clean Low pressure drop option	Sensible only Summer bypass difficult
Plate (sensible + latent)	50 to 75	50 to 72	As above and transfers moisture	Summer bypass difficult
Rotary (sensible)	50 to 85	0	Compact cross-section Low pressure drop	Moving parts
Rotary (sensible + latent)	50 to 85	50 to 85	As above and latent heat transfer	Moving parts Additional cost
Run-round coil (sensible)	55 to 65	0	Exhaust airstream can be separate from supply airstream	Sensible only Requires pump and piping

The mechanical supply of fresh air requires a fan to drive the air flow. The two main types of fans used in air handling units are axial and centrifugal. The main performance difference is the relationship between the pressure generated for the same flow rate and the air flow path. To supply the Active Beam and drive the induction effect, a pressure of at least 60 Pa (Frenger Systems 2011) is required. In addition, the pressure drop of the dampers has to be provided, which is normally around 15 Pa. This necessitates the use of a centrifugal fan rather than an axial fan to match the flow rate to the pressure drop. Many manufacturers provide the fan as part of a Heat Exchanger unit.

Heat Exchangers are available in a variety of sizes and different performance characteristics. The Heat Exchangers available on the market are shown in Table 4.4 together with their effectiveness and most important pros and cons for this project. A major consideration for the choice of Heat Exchanger is whether latent heat recovery is needed as the Heat Exchanger material has a higher capital cost and higher maintenance costs. This is dependent upon the balance between the sensible and latent loads[1] within the space and the comfort requirements. Using the room load data from the previous thermal analysis together with the heat recovery performance, a psychrometric chart was drawn up to assist in the decision making process and is shown in Figure 4.11. The chart shows that under the design winter condition, a sensible only Heat Exchanger introducing fresh air at condition 'SA1' would not provide the mix condition on the room ratio line or in other words, the occupied space would drop in relative humidity below the recommended limit. On the other hand, a sensible and latent exchanger introducing fresh air at condition 'SA2' would provide a suitable mix condition 'M2' along the room ratio line and maintain the humidity within comfort limits at all times. The type of Heat Exchanger needed is therefore restricted to plate and rotary types which provide latent as well as sensible heat transfer.

[1] Latent heat here refers to water moisture content in the air (a vertical line in the chart) and sensible heat is associated with dry heat (a horizontal line in the chart.

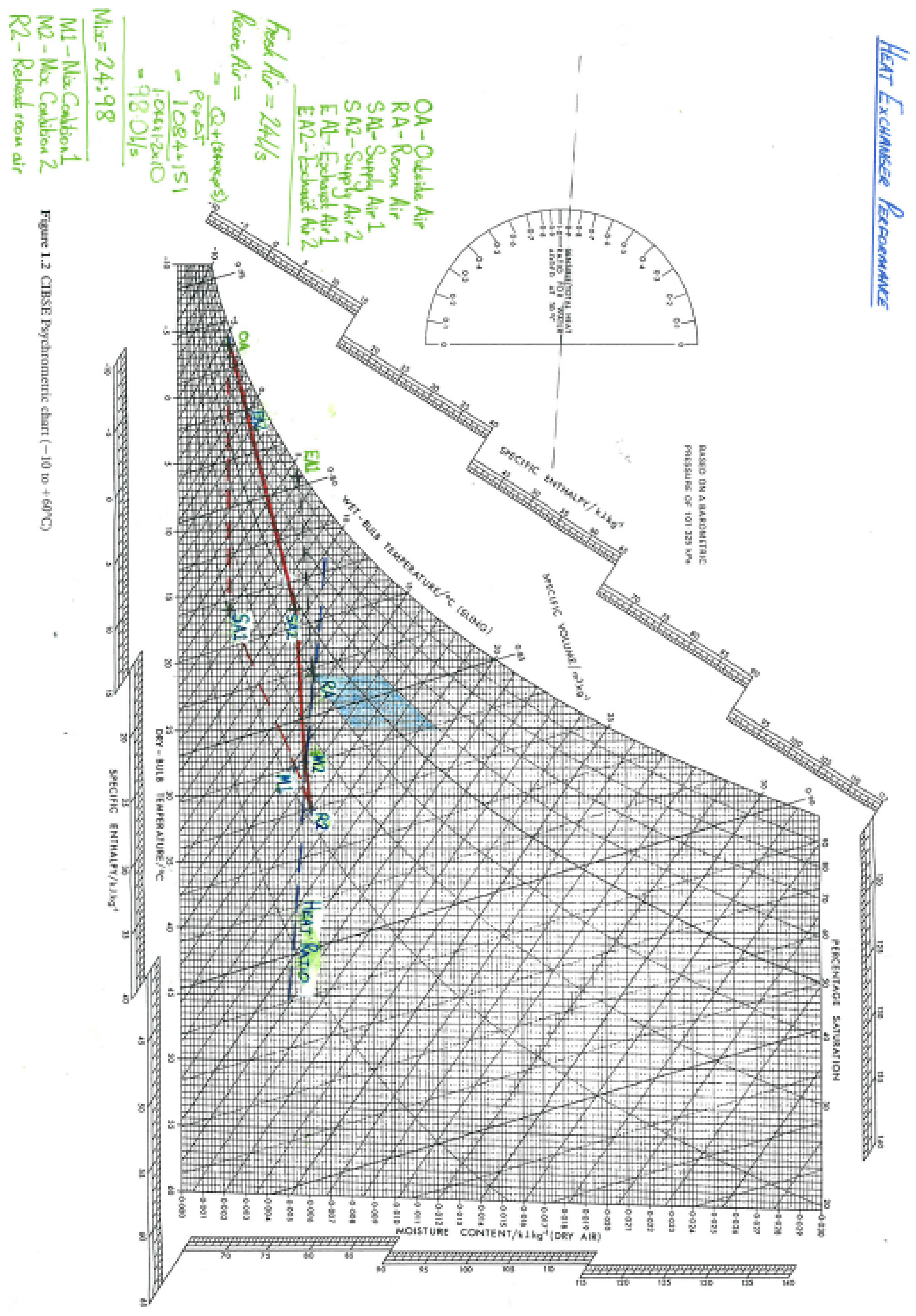


Figure 4.11 Psychrometric process for a sensible only, and sensible and latent, Heat Exchanger

4.4. HEATING, COOLING AND FRESH AIR DELIVERY

The heating and cooling delivery system needs to provide the required loads into the space and prevent asymmetric thermal conditions. The fresh air delivery system needs to ensure that the required air volume is provided. The most suitable method of distributing the fresh air, heating and cooling was identified in Section 2.13 as an Active Beam. This provides excellent comfort and energy performance however the thermal outputs are a limiting factor to their use. A closer examination of the thermal performance is therefore needed.

The capacity of an Active Beam is typically 500 W/m for cooling and 250 W/m for heating. Assuming the Heat Exchanger occupies 1.2 m, a perimeter type Active Beam can be up to 3.6 m (the remaining three bays of the modular office). If it was perpendicular to the facade it could be slightly longer at 4.8 m (assuming 6m deep office). In terms of cooling, a sensible load of 1800 W is present, which can be met in both cases. However the latent load cannot be met by the Active Beam as it does not have a condensate removal mechanism. In terms of heating, a sensible load of 1930 W is present which cannot be met in either configuration. An additional form of latent cooling and sensible heating is therefore required.

Extra capacity can be provided at floor level by a recessed (trench) unit, or an in-duct unit at high level, installed before the Active Beam. Their usage depends upon the beam configuration. For the perimeter beam, the in-duct unit would erode the length available for the Active Beam and provide insufficient capacity to satisfy the cooling load. The perpendicular beam in terms of space availability has both options available, but as the beam gets pushed further into the room, the air flow and area serviced moves away from the perimeter. This could cause asymmetric thermal conditions as the solar load is concentrated closer to the perimeter. In the perpendicular beam configuration, a floor level trench unit adjacent to the facade is therefore preferable as it would service the perimeter zone. An additional benefit of a floor level heating device is the prevention of any draughts and enabling preheating or background heating, during unoccupied hours without having to introduce fresh air (which would impose an additional heating load). In cooling mode, condensate removal would also be easier to achieve discreetly, but the refrigerant temperature would need to be lower than the dew point (see Section 4.2) and a fan to drive the cool air as it will not naturally circulate back into the room from the trench, as is the case when in heating mode. An Active Trench unit for heating, cooling and dehumidification was therefore added to the design and is shown in Figure 4.12.

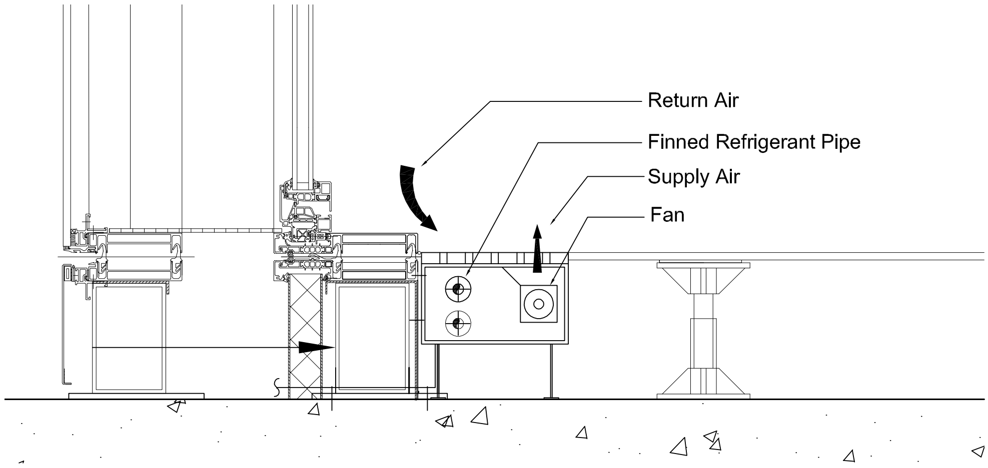


Figure 4.12 Trench heater design for additional heating

With all of the major components selected for the environmental system the next step is to examine their aesthetic impact and look at the ways in which they can be integrated to provide a desirable internal and external aesthetic.

4.5. EXTERNAL AND INTERNAL INTEGRATION

'Every technical detail that is altered lead to a whole series of positive and negative consequences. Each idea which created space for itself prevents other possibilities from fruition' (Petzinka & Busmann 2004, p.10)

The final aspect of the Active Environmental System to consider at this design stage is the challenge of integrating the components into the facade, to create a desirable external and internal aesthetic, ensure performance is maintained and provide a prefabricated solution. The Active Environmental System can be grouped into the internal and external components, and will be examined separately beginning with the internal components.

The internal components include the Active Trench, Active Beam and Heat Exchanger. The Active Trench is already integrated aesthetically into the floor.

On a prefabrication level it can also be attached to the facade. Further consideration is needed for the Active Beam and Heat Exchanger, which can be grouped together and will be referred to solely as the Active Beam in this section. It can be installed either adjacent to, or perpendicular to the facade each with positive and negative effects.

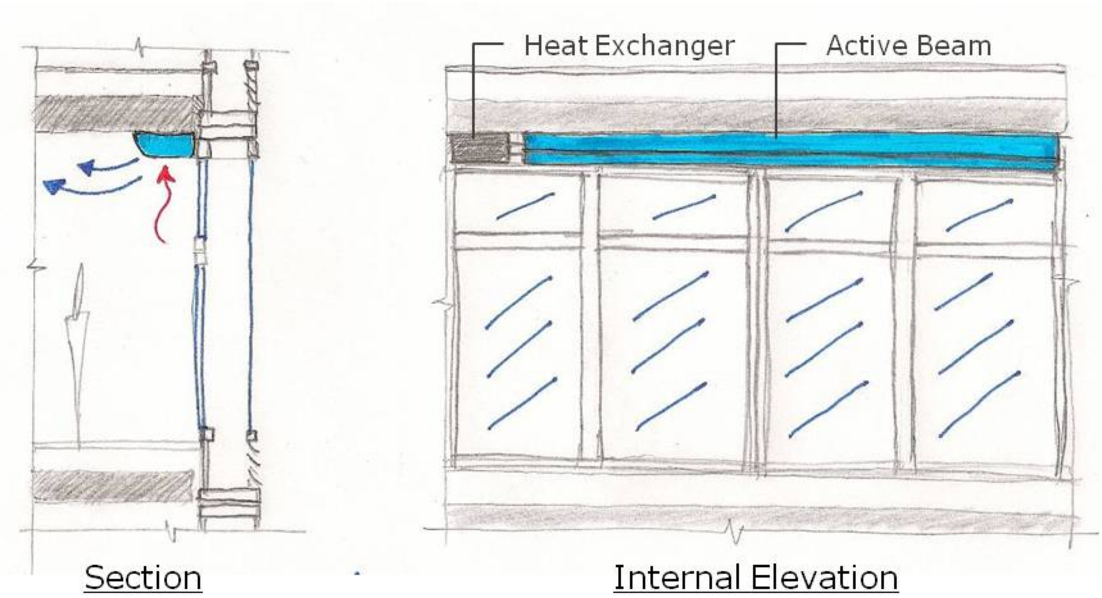


Figure 4.13 Active Beam adjacent to the facade

The Active Beam adjacent to the facade is shown in Figure 4.13. The main advantage is that it can be prefabricated as part of the facade to create a single component for installation fulfilling the original project brief. In addition, the cooling performance is improved by capturing the heat gains absorbed by the inner glass in summer. Extracting air at the facade also reduces the draught risk in winter. The main disadvantage is that the floor to floor glazing height in the room is reduced, which affects the degree of transparency. The external aesthetic will also be affected, as the spandrel zone will appear increased, whereas it is quite common for architects to keep the appearance of the spandrel zone to a minimum or merge it with the rest of the facade. In addition, if prefabricated artificial lighting was required as part of the Active Beam it would be difficult to achieve uniformity with luminaires only at the perimeter.

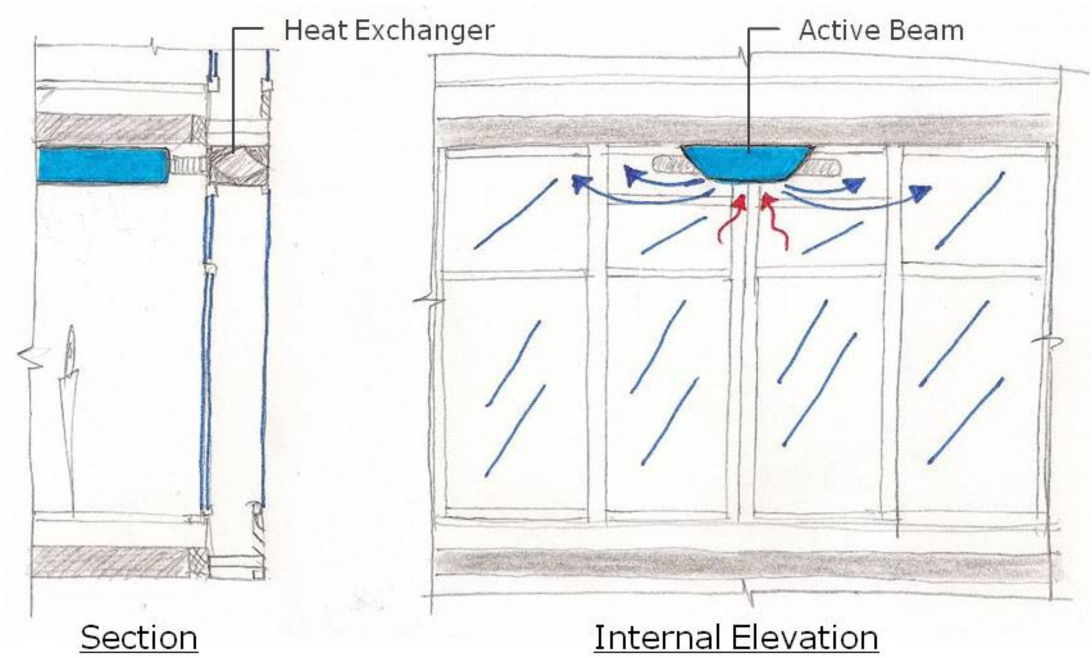


Figure 4.14 Active Beam perpendicular to the facade

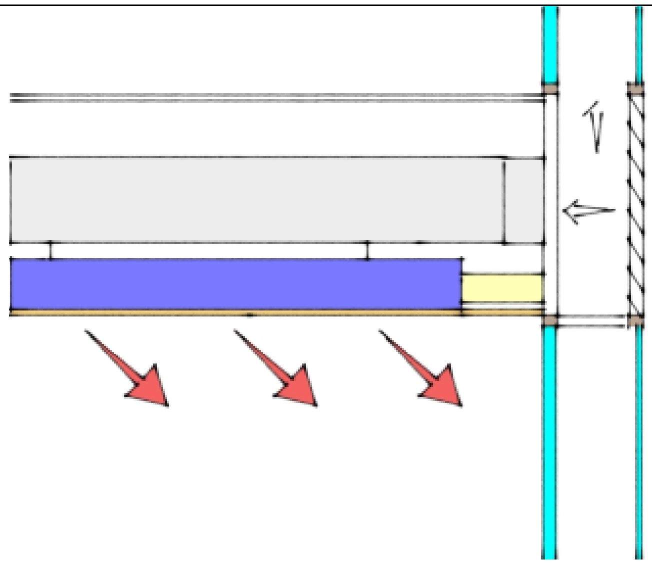
The Active Beam perpendicular to the facade is shown in Figure 4.14. It has the advantage of having a much reduced impact on the floor to floor glazing height and enables full height glazing over the majority of the facade. In addition, the cooling and heating capacity is increased by firstly, being able to discharge air in two directions and secondly, the length of beam can be increased. Lighting uniformity is also easier to achieve. The perpendicular design could also serve deeper plan offices. The major disadvantage to this solution however, is that the Active Beam would need to be installed separately on site, and there would be a degree of site assembly required to connect the pipework and ductwork. Aesthetically, the interface between the ducts, the beam and the facade could be considered undesirable if not developed further and integrated into a common enclosure.

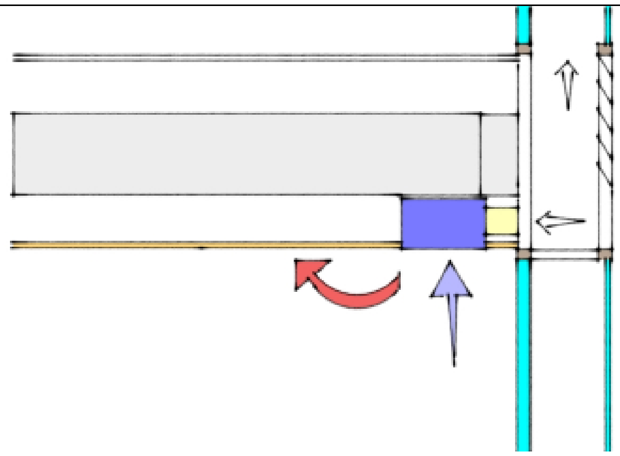
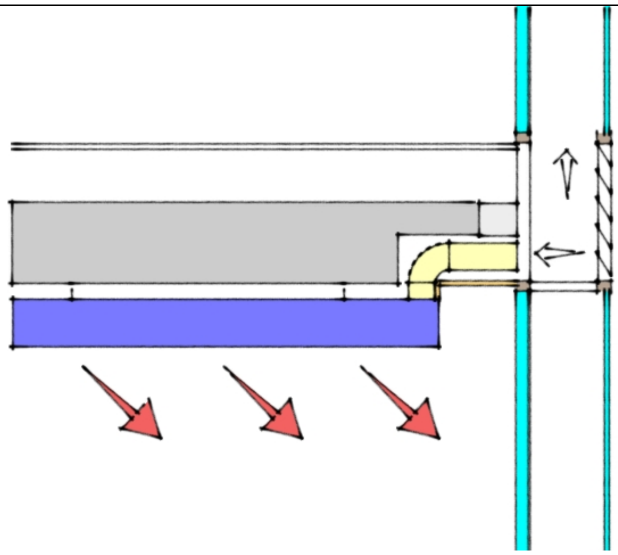
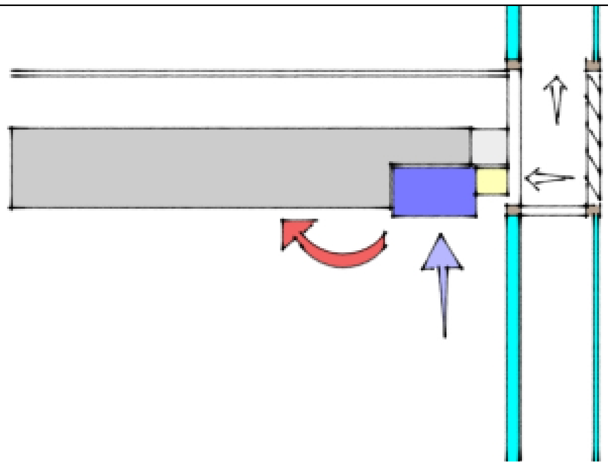
There is therefore no optimal configuration when they are treated very simply; each has positive and negative consequences in different design areas. To understand which areas are more important, advice and opinions from architects and engineers were sought. The main area that was considered important by these design professionals was the aesthetic consequences of each design and how this might be improved through design of the slab and the Active Beam. The construction professionals recommended a number of different desirable aesthetic intents which included:

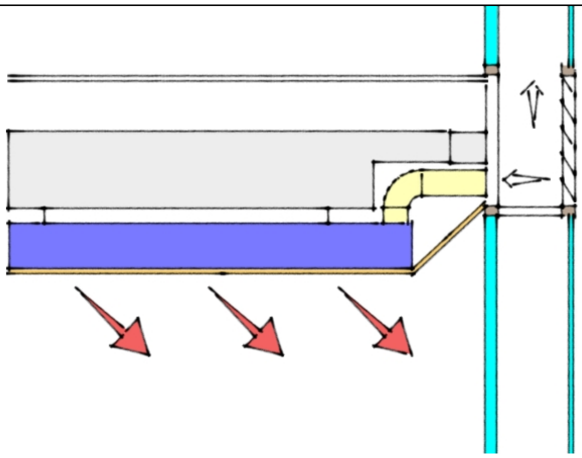
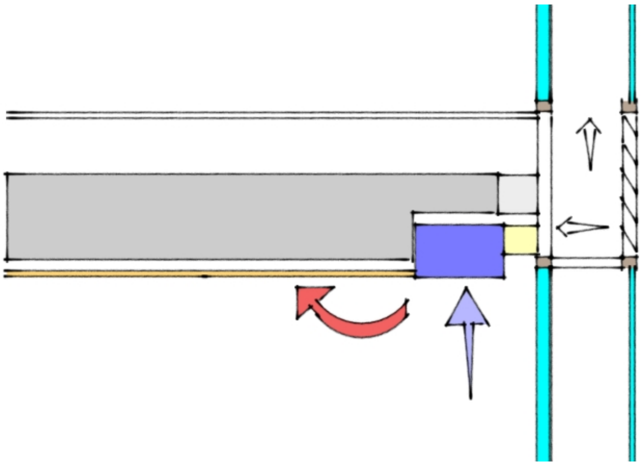
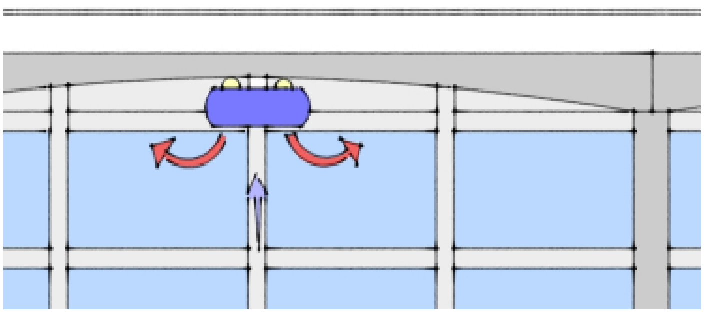
- A thin slab edge (to reduce the spandrel zone and maximise glazing height);
- Exposed thermal mass to provide fabric energy storage (and avoid using a suspended ceiling);
- Hidden services internally;
- Hidden services externally.

In response a number of different configuration options were developed and are shown in Table 4.5.

Table 4.5 Active Environmental System Options for different requirements

	Aim	**Detail and Changes**
A	• Standard slab design • Hidden services internal and external • Suspended ceiling	 Perpendicular Active Beam

B	• Standard slab design • Hidden services internal and external • Suspended ceiling	 Perimeter Active Beam
C	• Thin slab edge • Exposed thermal mass	 Perpendicular Active Beam
D	• Thin slab edge • Exposed thermal mass	 Perimeter Active Beam

E	• Thin slab edge • Suspended ceiling	 Perpendicular Active Beam
F	• Thin slab edge • Suspended ceiling	 Perimeter Active Beam
G	• Hidden external services (coffered slab) • Exposed thermal mass	 Perpendicular Active Beam

Each of the options 'A' to 'G' responds to a different hierarchy of requirements or mutually exclusive opinions. Between the main sponsor and the author, the three most preferable options were options 'B', 'C' and 'D'. The sponsor had a preference for Option 'B' as standard slab geometry could be used, in their experience commercial developers prefer a suspended ceiling and it would allow for a fully prefabricated solution (the beam can be part of the facade installation. However, this would remove the cooling effect of the thermal mass, have a negative impact on the energy performance and jeopardise the low carbon emission aims. This view could represent past practice rather than best practice. Out of options 'C' and 'D', the potential for a fully prefabricated solution (option D) was considered preferable.

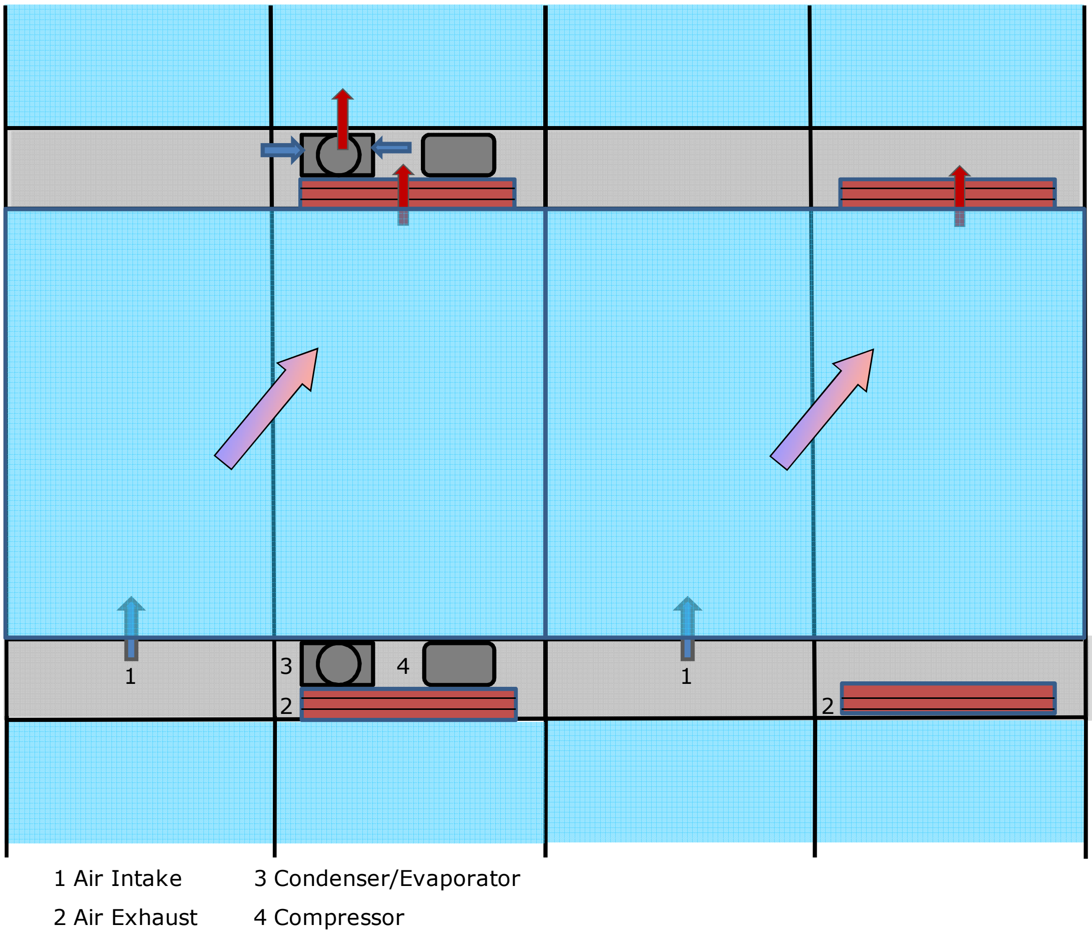
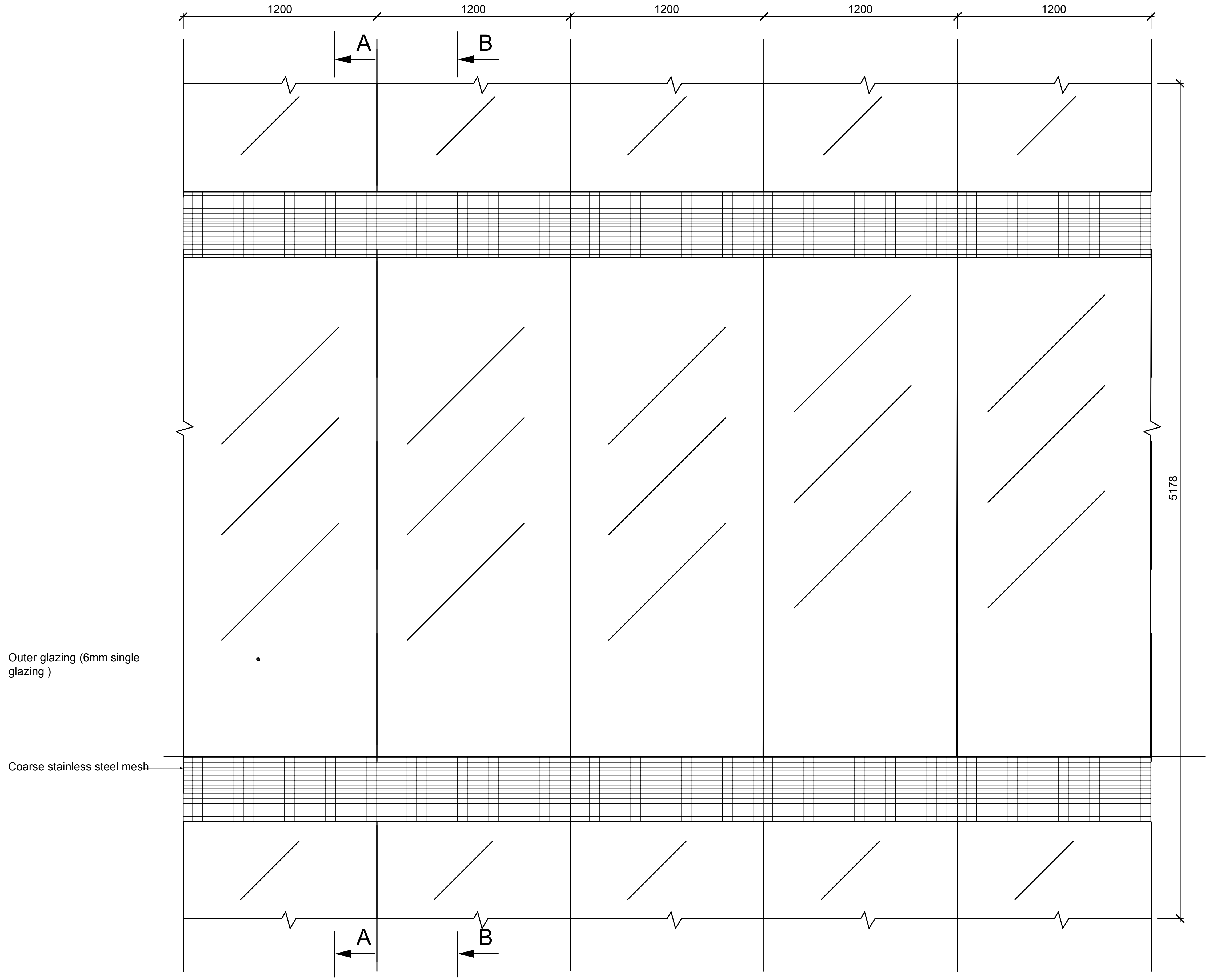


Figure 4.15 Location of heat pump components in relation to intake and exhaust louvres

The external components of the active environmental system comprise of those making up the Reversible Heat Pump (RHP) system and are to be located within the double skin facade in the spandrel zone to maximise the glazed vision area. This will mean designing the RHP system to fit within the spandrel space and will need to be discussed with manufacturers as to how best it can be configured (Chapter 5). The design of the spandrel itself needs to provide air entry and exhaust for the Condenser/Evaporator and the Heat Exchanger. This needs to also take into account the air temperatures within the double skin cavity and the relationship with the season. In winter the RHP discharges air at a lower temperature than ambient and in summer at a higher temperature than ambient. To avoid diminishing the performance of the double façade, the air should discharged to the outside and avoid entering the cavity. The cavity could provide air to the Condenser/Evaporator in winter at a higher temperature than ambient which would be beneficial, but in summer this would reduce the performance. If a heating only unit was provided this would be an option. Figure 4.16 shows how the condenser/evaporator is located to draw air in horizontally form an intake bay and then discharge it straight out through an exhaust bay. The final consideration is the aesthetic.

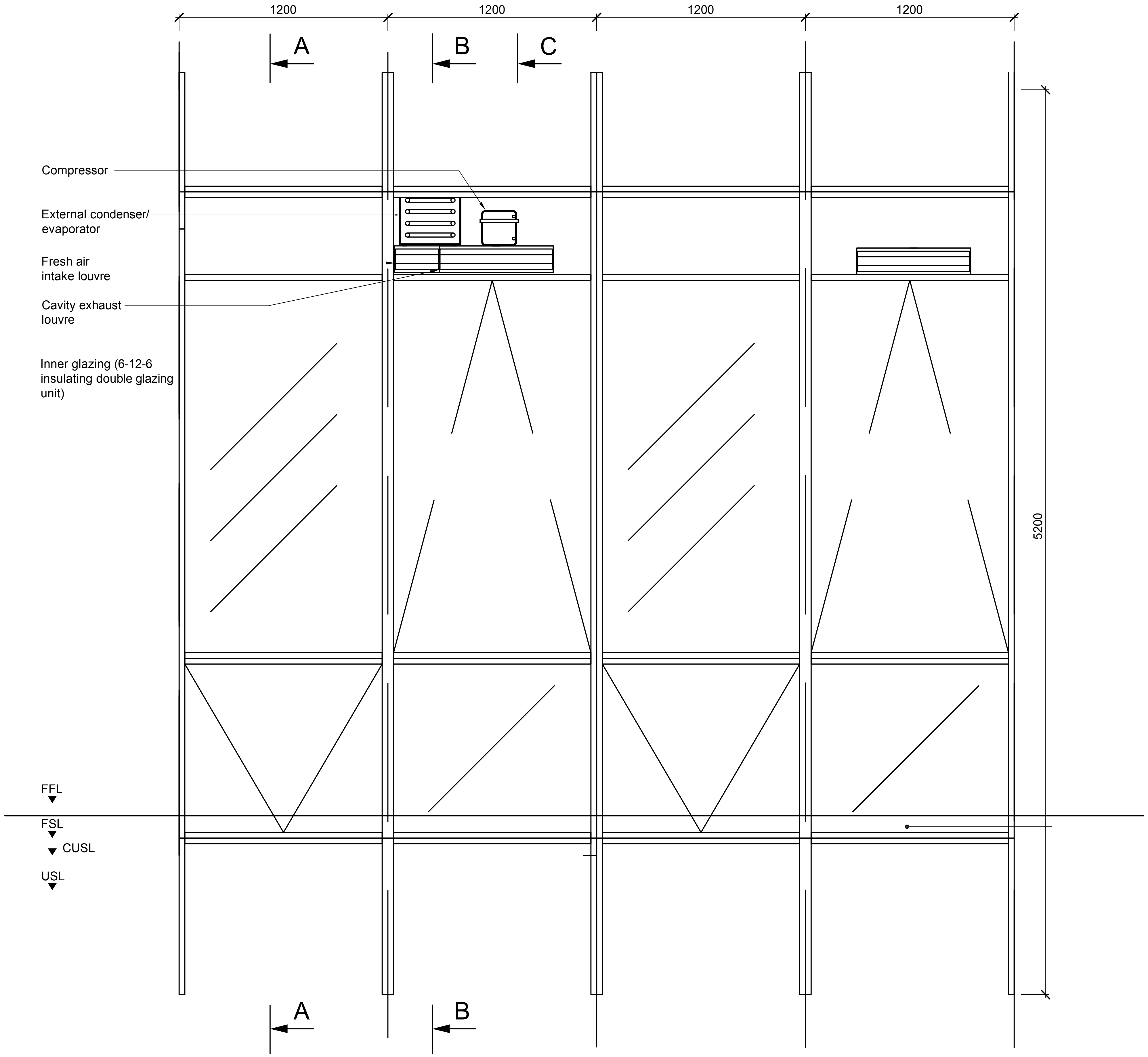
With the components of the air source heat pump and cavity louvers a very discontinuous look to the facade would be created as indicated in Figure 4.15. Therefore a stainless steel mesh, or similar detail, that would cover the whole spandrel zone continuously whilst providing a great deal of free area for the cavity and air source heat pump intake and exhaust is proposed.

Figures 4.16 through to Figure 4.19 provide detailed drawings of the integration of the environmental system with the double skin facade. A minor addition is an aluminium plate to the Active Beam. The intention here is to improve the interface between the Active Beam and the slab by creating a shadow gap and to draw the eye away from any discrepancy in distance between the slab and the beam that is likely occur due to the difference in tolerance between an Active Beam (+/-1 mm and a concrete slab +/-20 mm).



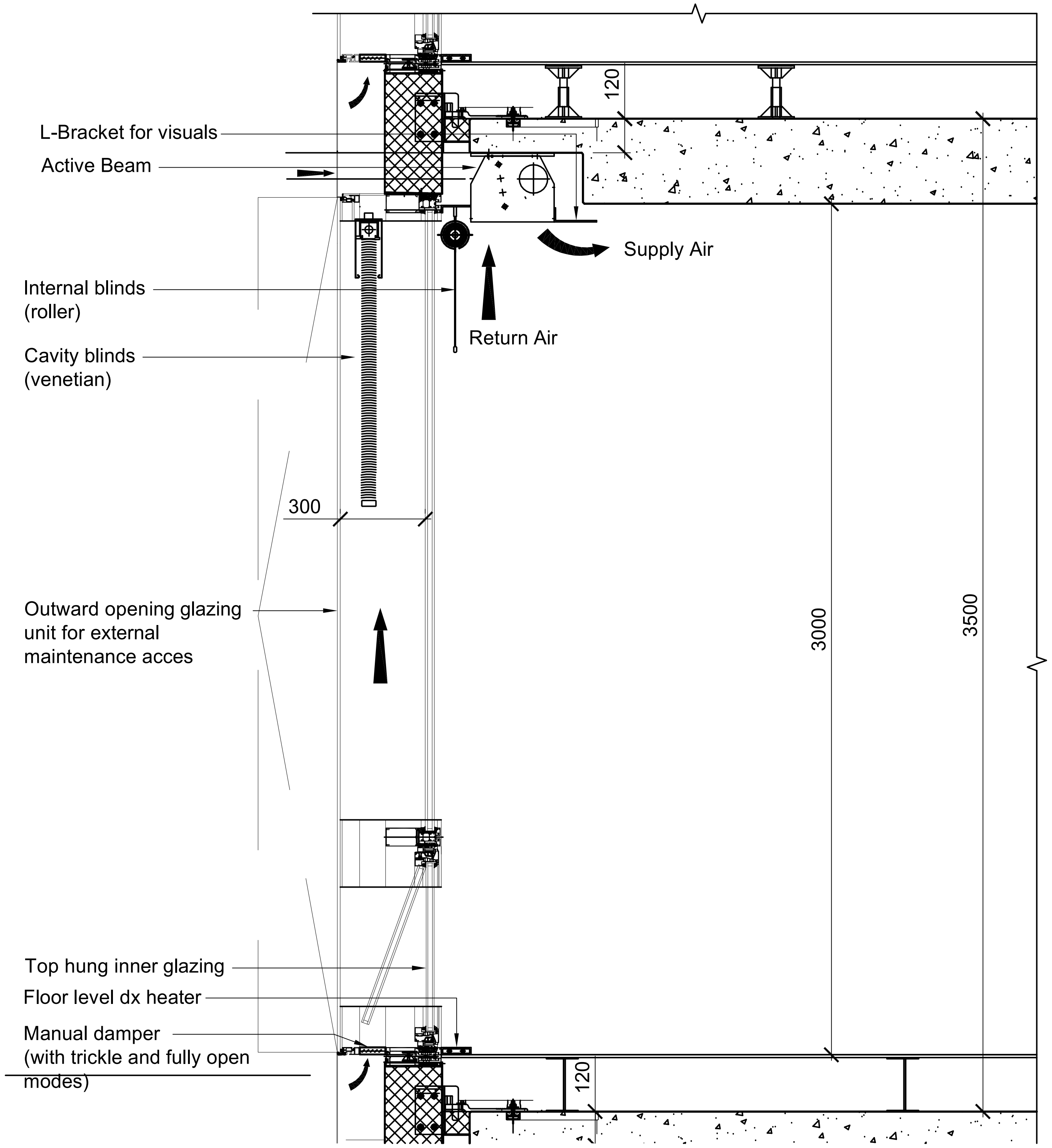
External elevation

Project: Integrated Facades for Offices	Type: Heat Pump with chilled beam	05/05/2010
Scale @ A3= 1:25	Description: External elevation	Figure 4.16

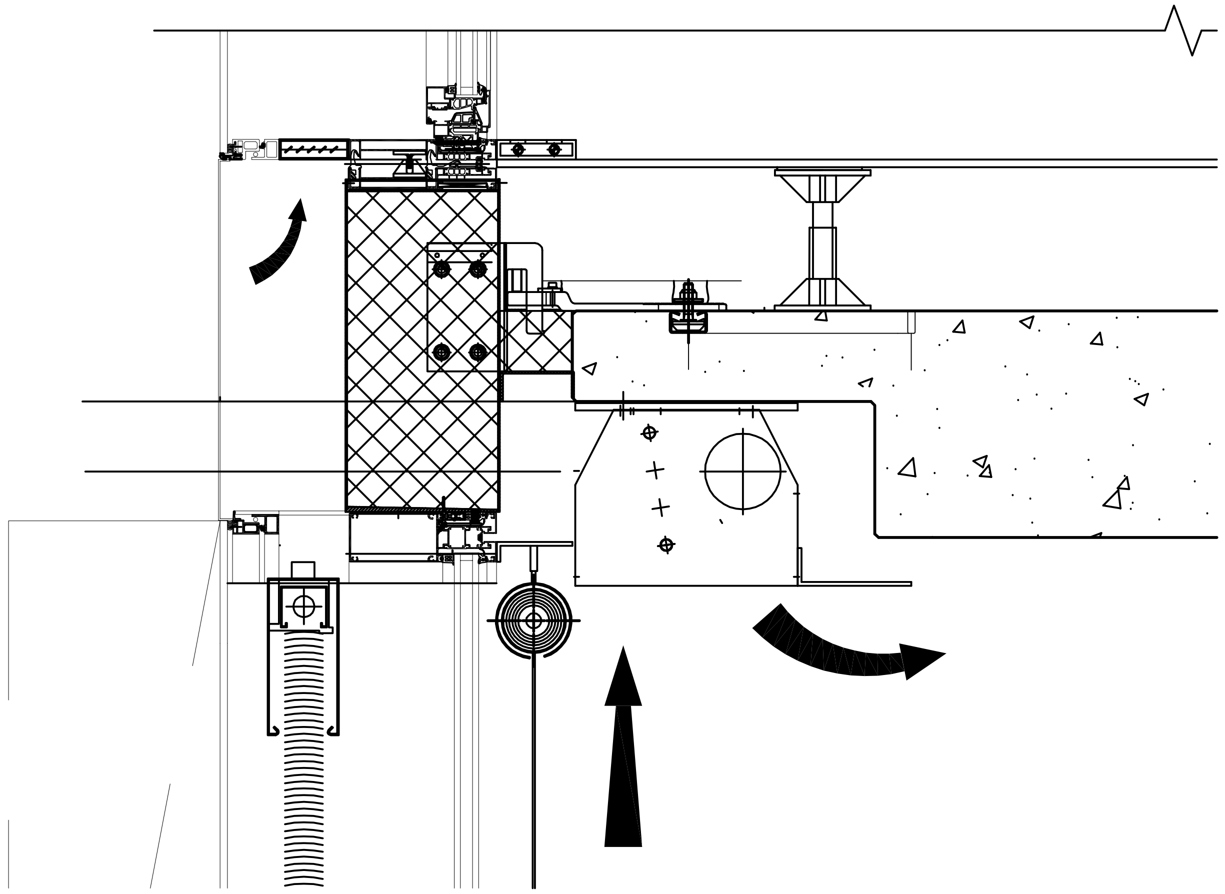


Elevation of inner skin

Project: Integrated Facades for Offices	Type: Heat Pump with chilled beam	05/05/2010
Scale @ A3= 1:25	Description: External elevation	Figure 4.17

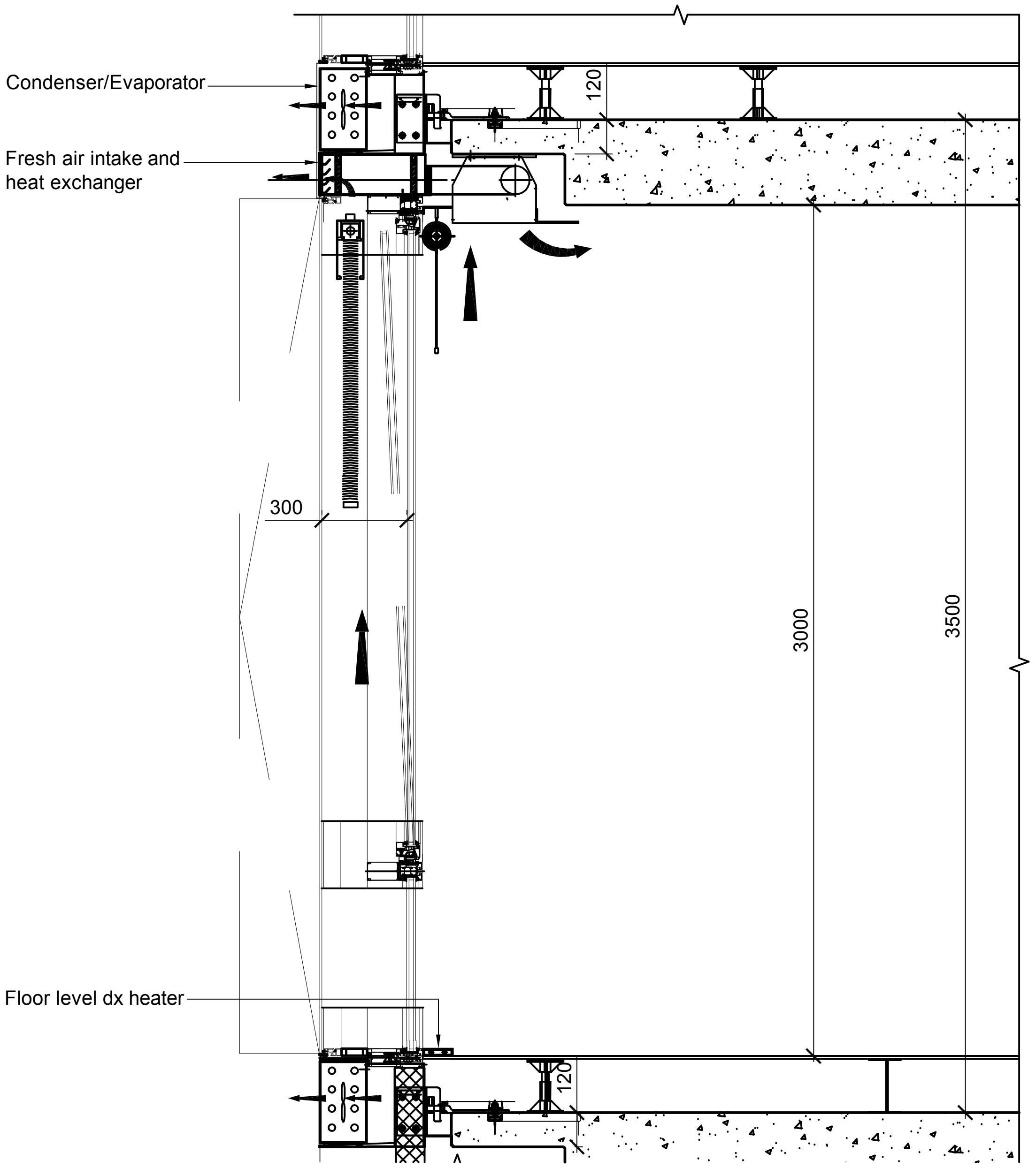


Section A-A 1:20
Fresh air and cavity inlet

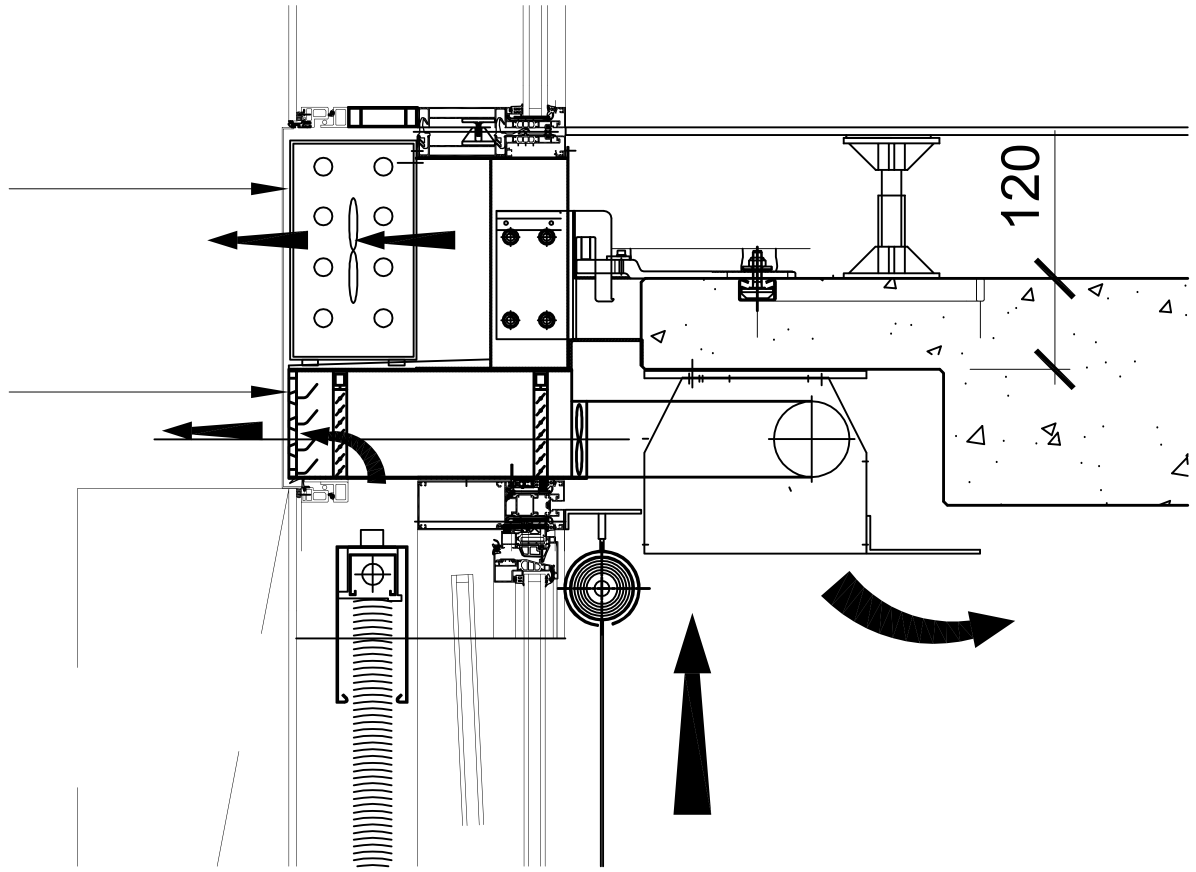


High Level Detail 1:10

Project: Integrated Facades for Offices	Type: Heat pump chilled beam	05/05/2010
Scele@ A3 = 1:20 and 1:10	Description: Section	Figure 4.18



Section B-B 1:20
Exhaust



High Level Detail 1:10

Project: Integrated Facades for Offices	Type: Heat Pump with chilled beam	02/10/2009
Scale @A3= 1:20 and 1:10	Description: Section	Figure 4.19

CONCLUSIONS

The chapter has analysed the various options for the Active Environmental System and the detailed design of a Double Skin Facade, with an Integrated Active Environmental systems has been achieved. This can be termed an Integrated Passive and Active Double Facade System (IPADFS). The heating and cooling supply and delivery options for a decentralised system were established in Chapter 2. In this chapter, the heating and cooling supply options have been analysed based primarily on carbon dioxide emissions, but also ease of integration, cost and developmental work required. Out of this analysis, a reversible air source heat pump (RSHP) was selected because of the low CO_2 emissions and prefabrication and decentralised servicing potential.

The RSHP system has been developed from a concept schematic into a detailed design, addressing environmental issues, operating parameters and prefabrication. Instead of using conventional refrigerants, the RSHP system has been based on propane, an environmentally friendly refrigerant to future proof the design. The operating parameters of the RSHP system have also been specified, to ensure high efficiency and provide control of the room air temperature and humidity. The size and configuration of the RSHP can also be installed as part of the facade fulfilling prefabrication requirements. The RSHP system therefore achieves the reduced carbon emissions necessary as part of the sustainability objectives outlined in Chapter 1 and can be integrated into the facade on a zone by zone basis fulfilling the prefabrication and decentralised system objectives discussed in Chapter 2.

The supply of fresh air through the use of a Heat Exchanger was introduced in Chapter 2 to allow for the air to be preheated and avoid draughts when introduced into the space. Through psychrometric analysis of the heating process, the requirement for latent, as well as sensible heat recovery has been established. This requires the use of a either a plate type or rotary type Heat Exchanger as both can provide latent heat recovery. The decision will be made following discussion with manufacturers and suppliers in Chapter 5.

The delivery of the fresh air, together with heating and cooling via an Active Beam was established in Chapter 2. Calculations of the heating and latent loads that can be achieved by the Active Beam have revealed that additional capacity is needed. An Active Trench has therefore been added, which can provide dehumidification to the room air, as well as additional heating and cooling capacity.

The final part of this chapter has looked at how the environmental system can be integrated into the facade and the office space. For the internal components, there are a number of options and no single solution that optimally addresses the issues of aesthetics, prefabrication and environmental performance. This is due to differing aesthetic preferences and hierarchy of requirements. Based on discussions between the sponsor and the author, an option where the Active Beam and Heat Exchanger are located at the perimeter adjacent to the facade has been chosen. Apart from providing a satisfactory aesthetic, it can be fully prefabricated, can be installed with or without a suspended ceiling and maintains a slim spandrel zone.

Many of the decisions made during both the facade design in Chapter 3 and the Active Environmental System in this chapter have been made without advice from industry and aesthetic judgements based on drawings, scale models and the author's opinion. As discussed in Section 2.4, an important part of the design process is to involve industry, in order to improve the design based on their knowledge, available components and to fabricate a full scale prototype. With the full scale prototype a more informed aesthetic appraisal by the author and other stakeholders can be made which is included in Chapter 6. This can then feed back in to the design of the facade and the Active Environmental System. The IPADFS is now sufficiently detailed and clear, for the industrial development design stage to begin as recorded in Chapter 5.

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CHAPTER 5

INDUSTRIAL DEVELOPMENT AND PROOF OF CONCEPT PROTOTYPE REALISATION

'It may well be that the present formula, which consists of displaying a drawing and requesting a builder to follow it, is at the present root of our decay…An honest approach must lead to that osmosis of science, the mind and the hand…Such an osmosis seems difficult, perhaps impossible to achieve as long as the men concerned are working apart...' (Prouvé 1971, p.13)

One of the startling occurrences about many recent projects in the construction industry is the difference between the 'tender' drawings produced by the design consultants and the 'as built drawings' produced by the sub-contractors. This could be attributed to the lack of involvement of designers in the production process itself which is amplified in Design and Build forms of contract where at best, the design team is 'novated' and part of the contractors team and at worst, are powerless observers during the construction process. This can result in what Professor Michael Stacey refers to as the ugly 'gunked-up' site detail (CAB 2008, p7) and the missed opportunity to learn from mistakes. This separation of design and construction is also given as one of the factors limiting innovation in construction (Reichstein et al. 2005). To breach this divide and come face to face with the difficult details that either stem from the difficult sections that many consultants like to omit or through ignorance of the production process, a full scale prototype has to be realised. This can only be done by leaving the comforts of the office, entering into the domain of industry and understanding the realities of construction in the 'real world'.[1]

To realise a full scale prototype which comprises of a number of different components, and of such a large size, within the time limits of a PhD and the funding and University facilities available, is a difficult undertaking. The first difficulty is the production of the bespoke components as 'one-offs' can be uneconomical for industry. The University facilities can be used for the production of bespoke components, but this is also quite challenging as both

[1] 'this is the real world' is a favourite expression of Roger Philips, Managing Director of Crown Aluminium to remind designers of the obstacles faced in reality. Crown Aluminium is the fabricator of Double Facade Prototype.

technician time and expertise in the areas of curtain walling and refrigeration, is limited.

A balance will have to be made to overcome these constraints where some bespoke components will be replaced with standard components so that they can be provided by industry. If the compromise is too great, they will be made within the University and technician expertise or time constraints overcome by the involvement of the author and external specialists. The second difficulty is the integration and assembly process. Without a crane or glass manipulator the integration of heavy components and assembly will have to be modified.

The aim of this process is not only to realise the prototype, but also to provide an insight to the intended production process and gather knowledge and advice from industry. In this way the barrier between design and construction introduced in Chapter 2, can be overcome. The design development of the prototype with industry is documented firstly in terms of the environmental system, followed by the facade and covers the design changes made. The final design is then presented and the assembly and manufacture route fully described.

5.1. ACTIVE ENVIRONMENTAL SYSTEM DEVELOPMENT

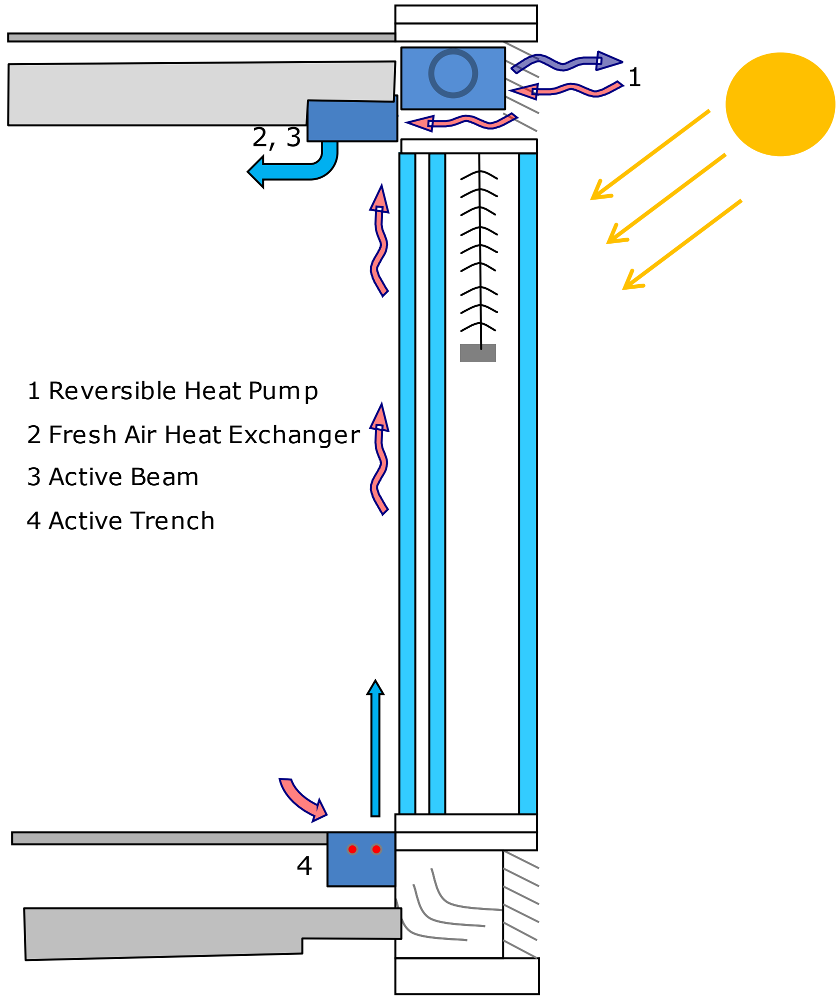


Figure 5.1 Diagram of the IPADFS Active Environmental System components

The Active components of the IPADFS prototype can be grouped into four parts:

- Active Beam;
- Active Trench;
- RSHP;
- Fresh Air Heat Exchanger.

All of the components are available on the market however, the way in which they are to be used is new and necessitates varying degrees of changes. The development and manufacturing or assembly process for each will be described in turn as the industrial suppliers for each of these components is different.

5.1.1. Active Beam Development

The Active Beam provides the fresh air and a portion of the heating and cooling. In a typical office, fresh air and extract is provided by a central air handling unit, and the heating and cooling supplied by a low pressure water circuit. However in the prototype design developed in Chapter 4, the air is fed from a local Heat Exchanger supply and extract unit, and instead of water, high pressure refrigerant is used for heating and cooling. The issues that need to be addressed by the Active Beam are ensuring the required loads are still met and the change from water to refrigerant. The implications of these changes are best addressed with an Active Beam manufacturer.

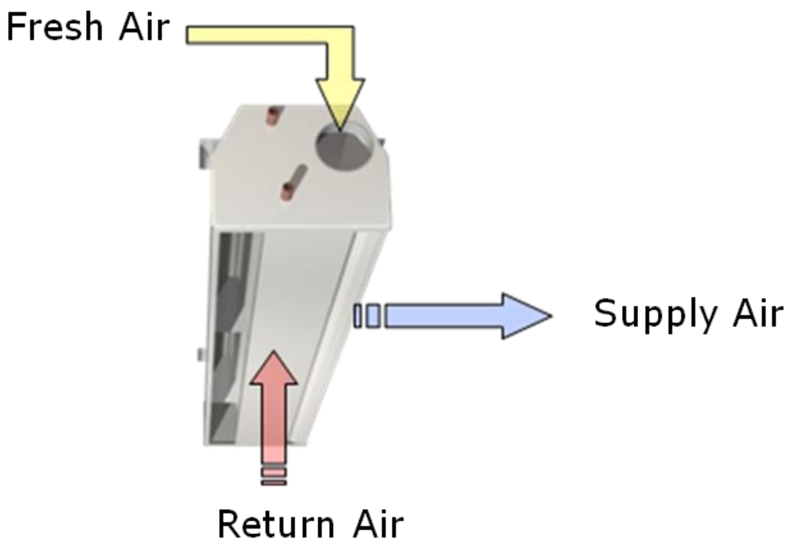


Figure 5.2 Perimeter type active beam 'Polaris' manufactured by Frenger Systems (source: Frenger Systems)

In the UK, the leading manufacturers of Active Beams include; Flakt Woods (www.flaktwoods.com), Trox UK (www.troxuk.co.uk) and Frenger Systems (www.frenger.co.uk). They were all contacted to give advice on the supply of an active beam that would be suitable for refrigerant and that meets the product specifications. Of these manufacturers Frenger Systems based in Derby, UK, were most interested in the project and to fully understand the manufacturing, assembly and range of active beams, a meeting with their technical director and a factory tour was arranged. During the meeting the different types of active beams were explored and one of the products, the 'Polaris' shown in Figure 5.2 was found to be most suitable for perimeter application. In this model the intake is vertically up and the discharge is in one direction. Care has to be taken with this model since the discharge is in one direction only as shown in Figure 5.1

and the air volume flow rate and therefore output is reduced in half. This is partially offset by the increased temperature of the return air coming from the glass (cooling output is related to change in temperature as well as flow rate), but still reduced compared to other two-way active beams. To verify whether the output would be sufficient, software developed by Frenger Systems (Active Calculator V2.0) was used to calculate the output of the beam. Using the refrigerant temperatures and the fresh air rate, it was shown that the Polaris type Active Beam could provide sufficient heating and cooling provided that the Active Trench made a contribution. This left the issue of refrigerant usage in place of water to be addressed.

The supply of heating and cooling in Active Beams is normally via hot or chilled water since the lengths of pipe work involved in a centralised system are too long for refrigerant. In this application it is not an issue and refrigerant can be used directly. Replacing water as the working fluid with refrigerant presents no issues thermodynamically, but because operating pressures will be higher using refrigerant, the type and size of copper tube needs to be of a higher quality and strength. For the higher pressures used in refrigeration a thicker wall of copper tube is required and any joints in the system need to be silver soldered or consist of flare fittings. Frenger systems were able to modify the joints to silver solder and confirmed that the copper type being used would be suitable for the higher pressures encountered. It would however be supplied as metric to reduce the setup costs involved in fabricating a finned copper pipe.

5.1.2. Active Trench Development and Manufacture

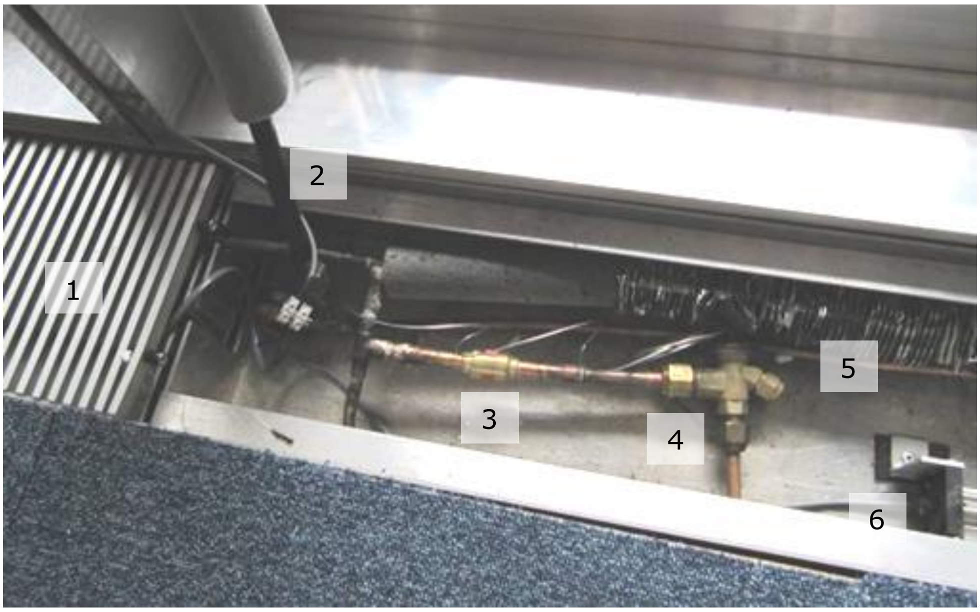
The Active Trench provides additional heating, cooling and dehumidification. There are a number of trench heaters available on the market designed for use with water. The prototype design necessitated quite a specific specification with fan assisted operation, cooling as well as heating, condensate removal and use with refrigerant.

A number of manufacturers were contacted to find out whether any of their units could be adapted or made bespoke. The only company which provided a unit close to the project requirements were S&P Coil Products (www.spcoils.co.uk/) through their 'MiniB' range. However the copper pipe in this model was only suitable for water and modifications for use with refrigerant, were prohibitively expensive due to the set up costs incurred for such small numbers of units. The decision was therefore made to design and manufacture the Active Trench Unit within the University of Nottingham.

The design of the unit is shown in Figure 5.3 and shows the main components. The fabrication sequence of the Active Trench Unit was:

1. Cut aluminium sheet to size and provide holes for pipe work penetration;
2. Weld/rivet angle bracket to the wall of the box for the grille;
3. Cut finned copper pipe to size;
4. Solder finned copper pipe to flared ended copper pipes;
5. Solder together the refrigeration valves into the pipe work;
6. Fix the fans into the boxes;
7. Pressure test the completed installation.

The fabrication of the Active Trench Unit was relatively straightforward and provided the opportunity to integrate the refrigeration valves into the boxes, which would not have been possible using S&P Coil Products. The main issue in the fabrication of the box was the cost of the finned pipe and the covering grille. To achieve a cost reduction on the finned copper pipe, condenser finned pipe from previous projects was cut into single arrays. The grille chosen to cover the box was made from aluminium and quite expensive. The supplier indicated a significant cost saving if replaced with a timber grille, but aluminium was kept as it was important to keep the material mix to metal and glass and achieve the precision and intended aesthetic. The Active Trench was made in 1.2 m lengths to enable it to be transported from the workshop to the laboratory easily. The pipe work connections were made as flare fittings to avoid soldering in an awkward and difficult position. The fans used for increasing air flow rate were riveted down into the boxes. The completed Active Trench is shown in Figure 5.3.



1 Aluminium Grille
2 Refrigerant Supply/Return
3 Check Valve
4 Thermostatic Expansion Valve
5 Finned Copper Pipe
6 Fan

Figure 5.3 Active Trench Unit as installed in the prototype

5.1.3. RSHP Development and Fabrication

The RSHP supplies the heating and cooling to the Active Beam and Active Trench Unit through the use of the vapour compression cycle operating on the reversed Carnot cycle. The system can be operated as a heat pump or refrigerant system by reversing the flow of refrigerant as discussed in Section 4.2.

The system comprises of a number of components which can be grouped into three parts. The external module comprised principally of the Compressor and Condenser/Evaporator and the internal components enclosed with the Active Trench and Active Beam. The intent was to find a manufacturer or supplier able to supply the external module as a complete unit, much like the condensing units available on the market with the exception that it was to be modified to match the load requirement and to use Propane as the refrigerant.

A number of smaller manufacturers were contacted who specialised in providing refrigeration based on alternative refrigerants since the large players in the market did not sell anything close to the required unit. The two companies contacted were Earthcare products (http://www.earthcareproducts.co.uk/) and Star Refrigeration (http://www.star-ref.co.uk/) based on recommendations from

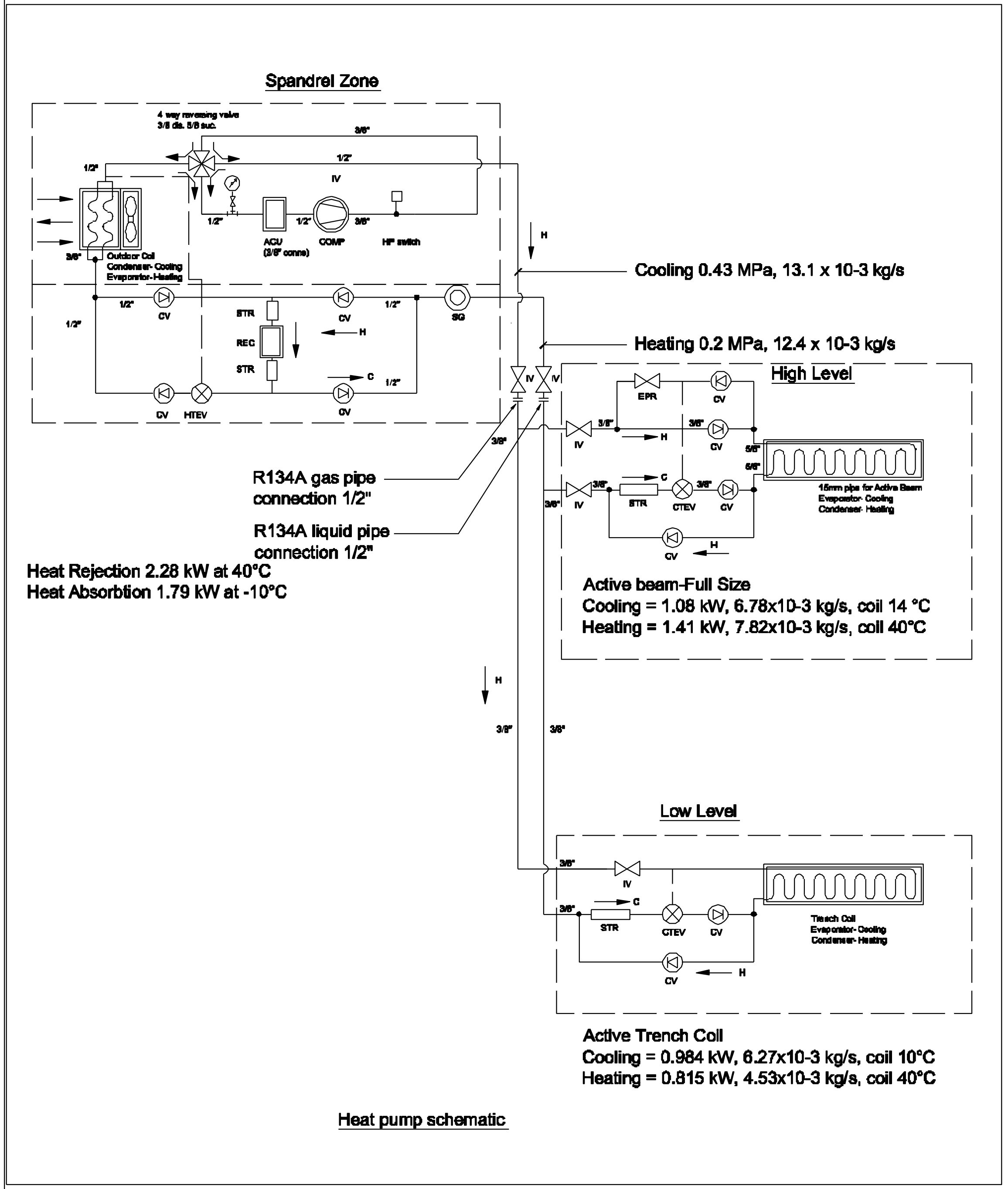
Buro Happold Ltd. Only Star Refrigeration responded and a meeting was arranged to discuss and understand more about the use of alternative refrigerants. They were only able to give advice on the choice of refrigerant and critical points that needed to be addressed. They were not able to fabricate a unit as the design work and set up costs involved in a single unit were prohibitive. The alternative of making the unit component by component at the University was then the only option. Components were sourced and technical assistance was gained from Dean and Wood Ltd (http://dean-wood.com/). After a meeting with Dean and Wood Ltd, an early decision was made to change the refrigerant from Propane to a more conventional refrigerant, as the parts for Propane were difficult or not available as Propane is a relatively new refrigerant on the market. The system was instead based upon refrigerant R134A[2] since the components are available; it has physical properties very similar to Propane and therefore the spatial requirements also. In future it would be straightforward to change to Propane.

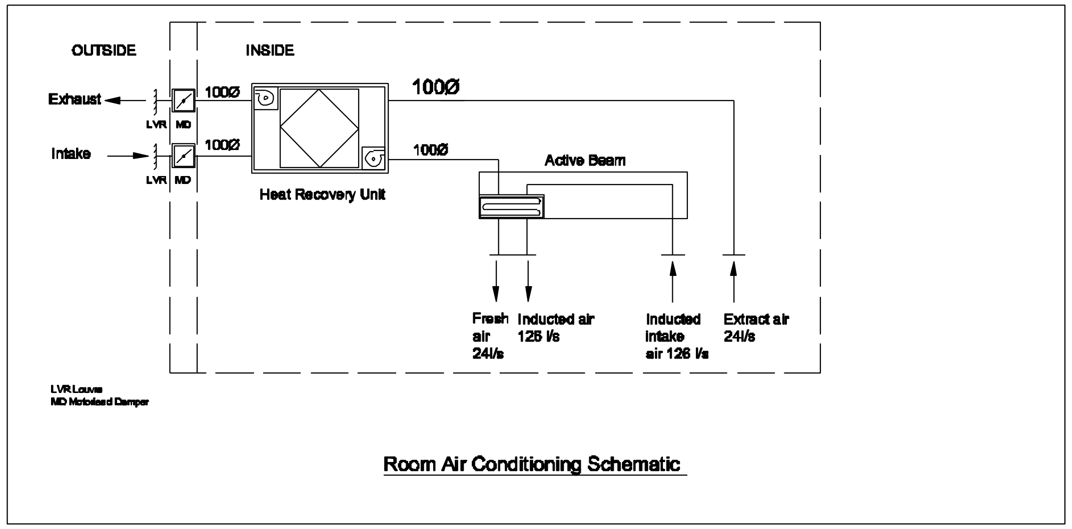
For the optimum operation of the RSHP, Dean and Wood's technical adviser assisted the author in the development of the simple schematic shown previously in Chapter 4 into a more detailed schematic (see Figure 5.4). This included a number of changes and additional components. The key differences are an:

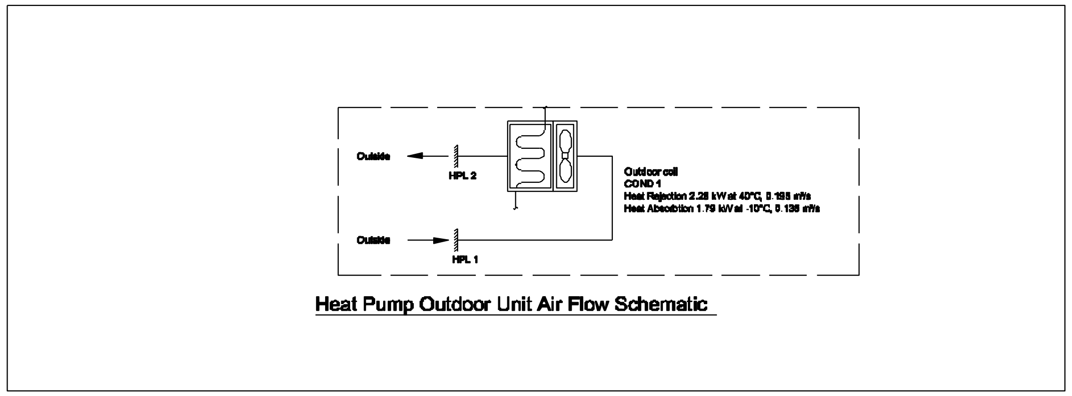
- Accumulator (ACU) located before the compressor to prevent any liquid from entering the compressor as this would cause severe damage;
- High pressure switch located after the compressor to cut the power to the compressor to prevent any excessive high pressures;
- Receiver (REC) to hold excessive refrigerant in the system which will be the case as the heating loads and cooling loads require different quantities;
- Isolating valves (IV) to allow the unit to be made in two parts- an outdoor unit and an indoor unit and to assist in maintenance and leak direction;
- Evaporating pressure regulator (EPR) located by the active beam serves to ensure that the evaporating temperature is controlled above the dew

[2] A refrigerant which has zero ODP, a high GWP and a higher practical limit than Propane (18 kg allowable within the room). See Section 4.2 for further details.

point to prevent any condensation occurring on the beam and allow it to operate at a temperature different to the Active Trench.







Nomenclature		Nomenclature	
Reference	Description	Reference	Description
PG	Pressure Gauge	ACT	Low pressure vapour Accumulator
IV	Isolating Valve	COMP	Compressor
HPL	Heat Pump Louvre	HTEV	Heating Thermostatic Expansion Valve
SHD	Shut off damper	CTEV	Cooling Thermostatic Expansion Valve
MD	Motorised damper	REC	Liquid line Receiver
SV	Solenoid Valve	EPR	Evaporating Pressure Regulator

PROJECT: INTEGRATED FACADES FOR OFFICES	TYPE: HEAT PUMP	11/08/2010
DWG NO.	DESCRIPTION: SCHEMATIC OF RSHP	FIGURE 5.4

Figure 5.4 Tender stage refrigeration schematic

The pipes were sized in accordance to velocity guidelines given in ASHRAE (ASHRAE 2006, p.2). The final schematic used for the production of the prototype is given in Figure 5.4 with the dashed line indicating how the components are intended to be grouped together as modules.

The controls on the refrigeration system need to be able respond to varying amounts of cooling or heating demand, change between the two and allow the occupant to modify the internal temperature. For this reason advice was sought from controls specialists at the manufacturer Carel (www.carel.com) and a schedule of equipment suitable for the application developed. The controller selected was the 'Microchiller 2 SE' which allows for the control of the majority of the refrigerant equipment together with a wall mounted display remote display and controller to allow for temperature control of the room from within the room. The Heat Exchanger system could not be integrated into the system as there was only a single channel available for fan control. To include this would have meant a custom controller and programming which would have presented too great a complexity and time requirement at this stage of development. The only drawback is an extra rather bulky control unit in the room, which is not a problem at the proof of concept prototyping stage.

By sourcing the components individually from a wholesaler and assembling them within the University the spatial and performance requirements were achieved. In the next stage of development a review of available components for propane should be carried out to discover whether a Propane based system can be prototyped and some form of partnership developed with a refrigeration specialist to assist in fabricating the unit whilst avoiding their set up costs (e.g. closely advising the process at the University). The controls for the system have also been specified to control all of the components and give the usability required. On a production run where greater numbers are required, a custom made controller can be developed to control all of the components.

5.1.4. Mechanical Fresh Air System

The fresh air supply to the room when the windows are closed is provided by the mechanical fresh air system. This feeds the Active Beam with fresh air at sufficient pressure in order to drive the induction effect. It comprises of the Louvre, Damper, Heat Exchanger and connecting Ductwork.

The manufacturer contacted for the Louvers and Dampers was the Ruskin Air Management Group (http://www.ruskinuk.co.uk/). The Louvre for the fresh air intake was specified as a Single Bank Louvre as the external grille was considered to provide a degree of weather protection. After the Louvres lies the Dampers, which are needed to seal the penetration and prevent unwanted heat loss during unoccupied hours. Working with the manufacturer, a 5 Nm Belimo actuator was selected based on the size of opening and circuited to provide a fully open or closed operation.

A market review of packaged Heat Exchangers was undertaken to understand the costs and availability of units of Rotary and Plate type Heat Exchangers suitable for the project. This revealed that for the low air flow rates required, the only Heat Exchangers available were sensible only units. This is because the size of unit needed is mainly manufactured for the domestic market where moisture transfer and the increased cleaning frequency associated with a sensible and latent exchanger is unwanted. The option of a custom made sensible and latent heat recovery module was therefore investigated, but the cost and time needed were prohibitive given that the Active Trench and RSHP were already being fabricated 'in house'. Details of the two most suitable units from a market search are shown in table 5.1 which are both sensible only Heat Exchangers. The impact on the room conditions was therefore investigated.

Table 5.1 Suitable Heat Exchangers for the project

Product	**Type**	**Pros**	**Cons**
Duplexvent Uno by Airflow Ltd	Plate sensible only	Shallow depth Upgradeable filters	High cost Very wide Condensation drain required
Integra by Vent Axia	Plate sensible only	High efficiency Lowest cost Good availability	No latent transfer Condensation drain required

The impact of sensible only heat exchange over a year was analysed using 'Climate Consultant 4' (Milne n.d.) as the design winter condition is an extreme condition. This analysis is shown in Figure 5.5 and shows that the humidity levels would fall below comfort requirements for 259 hours per year, quite a significant duration. The humidity level during this time would be between 30-40% R.H.; below the recommended limit of 40%, but not low enough to cause static electricity build up or dry eyes and skin. A sensible only Heat Exchanger is therefore acceptable at this stage.

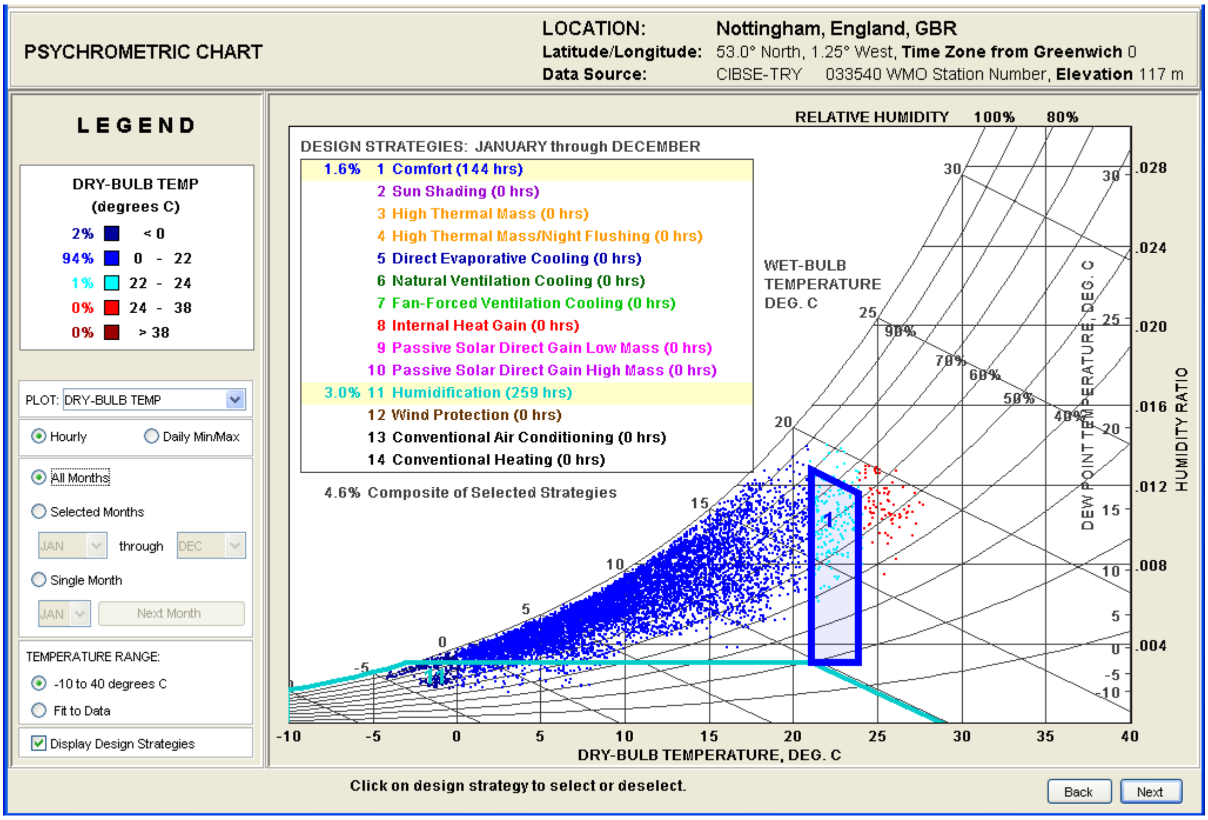


Figure 5.5 Plot of climate data for Nottingham UK, giving an indication of the need for humidification - 259 hours in total

The final issues were the flow rate, pressure drop and controllability. This is best matched by use of a voltage transformer available with the Integra unit. There is scope never the less to reduce the size of the Integra unit and better match the pressure drop and flow rate. A sensible and latent heat recovery module of smaller capacity and hence smaller size, should be included as part of the next product development phase.

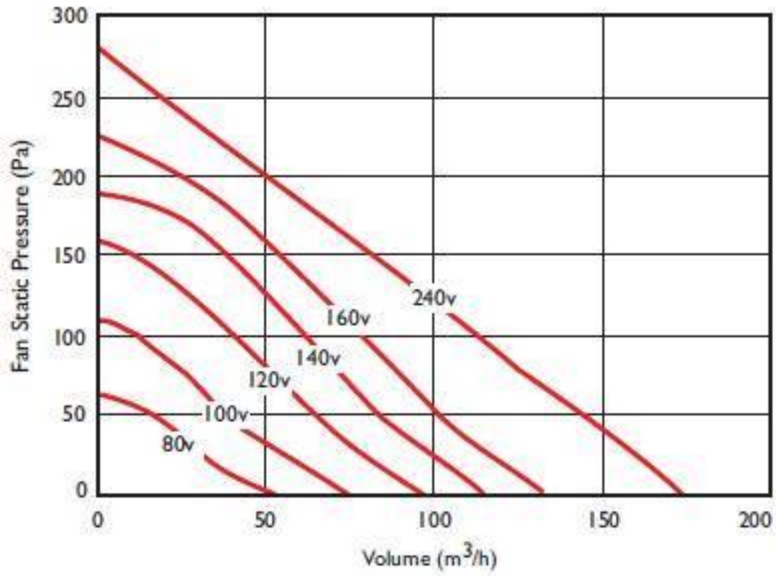


Figure 5.6 Variation of flow rate and static pressure for the Vent Axia Integra unit when used with a transformer

Within this stage the four components of the Active Environmental System have been developed with industry and realised. The Active beam has been developed with Frenger systems to achieve the necessary output and adapted for use with refrigerant. The Active Trench has been manufactured within the University of Nottingham because of cost. This turned out to be beneficial as certain refrigeration components could be integrated. The RSHP components have all been sourced from industry and assembled at the University due to the bespoke requirement for heating, cooling and the spatial configuration required to integrate into the facade. A major change has been the use of refrigerant R134A, instead of Propane. The Heat Exchanger has also had to be altered in specification from a 'sensible and latent' type to a sensible only due to market availability and is also over capacity. In the next product development stage, research into the availability of components for Propane should be repeated and a heat exchanger developed, that is better suited to the flow rate and provides latent heat exchange. The numbers of suppliers involved in the active system are numerous (see Appendix L) and it could be argued that it would be beneficial to reduce this number to reduce risks, complexity and integration of components.

The next step is to begin the development, fabrication and assembly of the facade and integrate fully the active environmental system components now that their spatial and performative requirements are known.

5.2. DOUBLE SKIN FACADE DEVELOPMENT AND REALISATION

The typical route for the procurement of a facade is for the main contractor to allocate the facade contract to a specialist sub-contractor based on the project specification developed by the architects with the design team engineers. After this the contract can and is divided up in an ever expanding number of different ways. The different roles that need to be performed can be considered as:

- System design;
- System manufacture;
- Curtain wall design specific to the project;
- Fabrication;
- Installation.

The allocations of roles within an organisation in the curtain walling industry commonly found today are shown in Figure 5.7. The fully integrated solution includes large, usually global facade specialists such as Permasteelisa and Schmidlin who restrict their activities to larger projects. The system providers include Schueco, Kawneer and Raico who provide the technology and curtain wall systems fabricators and installers. The fully integrated companies specialise in providing bespoke solutions to their clients, where as the system providers rely on their existing repertoire of designs being able to provide the design intent. For advice on the most suitable supply chain, Crown Aluminium, an aluminium fabricator was approached.

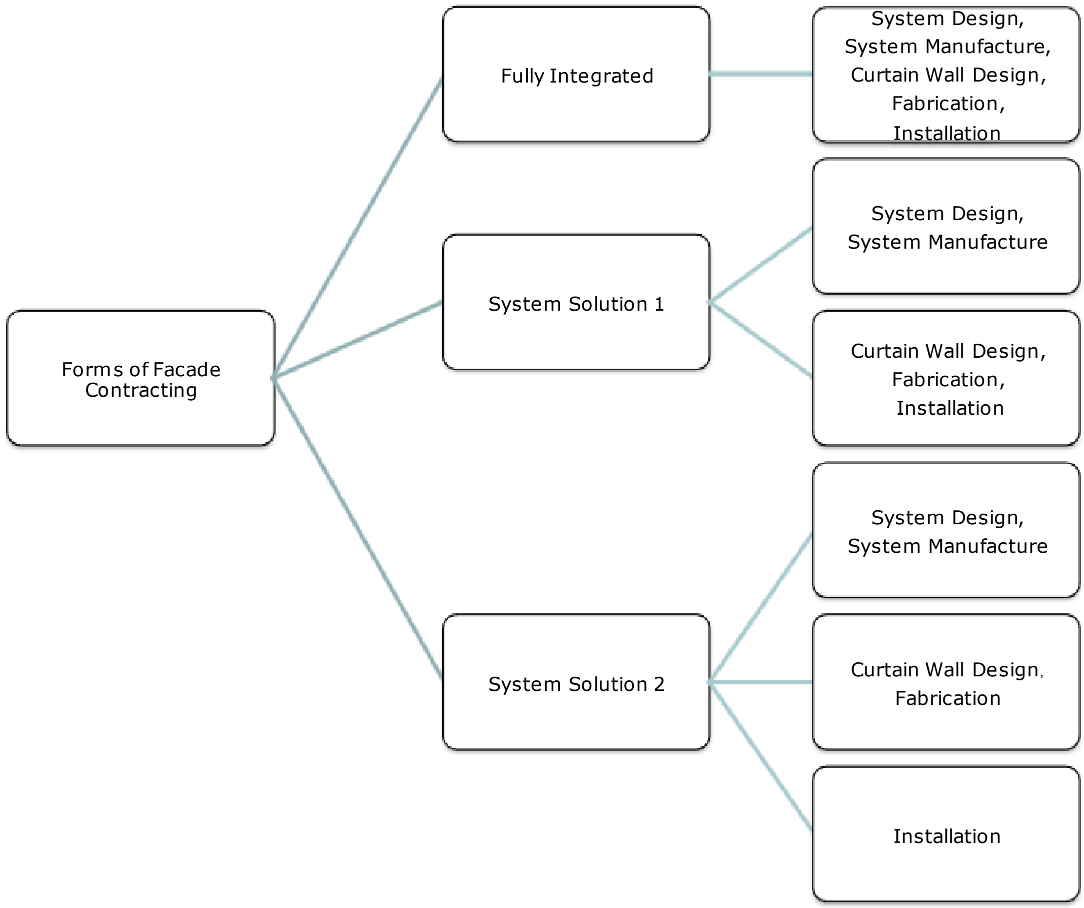


Figure 5.7 Common ways of handling the facade contract, boxes on the right group the services provided by a company

Roger Philips,[3] Managing Director of Crown Aluminium could be entrusted to give advice on the most suitable route to providing a double skin facade as he has many years of experience in the curtain walling industry. The design at the time of the initial meeting with Roger Philips was based upon mainly bespoke profiles to allow the integration of building services and achieve improved material and spatial efficiencies. However it was pointed out that system development and bespoke profiles and gaskets, due to the cost of the die and extrusions can only be economically produced on larger projects where there are a significant number of multiples. In addition the integration of building services is problematic for a fabricator and will be returned to. Bespoke profiles also entails extra developmental working in resolving details for joints, openings and testing. Instead a 'system' approach was recommended as it would be more economic to

[3] Roger Philips' experience in curtain walling is extensive and includes cladding and curtain walling of Heathrow Terminal 4, Architects Scott Brownrigg and Turner, 1986

procure, the details and joints already resolved, and already be tested and certified. It was also recommended that the Active Environmental System be separated from the Double Facade; the implications and changes necessary are discussed in Section 5.3. In this case therefore the facade production would be based upon 'System solution V2' in Figure 5.7, where Crown Aluminium would be the fabricator, and the author responsible for the curtain wall design and installation. However, using a systems supply company would mean that the design would need to be changed to use their profiles.

5.2.1. Adaptation to a Curtain Wall 'System' Solution

System supply companies provide a range of 'off the shelf' facade and window products together with machinery and technical expertise. Of a number of system companies in the UK, Schueco UK were recommended based upon Crown Aluminium's experience with them and the range, flexibility and quality of their systems. Although Schueco had undertaken double skin facades before, they were bespoke and not part of their standard product range. The design of the prototype therefore had to adapt Schueco's unitised single skin range of profiles into a double skin. The 'Unitised System Construction' (USC 65) and 'Unitised Customised Construction-Structurally Glazed' (UCC 65 SG) were selected for the inner and outer skin respectively. A meeting with Schueco UK's Managing Director, Marc Von Briel was positive and a further meeting with the UK Technical Director, Mike Tanner was arranged. During this meeting a number of technical issues were identified and a further review by their project office suggested a number of changes which include:

- Improved weather protection in the spandrel zone;
- Inner skin mullion arrangement;
- Maintaining the cavity from the inside;
- Reducing thermal bridges;
- Utilising the e-box profiles.

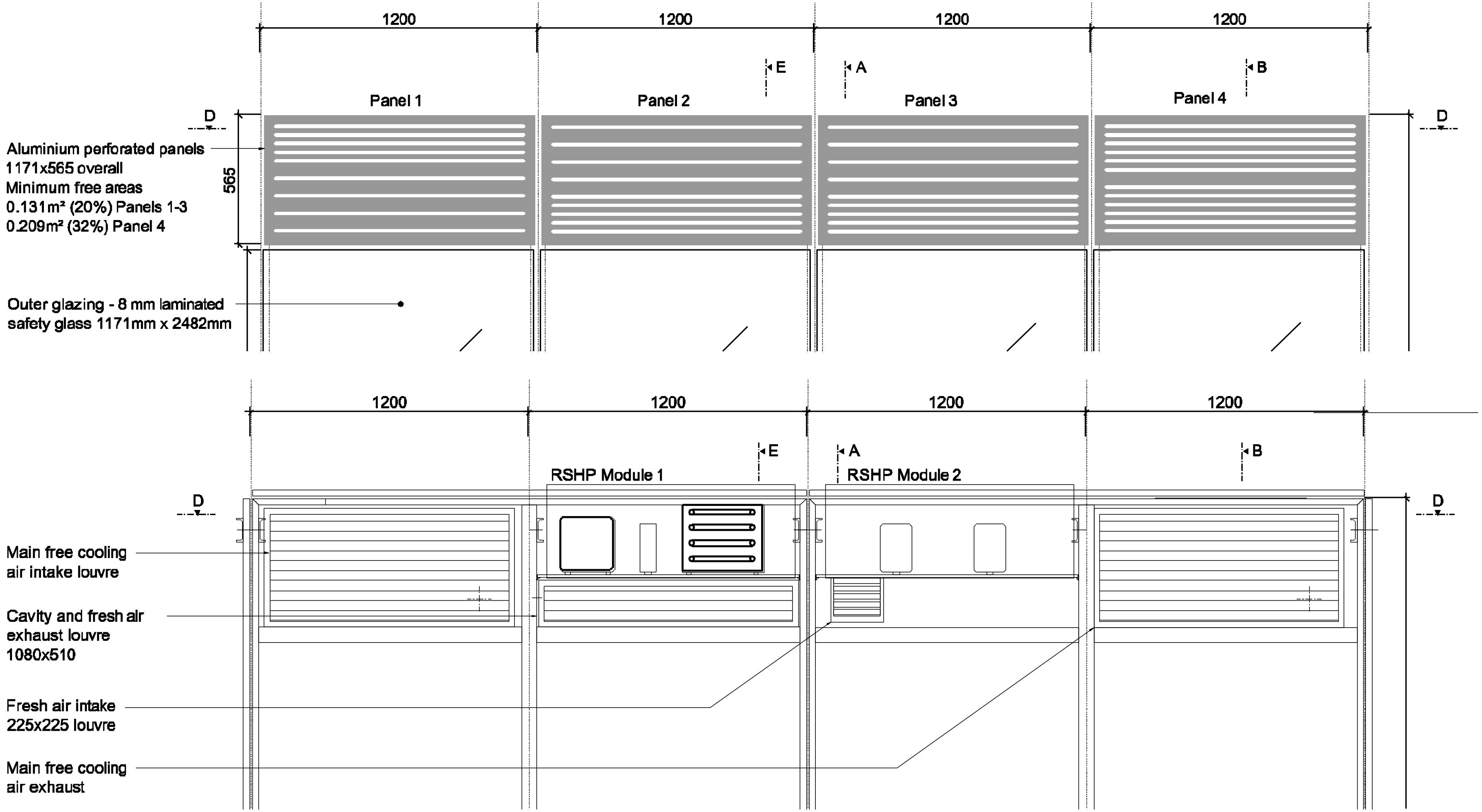


Figure 5.8 External spandrel zone change to perforated panels

The initial concept for the spandrel zone was to cover it in stainless steel mesh to offer a high proportion of free area as well as provide some degree of masking all the disparate elements of HVAC equipment, but at the same time not seek to hide them completely. However Schueco were quite concerned about the wet zone created in the area and suggested that it be fully louvred instead. Apart from creating some difficulties in providing sufficient free area, the uniform aesthetic created by such a treatment was unwanted. To provide greater weather protection in the spandrel zone aluminium panels with laser cut slots replaced the stainless steel mesh. The free area in each bay was calculated together with a consideration of where the free area was needed; at low level or high level. This informed where the slots were to be located and their concentration, to maintain the design intent of acknowledging the processes happening behind as shown in Figure 5.8.

The design could be altered to suit a designer's requirement so long as the free areas were maintained. The main change however insisted upon by Schueco was to locate the main body of the inner skin profiles in the room due to the drainage principles of their current system. This had a number of negative knock-on effects on the ventilation performance, maintenance strategy and material efficiency; however this is only the proof of concept prototype.

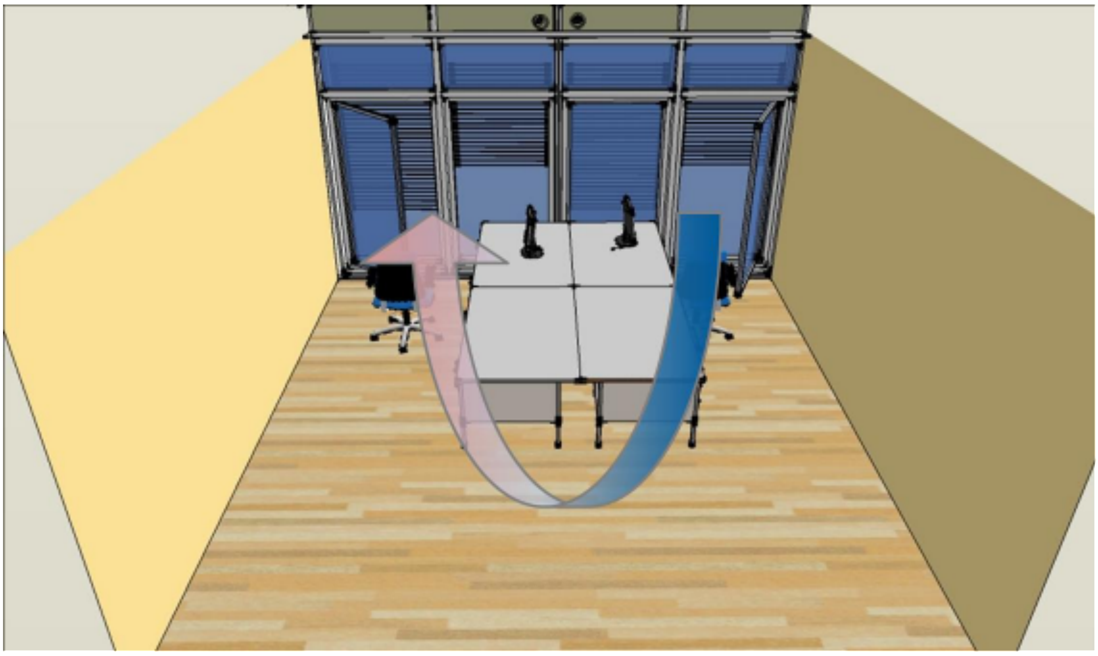


Figure 5.9 Ventilation path in summer using internal access strategy

The openings available in the unitised system open inwards, based upon its signal skin application and the prevention of rain entry. With the insistence on the main mullion being in the room, this could not be reversed and prevented the existing ventilation strategy in summer working effectively as well as making an externally accessed cavity very difficult. In any case Schueco advised on an access arrangement from the inside based on health and safety concerns.[4] To meet both ventilation and maintenance needs the internal access arrangement outlined in Figure 3.12 was implemented. This is based upon tilt-turn door height openings in each bay. This altered the summer ventilation strategy to an opening in the first and last bay as shown in Figure 5.9 where cool air enters through an inlet bay, circulates through the room and leaves through the final bay which is an exhaust. In both bays the louvre free area is increased to provide a higher ventilation flow rate. The winter strategy for fresh air introduction is possible by using one or both of the windows in the tilt mode. The maintenance of the cavity can be carried out internally by the inner skin openings provided in each bay; the external skin of the outer skin would need to be accessed externally. With this configuration the system based configuration could still provide natural ventilation in summer and winter as well as an acceptable maintenance strategy. In future development, the openings would be designed to maintain the existing strategy.

The material usage in the system based configuration did not however reach an acceptable conclusion. A plan view of the inner and outer mullion is shown in Figure 5.10. In the revised configuration the outer skin frame must be stiff enough to withstand the loads in isolation, no contribution is possible from the inner skin, and the inner skin mullions have relatively little work to do. The aluminium and gasket usage is therefore effectively doubled, with a significant lack of material efficiency. There was some discussion with Schueco regarding the reduction of gaskets since there are effectively six gaskets instead of the usual three. They were however very reluctant to any change of the system mainly because of the weather line around the spandrel zone not being in line with the outer skin. To reduce the weather protection of the inner skin Schueco would need proof that the outer skin spandrel zone provides full weather protection. This will form part of the testing regime in Chapter 6. Further design development overall would be needed to produce a more efficient assembly including a weather test and wind load to BS EN 13116:2001.

[4] External Health and Safety is achievable, but possibly more expensive and as discussed in Chapter 3, the outer pane still needs to be cleaned, and a client may insist on external access to minimise disruption or for security concerns.

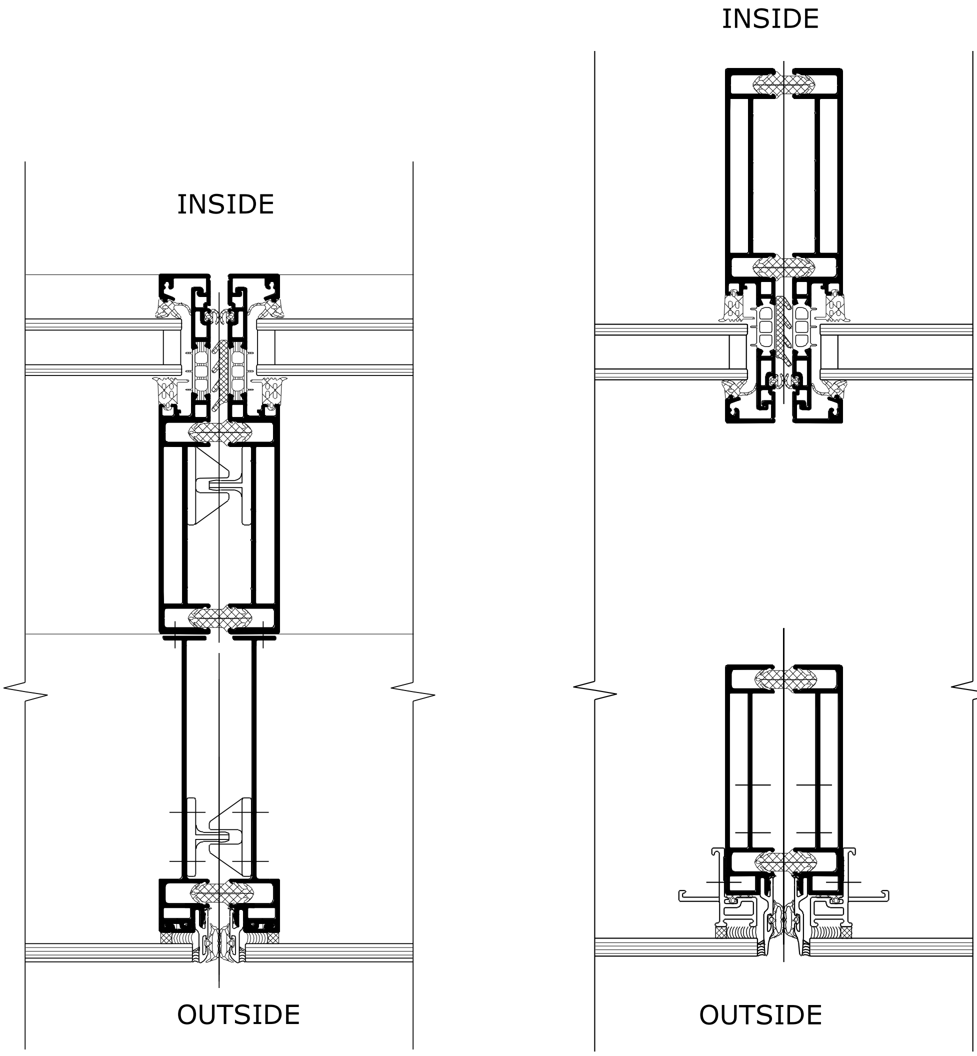


Figure 5.10 Original and amended mullion design to use Schueco system profiles

Another important issue for Schueco was the thermal bridge created by the connection of the external skin to the internal skin. This would compromise the thermal insulation levels and simply providing insulation around the connecting bracket was considered a major flaw in the design. To overcome this number of alternatives were investigated including use of a Schueco facade attachment fitting shown in Figure 5.11. As with the mullion design, Schueco were not prepared to have their fittings used in an unorthodox way and the use of a lower conductivity material was therefore investigated. A glass reinforced polymer (GRP) bracket was used as it has low thermal conductivity value compared to aluminium and steel, as well as being relatively stiff. It could also be easily machined. The specific bracket chosen was a channel section to increase the stiffness even though it required more volume and was sourced from Fibreline composites (http://www.fiberline.com/). Figure 5.12 shows the use of the composite bracket as opposed to the heat conducting aluminium plate.

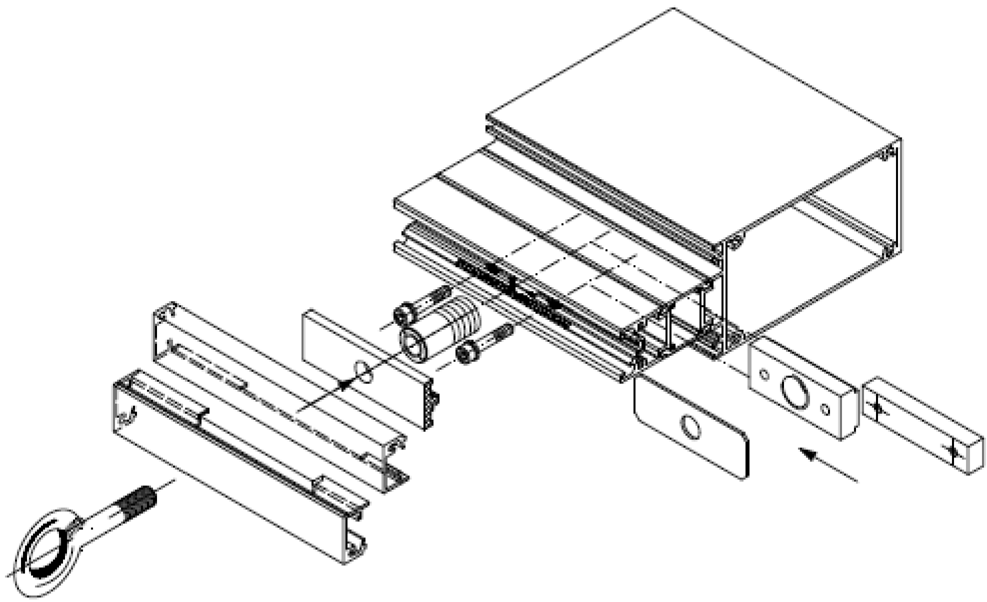


Figure 5.11 Facade attachment kit (Schueco International KG 2009, pp.Accessories 3-20)

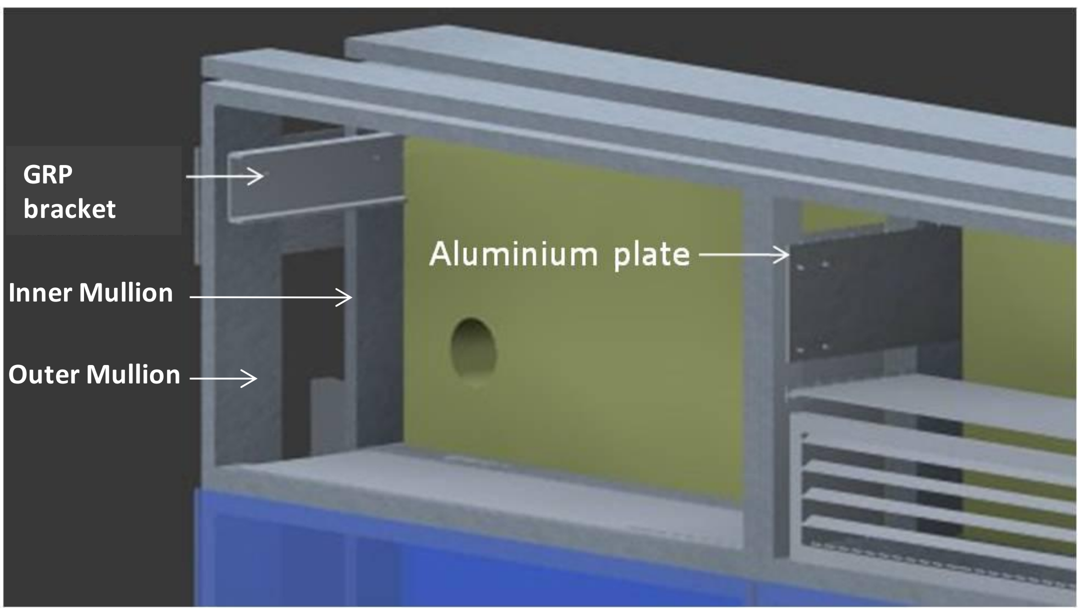


Figure 5.12 Outer skin attachment options

The original design included penetrations in the profiles to allow the refrigerant pipe work to pass through. During discussions with Crown Aluminium it became apparent that it would be quite difficult to do in practice and could compromise the structural integrity of the frame. Instead use was made of the 'e-box' profile available within the Schueco USC 65 system, which is normally used for electrical cable distribution. As shown in Figure 5.13 the profile has a detachable back plate and could just as easily be used for housing the refrigerant pipe work discreetly to create a cleaner aesthetic.

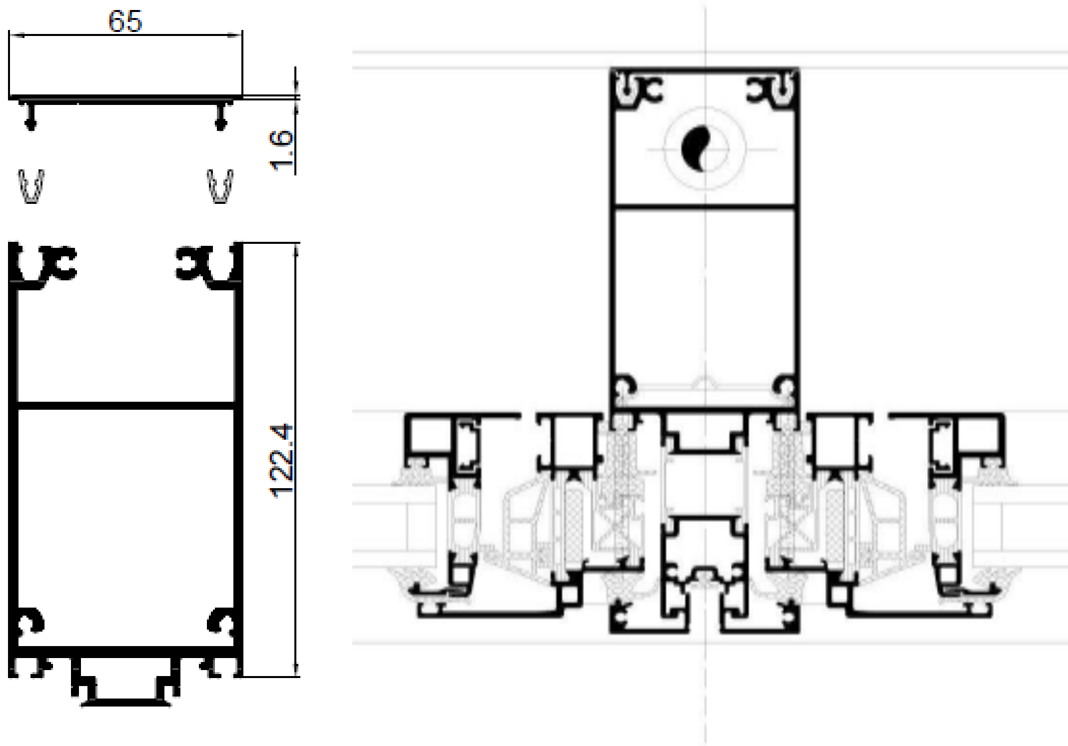


Figure 5.13 Plan view of Schueco e-box profile and actual drawing utilising the profile

The adaptations necessary in order to utilise the catalogue of profiles available within the Schueco system required a number of changes and custom made interventions, but the design requirements of providing natural ventilation, a rigorous maintenance strategy and integrated pipe work were maintained. Future design development work can address an externally accessed cavity and material efficiency. Testing is needed to understand and develop the weather protection detailing and will be carried out in Chapter 6. The design changes once implemented on to the drawings, provided Schueco with enough confidence to approve the drawings and continue their involvement in the project.

5.2.2. Facade Supply, Fabrication And Assembly

Following Schueco's approval of drawings, the fabrication process based on a 'systemised' double skin facade could begin. The first stage was to arrange for the ordering and supply of material, to be followed by the fabrication and assembly.

To enable a clearer communication of the material requirements to Crown Aluminium, the facade was broken down into three sub-components; the outer skin, inner skin and internal openings with an accompanied specification. With this information Crown Aluminium were able to input the information into Schueco specific estimating software 'SchuCAl' (Schueco International KG 2005), which provides a complete list of material requirements including every screw, gasket and accessory as well the profiles. It was noted that Crown Aluminium have the software for most major curtain wall system companies and so changing to another system company is quite easy for them to do. The material list was then priced by Schueco who gave a cost of circa £10,500 for the aluminium profiles, gaskets and accessories. This is significantly higher than the market cost for other double skin facades,[5] but attributable to the use of two single skin facades and having to buy minimum order quantities which sometimes exceeded requirements. Fortunately Schueco provided a substantial discount, as the product contributed to their research and development goals and would provide positive marketing potential. This enabled the project to proceed within budget and the material list resent as a 'works order' from Crown Aluminium to Schueco. The order acknowledgement from Schueco was accompanied with a number of queries and supply difficulties.

Although the unitised range from Schueco is part of their 'off-their shelf' range, its use in the UK has been limited and therefore not all of the items are held in the UK nor 'on-the shelf' to reduce storage space. The first item that caused a problem was the e-box profile which was used to contain the pipe work. Even though the material list was developed with Schueco UK, the e-box profile turned out not to be a stock item neither in the UK nor in Germany, and needed to be extruded especially for the project with a minimum order of seven bars,

[5] A tender price obtained in 2010 from Buro Happold for a narrow depth double skin facade was 950£/m² which equates to £14,100, the material proportion of which is £4205 (29%, (Smith 2005)). Allowance for a mock-up construction and testing is £250,000 (Parker & Jones 2011).

set up costs and a six week lead time at least if approved. It was therefore changed to a standard bar to reduce the delay.

The second item was the outer glazing structural silicone profiles. The initial message filtered back was that the profile is blocked for sale within Europe due to warrantee issues in structural glazing directly onto aluminium. After contacting Schueco and explaining to them that an adapter profile would be used they agreed to supply the profile, but only if it was bronze anodized in Germany at a specific facility so as to guarantee the structural silicone would adhere to the aluminium and not cause any corrosion in case the glass was bonded to the profile. After resolving these issues all of the material arrived at Crown Aluminium and preparation for fabrication could begin.

To fabricate a unitised system or any window frame seamlessly together, preparation of the individual bars is key and represents an examination of component design to a very high detail. Schueco provide a number of fabrication drawings and the machinery to allow this. These fabrication drawings had to be studied and in some cases almost deciphered to implement the preparation requirements onto the individual bar drawings. Each individual transom was therefore detailed with its overall dimension, the end preparation whether mitred or straight together with any holes or notches to fix accessories such as cleats. This process took many working hours as the author had to fully understand how the system is put together and the necessary preparations required to a high level of accuracy. In part Roger Philip's of Crown Aluminium wanted the author to fully understand how the system is made to a finer detail and it would also save the time cost for the CAD operators; one of his more expensive workers. Fortunately on a project, Crown Aluminium would invest the time in translating the detailed design CAD drawings into bar preparation drawings using their own customised software. This software automatically provides bar drawings once the sizes, dimensions and the system being used is inputted. An example bar preparation is shown in Figure 5.16. The detailed bar drawings provided by the author could then be used by Crown Aluminium to begin the fabrication and assembly process.

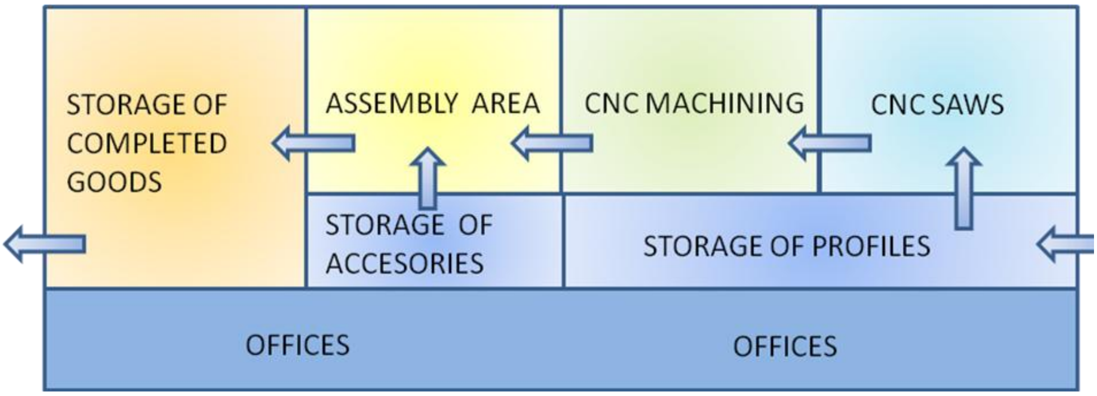


Figure 5.14 Flow of material and basic floor plan of Crown Aluminium

Figure 5.15 External view of works

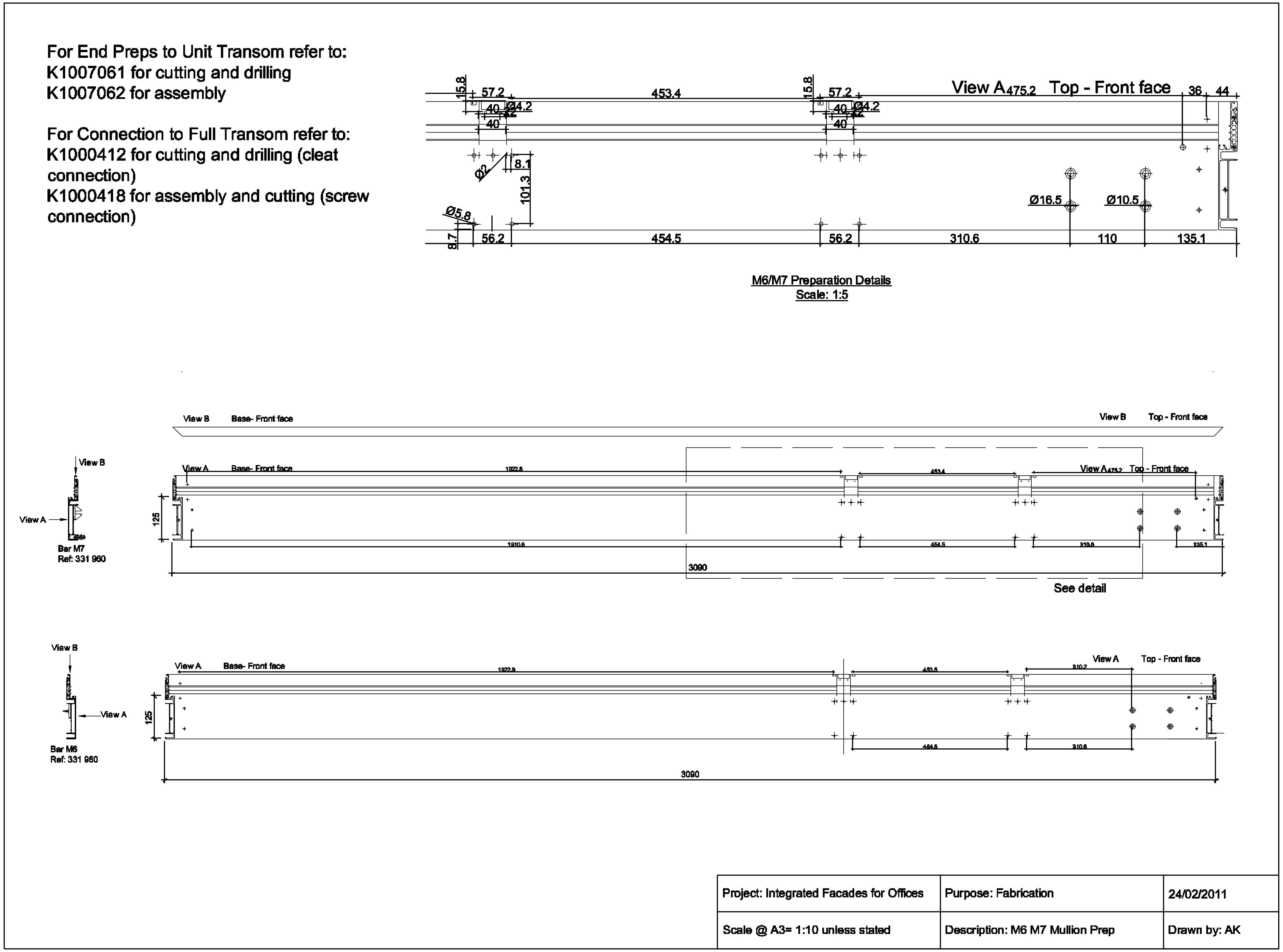
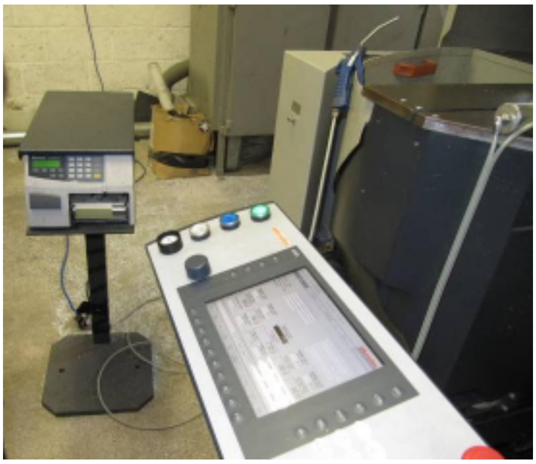
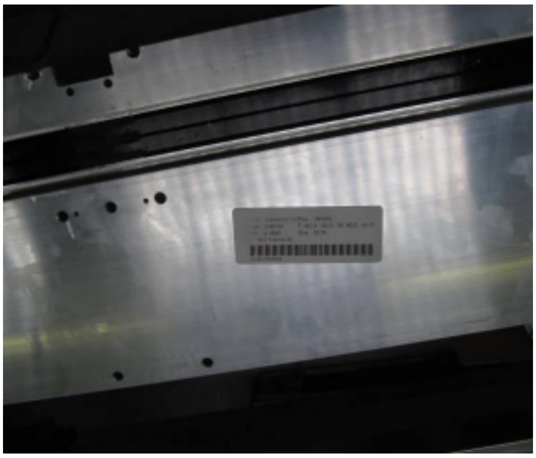


Figure 5.16 Example bar preparation drawing



Compound mitre saw, control station and sticker machine

CNC Machining centre



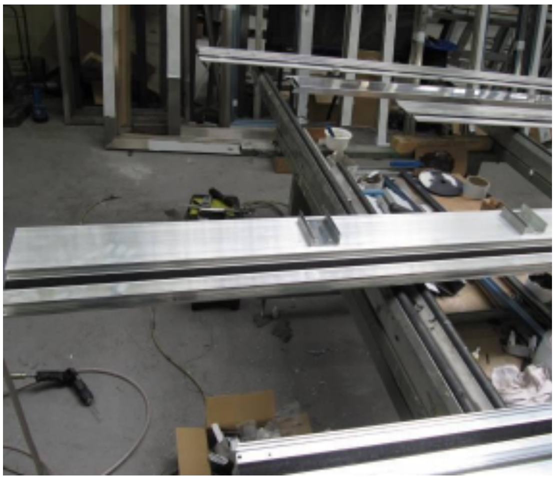
Machined bar and stickered bar

Completed machined bars in the assembly area

Figure 5.17 CNC Machining Stage at Crown Aluminium

The fabrication and assembly of the prototype was treated no differently to other projects at Crown Aluminium and the typical workflow which they usual employ was followed as shown in Figure 5.14. This consists of a number of carefully coordinated stages. The first stage is the delivery of material which is sent to the appropriate area on the shop floor. The profiles being the largest item are stored very close to where the delivery first enters. The second stage is the CNC cutting and machining shown in Figure 5.17. The bar drawing information is first translated from the CAD files and then sent via the network directly from their offices to the computer numerical control (CNC) machines. The first machine that is used is a CNC double mitre saw to cut the profiles to length and mitre them if necessary. The operator simply reviews the information on the screen to identify the bar required, loads on the specific bar and the machine then automatically measures and cuts the bar to size from the information sent via the network. After this a sticker is produced containing the fabrication information specific to the bar which is then used in the CNC profile machine.

To machine the holes and notches from the bar, two CNC profile machining centres with interchangeable heads have been installed adjacent to the CNC double mitre saws at Crown Aluminium, at an approximate cost of £250,000. These machines can also be programmed from CAD file information and machine details to a high level of accuracy. The stickered information ensures that the correct bar is loaded and the machine then automatically measures the bar, sets out the penetrations and machines them changing the machining tool automatically when necessary. With the bars fully prepared as per the CAD drawings the profiles are loaded onto a stillage and sent to the assembly area.



Hand preparation of mullions

Assembly of inner frame

Inner Frame with hanging brackets

Assembly of outer frame

Completed outer frame

Installation of glazing (notional)

Figure 5.18 Assembly stage at Crown Aluminium

In contrast to the sophisticated, state of the art technology used for the bar preparation, the assembly of the bars into frames is done by hand as shown in Figure 5.18. The bars are fixed together by first attaching any cleats or corners brackets, and then screwed, nailed and glued with the other profiles. This is quite straight forward and quick since all of the holes and cut outs have already been prepared in the correct positions. The final stage is to add the gaskets which, is the most difficult part due to the tight fitting of gaskets making installation difficult. Not all of the gaskets were fitted since the units were to be glazed on site. The whole process of fabrication and assembling the frames took six working days.

The only item of the Double Facade not involving Crown Aluminium were the aluminium laser cut panels. It was the intention to make these within the faculty, but a discussion with the technician responsible for the laser cutter revealed that the time required for such as design would be prohibitive since the selection of each individual cut line is necessary and would incur a significant labour cost. Instead a local company Lasershape (http://www.lasershape.com/) was used whose CAD/CAM software could directly translate any AutoCAD file into a data file for the laser cutter; an example of how software can be used to completely transform the flexibility available in manufacture. The design could therefore in theory be tailored to the architect's choice as long as the minimum free areas in each bay are achieved.

The assembly of the facade at Crown Aluminium could have continued beyond the frames towards glazing of the two skins and connecting them together to create a fully unitised Double Facade component. Without a crane or heavy lifting machinery suitable for facade assembly at the University, and the difficult access arrangement within the confined laboratory, the unit weight needed to be kept within manual handling practical limits and so the assembly at Crown Aluminium continued no further. What would be sent to the University would be the inner frame, the outer frame and the opening units, together with the glass on a stillage. This ensured the maximum weight of each sub-component was below 60kg to enable manual handling.

Developing the Double Facade from a bespoke design into a design which utilises single skin system profiles has required further design development and a number of adjustments. Whilst not being ideal in terms of material efficiency and expected cost, it has closely replicated the actual production process and allowed a proof-of-concept prototype to be realised. The involvement of ‘systems’ provider such as Schueco has shown that many of the profiles provided are not off the shelf, only the dies and details have been developed. With the investment in software by both Schueco and Crown Aluminium, considerable time is saved in scheduling and preparing fabrication drawings. Adapting the Schueco system to provide greater material efficiencies, yet still use the underlying logic of assembly and fabrication of the units would save significant amounts of time in the next prototype and should be considered rather than a fully bespoke system. How the environmental system can be integrated into the design and production process is the next challenge.

5.3. INTEGRATION OF THE ENVIRONMENTAL SYSTEM INTO THE COMPONENT FABRICATION PROCESS

A fully integrated, prefabricated facade which includes the Active Environmental System is one of the design brief requirements of this thesis. In Chapter 2 the facade supply was proposed as the chassis for which the active components would be added. This cannot be achieved without understanding and having a dialogue with the facade industry. Design changes can then be made which ensure that the integrated product can be fabricated with a greater level of prefabrication. The organisation with a key part to play is the facade fabricators which for the prototype were Crown Aluminium.

Early on in the discussions with Crown Aluminium, the concept of integrating active components with the facade, to create a fully prefabricated facade was discussed and revealed a number of unforeseen obstacles to integration. In common with most fabricators, Crown Aluminium has to process material under very tight schedules, almost on demand. Frequently, by the time the finalised production information and material has reached them, the contingency for delays has been used up and so any delay, even of a day has a disproportionate effect on the work flow of installation on-site. To keep to time, the number of suppliers and workflow is kept simple. On a project requiring aluminium profiles only for instance, they will have a single supplier in their supply chain which reduces the risk of delay and coordination problems. Even with the addition of glazing, the number of suppliers only increases to two. At this stage of development the prototype Active Environmental System however, has a numerous number suppliers (see Appendix L for details) whose products were coming together for the first time. The risk of delays and coordination problems on a novel prototype is therefore quite high. Furthermore, fabricators as yet do not employ personnel specialising in services except for photovoltaics and do not have the skills or confidence to carry out work of this kind. A revised approach was therefore needed for the Active Environmental System, based upon the need to minimise the risk of disruption to the facade fabrication process and maintain timely delivery. The individual characteristics and potential for integration of the RSHP, Active Beam, Heat Exchanger and Active Trench, are considered in turn.

The external components of the RSHP were the one part of the system that took the most time to fabricate and so may not seem like the most likely candidate for integration. The time requirement however, was due to the relatively new concept of providing both heating and cooling from such a small system, establishing suppliers who would be able to supply individual parts and spatially coordinating the components and pipe work, with the volume allocated to the RSHP in the spandrel zone. These difficulties were overcome and are ones associated with fabricating the unit for the first time. On a project where multiple units would be made fabricated, a number of specialised refrigeration companies such as Star Refrigeration would be able to assemble units in advance of the facade, so that the timely delivery to the facade fabricators could be guaranteed. The work then needed to integrate it into the facade is simply moving it into place whilst the facade is vertical. The overall spatial dimensions and lifting strategy remain the same for transport since the module sits within the facade envelope. The two modules of the RSHP could therefore be integrated at the facade fabrication stage.

The Active Beam similarly, only needs to be fixed in place and the connections required do not require a skilled workforce, however it does change the spatial dimensions of the facade envelope quite considerably; in terms of rectilinear volume it is doubled. It is also quite delicate in comparison to the facade and needs to be very well secured and well protected during transportation and lifting. It is therefore not considered suitable for integration at the facade fabrication stage. With the Active Beam as a separate unit the argument upon which it was designed as adjacent to the facade is weakened.

Both the perpendicular and adjacent configurations have pros and cons. For the adjacent configuration they are:

+ Air distribution pattern allows for good distribution of air and high efficiency due to higher intake temperatures adjacent to the facade

- Thick slab edge for good external aesthetic and slightly reduced view to the outside

For the perpendicular condition they are:

+ Thin slab edge for good aesthetics externally and internally

+ Artificial lighting can be incorporated which can serve the whole space reducing site work further

+ Deeper floor plates can be easily served/adapted to

- Air distribution to the area adjacent to the facade is not ideal (although the Active Trench will minimise the effects)

It was therefore decided in light of these pros and cons that a perpendicular solution would be more preferable due mainly to the improved aesthetic and being able to provide a cleaner internal facade sightlines. The remodelled environmental system was again developed with Frenger systems, but instead of the 'Polaris' unit which is adjacent to the facade, a perpendicular Active Beam, 'Professor' model was selected.

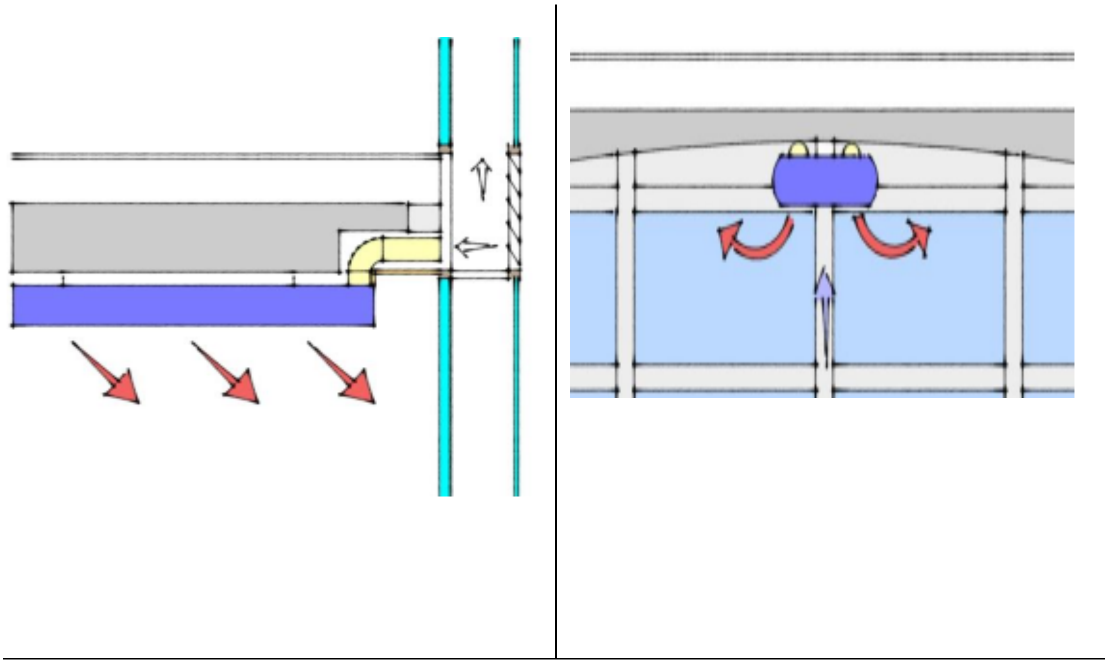
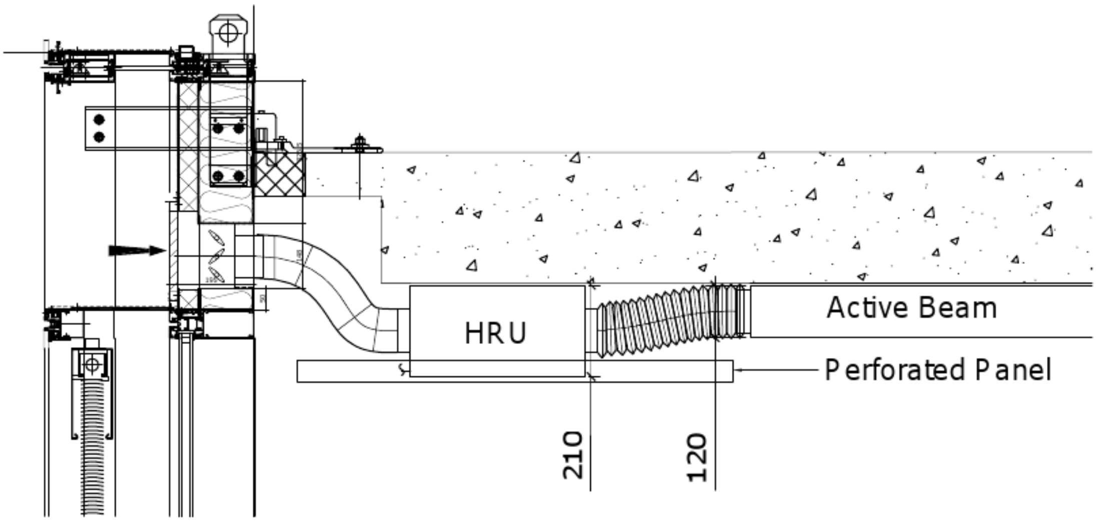


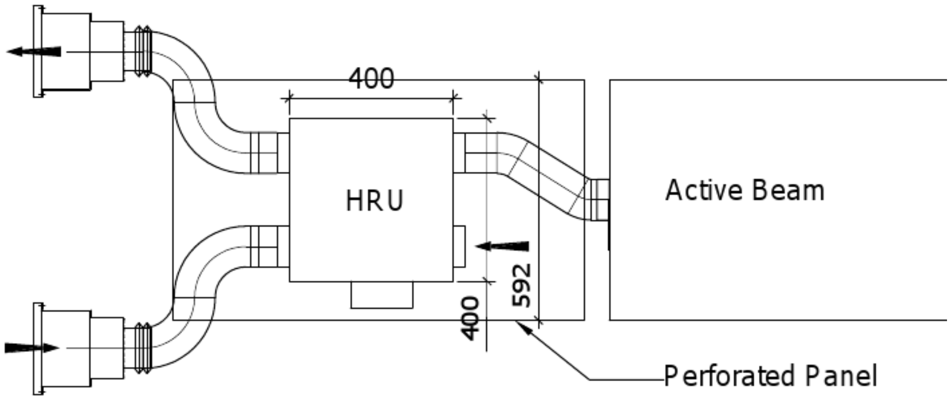
Figure 5.19 Options for integration of the Active Beam; option 'C' stepped slab (left) and option 'G' coffered slab (right)

With the separation of the Active Beam and it now being perpendicular to the facade, the aesthetic integration strategy for the facade and soffit area previously discussed needed to be returned to. The different options for Active Beam configuration and integration to maintain a pleasing aesthetic were discussed in Section 4.4. Two options 'C' or 'G' repeated in Figure 5.19 show how a perpendicular Active Beam could be integrated. For a simpler slab construction option 'C' is to be considered. This option considers that the slab is thinned where the ductwork needs to penetrate the facade and therefore not impact on the full height glazing.

The other two sub-components for the environmental system at high level are the associated piping for the Active Beam and the Heat Exchanger. Both the refrigerant piping and the Heat Exchanger are located at the 'facade' end of the Active Beam and so have a big impact on the facade to slab interface. The refrigerant piping can be contained within the void created with the thinned slab. The Heat Exchanger is however much larger. The overall dimensions are shown in Figure 5.20 where it can be observed that the height of Heat Exchanger exceeds that of the Active Beam. To lessen the impact of the Heat Exchanger as well as place the pipe work in a more accessible position a perforated panel is added below the Heat Exchanger to lessen its visual impact and provide some continuity of the aesthetic along the Active Beam sight line. Further design development to integrate these components is required in the next product development stage and is discussed further in Chapter 7.



Section View



Plan View

Figure 5.20 Section and plan showing dimensions and intervention of perforated panel for aesthetics

The Active Trench is similar to the Active Beam in terms of integration into the fabrication process as it changes the rectilinear envelope of the facade and integrated as an add on construction, makes it difficult to attach securely, prone to damage as well as added difficult in transportation. In the next design development stage to overcome these difficulties, it should be investigated whether it can become part of the floor level transom and therefore lessen these obstacles.

The final design drawings used for purchasing, fabrication, and as a basis for assembly and installation are shown in Appendix M and rendered images shown in Figures 5.22 to 5.24. In terms of aesthetic integration, changes have been to the external spandrel zone, the appearance of the Heat Exchanger and Active Beam pipe work. The full impact can only be fully understood once the prototype is evaluated at 1:1 in Chapter 6 and further changes made if necessary in the next design development stage.

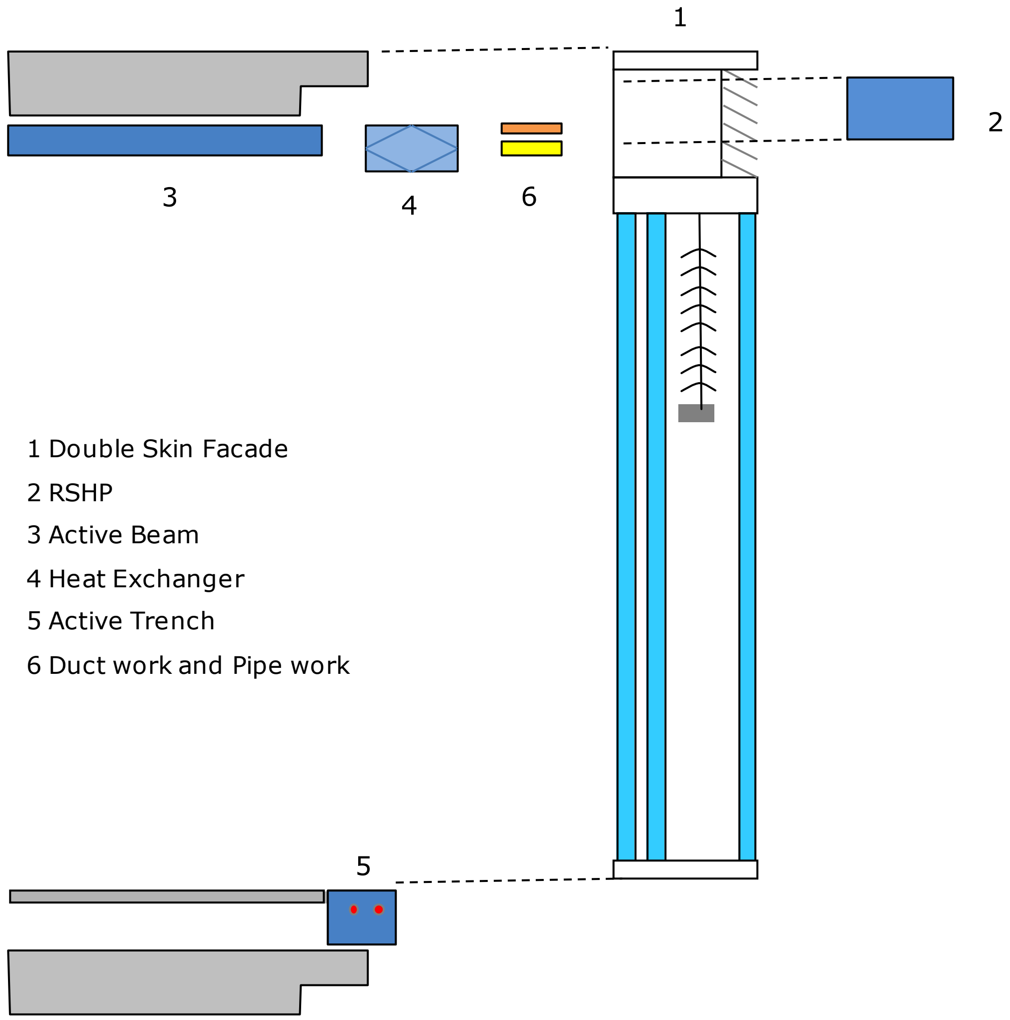


Figure 5.21 Components for the IPADFS at Proof of Concept Stage

The full integration of the prototype as a fully prefabricated assembly has not been possible at this stage of product development. Instead the prototype comprises of the following components:

1. Double Skin Facade;

2. Two RSHP Modules that fit within the facade spandrel zone;

3. Active Beam;
4. Heat Exchanger;
5. Four Active Trench Units;
6. Associated pipe work and duct work connections.

The site work required is still reduced substantially as it is limited to locating the components and then the installation of three short 100 mm ductwork connections, flare connections of copper pipe work, and electrical connections. The main obstacle has been the high number of suppliers in the environmental system and the unknowns in the assembly. This presented too great a risk to disruption of the fabrication process. The supply chain however is now established and risks during assembly mitigated to some degree. The RSHP integration into the facade is a definite possibility, and further integration of the other components will be examined in Chapter 7. The site assembly and installation process in the next section will also help inform as to whether the site installation work is as straightforward as imagined.

Figure 5.22 External elevation

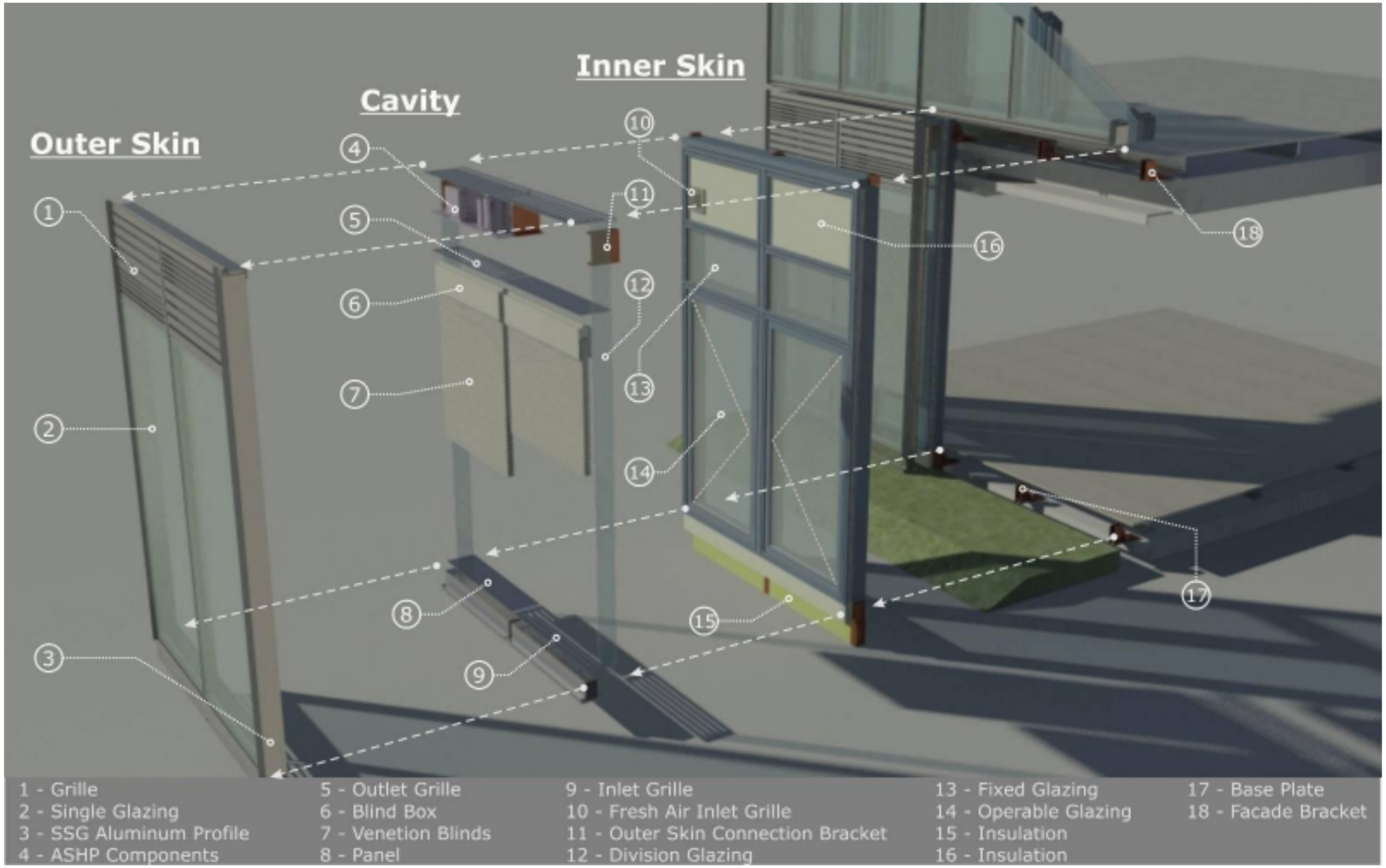


Figure 5.23 Exploded view of the Double Facade components

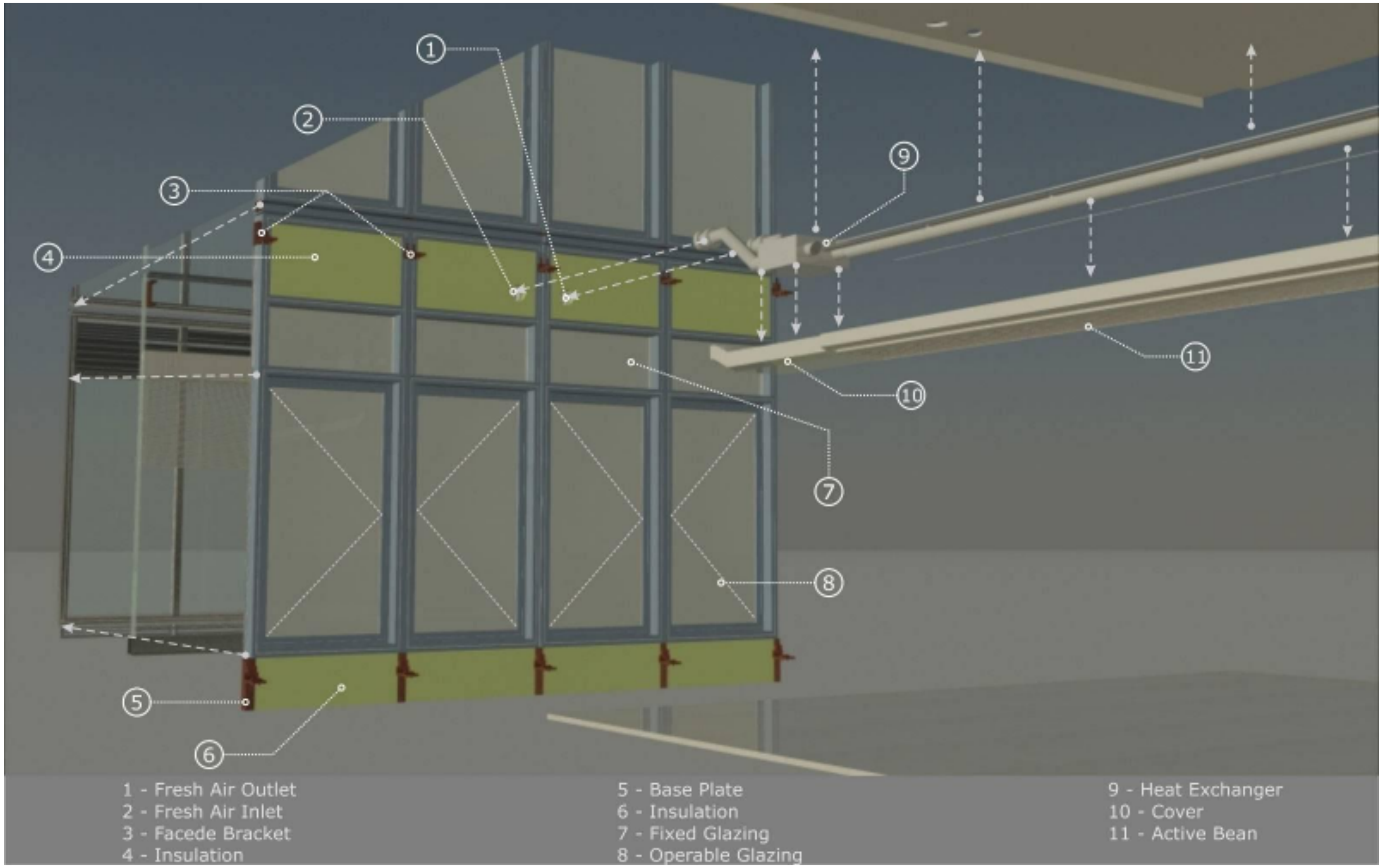


Figure 5.24 Exploded view of the environmental system components

5.4. ASSEMBLY AND INSTALLATION AT THE UNIVERSITY

Bringing together the prototype components in a way which replicates the site conditions will provide an opportunity to discover any coordination issues and the actual site work that is required. This will provide an opportunity to prove the initial concept that the IPADFS reduces site work by being largely prefabricated and improvements to negate any unforeseen difficulties. The assembly and installation process is documented in terms of the facade and then the environmental systems. Before the components could be assembled, the question of how to recreate the site conditions needed to be addressed.

5.4.1. Cellular Office Mock-Up Construction

The IPADFS has been developed based on a cellular office 4.8 m wide and 2.6 m floor to ceiling height (see Section 3.6). This meant that a room of equivalent width and height needed to be created. In addition a base to support the floor brackets at 3.1 m above the ground (the floor to floor height) and a stepped slab to provide the aesthetic integration of the ducts was required. The depth of the office being served is limited to 7.5 m (half of the 15 m full depth). This was one of the largest rigs ever proposed as part of a PhD project to be sited within the Department of Architecture and Built Environment (DABE) at the University of Nottingham.

The main issue was the height of the unit; at least 3.5 m was needed for manoeuvrability. The main research laboratory was insufficient and so the project was allocated to a laboratory based inside a disused squash court due to be converted to a workshop which put a great deal of pressure on the realisation and testing phase. In the disuses squash court a number of disused rigs were present. The principal rig consisted of a three storey steel structure with a 'wind-catcher' on the top. Before the space could be used this rig needed to be dismantled. To minimise further cost and time, as much of the steelwork was retained and adapted for use. The changes were limited by moving one of the steel columns to a distance of 5 m from one of the other beams. An additional 100x100 steel beam with L-plates welded on at floor bracket locations was also installed to provide the edge of slab condition and support for the facade brackets.

Figure 5.25 Cellular office space being constructed by the author

To enclose the space, partition walls and a suspended ceiling needed to be assembled. The partition walls were made by constructing 4”x2” frames on the floor and then securing these into place with floor brackets. Plasterboard was then screwed into this frame. The soffit was made by using by spanning the two sides with 2”x 2” timber beams, installing short cross members between them and then screwing the ceiling board into this frame. A work in progress picture is shown in Figure 5.25. Additional reinforced areas were created in the suspended ceiling where the Active Beam and Heat Exchanger were to be supported. The majority of this work had to be carried out by the author with family and friends as there were no University technicians available to help at this stage. This actually took the most time in terms of site based work. With the steel beam in place, room frame up, boards attached, painted and sealed, assembly and installation of the facade could begin.

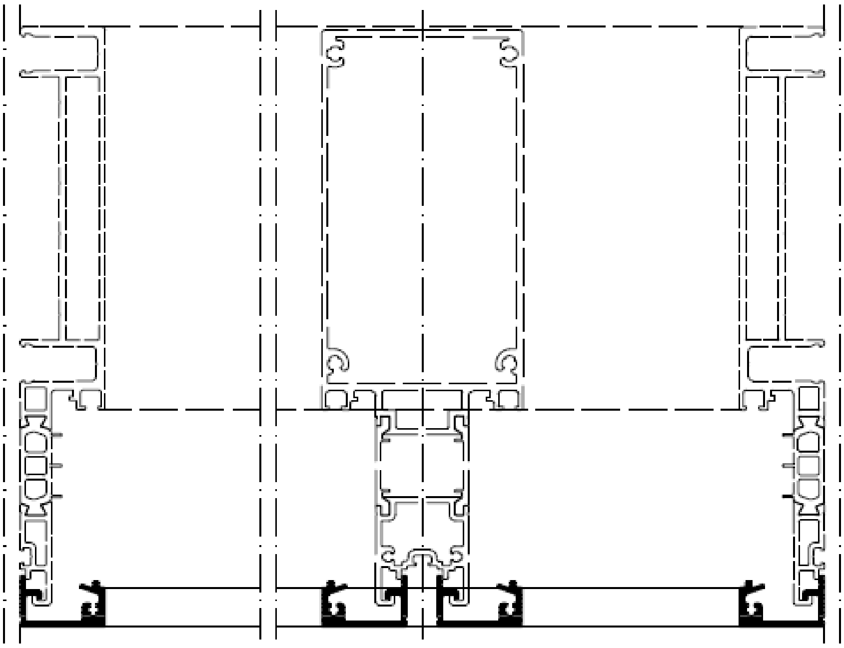
5.4.2. Double Facade

One of the strange aspects of the prototype was that the design of the facade is based upon a unitised system which is fully prefabricated. However, the lifting capabilities and spatial constraints of the laboratory at the department meant the facade had to be installed in stages in order to reduce the individual weight of components and make them within manual handling limits. Additionally the spatial constraints meant the frames and larger glass units needed to be manoeuvred in horizontally and rotated before being put into place. In short more difficulties than an actual site were presented, but were overcome. The full sequence of the facade installation is shown in Appendix N, but there were a number of items worth mentioning in greater detail.

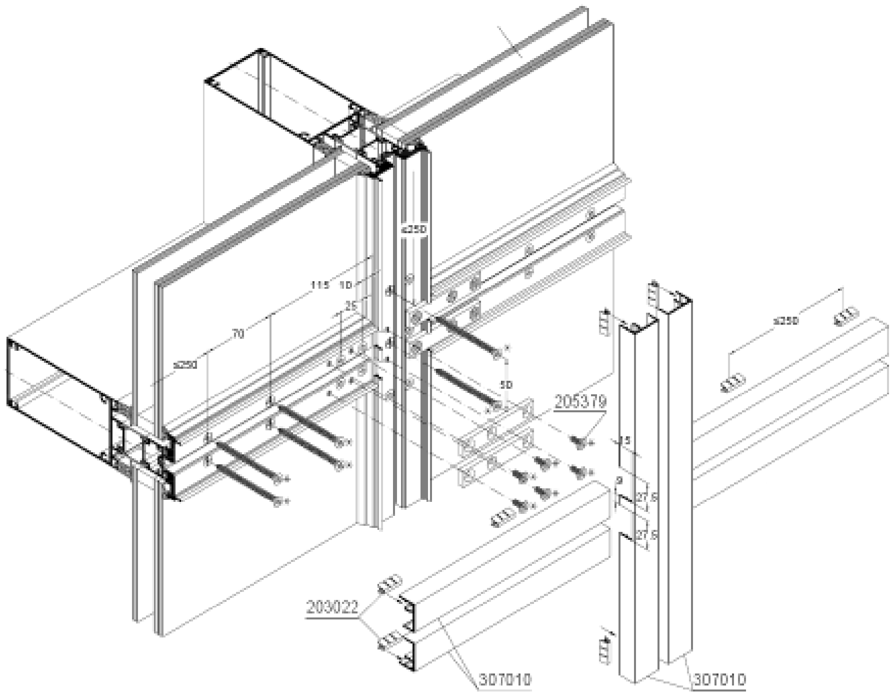
The very first installation component was the floor brackets. In the case of the laboratory they were to be installed onto the prepared steel beam with L-plates and predrilled holes to allow bolts to pass through. The holes of the brackets and the plates supplied did not however line up. The information on the bracket drawings was not consistent with the physical object. This would not be a problem on site since channels with locking nuts provide adjustment and there has therefore never been a prompt to update the CAD drawings. The steel beam with the predrilled holes did present a problem as a slot similar to that provided in the concrete slab is difficult to machine especially when the beam is already three metres high in the air. The solution to this predicament was to machine an additional 15mm in the slot of each floor bracket to allow the holes to line up.
With the brackets modified and secured the inner skin frame could be attached. The inner skin is supported via hooks into the floor brackets and has to slide across to engage the gaskets of the adjacent unit and the plastic male/female couplings. Supporting the unit could only be done from below with the fork lift truck due to spatial constraints however, this made it impossible to keep the unit truly vertical and because of the tight tolerance between the hook and the bracket it was almost impossible to adjust the facade without a lot of persuasion with what the technicians termed the 'Birmingham Screwdriver' more commonly known as a lump hammer. Fortunately the frame was not damaged by hammering the frame sideways. The time taken to install the facade was therefore much longer than anticipated and revealed the importance of ensuring the supporting brackets for installation hang the unit vertically.

Figure 5.26 External tower crane for facade installation on Stadttor Gate, Dusseldorf, Petzinka, Pink and Partners (photo credit: Josef Gartner)

The design at this moment only had supporting brackets at the top of the inner skin and is a workable solution in practice if the inner and outer skins are installed separately. However if the facade was fully prefabricated with the outer skin, the centre of gravity would shift into the cavity and when supported by the inner skin brackets only, the unit would rotate in order to bring the centre of gravity in line with the support. This would make locating the double skin facade when supported by a crane in an actual situation just as difficult as the situation presented in the laboratory. The solution would either be to increase the clearance in the brackets or more preferably insert an additional support point on the external skin of the double skin facade so that the unit can be hung truly vertical as shown in Figure 5.26.



Bead hooked into main profile



Screw and clip in beading

Figure 5.27 Beading types for unitised system installation (Schueco 2009)

Another area where great difficulties were presented on site was the beading on the inner skin. The first reason was the access as working at height is difficult and the beading is meant to be applied when the facade is lying flat. The beading type had also been incorrectly specified by Crown Aluminium as the presence of a dummy mullion makes it possible to secure the bead at one end only; a detail which is easy to overlook. A clip in type beading available shown in Figure 5.27 from Schueco should be specified and used in future.

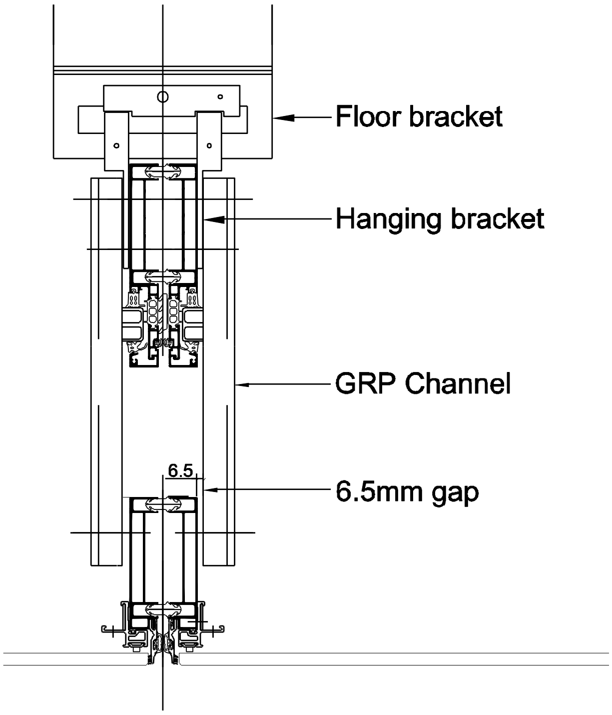


Figure 5.28 Realised detail of hanging bracket and GRP channel bracket showing the creation of a 6.5mm gap

The GRP channel support brackets for the external skin will also require a slight design change in future. During installation whilst tightening the bolt and nut connecting the GRP bracket to the outer mullion, it was revealed that the outer skin was becoming skewed. This could be traced back to the gap between the supports on the inner skin and bracket on the outer skin. As shown in Figure 5.28 the small gap had not been appreciated. The inner skin had additional hanging brackets in place where as on the outer skin there were none. To make up this extra distance and square up the facade wooden blocks were inserted between the GRP brackets and the mullion. In the next development stage a PTFE or polyamide shim with holes for the securing bolts will be inserted instead to give greater reliability and faster installation time. The final facade component added during site assembly was the external glazing.

The external glazing had been designed for use with structural silicone adhesive to attach the glass onto the frame without having to use a pressure plate and visible external framing. Structural silicone itself comes in two forms; a two part mixture which cures in two days and a single part mixture which cures in seven days. In both cases the glass has to remain flat. To achieve a good quality bond it is recommended that this be done in a dedicated facility and under the environmental conditions outlined in BS EN 13022-2 it would be difficult to carry out structural silicone glazing on site. For a fabricator only organisation such as Crown Aluminium, the adaptor frame or outer frame needs to be assembled, sent to a structural glazing facility along with the glass, sealed and then returned back to the fabricators. A possible alternative is for the adapter frame and glass to be sent to the factory to be structurally silicone glazed and for this to be attached to the main frame on site, either at ground level or at its final location by transporting the glass internally and securing it with the use of a manipulator through the open internal glass units. In this way the fabrication time of a single unit could be reduced, but would need more site work. The decision can be made on a project by project basis.

The solution at the University was much different however. Due to the major delay on the facade material and the fact that the laboratory being used was due for refurbishment and had to be cleared imminently, there was insufficient time to send the glass to the structural glazers if there was to be time left for testing. Instead the use of a special tape '3M VHB' type was investigated. The adhesive specialist at 3M (www.3M.com) was contacted and the project discussed with them. The determining factor for its use was revealed as the load capability. A quick calculation revealed that this would not take the dead weight of the glass on its own and in a high rise situation would not be able to take the wind load either. Its use would therefore be better suited to smaller a glass size where the ratio of perimeter to area is greater and therefore bring the load limit within the tapes capability. Fortunately in the case of the Schueco UCC 65 SG profile system, the dead load of the glass (as long as it is vertical) is supported by metal clips at the bottom. In terms of wind load, the laboratory provided protection from the wind, and wind load tests were not part of the test regime for the prototype as data already exists and is valid on the performance of the Schueco system. The tape could therefore be used at this proof of concept stage, but is not applicable in a developed product due to the presence of a greater wind load and other eccentric loads prevailing during erection.

The sequence of installation for the external glass was to first install the plastic adapter into the frame as better access for screwing was possible and then the tape was applied. The glass was then lifted using suction pads and offered into the frame. Two problems became apparent. Firstly, due to the weight of the glass and using four people to lift, it was very difficult to offer the glass into the frame at exactly the right location and no adjustment of the glass location was possible as the tape adhesive once contacted would not release. With silicone bonded outer glass, the lifting would be done by glass manipulators which allow fine adjustment and therefore more precise location. Secondly the height of the glass was slightly short of the frame size. On investigation of the glass size discrepancy it was found that there was an error on one of the bar drawings and the transom location was slightly incorrect. This could have been caused by moving the bar drawing outer lines without selecting the lines indicated the transom fixing location or a late change to the layout drawings without changing the bar drawing. To close this gap in the outer skin, a piece of acrylic was precisely cut and fixed into place. To prevent this in the next development stage either a more vigorous checking procedure is necessary or alternatively some parametric or BIM system should be put into place. This would maintain coordination between the layout drawings and the bar drawings so that the bar drawings are automatically updated if a layout change is carried out.

The final assembly work required for the facade was to close off the cavity in the relevant location to ensure cascade type air flow was achieved. This was very difficult to install due to time constraints at the fabricators and Schueco sending the wrong fittings for the internal doors, only two of the four internal openings were fitted with hinges and could be opened. In any case the fixing detail for these panels needs to be improved to make it hidden and fit more neatly into the cavity in the next double facade development stage.

5.4.3. Active Environmental System

The RSHP was fully constructed at the University from supplied components. During its assembly it quickly became apparent that extra space was needed to allow the copper pipe work to be routed from one component to the next. The space became especially constrained due to the large receivers. In addition one of the receivers was damaged and would not be replaced by the supplier because 30 days had elapsed since its delivery. The refrigeration circuit was therefore reanalysed to see if one of the receivers could be omitted. After discussion with colleagues and technicians a bridging circuit was designed and implemented in order to omit a receiver as shown in Figure 5.29. This saved on space, time and if implemented in the future, save on material costs for two check valves and a receiver. Testing in Chapter 6 will verify whether it still performs adequately.

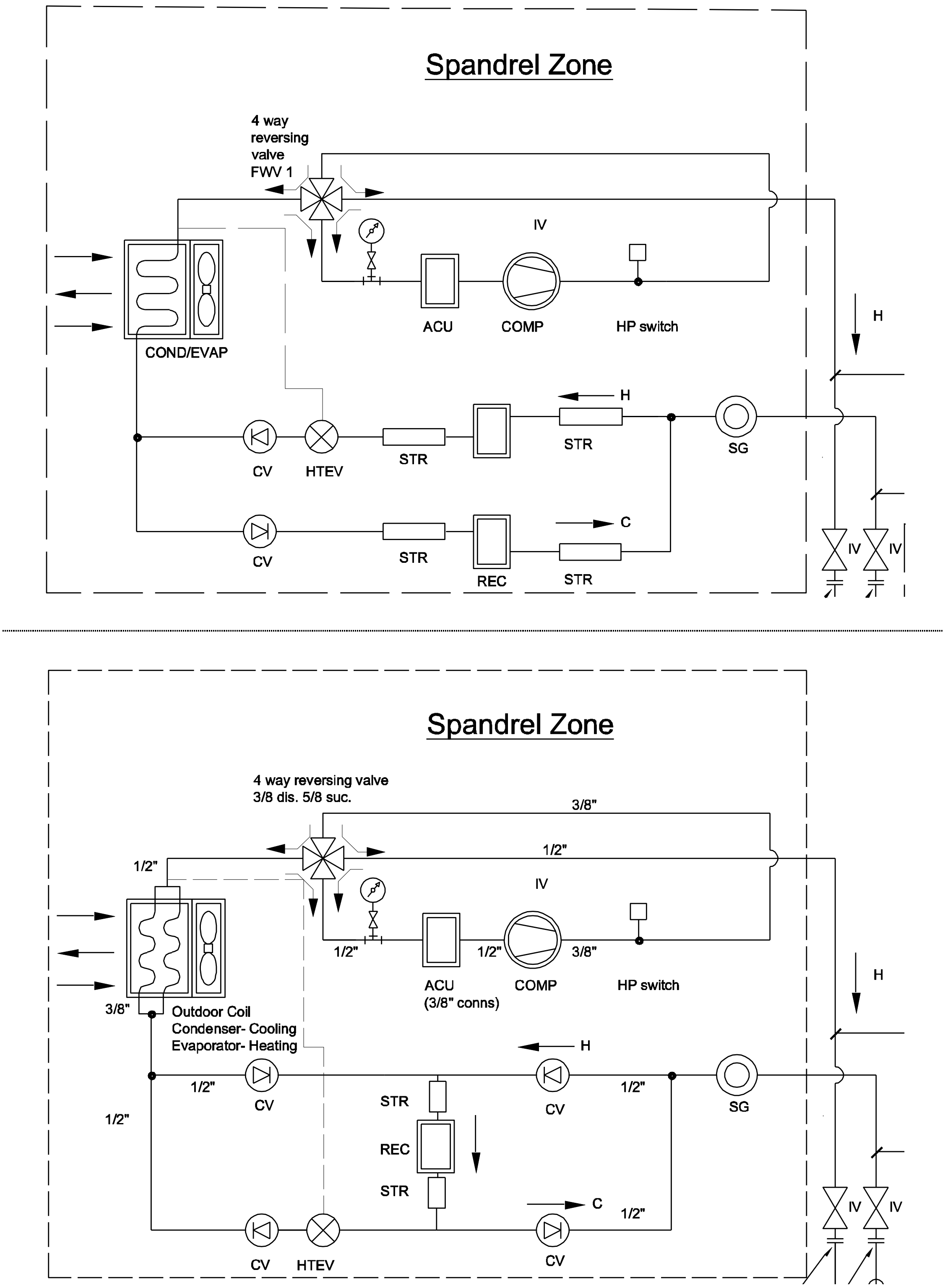


Figure 5.29 Schematic of refrigeration system using two and one receiver using a bridging circuit

The installation of one of the RSHP modules was also not as straight forward as imagined. The module consisting of the receiver was lightweight and could easily be positioned in place. The other module however consisted of the Compressor, Accumulator, Condenser/Evaporator and associated Valves. This module however was very heavy due to the weight of the compressor and with the installation taking place manually on ladders very difficult to do safely. An alternative to installing it into the facade and manually is required, and will be considered in Chapter 7.

The internal installation of the prototype comprised of the Active Beam, Heat Exchanger, connecting pipe work, the Active Trench and the Electronic Controls. The installation of the Active Beam proceeded before the facade was in place to allow fork lift access. To secure the Active Beam in place, the bottom cover needed to be opened which exposed the delicate finned pipe. To avoid damage a two metre piece of rigid insulation was placed between the fork lift and the Active Beam, with the door hanging to the side. It was then raised up, located into position, secured first at the ends and then with the fork lift truck removed, the central support bolts secured. Fortunately the drop rods were precisely fixed and perfectly aligned which allowed the supports to find the slots in the beam without problem. The same kind of attention to detail has to be taken on site or some form of adjustment mechanism built in. The Active Beam did allow for some discrepancy in the *x* direction and so some form adjustment on the drop rods in the *y* direction would be beneficial.

The ductwork connection to the Active Beam was straightforward, but the pipe work connection presented a problem. A note on the Active Beam indicated that the copper pipe could not be soldered or twisted, and the metric 15mm pipe was not compatible with the 5/8" imperial pipe. Neither silver solder nor a flare fitting could therefore be used. To provide the connection, a standard water coupling had to be used together with pipe sealant to increase its pressure rating, albeit in an unconventional way. To make the imperial to metric change, a brass fitting was custom made in the DABE workshop. In the next development stage, to eliminate the requirement for a special fitting and avoid the use of site applied pipe sealant, the copper pipe in the Active Beam should be fabricated using an imperial 5/8 pipe not 15mm metric and the connection on the beam should be pre flared with a flare nut. This would greatly simplify and speed up the site installation.

The Active Trench was quite simple to fabricate, the only slight problem encountered was the transportation, even though it only had to travel the short distance of approximately 200 m from the metal workshop to the laboratory. The Active Trench was made in four 1.2 m boxes with two holes between the boxes to allow the copper pipe to pass through and the connection between the copper pipes in the individual boxes, flare type fittings. Once flared with the flare nuts on however the hole in the boxes were not large enough to let the flare nuts pass back through and the boxes could not therefore be disassembled. To avoid cutting around the copper pipes to open up the holes, the Active Trench units were all clamped together so that they could be carried as a 4.8 m long unit. To allow the boxes to be disassembled in future the holes between the boxes simply need to be large enough to allow the flare nuts to pass through.

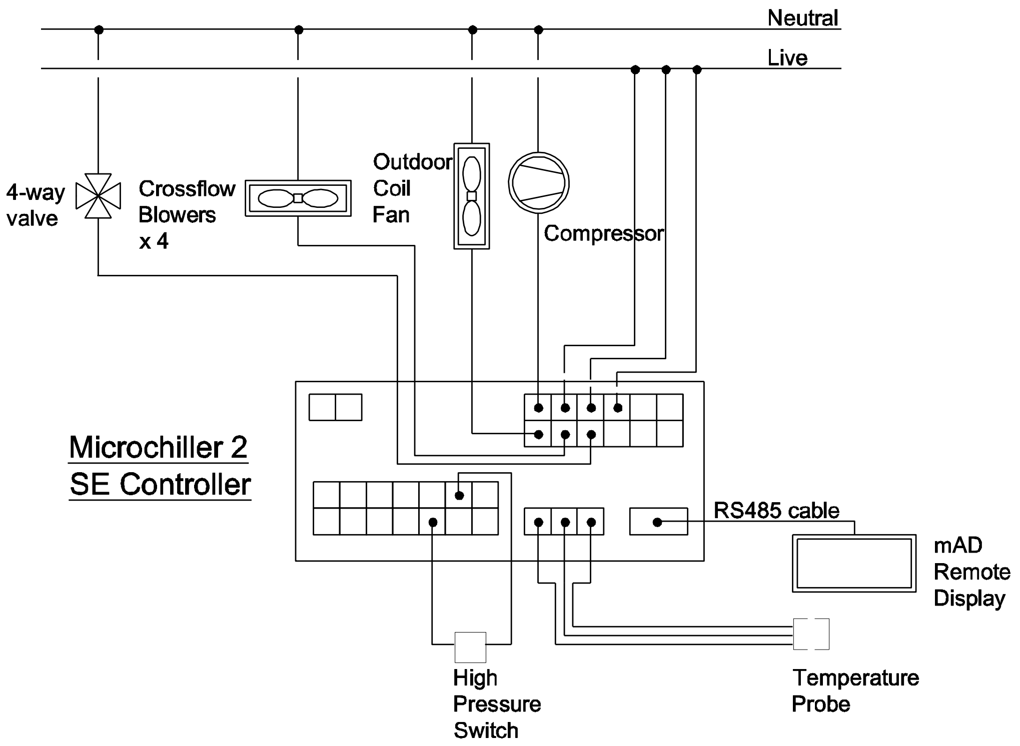


Figure 5.30 Connection diagram for MC2 SE controller

The final stage was the Electronic Controls and commissioning. The Electronics necessary for the correct functioning of the environmental system comprised of power connections and controllers. The different electrical supply voltages for the Fans, the Heat Exchanger, the Condenser/Evaporator and the Compressor meant that two transformers were required. The Control Unit itself needed a number of electrical connections to be made and a detailed programming of the controller. To programme the controller the user manual had to be studied to decipher the coding used and make parameter changes where necessary (e.g. Pr changed to 1 not 0). These changes are listed in Appendix P. This took some time to understand, but the actual programming procedure was quick and could be done in advance of the assembly work to speed up site set up time. The connections for the controller are shown in Figure 5.30. With the power connected and the Controller set up, the commissioning of the RSHP system could begin. This is discussed in Chapter 6 as part of the testing procedure.

CONCLUSIONS

Taking the design from detailed drawings through to a full scale proof of concept prototype has been achieved through the involvement of suppliers, manufacturers, fabricators, specialists and DABE technicians. The results of this process have been invaluable in revealing design changes for the subsequent prototype to improve production efficiency and quality in both the Active Environmental System and Double Facade.

The Active Environmental System has undergone major changes due to the necessity of using refrigerant R134A and its separation from the Double Facade. Further development work is necessary with industry in order to provide preassembled RSHP modules and an Active Trench and Heat Exchanger to the required specification. The Double Facade has also been reworked with Schueco UK, to utilise their system profiles which has meant that a number of major changes needed to be made. Further design development work is needed to improve the material efficiency, either by working with Schueco UK to adapt their existing profiles for use, or approaching a bespoke profile curtain walling company. To limit the developmental work and cost for the next prototype it would be cost and time effective to work with Schueco UK on developing an adapted profile which is detailed further in Chapter 7.

The full integration of the Active Environmental System into the Double Facade has been limited at this stage due to the levels of uncertainty in time and spatial coordination and the risk this presented to the fabrication process. Through completing the proof of concept prototype many of the risks have been ameliorated. In the next development stage the RSHP modules could be installed into the facade prior to installation on site. At this stage, the prototype IPADFS comprises of a total number of five major components. The site based assembly and installation work verified that the system, once some design changes are implemented, would be quite simple and quick to install. This has to a certain degree established proof of concept in terms of prefabrication performance. At the moment fabricators do not have the confidence or expertise to assembly and install air conditioning components. However greater prefabrication performance compared to a centralised solution has already been achieved and can be improved even further by focussing on integrating the components, to reduce their number and reducing the quantity and complexity of site work. Design changes to reduce the number of components for the next prototype will be presented in Chapter 7.

This chapter has established that the prototype can be realised and realised with a high level of prefabrication. To fully establish proof of concept the performance of the Active Environmental System and Double Facade needs to be tested and evaluated which will be addressed in the next chapter.

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CHAPTER 6

PROTOTYPE TESTING, RESULTS AND EVALUATION

Testing, and evaluating the results is an essential part of any product development process. Testing at an early stage of the process can prevent costly flaws from occurring as the further progressed a project becomes, the greater the cost of making changes. Testing processes aim to verify underlying assumptions on construction, functionality, and realisation to varying degrees. At the proof of concept stage, it is also important to verify that the initial aims of providing a component, which can be prefabricated, low in energy usage and carbon emissions, enhanced comfort performance and a good aesthetic has or will have the potential to be achieved.

In Chapter 5 the industrial development, fabrication and assembly of a full scale prototype has addressed its constructability and prefabrication potential. In this chapter the focus will be on testing and evaluating the Active Environmental System in regards to operating performance and efficiency for carbon emissions and comfort. It will also focus on the Double Facade in terms of weather testing and include relevant stakeholders in the product to obtain their feedback on aesthetics and other issues. At this stage enough information needs to be gathered to firstly highlight any problems so that the concept is validated and secondly, derive design improvements for the next design development stage to avoid costly changes.

The tests required are dependant firstly, on whether the component or group of components have previous test data and whether it is still applicable and secondly, the importance assigned to a particular feature. The first two sections comprise of functional validation tests, to provide information on the Active Environmental System and the Double Skin Facade. The third and fourth sections include exploratory and assessment tests to gauge opinions from key stakeholders on certain features of the design and how important or successful they are. (GDP Program 2010) (Ulrich 2003)

6.1. THE ACTIVE ENVIRONMENTAL SYSTEM

The Active Environmental System comprises of the RSHP, Active Beam, Heat Exchanger, Dampers and Controls. The untested components are the RSHP, as it was assembled from sub-components and the Active Beam, as it is using refrigerant instead of chilled water and is fed from an individual fan unit (the Heat Exchanger) rather than a centralised air handling unit. The Heat Exchanger, Controls and Dampers are used as per the manufacturer's tests and therefore only need to be tested to verify they are performing as intended.

6.1.1. Reversible Air Source Heat Pump

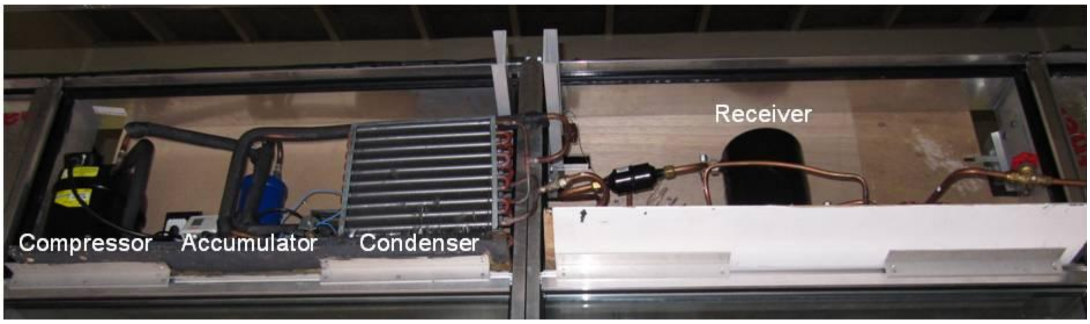


Figure 6.1 View of the RSHP modules as integrated into the facade (outer skin removed)

The fabrication and assembly of the RSHP within the DABE was an ambitious undertaking as neither the technicians nor the author had any prior experience in assembling a sophisticated refrigeration system from individual components. Testing this system was therefore an important as well as anxious part of the project. The procedure for commissioning and testing the refrigeration system consisted of the following stages:

1. Pressure testing, leak detection and cleaning;
2. Charging with refrigerant;
3. Switch on and adjust variables to achieve design parameters;
4. Measure the refrigerant and air temperatures.

Pressure testing is important to avoid leakage of refrigerant and ensure optimum operation of the refrigeration cycle. Pressure testing had been carried out on the grouped assemblies; the RSHP modules, the Active Trench and the Active Beam pipe work. However, the connections between the different assemblies needed to be tested to ensure that none of the joints has been damaged during transport. Since the DABE neither had suitable equipment nor personnel with appropriate certification to handle refrigerant R134A, a specialist from outside the DABE (Richard Smith of RDS Refrigeration) with certification to handle refrigerants was sub-contracted to carry out the commissioning and testing process.

The pressure test was conducted in stages. The first stage was to connect high pressure (48 Bar) Nitrogen gas to the system via the Schraeder Valve on the Compressor and the Rotalock Valve on the Receiver. The pressure was then increased to 5 Bar and all of the joints sprayed with a leak detector spray. Leaks were then found at the joints where gas bubbles began to form and grow. The majority of the leaks were found around the flare fittings and one of the solder fittings. The flare fittings only needed to be tightened in most cases, but on a single case needed to be cleaned, annealed slightly and then retightened. A single solder fitting showed some signs of damage and needed to be soldered again. Once the faulty flare fittings and solder joints had been rectified, the pressure was gradually increased up to 12 Bar and the joints continually monitored for any bubbles. At two bars above the maximum working pressure no leaks were found and the system maintained this pressure over a period of 15 minutes. The system could then be treated as leak free and able to hold refrigerant without it leaking. Before the system could be charged, it needed to be cleaned of any debris, moisture and air, which was achieved by using a vacuum pump. With the pressure test and vacuuming completed, the system was then ready to be charged with refrigerant.

The refrigeration system was charged by connecting the R134A gas bottle via a service manifold to the Compressor Process Line and Rotalock Valve (Discharge Line) as shown in Figure 6.2 and putting the system into cooling mode, in order to circulate refrigerant through the system. Providing the correct amount of refrigerant is important in refrigeration, as both too little and too much hinders system performance. The quantity of refrigeration needed can be calculated beforehand, but it can also be checked visually by observing the sight glass and filling until it becomes clear and almost full of liquid refrigerant. Appendix Q shows the calculation for refrigerant and gives a figure of 1.5 kg. Before and after charging the refrigerant bottle was weighed to ensure 1.5 kg was provided. With a charge of 1.5 kg however, the sight glass was still very cloudy (an indication of insufficient refrigerant) and so an additional 1.2 kg was inserted in order to clear the sight glass and reach the desired liquid level. This can be explained by the oversized receiver requiring extra refrigerant to reach the dip tube. Once the system was charged the controls and internal components needed to be commissioned and adjusted which is described in subsequent sections. The temperatures obtained at the Condenser and Compressor could then be measured.

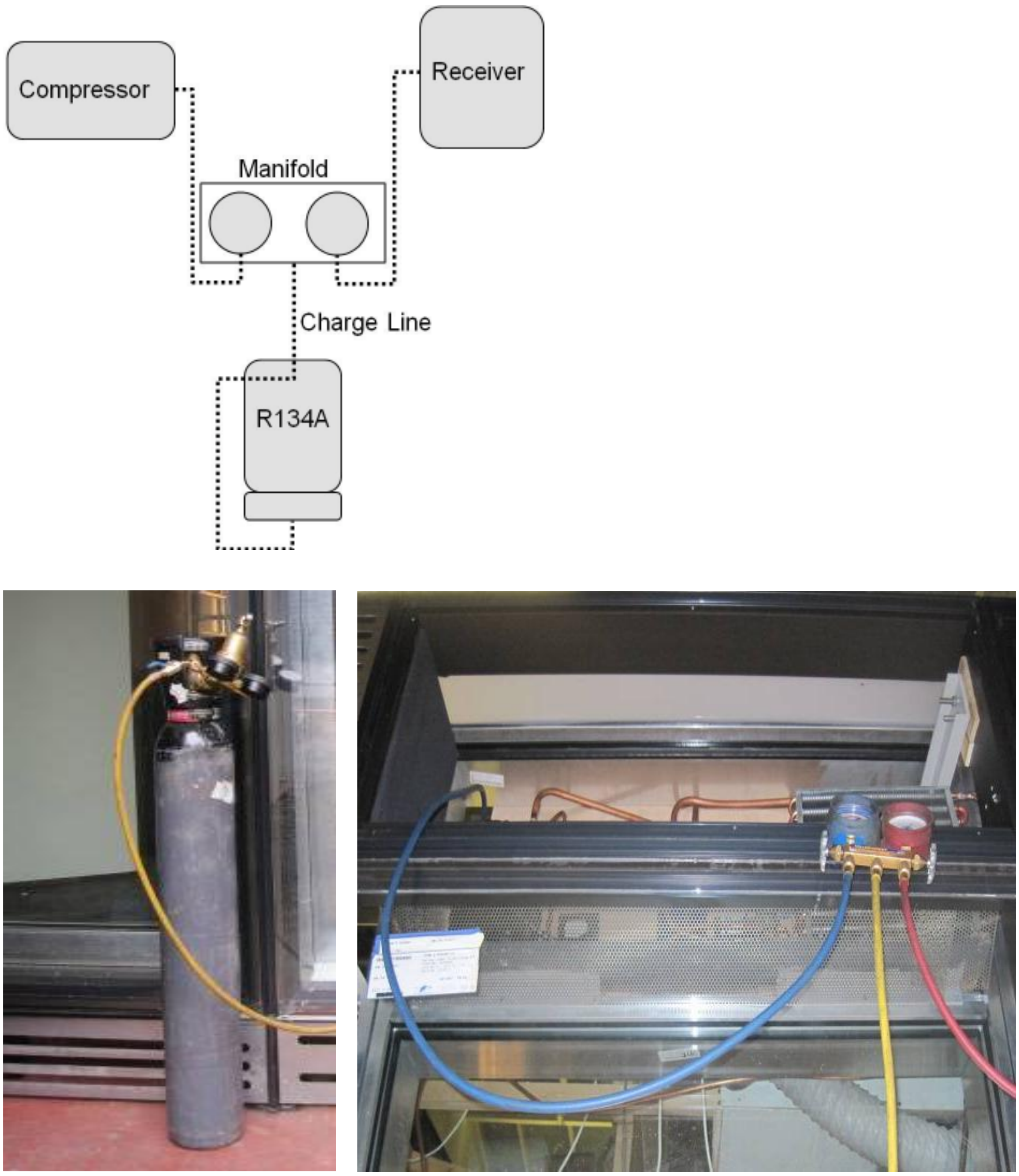


Figure 6.2 Refrigeration charging lines and set-up

Figure 6.3 Digital thermometer used for refrigerant temperature readings and hot-wire anemometer used for air temperature and velocity

To measure the refrigerant temperatures a thermocouple was used with the ends of the wires placed onto the copper pipe directly and waiting for the temperature to remain constant to +/- 0.1°C. The cooling mode temperatures are given in Table 6.1 and are shown on the refrigeration cycle in Figure 6.4. They show the temperature off the compressor as 55.1°C, 15°C above the design value. On leaving the compressor the refrigerant is cooled and is 40.2°C at the inlet to the condenser which is the required value. On leaving the condenser it is 27.5°C which is much lower than the design Figure 40 °C design value. These values are plotted in Figure 6.4.

Table 6.1 Results of temperature measurements for the RSHP in cooling

Location	**Temperature** °C
Condenser air inlet	21.5
Condenser air exhaust	27.7
Condenser refrigerant inlet	40.2
Condenser refrigerant exhaust	27.5
Compressor suction	1.0
Compressor discharge	55.1

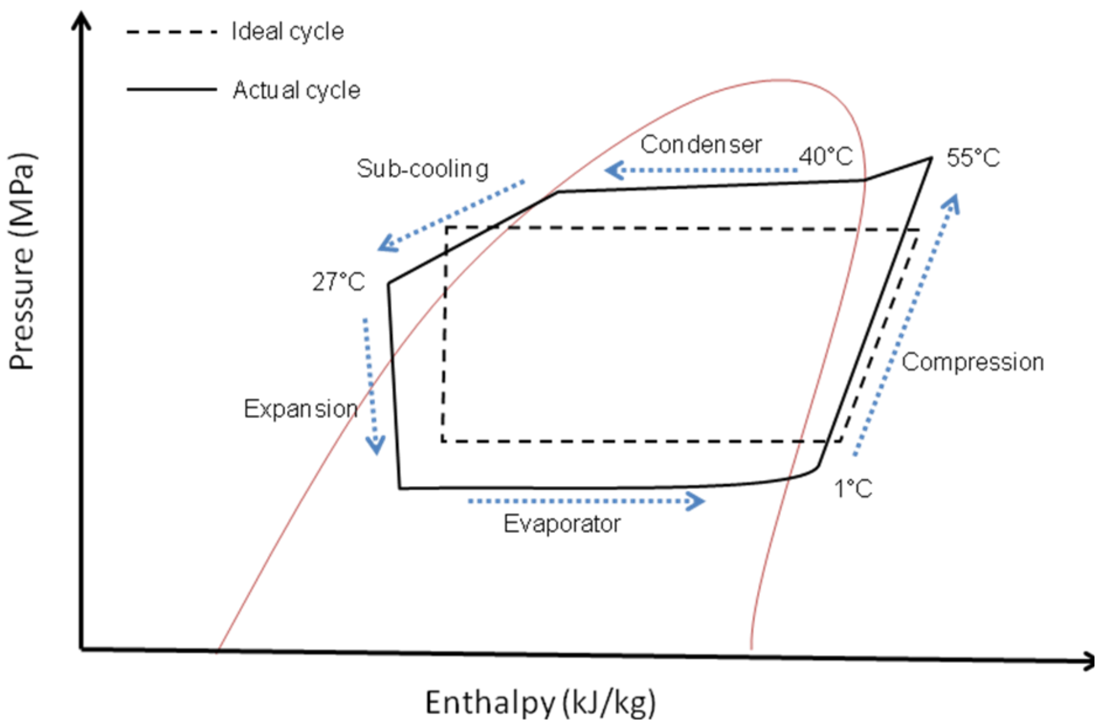


Figure 6.4 Pressure-enthalpy diagram for actual and ideal cycle in cooling mode

As shown in Figure 6.4, the effect of sub-cooling in the Condenser translates into a lower evaporating temperature since the thermostatic expansion valve (TEV) requires a minimum pressure difference. The solution to overcooling is either balanced port TEVs, or modulating condenser fans. Modulating Condenser Fans are much more cost effective and would require a Fan Control Speed Board, which is available as a plug-in for the Controller being used.

Table 6.2 Results of thermocouple measurements for the RSHP in heating mode

Location	Temperature °C
Evaporator air inlet temperature	16
Evaporator air exhaust temperature	14
Evaporator refrigerant inlet	2
Evaporator refrigerant exhaust	11
Compressor suction temperature	13
Compressor discharge temperature	55.2

To measure the temperatures in heating mode a thermocouple was used in the same way as in the cooling mode. The values obtained are given in Table 6.2 and the refrigeration cycle in Figure 6.5. In this mode the refrigerant is condensing in the internal components and evaporator is in the spandrel zone after the compressor. Again the refrigerant temperature after the compressor is 55.2°C, higher than the design value. The design inlet evaporator temperature in heating mode is -10°C, but the measured value was 2°C. In this case the TEV orifice assembly needs to be changed for one of a higher capacity. Another issue was super-heated margin at the evaporator with the temperature rising from 2°C to 13°C, which can be easily rectified by adjusting the superheat setting. A note on both modes of operation was the difference between evaporator/condenser temperature and the compressor signifying that better insulation of the connecting pipe work is needed.

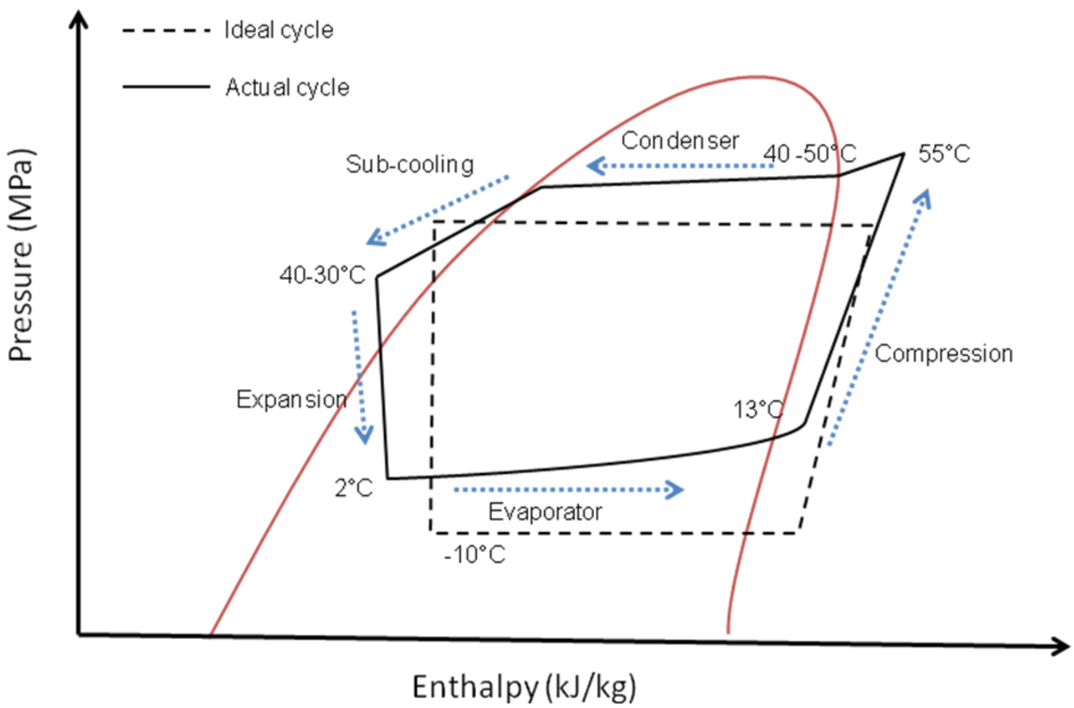


Figure 6.5 Pressure-enthalpy diagram for actual and ideal cycle in heating mode

During more extensive lengths of testing the noise generated by the RSHP was not subject to a detailed examination since the principal component; the compressor was hardly audible. However two design faults were identified, relating to the Condenser/Evaporator. Firstly, the Condenser/Evaporator had been installed the wrong way around (introducing an extra pressure drop) and secondly, in heating mode significant amounts of condensation collected on the evaporator which dropped into the cavity - artificial rain had been created unwittingly. The Condenser Fan having been installed the wrong way around did not adversely affect the performance, but should be corrected to improve the modulating fan control in the next evolution. The condensation problem was created by the wet bulb temperature of the air, being below that of the condenser pipe work. A simple drip tray located directly beneath the condenser and an outlet directed towards a rainwater collection is required to collect and discharge this condensate. Both faults can therefore be easily overcome.

In this section, the RSHP has been commissioned and tested. The commissioning process has revealed that significant site based work is required by a specialist for the pressure testing, cleaning and charging process, which should be examined as to whether they too can be relocated off-site. The tests have revealed a large discrepancy between the design and actual performance figures. For improved performance closer to the design values in both heating and cooling, an adjustment of the thermostatic expansion valve superheat setting, change of orifice and the addition of a modulating control for the condenser fan is to be implemented into the next design development stage.

6.1.2. Active Beam and Active Trench

For energy efficient as well as comfortable heating and cooling, the delivery through the Active Beam and Active Trench is also important. The Active Beam is a fully tested component from Frenger systems although, the tests carried out have used it with its normal cooling and heating medium, water and with fresh air from a central air handling unit. The aim of the testing procedure here, is to reveal whether there are any major differences and issues with using refrigerant and a local Heat Exchanger unit. In theory, the performance of the Active Beam should be the same or even better as refrigeration's latent heat exchange mechanism reduces the temperature difference between flow and return, and therefore provides a more constant heat flux. The performance of the Active Trench on the other hand is more uncertain as it was assembled from individual components in the same way as the RSHP modules and has no precedent data. The aim here is as with the Active Beam is to discover any issues with using refrigerant. Both components were tested with a similar procedure as follows:

1. Switch the system on and wait ten minutes for it to stabilise;
2. Take the refrigerant flow and return temperatures using a thermocouple;
3. Measure and record the air temperature and velocity using a hot wire anemometer;
4. Switch from heating to cooling;
5. Wait for the temperatures to stabilise;
6. Retake the measurements.

Before testing could take place however, a number of issues needed to be solved for the system to function in heating and cooling modes, which were very revealing in themselves. With the system in heating mode, only the Active Beam provided heating. Feeling the pipe work temperatures and noting they were still cold in certain sections, indicated that there was hardly any flow down the distribution pipe to the Active Trench. This can be explained by the culmination of a number of factors causing a major difference in pressure drop between the Active Beam and the Active Trench circuits.

Firstly, the Active Beam had oversized pipe work as it was designed for water, whereas the Active Trench pipe work was sized for refrigerant and therefore had smaller pipe work. The pressure drop in the Active Beam was therefore much lower based on friction loss alone. Secondly, the friction pressure drop in the Active Trench circuit was higher due to the higher complexity and number of bends in the routing. Thirdly, the Active Beam was situated higher than the Active Trench leading to a static pressure head difference. To get the system working in heating mode and overcome the pressure drop, the system was balanced by partially closing the Check Valve on the Active Beam in order to increase the pressure drop on the Active Beam circuit. This should however, be designed out in future as it causes an extra load on the Compressor and reduces the overall efficiency.

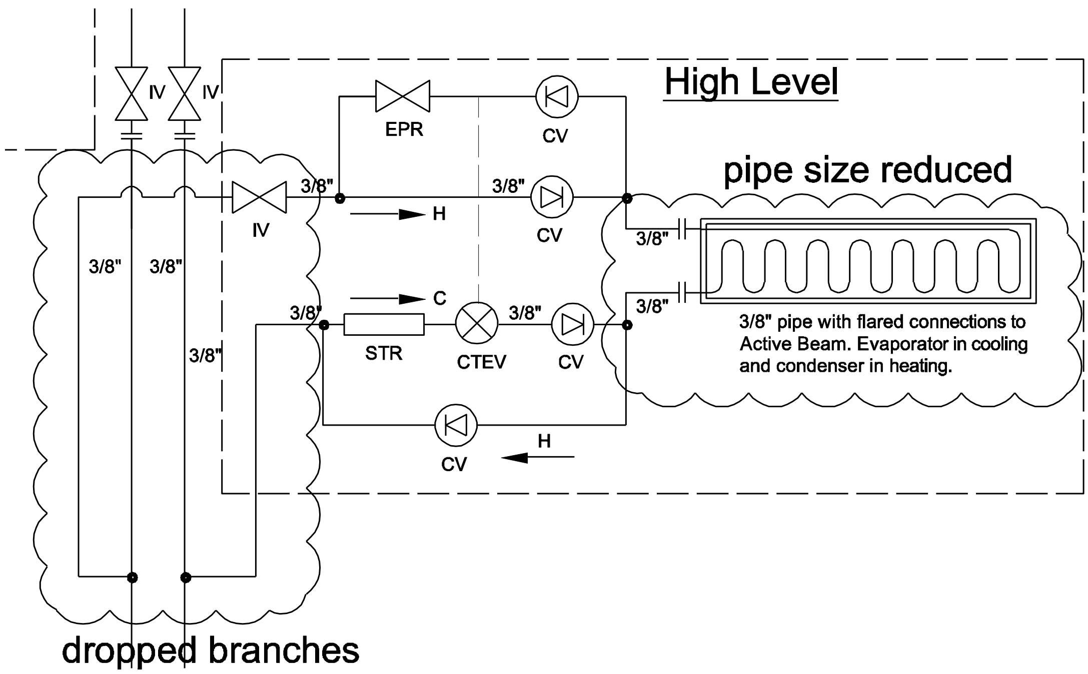


Figure 6.6 Design changes to the refrigerant circuit to reduce the pressure differential

The main measures that will be taken to alleviate this differential is to reduce the complexity and number of bends in the Active Trench circuit. This was caused by installing the RSHP modules and fabricating the pipe work before the facade had arrived (to save time) and then having to make further bends in the pipe work to coordinate the different assemblies. If necessary, additional measures can be implemented such as reducing the size of the Active Beam pipe work in order to balance the friction pressure drop, and dropping the take off for the Active Beam in order to balance the static pressure head difference. These changes are shown in Figure 6.6.

In cooling mode, it was the Active Beam that was problematic as refrigerant flow was at first limited to the Active Trench. It was found on further investigation, to be a combination of the Evaporating Pressure Regulator and the TEV. By adjusting the Regulator to regulate to a lower temperature, refrigerant began to flow through the circuit and the Active Beam circuit. This can be explained by the regulator being preset, to provide a minimum flow temperature of 14°C into the Active Beam (as to prevent any possibility of condensation on the Active Beam), if the temperature was lower it would close down. The Regulator however, had to accept a temperature of 12.5°C in order for it open, which was lower than designed for and initially set. This was due to the TEV. With more time available for testing, could have been adjusted either through the superheat setting or exchanging the orifice for a smaller one, to provide a temperature of 14°C. A modulating Fan Controller for the Condenser would also help alleviate the low temperature. With the system operational by adjustment of the Check Valve in heating mode and the adjustment of the evaporating pressure regulator in cooling mode, testing could still be carried out close to the design conditions to gather information on the overall performance.

The information needed to test the refrigeration circuit is the refrigerant flow temperatures and the air flow temperatures for both the Active Beam and Active Trench. This will signify firstly, whether the system can satisfy the room loads and secondly, an indication of the comfort conditions. The refrigerant flow and return temperatures were taken by using a portable thermocouple, locating the ends onto the copper pipe and waiting for the temperature to remain constant to +/- 0.1°C. The air flow temperatures and velocities were taken using a portable hot wire anemometer at the positions shown in Figures 6.7 and 6.8 for the Active Beam and Figure 6.9 for the Active Trench. The reading on the anemometer was taken once the value remained the same for 10 seconds.

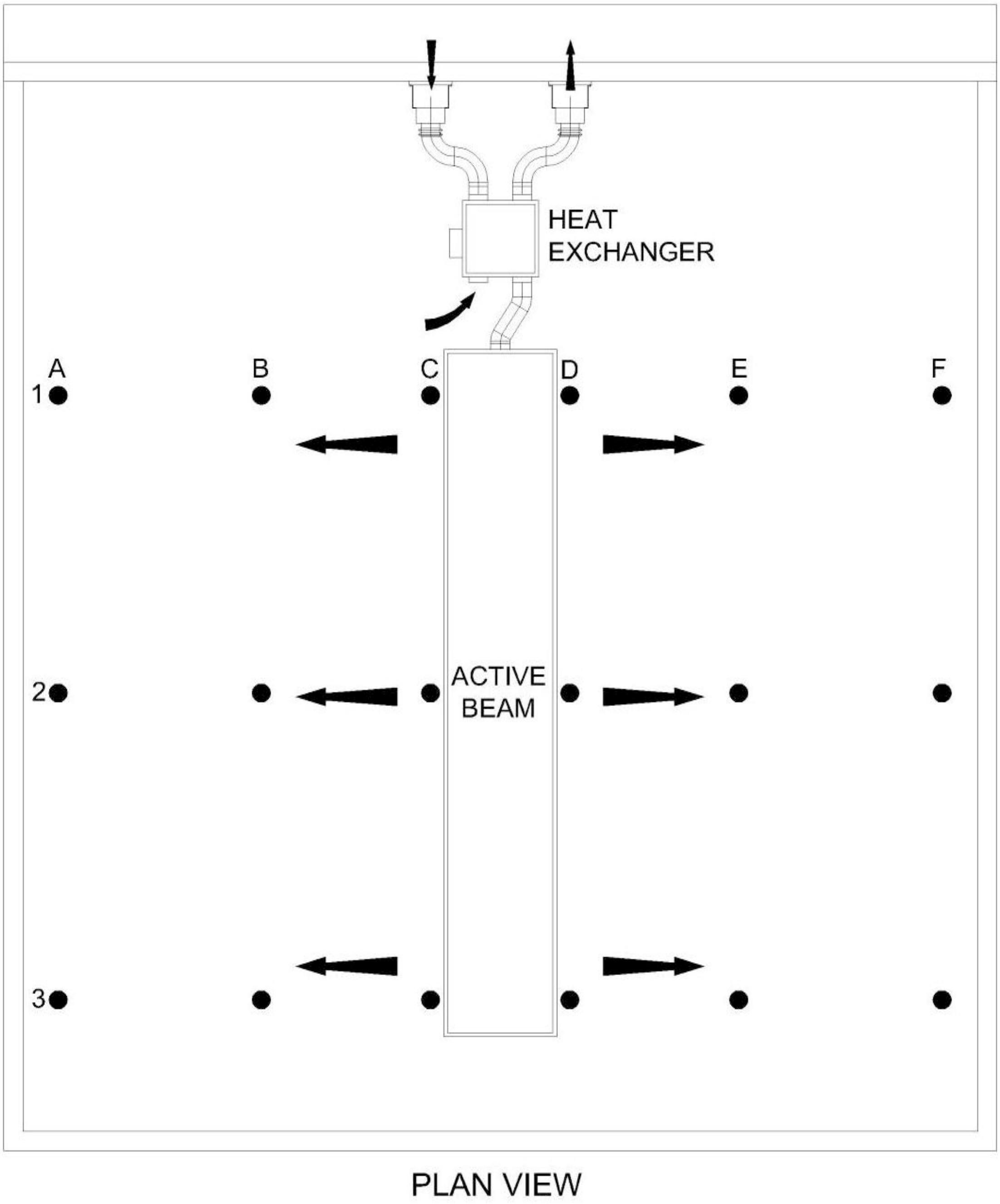


Figure 6.7 Locations for hot wire anemometer on the Active Beam plan view (dots indicate locations)

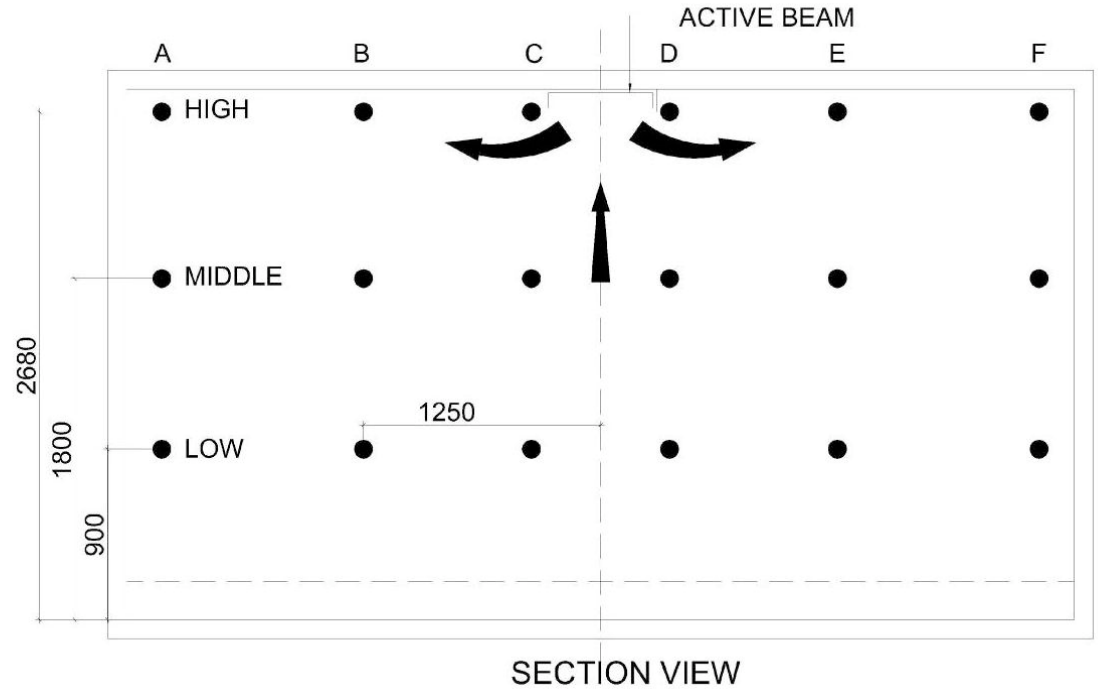
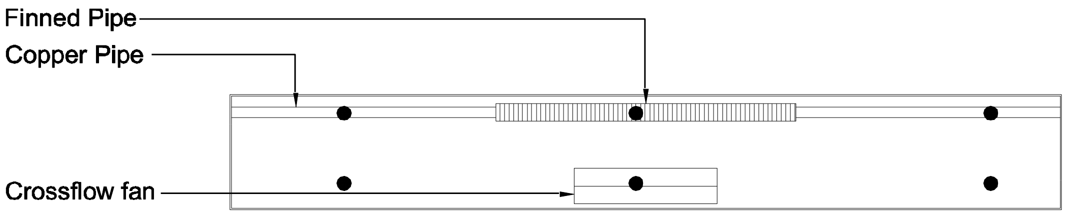
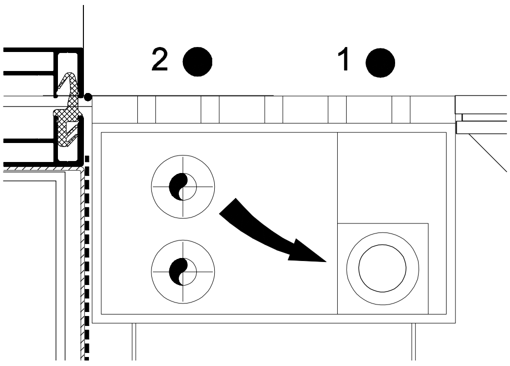


Figure 6.8 Locations for hot wire anemometer on the Active Beam sectional view (dots indicate locations)



Plan View



Section View

Figure 6.9 Locations of hot-wire anemometer readings for the Active Beam

Table 6.3 Refrigerant flow temperatures in heating mode

Location	**Temperature** °C
Active Beam refrigerant flow	54.7
Active Beam refrigerant return	41.2
Active Trench refrigerant flow	40.4
Active Trench refrigerant return	30.7

Note: 54.7°C was an estimate as it varied by +/- 5°C

Table 6.4 Refrigerant flow temperatures in cooling mode

Location	**Temperature** °C
Active Beam refrigerant flow	12.5
Active Beam refrigerant return	13.0
Active Trench refrigerant flow	-1.2
Active Trench refrigerant return	-1.9

Figure 6.10 Picture of hot-wire anemometer reading being taken for the Active Beam by the author

Table 6.5 Air flow temperature and velocity results for the Active Beam in heating mode

		A		B		C		D		E		F	
		deg C	m/s	deg C	m/s	deg C	m/s	deg C	m/s	deg C	m/s	deg C	m/s
1 (Front)	High	22.5	1.1	25.1	1.2	29.5	2.1	29.9	1.7	26.8	1.5	25.4	1.2
	Middle	22.4	1.1	22.4	1.1	22.4	1.1	24.5	1.1	24.3	1.0	23.7	1.2
	Low			22.3	1.1	22.2	1.0	23	1.1	22.8	1.1	22.6	1.1
2 (Centre)	High	27.6	1.1	28.1	1.3	29.7	2.1	30.7	2.1	28.1	1.3	27.2	1.1
	Middle	25.7	1.1	26.1	1.2	26.5	1.1	25	1.2	24.6	1.2	23.9	1.1
	Low	22.8	1.1	22.9	1.1	23.1	1.1	23.2	1.1	23.3	1.1	23.6	1.1
3 (Back)	High	28.7	1.4	29.1	1.6	30.7	2.6	30.9	2.7	27.7	1.2	27.2	1.2
	Middle	28.1	1.2	26.8	1.1	26.5	1.3	25	1.1	25.2	1.2	25.3	1.1
	Low	25.5	1.1	25.7	1.2	25.8	1.1	23.9	1.1	24.2	1.1	24.5	1.1

Table 6.6 Air flow temperature and velocity results for the Active Beam in cooling mode

		A		B		C		D		E		F	
		deg C	m/s	deg C	m/s	deg C	m/s	deg C	m/s	deg C	m/s	deg C	m/s
1 (Front)	High	20.7	1.0	20.3	1.1	18.7	2.2	19.2	1.6	20.7	1.0	20.9	1.1
	Middle	21.0	1.0	21.3	1.0	21.5	1.1	21.1	1.0	21.3	1.1	21.4	1.0
	Low	21.7	1.0	21.7	1.0	21.6	1.0	21.4	1.0	21.4	1.0	21.4	1.0
2 (Centre)	High	20.3	1.0	20.0	1.2	18.5	1.5	19.9	1.6	21.0	1.1	21.1	1.2
	Middle	20.6	1.0	21.0	1.0	21.3	1.3	22.1	1.0	22.3	1.1	22.3	1.1
	Low	21.8	1.0	21.7	1.0	21.7	1.1	22.2	1.1	22.3	1.3	22.4	1.1
3 (Back)	High	21.0	1.0	20.5	1.1	18.8	2.6	18.7	2.1	21.9	1.2	22.4	1.0
	Middle	21.4	1.0	21.7	1.0	21.7	1.0	22.5	1.1	22.4	1.1	22.1	1.0
	Low	22.1	1.0	22.0	1.0	21.9	1.0	22.5	1.2	22.4	1.1	22.4	1.1

Table 6.7 Air flow temperature and velocity results for the Active Trench in heating mode

	Temp. °C	Velocity m/s	Temp. °C	Velocity m/s	Temp. °C	Velocity m/s
	A		B		C	
1	22.1	0.9	20.7	1.4	22.7	1.0
2	21.4	1.0	18.2	6.2	22.6	1.1

Note: Room temperature is 20.0°C

Table 6.8 Air flow temperature and velocity results for the Active Trench in cooling mode

Cooling Mode

	Temp. °C	Velocity m/s	Temp. °C	Velocity m/s	Temp. °C	Velocity m/s
	A		B		C	
1	18.6	0.9	17.2	1.3	17.8	1.0
2	18.4	0.9	15.9	5.5	17.5	1.0

Note : Room temperature 21.5°C

The results for the heating refrigerant temperature shown in Table 6.3 for the Active Beam are higher than the design value of 40°C with a temperature of 54.7°C. Whilst this will still provide the heating load and comfort criteria, it will reduce the overall efficiency. The Active Trench refrigerant flow temperature is 40°C, but the return flow temperature is 30.7°C indicating a large pressure drop in the circuit. In cooling mode, the Active Beam flow and return temperature, is slightly low and there is a slight risk of condensation on the beam. The Active Trench cooling temperature shown in Table 6.4 is several degrees lower than the 10°C required, with a temperature of -1°C. This is another consequence of the higher pressure drop on the Active Trench circuit. Both the pressure and temperature is below the design parameters during the evaporating phase. The reason for this is the TEV providing a lower than designed for pressure and temperature. The measures discussed earlier should address this issue.

The air temperatures and velocities for the Active Beam shown in Table 6.5 and Table 6.6 show good agreement with the design space temperatures, and the air velocities are well within comfort ranges. The Active Trench results are given in Table 6.7 and Table 6.8. The air temperatures achieved in the heating mode do show some heating of the air steam, but as can be expected with the low temperatures, they are not as high as required. In cooling mode the air temperatures are lower than required due to the low refrigerant temperature. In both cases making the changes outlined earlier to the TEVs, pipe work routing and Condenser Fan should provide the design values required for optimum operation.

The final test carried out was to ascertain whether the output is sufficient to meet the design load requirements established in Chapter 4. To test whether the system has sufficient cooling capacity an electric fan heater and electric light with a total thermal output of 1800W (to replicate the design cooling load) were placed in the room. The set point was then reduced from 24°C to 21°C to test whether the system could deal with the load as well as reduce the air temperature. The set point was achieved after twenty two minutes of cooling operation. This indicated that the system did have sufficient capacity. The heating load was not carried out as it would have required the use of another chiller and there was insufficient time to set this experiment up. The heating load is however less than the cooling load and the system can be expected to provide the necessary heating since the heating output on a RSHP is higher than the cooling output.

Testing of the Active Beam and Active Trench have successfully shown that the system can provide cooling and heating from a facade integrated, local RSHP and air supply from a local Heat Exchanger. Issues with the Active Trench pipe work and TEVs have been found. Solutions have been presented and should provide a much improved performance once implemented in the next design development stage. Even though the system was not performing optimally the system output in cooling mode has been shown to be sufficient and by inference, the heating mode capacity will also be satisfied.

6.1.3. Mechanical Ventilation System

The provision of fresh air and the working principle of the Active Beam rely upon the correct operation of the ventilation system. The fresh air quantity needs to satisfy the requirement for two persons (24 l/s) and provide sufficient static pressure (80 Pa) at the Active Beam. The close proximity of the intake and exhaust also requires an assessment of the potential for cross-contamination of the air streams as noted in Chapter 4.

The mechanical ventilation system components are shown in Figure 6.11 and include: Louvres, Dampers, a Heat Exchanger and the associated controls. These components have all been factory made and have undergone testing by the supplier as single units. Extensive testing of their individual performance is therefore not required. What is needed is to verify that they function as intended and their collective performance.

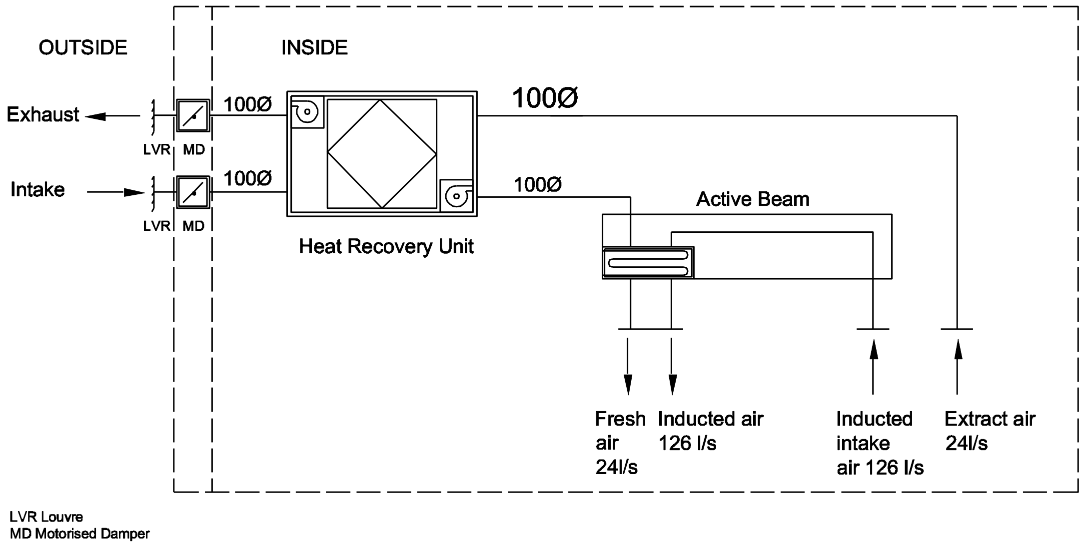


Figure 6.11 Ventilation system schematic

The correct operation of the Dampers is essential to permit mechanical air flow and reduce the infiltration outside hours of operation. Testing is needed to verify that they open and close in tandem, with the on/off operation of the Heat Exchanger to avoid any additional pressure drop, or air infiltration. The dampers were tested by observation during an 'on' signal and 'off' signal from the Heat Exchanger. On activation of the Heat Exchanger, the Dampers opened quite slowly and left the Heat Exchanger operating without air flow for around 30 seconds. With the Heat Exchanger turned off, the time to close the dampers was around thirty seconds again. In the closing of the Dampers, a delay of 30 seconds is not a major issue, since it will add a marginal addition to the infiltration loss. The 30 second delay period on opening, may cause damage to the Heat Exchanger and this was checked with the manufacturer Vent-Axia. They confirmed that this was not a problem and the product is commonly used with slow opening dampers.

The next component after the Dampers is the Heat Exchanger. The Heat Exchanger not only transfers heat from the intake to the exhaust air streams, but also provides the fresh air at a sufficiently high pressure for the Active Beam and extracts stale air from the room. The efficiency of the Heat Exchanger can be taken from the results of the manufacturer. The main aim is to check upon the air flow rate being delivered, the static pressure provided and any noise issues.

Figure 6.12 Measurement of air velocity and manometer for static pressure

The air flow rate can be found by measuring the air-flow velocity within the duct and multiplying this by the area. The number of readings and location is dependant on the duct size and location of the fan. Guidance provided by BSRIA (Parsloe 2001) suggests that for a 100 mm duct, a single reading is required and this should be a distance of ten diameters (1000 mm) away from the fan. A single reading was taken using a hot-wire anemometer, but at a distance of 300 mm as the length of ductwork present in the system was not long enough. The reading was noted once it stabilised for a period of ten seconds. The controller was set initially at a higher setting and then changed to a lower setting. At the lower setting a problem with the controller meant that the flow rate remained unchanged and a noise at the control box was heard which disappeared when the setting was reverted back to the higher setting. During commissioning when there was no real static pressure the air flow did reduce with the controller. The air flow rate at boost was above the required rate and does need to be reduced for two reasons. Firstly, there is extra ventilation heat loss and secondly, the high air flow rate was causing a high velocity, turbulence and therefore noise as noted by some of the visitors discussed later in the chapter, since the ducts were sized on a lower air flow rate. On discussing the problem with the manufacturer the cause of the fault is likely to be the controller working with a high pressure circuit and an alternative two-position rather than sliding switch controller, was recommended an is to be specified in the next development stage.

The total pressure within a duct comprises of static pressure and velocity pressure. A pitot-tube manometer (shown in Figure 6.12) was inserted into the holes made by the velocity test and the pressure read from the display on the manometer. A reading of 40Pa was taken, but this was not considered to be accurate since the Active Beam requires a pressure drop of 80Pa at least in order to produce the induction effect occurring and does not correspond to the fan curve provided by the manufacturer. The possible reasons for the error could be either the measurement being taken on a bend, an area of high turbulence or a measurement error in the equipment used. Since the pressure generated was sufficient to drive the induction effect on the Active Beam further investigation was not needed.

Table 6.9 Air flow measurements, static pressure and volume flow rate

Test	Area	Velocity	Static Pressure	Flow rate
	m^2	m/s	Pa	m^3/s
Supply	0.008	5.7	NA	0.0448
Extract	0.008	5.3	NA	0.0416

The possible cross-contamination as the air enters the intake louvre and leaves exhaust louvre air streams is important to quantify in some way since the distance between them is below recommendations (see Chapter 4). Cross-contamination will reduce the effectiveness of the ventilation and have implications on air hygiene and therefore comfort. The ventilation flow path should be where none of the exhaust air is recirculated and enters the air intake and into the room. To provide an indication of the flow pattern, a smoke bomb was lit inside the room adjacent to the extract on the Heat Exchanger. The Heat Exchanger was switched on and the flow of smoke in the spandrel zone and outside was videoed. On reviewing the video, the flow path of the smoke was straight out of the aluminium panels and then dropped down and mixed in with the outside air. There was some smoke gathering outside the intake bay, but this was only once the smoke had built up within the laboratory and a result of being inside an enclosure. Observing the intake, any change in concentration of smoke was below visual recognition. Further analysis can only be conducted by a duct mounted smoke detector device which will be able to measure smaller changes in smoke particle concentration and give an indication of the percentage re-circulated. The results obtained so far are positive and the reason a separation distance of lower than 2 m still prevents cross-contamination is the low air flow rates and the high velocity of discharge. A repetition of the test in the next development stage should therefore be conducted with the reduced flow rates and therefore lower discharge velocities.

The tests carried out on the ventilation system have revealed only a single change. The controller for the Heat Exchanger needs to be changed to a Controller more suited to alternative set points on a high pressure system in order to reduce the flow rate. The rest of the tests revealed no major problems. The tests on the pressure in the system could not be accurately measured, but from the exemplary performance of the Active Beam, sufficient pressure is being generated. The Dampers which restrict the infiltration loss during non-operating times function as intended. Cross-contamination of air stream is not visible from observation using smoke. Further testing should be carried out using more sensitive detection equipment and the reduced flow rate to give greater confidence. The final aspect of testing the Active Environmental System is the Controls.

6.1.4. Control system

Activating and controlling the various active components needed to be simple, usable and perform the desired functions. Many of the tests had already been carried out as part of the preceding tests already discussed. Remaining tests that needed to carried out and the results are shown in Table 6.10. They reveal that the controller does indeed work as expected and allows the occupant sufficient control of the environment. An aspect of the controls that needs to be developed in the next development stage is the housing shown in Figure 6.13. By integrating the Fan Controller with the RSHP Controller, the cost as well as number of control units and aesthetics would be improved.

The heating and cooling operation relies on the activation of the Solenoid on the 4-way Valve in order to reverse the flow of refrigerant. This was achieved by cooling the room down to 19°C and then altering the set point to 24°C so that heating would be called for. The result was that the solenoid valve, operated on the signal from the controller and the system switched into heating mode.

Table 6.10 Control tests carried out and results

Test	Confirmed yes/no
Heating initiated in response to fall in temperature below set point	Yes
Heating differential met	Yes
User able to alter the set point	Yes
Cooling initiated in response to increase in temperature above the set point	Yes
Differential met	Yes
User able to alter the set point	Yes

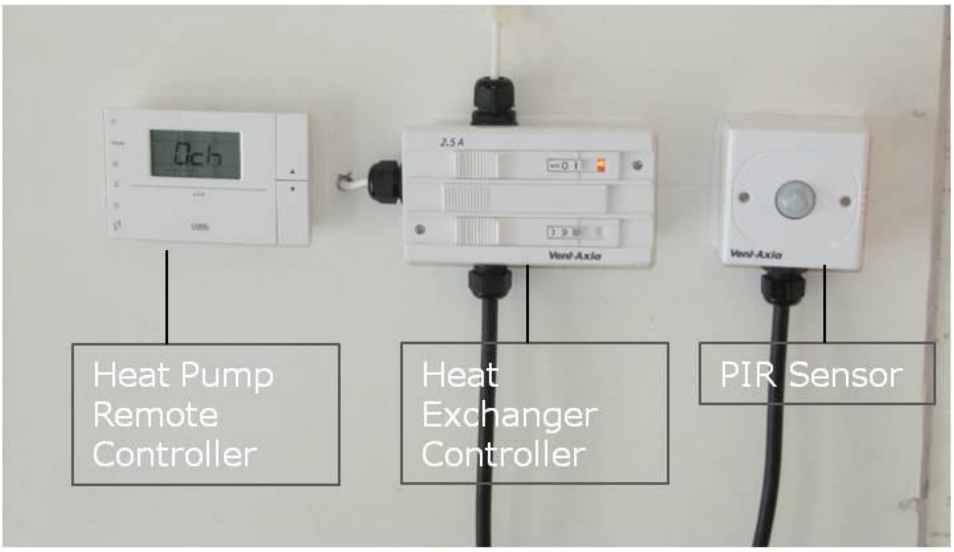


Figure 6.13 Wall mounted controllers

The Active Environmental System has been tested and has proven the concept of providing heating, cooling and fresh air from a fully decentralised system. A number of important design changes during the testing have surfaced. The major design changes considered essential are:

- Rotation of the condenser unit to improve performance;
- Addition of a drip tray below the condenser to prevent condensate entering the cavity;
- Amended pipe work to the Active Trench to increase refrigerant flow;
- Alternative Heat Exchanger controller;

There are also a number of changes which can improve the performance. These include pre-charging the RSHP and using hose-lock fittings to reduce the site based work by a refrigeration specialist. The TEVs also need to be modified to achieve performance closer to the intended design values. In terms of the controls, a single Controller for the whole system would provide both aesthetic and economic benefits.

Further testing is required in terms of the cross-contamination and overall performance. The cross-contamination test was carried out using smoke flow using visual observation. No recirculation of the smoke was visible, but a more sensitive detection device and the correct flow rate would be beneficial, to clarify the exact level of recirculation and conclusively establish whether any design changes are necessary to the mechanical ventilation system. In the next design development stage, the system should also be tested to replicate the winter and summer design conditions and provide the respective heating and cooling coefficient of performance (COP) and seasonal energy performance figures (SEER).

6.2. DOUBLE SKIN FACADE TESTING, RESULTS, AND EVALUATION

The importance of achieving the key performance criteria of air tightness, water penetration resistance and wind resistance, for any curtain wall facade, is reflected by the many tests that take place both off-site and on-site, and the quantity and rigour of industry standard performance requirements and test regimes. They can be found in *BS EN 13830* (BSI 2003) and *Standard test methods for building envelopes* (CWCT 2005b). The *Centre for Window and Cladding Technology* (CWCT) includes for instance, fifteen different tests. Standard components and systems such as Schueco's unitised range as with most, 'off-the shelf' systems have usually been extensively tested in credited facilities (Richardson 2007) and on project sites. Project based testing is only essential for bespoke systems or where new components have been used, or system components have been used in an unconventional way. Examining the design, there are two areas specifically, which meet these criteria. They are the use of GRP support brackets for the external skin, and the aluminium panels and louvers in the spandrel zone of the outer skin.

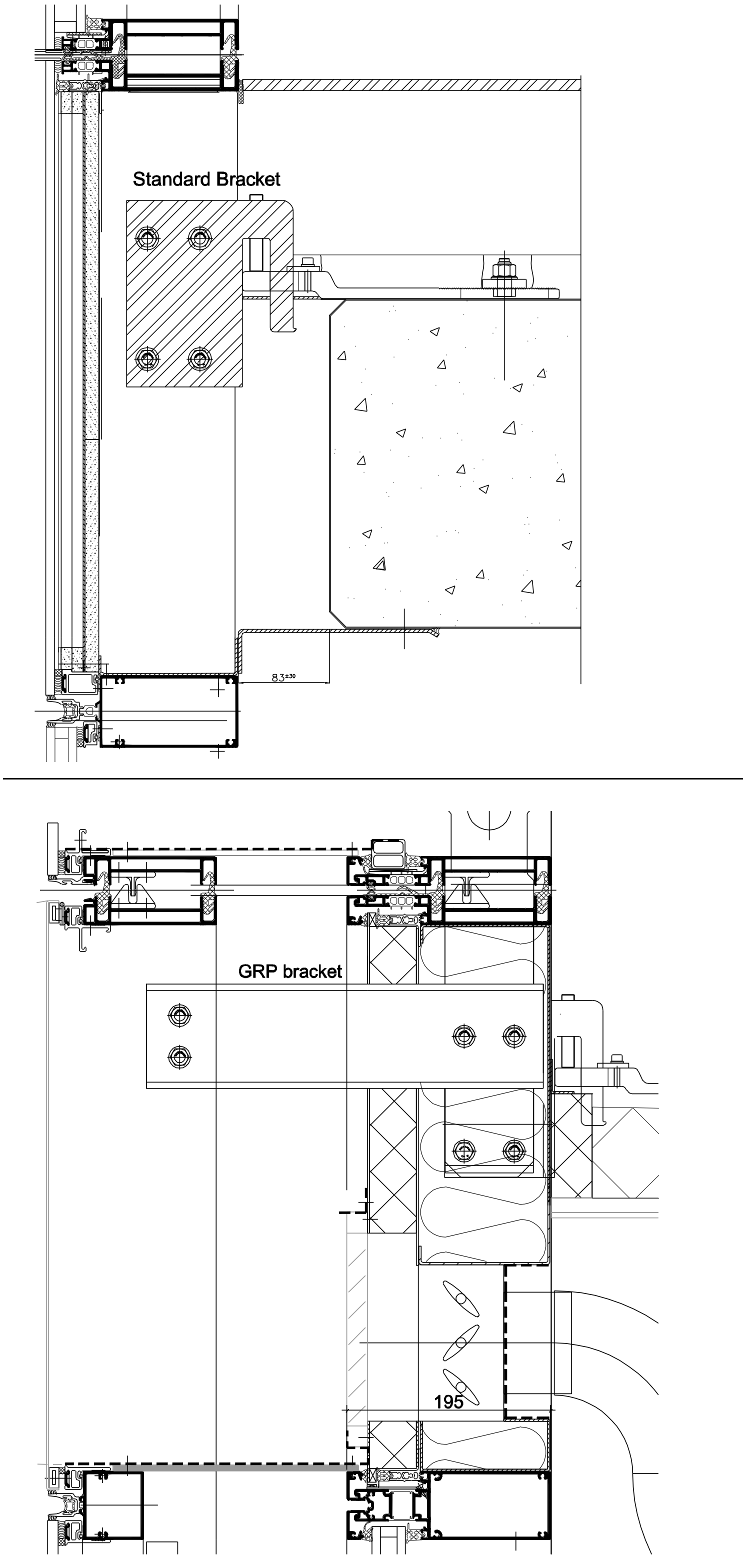


Figure 6.14 Standard fixing detail and GRP bracket

The external skin, the UCC 65 SG range from Schueco, is normally supported by a hanging bracket similar to that used by the inner skin, but instead a custom fabricated GRP bracket was used as shown in Figure 6.14. The tests that should be carried out relate to the wind resistance and fixing. These are in terms of the CWCT (2005) standard:

- Wind Resistance for Serviceability;
- Wind Resistance for Safety;
- Test for fixings (BS 5080 Parts 1 and 2).

The experimental set up for these tests are outside the capability of the department and need to be carried out at an independent testing company. In addition in order to comply with the CWCT standard the specimen size required is either:

- Full storey height plus a half-storey height above and below or
- Two full storey heights

The size required was considered initially at the design stage, but not possible within the constraints of budget and space. These weather and load tests should therefore be considered for future work in developing the proposal as a specifiable product. If the tests were to fail, a possible solution would be to increase the rigidity of the bracket, by either increasing its size or changing the profile from a channel to a box section or both. The consequences of a failure therefore are not catastrophic to the viability of the product as design alternatives are readily available.

The second design uncertainty is the performance of the spandrel zone since it incorporates louvres and panels outside the Schueco range. This is important to test and develop, since Schueco UK were not satisfied that the rain penetration barrier line would adequately be performed in the spandrel zone. Both the external skin and internal skin were therefore designed and assembled as external skins, which have led to a low material efficiency (see Chapter 5). Tests for water penetration are therefore required in this area to enable a reduction in material usage and simplification. The types of test required by the British Standard and CWCT for water penetration on specimens include:

- Water penetration – static method BS EN 13051

- Water penetration – dynamic aero engine test

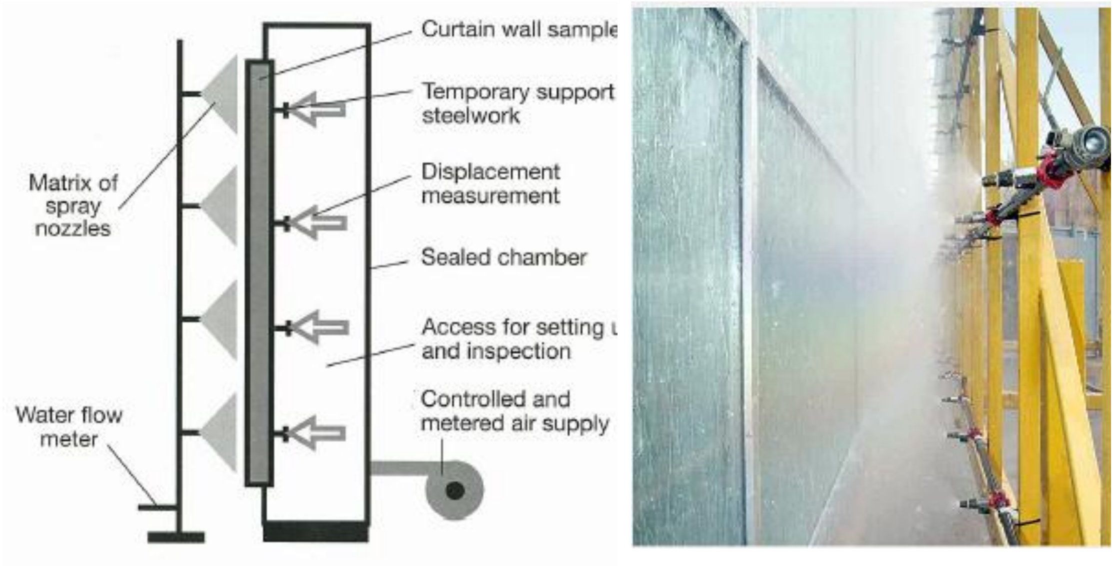


Figure 6.15 Experimental set up for water penetration static method test (CWCT 2005b, p.13) and actual rig (WINTECH 2011)

Similarly BS EN 13030, which covers the performance of louvres also requires simulation of wind driven rain by the use of spray bars and aero engines. Again the equipment needed for these types of tests is not available within the department and is usually carried out at a specialist organisation (e.g. Wintech). However an additional type of water penetration test included in the CWCT standard is the hose test, which is usually performed on site to test the workmanship of the installation. This can be used here as a simplified form of water penetration test, to gather information on the joints around the louvres; the specific area in which the spandrel zone is untested.

The hose test was performed based on the method described in the CWCT (Richardson 2007, p.9.5). This involves directing water with a flow rate of 22 (+/- 2) litres per minute at the joint and moving at approximately 1.5 m per 30 seconds at a distance of 0.3 m away, while an observer checks for any water penetration. However a water flow rate of only 15 litres per minute was the maximum that could be obtained using the department facilities. A second hose test was carried out to test how much protection the aluminium perforated panel provided to the louvre by increasing the water pressure.

The results of the initial test showed some water penetration between the louvres and the blocking panels joints. This was remedied straight away by the application of more butyl tape between the joints. After spraying water on these joints again, no signs of water penetration were visible. The results of the second test where the pressure was increased showed signs of water penetration. On closer inspection this was not through the joints, but through the louvre blades themselves. The stream of water passed through the slots of the aluminium panels unabated and had enough energy to pass over the louvre blades. Water penetration therefore occurred through faulty joints and when at a high water pressure, through the louvre itself.

The results of the initial test reveal that close attention has to be paid to the joints between the louvre, panels and frame, which is not ideal as access to this area is difficult and using the butyl tape is fiddly and messy. Improvements should focus on firstly, reducing the number of difficult joints and secondly, an improved joint itself. To remove the need for a joint between the blocking panel and louvre, the alternatives are to insert a transom to improve the joint or to completely louvre the area and remove the need for this difficult joint. Fully louvering the area is the best option as this will keep the frame design identical for each of the bays. Improving the joint design would ideally use the Schueco standard detail for weather proofing the external skin. This location is however already occupied by the perforated panel. Placing the panel directly onto the louvre however would restrict the available free area. A design which is based upon a Schueco detail has been developed and is shown in Figure 6.16. This will require a bespoke plastic extrusion similar to an existing extrusion and make use a Schueco gasket performing a similar role in its standard application. This will make it possible to fix both the aluminium perforated panel and the louvre without the use of butyl tape and improve the water tightness.

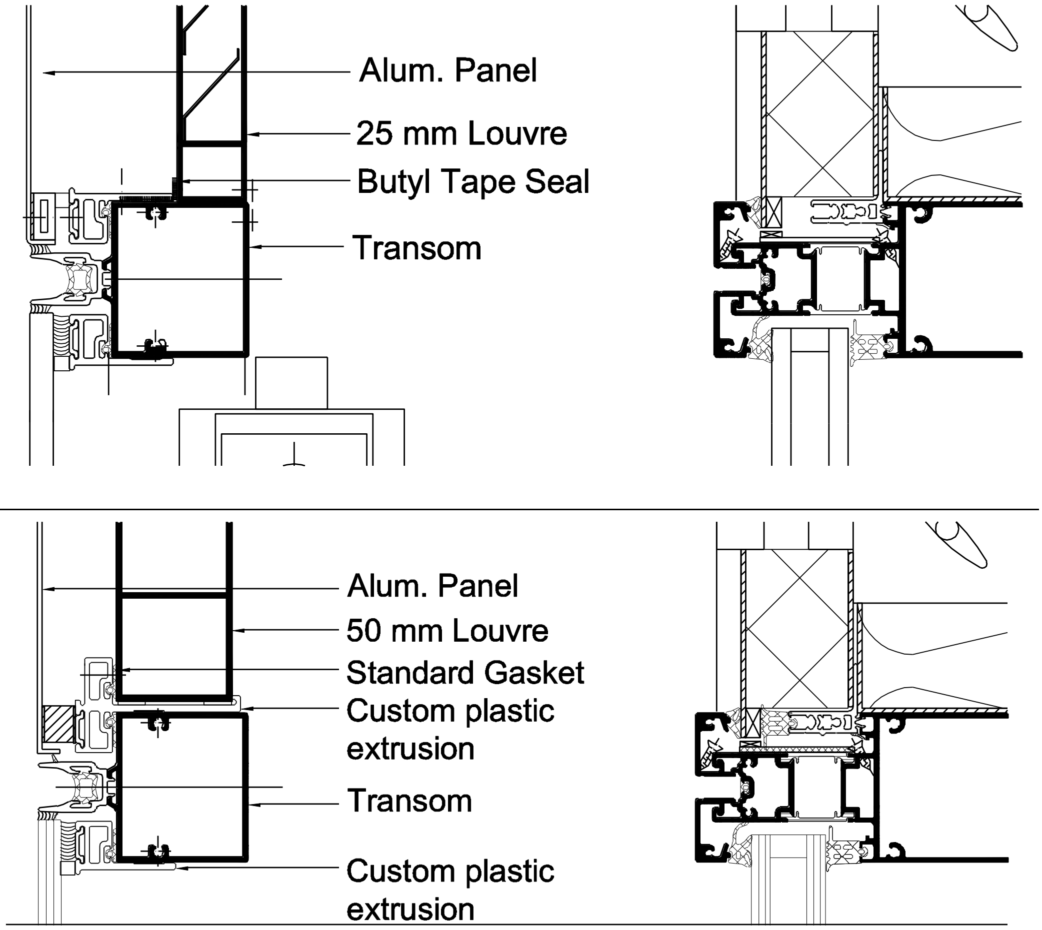


Figure 6.16 Prototype detail and alternative for louvre integration into outer skin

The results of the second test reveal that even without a more sophisticated dynamic aero engine test, the spandrel zone does not provide a robust a weather line. This is because the aluminium panels do not provide protection to the louvre as made visible by the water stream passing directly through. The louvers were however specified based on a sheltered location since the perforated aluminium panels were in front and assumed to provide some protection. If we are to allow design flexibility on the aluminium panels the louvre specification should be upgraded based on an exposed condition. On contacting the manufacturer, their advice was to simply use a deeper 50mm suited to an exposed location, rather than a 25mm deep louvre suited to a sheltered position. This can be integrated into the design without problem as shown in Figure 6.16. This should maintain the wet line at the outer skin which will need to be verified through further testing at the next development stage.

The alternative if this remains a problem is to treat the louvre as a rainscreen and provide internal drainage.

The double skin facade has been reviewed for the areas where testing is required; those without an applicable precedent, which have not already been independently tested. They are the support of the external skin in terms of wind resistance and the water penetration in the spandrel zone. For industry standard tests, a much larger sample and specialised equipment are necessary which is outside the ESPRC Case Study project constraints. A design alternative has been provided for the GRP bracket should future tests reveal an issue. The spandrel zone has been water penetration tested in a simplified manner by conducting a hose test. Although being relatively simple it has revealed some useful design changes to improve the reliability of the joints and a design change in the louvre specification from sheltered to exposed condition. With these changes greater confidence can be placed upon the external skin acting as the weather barrier and reducing the weather protection and material requirements for the inner skin. Further testing with the amended detail is necessary to conclusively prove the external skin and the spandrel zone specifically passes the water penetration test. At the next product development stage, it would be highly beneficial to conduct a full CWCT test as this is one of the key advantages for customers of an 'off-the shelf' system; the reduction of time and cost through the avoidance of testing and design development within the confines of demanding time scales and tight budgets of a project. The essential areas for the next product development stage are the GRP support bracket load test and water penetration tests (both static and dynamic) in the spandrel zone.

Before continuing to develop the Environmental System and Facade based on the results obtained so far, it is important to stop and check with stakeholders not yet involved whether the proposed product meets their requirements and possible changes needed to satisfy their demands.

6.3. ASSESSMENT OF KEY STAKEHOLDER VIEWS

Figure 6.17 Stakeholders in the design process for an Integrated Facade (based on a conventional mode of procurement)

In product design it is common practice to seek out and evaluate customer responses to a particular product. This confirms and verifies customer interest for future work to continue and prevent products being designed with no real demand. In this case the consumer decides whether to purchase the product or not and most market research focuses on this single consumer. In construction, the decision on whether to purchase a product is dependent on a number of stakeholders all with their own vested interests.

The main influence on the type curtain walling specified is with the Principal Architect together with influence from the client's quantity surveyor. The Architect will be interested in the space, environment, aesthetics and overall value where as the client's quantity surveyor will be much more focussed upon cost. The main contractor will then have an input on the decision based on the risks and constructability. The product's life however does not end at construction, in fact the major portion is spent is use by office occupants and being serviced by maintenance personnel.

In Chapter 5, the construction industry was strongly involved in the development process and prototype realisation. The constructability aspect of the prototype can therefore be considered to be satisfied for proof of concept stage. The requirements of architects, quantity surveyors, occupants and maintenance personnel have been built into the brief, based on an interpretation of their requirements drawn from literature and experience of the author and the sponsoring company. With a full scale functional and visual prototype, there is an opportunity to verify and confirm that their requirements have been met and changes that may be required before the product enters the market. Two different methods were used depending on the target group; either a questionnaire or a discussion related to a specific interest.

Table 6.11 Results of the questionnaire

	NEGATIVE	NEUTRAL	POSITIVE	COMMENTS
AESTHETICS	-	=	+	
External Facade Appearance	0	0	7	None
Internal Facade Appearance	0	1	6	None
Active Beam	1		6	Design change suggested
Heat Exchanger	4	1	2	Design change suggested
Ductwork	4	1	2	Design change suggested
Active Trench	1	1	5	
ENVIRONMENTAL SYSTEM	NEGATIVE	NEUTRAL	POSITIVE	Comments
Ease of Use of Controls	0	3	4	
Thermal Environment	0	0	5	
Noise	1	1	3	Heat exchanger identified as being noisy
View to Outside	0	0	5	

A questionnaire was used for the group of Architects and Engineering PhD students acting as end-users. This is divided into two sections, one on aesthetic performance and the other on the internal environment, and includes open-ended and closed-response questions. Before being given the questionnaire, both groups were shown around the prototype and given information on the concept, functionality and potential. A total of seven questionnaires were returned filled in. Of the seven, four were Architects and the remaining three Engineers. More visits would have been organised, but due to time constraints on the laboratory space only a limited number could be completed.

The results of the questionnaires are shown in Table 6.11. The feedback on the aesthetics of the facade both internal and external was almost completely positive. The main area which was viewed negatively was the Heat Exchanger and ductwork. The suggestions for improvement included hiding the Heat Exchanger, the ductwork and levelling the perforated panel with the Active Beam. One of the respondents thought that the Active Beam itself does not match the high-tech look of the facade and is need of an upgrade. In terms of the Active Environmental System there was a mixed response. The thermal environment results are positive; no draughts could be felt and a comfortable temperature achieved. The perception of the controls is inconclusive as a number of respondents had not had a chance to use and understand the controls. The noise of the Active Environmental System was mixed-some viewed it as slightly noisy others as acceptable in an office environment and the air turbulence noise perceived as useful masking noise. The perception of the adequacy of view to the outside is 100% positive, which was slightly surprising given the extra framing required for the openings and the prototype being a room within a room.

Figure 6.18 View of Heat Exchanger and Active Beam

The main area for further development resulting from this evaluation is the integration of the Heat Exchanger unit into the Active Beam. This was to be addressed as part of the prefabrication strategy as well and so it should be straightforward. The single respondent who had an issue with the appearance of the Active Beam could also be provided with a custom-made unit as this is one of the services that Frenger Systems, the manufacturer offer of the Active Beam offer. Further research regarding the occupant and controls is necessary. As mentioned in Section 6.1, the noise emanating from the environmental control system is due to the higher flow rate than designed and would be reduced once an alternative controller is used. The overall aesthetic of the facade, potential for an improved aesthetic of the Active Environmental system and the comfort provided, indicates market potential for the product, although this is based on a rather limited focus group of architects and users. In the next development stage a larger focus group is to be invited to include architectural practices involved in the typology of office developments being addressed in this thesis.

The other stakeholders whose opinions were sought included a commercial property consultant/ quantity surveyor, a refrigeration engineer for a maintenance perspective and a volunteer who had cleaned the facade. Discussions relating to their area of interest or experience were then conducted.

The commercial property consultant from Innes England was very interested in the project and the potential benefits it could bring to space restricted sites particularly in London, where footprint and height are restricted. The main issue from his point of view was the depth of the facade in comparison with a well-insulated wall and its effect on the net rentable area. At 300 mm the double skin facade is similar in depth to a well insulated wall and therefore comparable on a net usable floor area basis. With the reduction in riser and plant room space and the reduction in facade area per storey [1] the comparison becomes more favourable to the IPADFS (see Chapter 7 for more details on cost performance). If the facade is made any wider, the benefit is lost since the cavity is not considered to be usable space. The accompanying architect however debated the rationale behind this since a wider cavity would allow the space to become an amenity for occupants. They would be able to enjoy the view, the sounds and an alternative thermal environment, which could have a very refreshing impact and improve many aspects of an occupant's sense of well being and therefore productivity. As with many concepts in architecture however, if this does not easily translate into a tangible benefit and benefit the *bottom line* (for either the owner or the developer), it is likely to fall under the axe of the value engineering process. In the cost consultants view, a 300 mm deep cavity is not to the detriment of the net to gross ratio and together with the benefits in terms of the omission of suspended ceiling, riser space and plant room space, the product has potential application.

A refrigeration engineer was asked questions regarding the ease of maintenance and any concerns he would have. The maintenance requirements of the system are:

- Charging with further refrigerant;
- Replacement of filters;
- Replacement of compressor.

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[1] Typical floor space requirement for HVAC services is between 3.6% to 7.8% (Pennycook 2003) and the omission of a suspended ceiling and reduced floor to floor heights will result in a facade area reduction of 13%.

Charging with refrigerant requires the connection to a gas bottle from the compressor and the receiver. With the present design this would need to occur from the outside or the insulation in the spandrel zone removed for access. If internal access is required, to avoid the potential for damage to the insulation a design development in the next stage is to extend the charge point inside the room into the integrated Active Beam/Heat Exchanger. The replacement of a strainer would be straightforward from either the inside or outside as it can be via flare nut fittings. The indicative life of the compressor is 15 years (CIBSE 2008, pp.13-16) and so can be expected to need replacement before the facade.[2] In regards to any change of components, the replacement of the compressor is the more difficult because of firstly the weight of the component and secondly the solder connections. This is difficult to carry out from the inside due to the awkward location of the compressor either working at height or if from above bending down. From the outside improved access can be provided, but is dependent on the weather conditions and the refrigeration engineer confident enough to work from a gantry/cradle at height. To eliminate any soldering work the connections to the compressor could be changed to flare/hose lock fittings. Overall a couple of minor modifications to the pipe work and fittings would simplify the maintenance and replacement strategy and should be implemented into the next design development stage.

[2] Aluminium facade finishes are guaranteed for at least 25 years (CWCT 2005a, p.21)

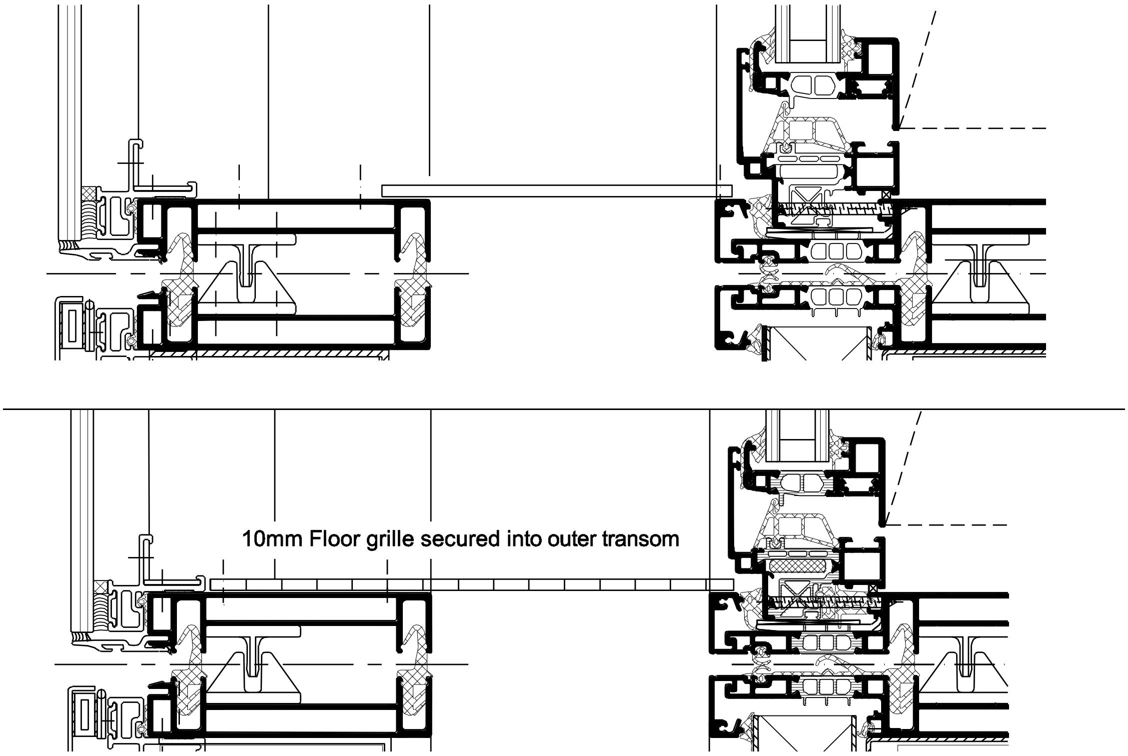

Figure 6.19 Cavity detail showing previous and new floor grille for improved access

Cleaning of the inner and outer glass facades was conducted by a volunteer and then questions were asked on how easy the facade was to clean and any suggestions to change the design. The responses indicated that it was difficult to clean the high points without being able to put a support in the cavity floor space. (During the cleaning one of the cavity floor panels was actually damaged by being stepped upon even though it was indicated that they were delicate and should not be stepped upon.) The suggestion to improve the design was to allow the cavity floor to be stepped on which in hindsight is rather obvious. Therefore the cavity separation panels at floor level need to be made more robust and suitable for improved access. An amended design is shown in Figure 6.19 to provide a floor grille supported by the outer skin.

Overall the reaction from stakeholders has been very positive. The main changes required to make the product more aesthetically pleasing is to amend the Heat Exchanger section. In terms of internal environment, occupants enjoyed the look and transparency of the facade, but further work is required to confirm the controls strategy is easily understood and beneficial to occupants. Feedback from a commercial property consultant has been positive, due to the improved space ratios possible and the equivalence in external thickness between the IPADFS and a well insulated wall. In terms of maintenance, a couple of changes are needed to the refrigeration circuit and floor of the cavity which will be implemented in the next design development stage.

CONCLUSIONS

The full scale prototype has been tested, evaluated and has proven that the product can provide heating, cooling and fresh air for occupant comfort, and with a number of design changes the potential to lower carbon emissions and provide a desirable aesthetic.

The different components of the active environmental system that have been tested depended upon the availability and applicability of precedent data. The RSHP being fabricated from individual components was extensively tested and shown to successfully provide both heating and cooling. The fresh air supply via the Heat Exchanger and heating and cooling through the Active Beam was also successful. In both the fresh air and RSHP system, important design changes are needed to improve the efficiency and performance. The control of the Active Environmental System was made available for the occupants successfully, fulfilling the criteria for greater occupant control. Overall the testing process has revealed that the IPADFS can provide heating, cooling and fresh air, to satisfy comfort requirements, and with some design changes the potential for low carbon emissions and high energy efficiency as predicted in Chapter 4.

The Double Facade was fabricated and assembled from an 'off the shelf' system which had already been independently tested. However, a number of new components had been added to the system and it was being used as a double rather than single facade. The spandrel zone and outer skin support specifically needed to be tested. Independent testing to British Standards was beyond the constraints of this design stage. However, simplified water penetration tests were performed and revealed a problem with water penetration in the spandrel zone, which has prompted a design change to be included in the next stage. Further tests are needed to satisfy that the product meets weather protection criteria and the outer skin bracket is adequate for the load.

The questionnaires and discussions that have taken place with stakeholders in the design process has also been very insightful and prompted some design changes. Stakeholders liked the overall aesthetic with the exception of the Heat Exchanger and visible duct work and pipe work around that area. The controls strategy for the Active Environmental System needs to also be more easily understood. There are also a couple of changes needed regarding ease of maintenance of both the Double Facade and the RSHP unit.

In each part of the testing and evaluation a number of design changes have been necessary or beneficial and they will be incorporated in the next design development stage. At this point, with the prototype realised, tested and the results evaluated, the product can now be critically appraised as to how well it has successfully met the initial aims and objectives of this thesis.

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CHAPTER 7

PRODUCT APPRAISAL AND FUTURE WORK

The design and construction of offices at the beginning of the twenty-first century (1998-2011) has become increasingly challenging. The construction industry has been challenged to improve build quality, timeliness, health and safety and cost efficiency, in line with the performance of other industries. It has also progressively tightened legislation in regards to carbon emissions. Clients are also demanding improved quality of space for occupants to improve their productivity and well-being. The design of the Building Envelope and the Environmental System are instrumental in addressing these challenges.

The building facade has undergone a technological transformation in response to these demands. Initially the building facade was limited by the need to provide structural support to the building. Visionary architects such as Mies van der Rohe in 1919 saw the potential of glass and curtain walling technology to dissolve the outer skin and create new spatial dynamics through highly glazed facades, offering greater views and daylight for occupants. Highly glazed facades then steadily increased in popularity, particularly in the second half of the twentieth century. The environmental consequences however, meant building services were relied upon to create a comfortable internal environment. This had a high energy penalty as the highly glazed curtain walls, which were singly glazed with no coatings, meant high heat loss in winter and high heat gain in summer - in opposition to the thermal requirements of the particular season. Occupant comfort was also affected as a result of the poor U-value, and losing their ability to control and regulate thermal conditions inside as artificial systems took over.

Progress has been made to improve the energy balance through improved U-values, and solar and light transmission factors. Further improvements are needed however for occupant comfort and energy performance. Double skin facades are a promising option as they can respond to changing seasonal requirements and rebalance the energy equation without relinquishing the transparency, views and daylight provided by highly glazed facades. For difficult microclimates, such as noisy urban areas, they provide acoustic isolation and allow natural ventilation, which brings comfort benefits and reduced energy usage.

Active Environmental Systems have also undergone technological changes, but an area where development has been lacking is prefabrication, even though it occupies a large proportion of the budget and construction timeline. Prefabrication levels are low because of the complexity of installation from a centralised location to distributed locations and the fragmented nature of the trades involved. The environmental system is also under pressure to reduce energy usage and improve occupant comfort. A decentralised system that can be prefabricated, reduces energy usage, improves occupant comfort and provides greater spatial efficiencies by deleting the central HVAC system and distribution is a potential solution and the aim of this thesis is to design such a component.

7.1 PRODUCT APPRAISAL

This thesis has presented the initial stages of the design and development process for an Integrated Passive Active Double Facade System (IPADFS), which can be specified for new office developments in the UK. Its aim has been to combine the Building Facade with the Active Environmental System and provide:

- Increased overall space efficiencies;
- Enhanced comfort and working environment;
- Reduced overall energy usage/carbon emissions and environmental impact;
- Improved construction performance through prefabrication;
- A desirable aesthetic.

This thesis has focussed upon the inner city, medium to high-rise office typology, even though it poses a challenge for occupant comfort and energy sustainability, due to the wider environmental and socio-economic benefits that such a location provides. The stages that have been included in the thesis so far include:

- Conceptual design looking at suitable facade and environmental options;
- Detailed design developing the chosen concepts;

- Design development with industry;
- Fabrication and assembly of a 'proof of concept' prototype;
- Testing and evaluation.

With these stages completed the prototype can be appraised firstly, in regards to whether 'proof of concept' has been reached i.e. the key aims have been proven, and secondly, the changes and future work necessary in order to offer a specifiable product to the built environment.

7.1.1. Spatial Efficiency

One of the initial motivations for the sponsor conceiving the project was the commercial appeal of greater spatial efficiencies by integrating the HVAC into the facade and deleting the central HVAC system. This would reclaim riser area and distribution space as well as the central plant area. The new facade system would need to provide heating, cooling and fresh air on a fully decentralised basis.

Before designing the active part of the Environmental System, the Facade was designed to minimise the heating and cooling loads within certain constraints. A Double Skin Facade concept was found to meet a number of comfort and energy requirements. The cavity depth was minimised to 300 mm to maximise usable office area whilst preventing overheating in the cavity. This is similar in depth to a well-insulated wall.

A number of different options were then reviewed for the heating and cooling system. The use of a Reversible Air Source Heat Pump (RSHP) system was selected in part, as it would be small and flexible enough, to fit within the double skin spandrel zone. The fresh air and extract is provided by a heat exchanger located at high level and draws air in and rejects air through the facade. The supply side therefore requires no distribution or central plant achieving the primary objective. The delivery of the heating, cooling and fresh air is achieved by an Active Beam and Active Trench. The Active Beam is surface mounted on the soffit and the Active Trench within a 200mm floor void, which is needed for small power distribution. The realised design can therefore allow for firstly the deletion of the centralised HVAC systems and risers (related to the office space) for higher floor area ratios. Secondly, the omission of ceiling voids will provide reduced floor-to-floor heights and external wall areas, without degrading spatial efficiencies elsewhere. This strategy works well with Fabric Energy Storage if a concrete structure is also specified by the project design team.

Based on rule of thumb data for space allowances an estimation of the increased space efficiency can be made. The space for the cooling plant, air handling units, boilers and risers comes to a total of between 2.8% - 6% of gross floor area[1] (Pennycook 2003, pp.2–3). This is out of a total of 6% - 10% of all services for offices (ibid) and the use of the IPADFS will therefore represent a saving of around 50% of the area used for mechanical and electrical services. The floor-to-floor height saving described in Chapter 2, by the deletion of the ceiling void[2] will provide a saving in the total facade area of 13% per floor and if the same building height is used an increase in floor area of 15% as shown in Figure 7.1. Some developers may however see the reduction of floor to floor height as a risk for future flexibility and retain the same floor to floor height to allow for a ceiling void in future whilst providing the minimum recommended floor to ceiling height.

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[1] There will still be some central HVAC or dedicated HVAC, with space requirements for servicing other uses such as toilets, kitchens and server rooms and so the higher limit will reduce slightly as the dominant space allocation is for offices.

[2] New floor to floor height 3.1 m, ceiling void omitted 0.45 m, floor dimensions 37 m x 15 m.

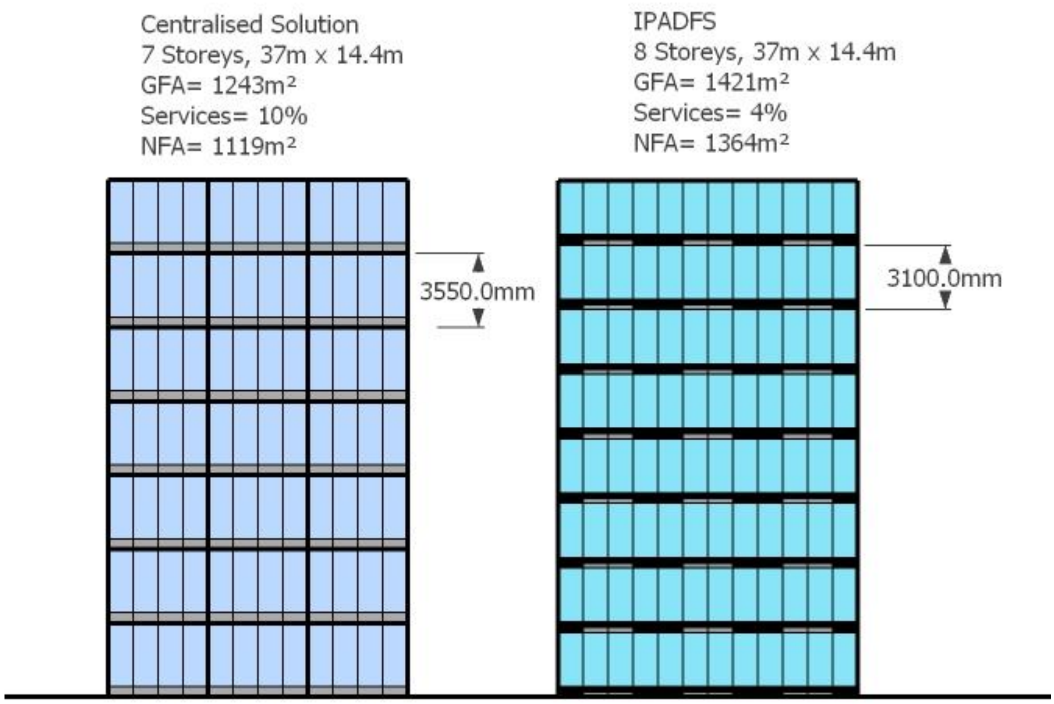

Figure 7.1 Facade and floor area differences between a standard solution and the IPADFS

7.1.2. Occupant Comfort and Enhanced Working Environment

One of the main aims of the product is to provide a system of components that improve the comfort level of occupants in offices. A review of literature in Chapter 2 revealed the key factors relating to the facade and environmental system for improved occupant comfort.

The facade was designed to implement the key requirements in realising enhanced comfort which included:

- Occupant controlled natural ventilation for air hygiene and free cooling;
- Predominantly day lit environment;
- Good views to the outside.

A Double Skin Facade was designed, and realised these comfort requirements whilst satisfying other project requirements. For the office typology considered an aspect that needs to be clarified is the acoustic performance. On the basis of previous tests (see Figure 1.11) the Double Skin Facade should provide sufficient attenuation to provide natural ventilation in the typology considered. Future testing needs to be carried out to verify the level of acoustic attenuation achieved.

The design of the Active Environmental System considered the thermal and air quality requirements in offices. To enhance comfort, personal control over the temperature and an air supply rate of at least 10 l/s/p was required. This was successfully implemented in to the design and tested to prove that sufficient fresh air, heating and cooling was being provided and local controls provided for occupants to vary the temperature. Due to market availability the Heat Exchanger used for the prototype was sensible only and instead of a latent and sensible heat exchanger to provide moisture carry-over and thereby ensure that humidity levels in winter do not fall below comfort limits. In the next prototype this will be resolved, together with extended testing to ensure that the controls are comprehensible, and provide the improvements in personal control anticipated. Further tests are also required to provide greater confidence that there is little recirculation of supply and exhaust air streams.

7.1.3. Energy Sustainability and BREEAM Assessment

Energy usage and carbon emissions in offices are regulated and are becoming increasingly stringent through building Regulations Part L2A. Organisations are also increasingly using BREEAM assessment methods as part of their own corporate social responsibility agenda. The aims for the prototype were therefore to lower operational energy use and ensure it scores highly in the BREEAM categories relating to the facade and environmental system.

The different energy demands within the influence of the facade and environmental were identified in Chapter 1 as: heating; cooling; artificial lighting; fans and pumps. The strategy followed was first to maximise the potential of the facade to provide suitable environmental conditions within certain comfort performance constraints and then to design the environmental systems efficiently, a passive first strategy and active second.

Suitable environmental conditions go beyond simply providing the correct comfort criteria and extend into providing a space that enlivens the senses. The facade is crucial in this respect as it allows contact with the external world through view, light and access to natural ventilation. A dichotomy was therefore presented for the facade design where on one hand transparency and openness was required and on the other, minimisation of energy use through protection from solar gains. This called for some form of dynamic intelligent skin. To address these requirements in a medium or high-rise office a cascade type double skin facade was found to be suitable, see Chapter 3. This type of facade allows the day lighting performance and solar gain to be optimised depending on the season. Importantly the double skin also provided the potential for natural ventilation.

In the office typology chosen, natural ventilation is difficult because of noise and air speed issues. The Double Facade is able to buffer these factors and through detailed calculations and modelling, a solution where natural ventilation for free cooling is provided during major parts of the year instead of using active systems. This was coordinated with spatial requirements for the Active Environmental System and the opening strategy for natural ventilation and maintenance.

During the industrial or prototype development process some changes to the natural ventilation strategy had to be made as a result of using a systemised 'off the shelf' solution. Working with the system supplier, the profiles necessary for the preferred original strategy of an externally accessible cavity should be developed in the next stage. Further work should also concentrate on an improved U-value for the inner skin frame as the high number of openings creates a large frame area and makes a sizable contribution to the overall heat loss, Schueco for example are developing FRP based framing systems.

Examining the energy used by environmental systems in offices, potential for reduced carbon emissions through the fans and pumps was noted along with the high heating, cooling, lighting and humidification loads. Fan and pump energy is high because of the distance and complexity involved in servicing office spaces from a central location. The fan and pump energy associated with IPADFS is estimated at 2.25kWh/m².a this compares well with 30kWh/m² figure from good practice offices although it does ignore other energy associated with other areas of the offices such as kitchens and bathrooms. Chapter 2 identified alternative options to the centralised solution and concluded with a fully decentralised zone by zone approach as it minimised the distribution and had potential for being fully prefabricated into the facade. This was designed and realised with only a small amount of energy used by Heat Exchanger fans which is used to full effect by providing heat exchange between intake and extract air streams and driving the induction effect in the Active Beam. No pumps are required in the system since the compressor also pumps the refrigerant through the circuit. A decentralised strategy will also reduced by energy usage by virtue of the increased zoning. Each Active Beam unit is supplied and controlled locally and therefore unoccupied zones will not be serviced. Actual figures on the reduction through zonal operation will be dependent on the office occupancy patterns.

The carbon emissions associated with the heating and cooling source were examined in Chapter 4. An analysis of the different options for a decentralised system included factors such as spatial needs, carbon emissions and integration potential. This concluded with an air-source reversible heat pump system (RSHP) based on Propane refrigerant. The lower carbon emission solutions such as biomass boilers and ground source heat pumps had to be discounted due to their scalability. Compared to a typical centralised solution however, the RSHP is an improvement over gas boilers and comparable to an air-cooled chiller in terms of carbon emissions per kWh of heating and cooling delivered (see Chapter 4). The drawback to the design is the additional maintenance requirement of multiple units and reduced lifetime. In future work efforts to reduce and clarify the maintenance requirement is needed together with testing to provide accurate COP figures, combined with the changes discussed in Chapter 6 to improve the performance. Further improvements can be made by examining a split unit on the south and north as suggested in Chapter 4 and further developing the use of phase change material as this was shown in Chapter 4 to be lower in carbon emissions than a vapour compression system although it cannot be the only cooling mechanism due to the issue of moisture control.

For the delivery of heating, cooling and fresh air, an Active Beam was designed to be used with refrigerant and a local ventilation unit instead of chilled water and a central air handling unit. The Active Beam was successfully adapted and tested to prove loads were met. Minor changes are needed to the design of the controller to lower the air flow rate to the design figures and the refrigerant pipe work.

To reduce the heating and cooling energy usage further through the design of the Double Facade and Active Environmental System, a number of strategies are possible. They include:

- Improving the U-value of the frame;
- Enthalpy type heat exchanger instead of sensible heat exchanger;
- Supplemented cooling with phase change materials.

Further reduction of overall carbon emissions can also be achieved by the integration of photovoltaics into the facade as discussed in Chapter 3.

As well as reduced carbon emissions a high score BREEAM was required. With a completed prototype, a partial BREEAM assessment has been undertaken by examining those areas related to the facade and environmental system. [3] Appendix S provides information on the scores in the different criteria. The prototype scores 48/67 and when the category weightings are applied achieves 76%. This corresponds to a BREEAM rating of Excellent. To achieve an overall score of 'Outstanding' a score of above 85%[4] is required and could be achieved by ensuring that the project scores highly in the other categories. To improve the score in the categories related to the facade and environmental system two changes could be proposed. Firstly, the integration of photovoltaics as discussed in Chapter 3 as it would increase the score in Energy Performance and pollution from NOx emissions for heating (Pol 4). The second change would be in the materials specification if possible (Mat 1).[5]

Out of the different building parts in an office building the Building Facade comprises a high proportion of the material used, especially with a shallow plan floor plate. For the building considered for example, the facade to floor area ratio is 0.6 and the impact of the ground floor and roof are minor. The material used for the facade therefore makes a big impact on the credits awarded for materials as it is weighted according to area. The credits are derived from the Green Guide to Specification (Anderson 2009, p.186) and calculating the aluminium material usage at 4.3 kg/m profile the lowest rating of E is achieved for an aluminium curtain wall. This is due to the high use of Aluminium in the unitised profiles and the poor rating of aluminium in the Green Guide. The Schueco single skin system UCC 65 SG on its own has 1.94 kg/m and would still be rated as E as it is above the 1.75kg/m threshold. The rating system however in the Green Guide is suspect. Apart from the use of a 1m² functional unit (very few curtain walls are framed in this way), the recycled content is taken as 17%

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[3] The facade and environmental system relates to 63 out of 112 of the total points available.

[4] Outstanding also requires minimum performance standards for certain categories (those pertaining to the facade have been met) and a post construction evaluation.

[5] Only an estimated score could not be completed as BRE do not provide the spreadsheet tool necessary to complete the scoring to non-BREEAM accredited assessors.

and end of life recyclability as 75%, whereas studies have shown the rates are much higher in the building sector.[6]

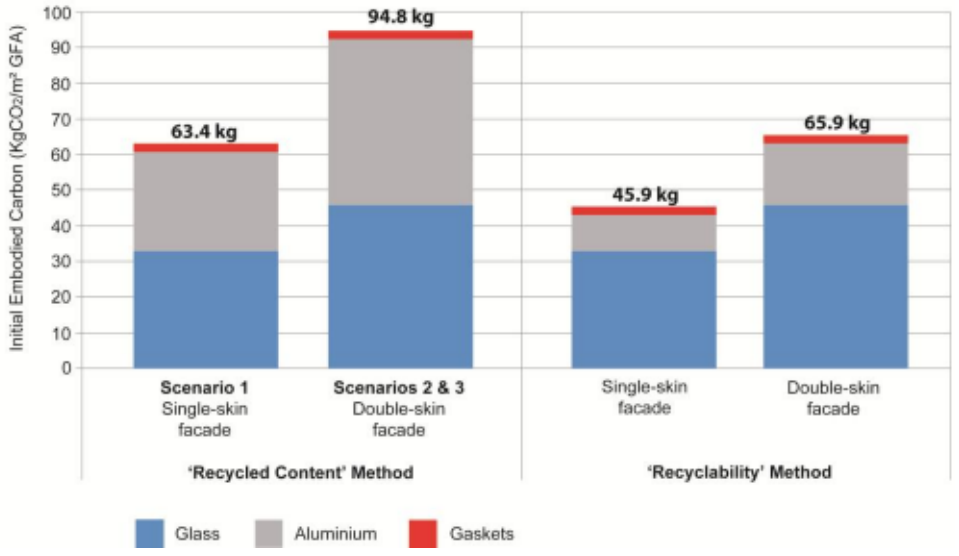

Figure 7.2 Contribution to embodied carbon of the major elements of an office building (Kilaire & Oldfield 2010)

A more thorough assessment of the impact of aluminium in terms of carbon emissions has been conducted by Kilaire and Oldfield (2010) where the double skin facade was estimated at only 11.7% of the total embodied energy (Kilaire & Oldfield 2010). The contribution of aluminium in terms of the facade is shown in Figure 7.2 and depends on the method used.[7] Using the recycled content method, it is approximately half the total embodied energy of the facade and therefore relates to only 6% of the total embodied energy of the building considered. Its impact could be considered to be too great although other aspects apart from embodied energy are considered in the rating. The substitution of aluminium for a lower embodied energy material such as timber is not straightforward since it creates issues with many other aspects of the building design concept. Aluminium facilitates a more sophisticated

[6] Recycled content of 31% found in the Future Generations programme and recyclability at end of life 92-98% were found in a University of Delft study (see CAB 2008, p.18)

[7] The recycled content method considers the industry average amount of recycled aluminium used for the incoming aluminium. The recyclability method considers the end of life amount of aluminium that will be recycled, which is much higher, and therefore has a much lower embodied energy. See http://wiki.bath.ac.uk/display/ICE/Recycling for more information.

environmental design concept particularly for double skin facades, good extrudability to allow complex profiles for the unitised system and off-site construction, excellent weather ability and a relatively high strength to weight ratio facilitating smaller width profiles. To improve its rating, it is suggested that further work be carried out with suppliers to guarantee recycled content, end of life recycling and a bespoke assessment for the Green Guide to Specification.

7.1.4. Increased Prefabrication

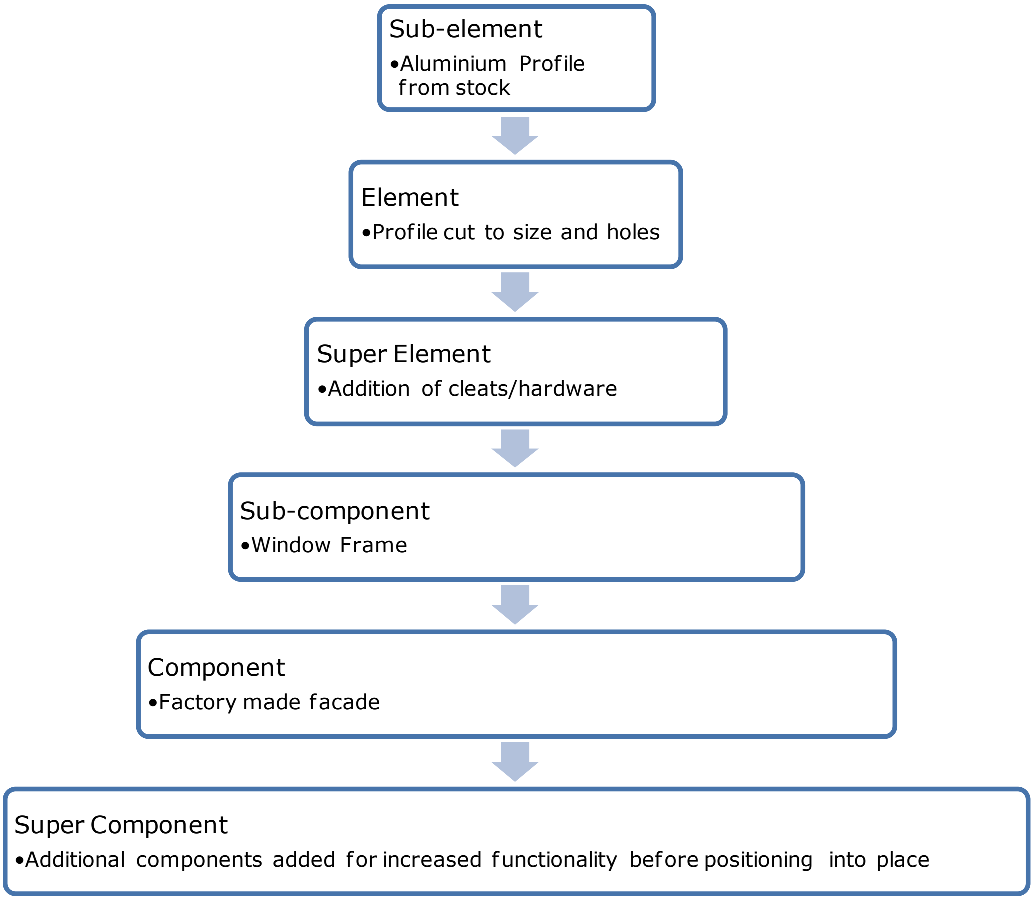

Figure 7.3 Prefabrication hierarchy and terminology with the example of the facade - adapted from Eekhout (2008, p.47)

The initial brief was to provide a fully prefabricated system including both the Building Facade and Environmental System. Under the terminology in Figure 7.3, this is a 'Super-Component'. During the design stages in Chapters 2 to 4 both the Facade and Environmental System were designed upon this basis. The Facade has existing technology to allow for prefabrication. It was based upon unitised profiles which split the frame into two sections. The size of the Facade units was set at 2.4m for dimensional coordination reasons, as well as providing a balance between allowable size and weight for transportation and installation reasons. The Active Environmental System was based upon a decentralised strategy, as this would provide a solution for different buildings regardless of internal layout and distribution patterns. The technology chosen for heating and cooling supply was a RSHP as it could be fabricated into two independent modules which would fit into the spandrel zone and there would be minimal on site work required. For fresh air, a Heat Exchanger was incorporated as this could provide heat reclaim and a local supply of fresh air. Changes to the design were required however during the industrial development stage.

The major change was the separation of the Double Facade and the Active Environmental System for two main reasons. Firstly, the Facade is a very critical time component; a simple supply chain with a minimum number of suppliers is preferable. Adding an Active Environmental System could increase the number of suppliers substantially. Secondly, the fabricators do not have the skills or confidence to install an Active Environmental System. Both could be overcome in the next version as the risk inherent in the supply chain for the HVAC could be simplified and the environmental system components made in advance of the facade. This will allow the manufacturer/fabricator to focus on the quality and timeliness of their individual component, but still results in a number of components being assembled on site instead of one 'super-component'.

Assembling a number of components in site need not be detrimental however if it is correctly managed. In car production it is overcome by focussing on the joint between the different components. The first type of joint is assembly joints which are designed to be quick to fix, such as an electrical plug rather than a junction box. This has already been addressed in the design and in Chapter 6 with the use of flare and hose-lock fittings. The second type of joint is the closure joint which provides the visual finish. This can be a reveal, controlled gap, or a lap joint and is designed to be impossible for misalignment to occur. This should be a focus of attention for the next development stage now that the components are known.

Another way of addressing the problem of joints on site is to reduce their number. The prototype at this stage consists of five independent components which are:

1. Double skin façade;

2. Heat Pump Modules;
3. Active Beam;
4. Heat Exchanger;
5. Active Trench.

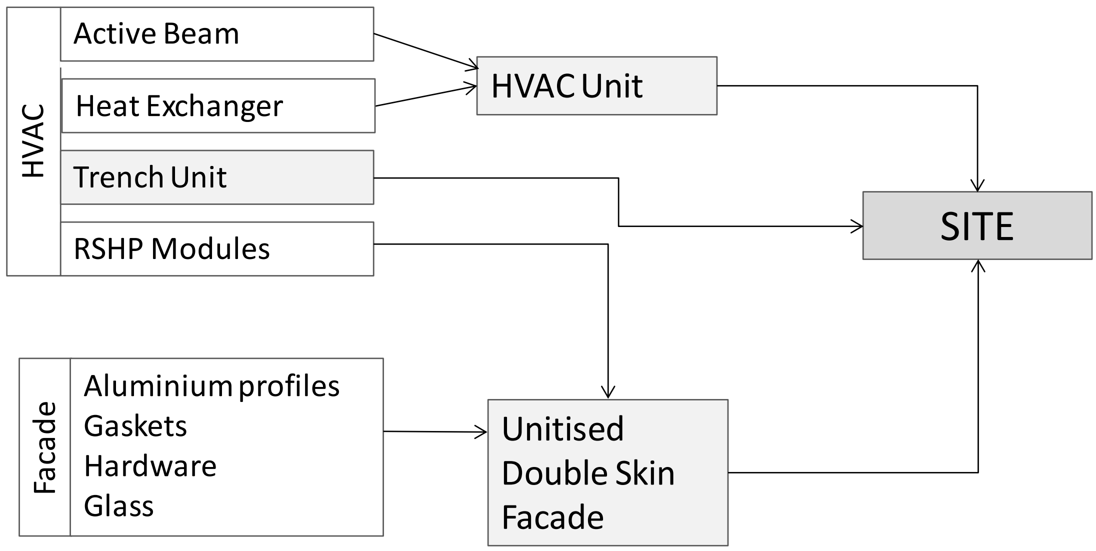

Figure 7.4 Prefabricated components of the Integrated Facade system

With the next prototype it would be feasible to reduce the number of components to three as shown in Figure 7.4, with the Active Beam and Heat Exchanger becoming a single unit and the RSHP modules fixed into the Double Facade prior to installation. The assembly process has illustrated that the Active Beam is a delicate piece of equipment and adding this onto the facade would create difficulties in handling, as well as reduced space efficiencies during transportation. The installation of separate artificial lighting is also necessary if the Active Beam is adjacent to the facade. It makes sense therefore to retain the configuration as perpendicular to the facade as the number of installation steps will be the same, artificial lighting can be integrated into the Active Beam, and this avoids creating additional facade transportation and handling difficulties.

The integration of the RSHP modules into the facade, the separate installation of the Active Trench and the combined Heat Exchanger-Active Beam is one which still, reduces site-work significantly with only three components being installed. The only site work necessary is the connection of pipe work, duct work and commissioning.

The process of producing the facade has revealed that there are considerable obstacles to the ideas of Kieran Timberlake (Section 1.4) into a much more integrated supply chain. As commented in Chapter 5, the curtain wall fabricator was not willing to take on the additional responsibility of the HVAC components because of the time and risk implications. It can also be foreseen that the main contractor would also have issues with a integration of the HVAC into the facade. It is quite common for main contractors to want to split the contract into a number of chunks and contracts in order to reduce the risk to the timeline and funding should any single contractor underperform or go into liquidation. It would also allow the contractor to tender to a number of different companies for price competitiveness. These barriers can be overcome in some part by having a client who is willing to accept the risk and instruct the contractor that a single source supplier is acceptable. The position of Buro Happold as consultants will help greatly as they will be able to influence the client and design at an early stage. The procurement route could also be modified.

The proof of concept prototype sought to have the facade fabricator produce the integrated product. However there is little net benefit in doing so and considerable risk. The main benefit of the system is actually for the M&E contractor and main contractor, not the Facade Contractor. In the next stage it may therefore be worth approaching a large M&E Contractor such as NG Bailey on developing the system as one of the barriers to M&E prefabrication is actually that a supporting structure is required. The M&E contractor in this case could subcontract the Facade package and make use of the transoms and spandrels instead of providing its own supporting structure.

The compromises endured during the process have also illuminated the tension between suppliers and consultants. Suppliers find it difficult to provide one-off bespoke products as they are largely uneconomic to produce. Engineering design however at a product development scale is difficult to progress without bespoke components. With a prototype now produced it will be easier to progress towards a building scale demonstration where bespoke components can be produced more economically. The next step is then to systemise the components and establish the design rules where variants of the product can be provided to meet slightly different needs, but are still economic to manufacture.

7.1.5. Aesthetic Performance

The proof-of-concept prototype provides a close visual resemblance to the intended design and was sufficient to be assessed by questionnaires and by stakeholders. With the exception of the Heat Exchanger unit, the reaction to the prototype has been positive. Further development will address negative issues raised by integrating the Heat Exchanger and the high level internal pipe work and ductwork, into the Active Beam enclosure for an improved aesthetic. The Active Beam can be tailored to suit individual client requirements. The external facade can also be modified, without losing design intent, through the choice of glazing retention method and spandrel treatment (subject to free area constraints). A desirable aesthetic can therefore be achieved by integrating components into the Active Beam, and through the flexibility available in both the Double Facade and Active Environmental System appearance.

7.1.6. Cost Consideration

The cost consideration of this proposal was not to minimise costs, as the extra investment in the HVAC system proves economic so long as comfort is improved as shown in Chapter 1. The comfort measures necessary for an improvement have been implemented and would justify the extra investment. It is useful and prudent never the less to discuss ways of reducing the capital cost of the facade and environmental system and carrying out a life-cycle analysis.

The double skin facade was originally based upon bespoke profiles which used the aluminium profiles in a structurally efficient way. The realised prototype however had to use system profiles based on a single skin solution. This was structurally inefficient, which meant higher amounts of aluminium were needed and higher cost. The use of bespoke profiles as originally intended would reduce the cost on an actual project or marketed system, where the set up costs and extrusion die costs be amortised by the reduced aluminium usage.

The use of a decentralised system and individual zone heating and cooling supply systems was introduced in Chapter 2 and allowed for cost benefits in relation to reduction in floor to floor heights, greater usable floor area and cost of distribution. The increase in heating and supply RSHP units will however be a source of additional cost compared to a centralised solution when examined in isolation. To reduce the total cost of the RSHP units, they could be increased in capacity to serve two zones instead of one. The majority of the components would remain unchanged as they were oversized for a single unit (because of market availability). The main change will be the Condenser/Evaporator size and compressor which will be increased in capacity not number and a small increase in price and space. Sufficient space is available for doubling the size of the Evaporator/Condenser and increasing the Compressor size. Distribution through the refrigerant pipe work can be achieved either in the spandrel zone or at high level at the edge of the slab to avoid any aesthetic impact. The subsequent design development stage should verify the cost savings and ensure sufficient space is available within the spandrel zone.

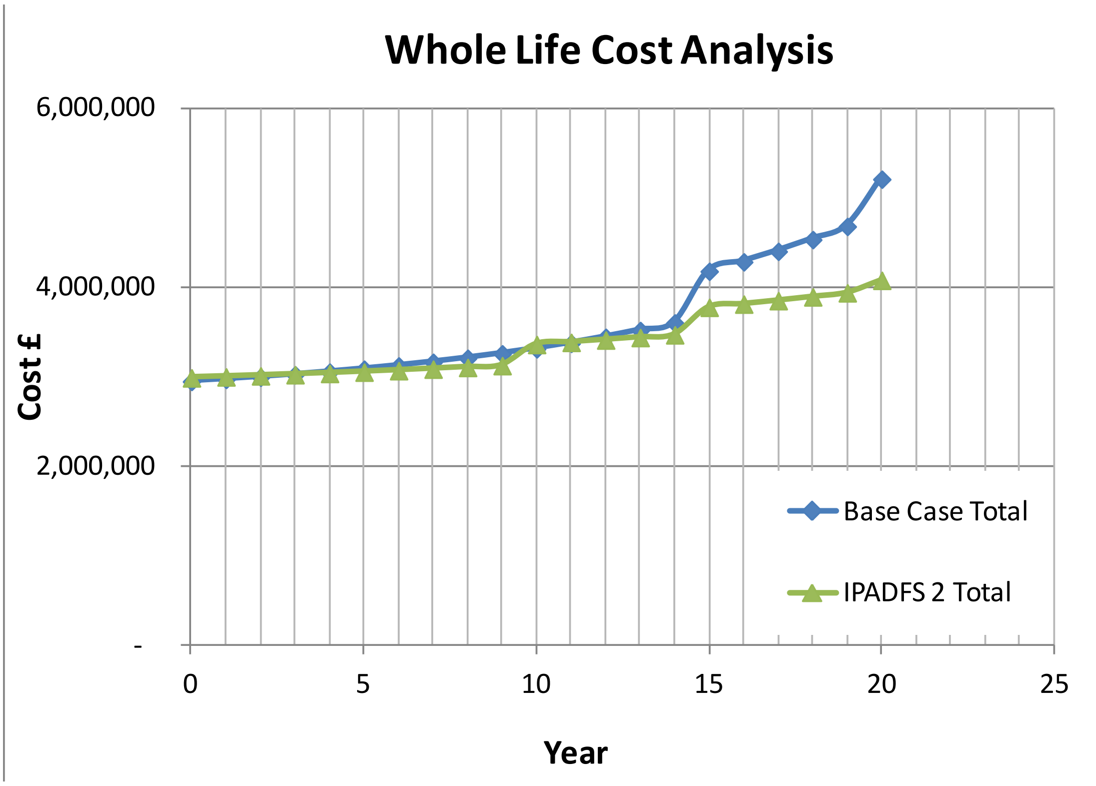

Figure 7.5 Life cycle cost analysis for the same floor area

A whole-life cycle analysis has been carried out by comparing a project using the IPADFS with a base case building (Appendix T). When comparing two office buildings with the same floor area, the overall capital costs are similar. Over the twenty year period examined, the building using the IPADFS has a lower life cycle cost as shown in Figure 7.5, even with the increased maintenance and replacement costs. This also does not include any rent premium for a more comfortable, sustainable and productive building.

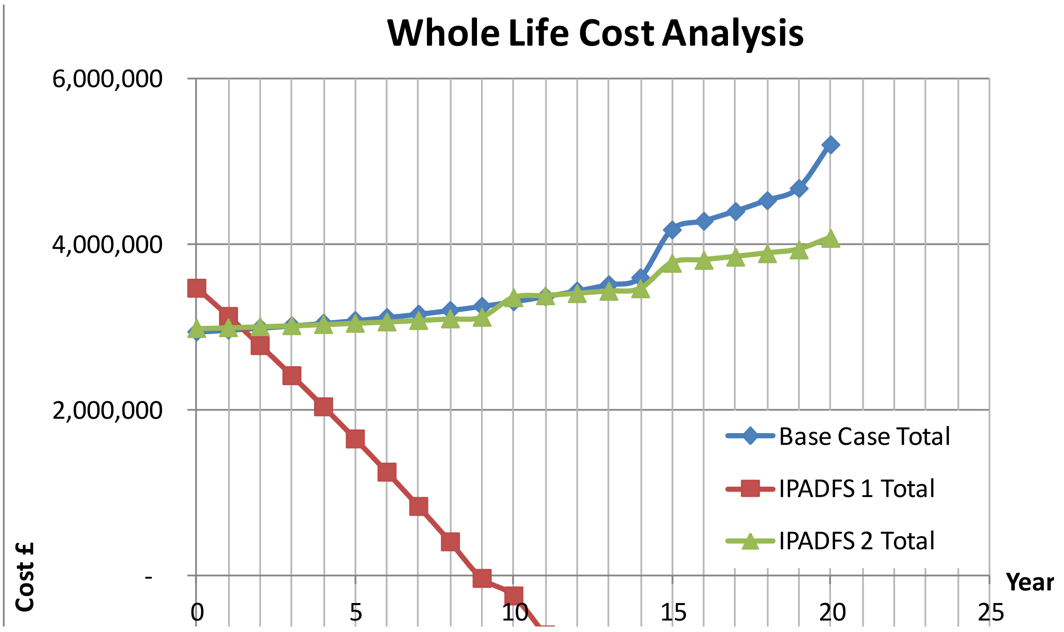

Figure 7.6 Life cycle cost analysis for the same building height

An alternative comparison can be made by examining two buildings with the same height. Using the IPADFS, extra floor space will be gained (16 storeys instead of 14) by the omission of a suspended ceiling. This is shown in Figure 7.6, where the IPADFS1 includes the additional floor area and rental income. This shows that the use of an IPADFS would actually be cost beneficial by year nine.

7.2. FUTURE WORK

In this thesis the design process has focussed upon reaching 'proof of concept' stage and completing stages 1 to five as shown in Figure 7.7 this has been achieved. Future work will implement the design changes to refine the design and produce a functional or 'beta' prototype which will closely resemble the pilot application and following successful testing and evaluation be suitable for pilot application. After the pilot application, an in-use evaluation needs to be carried to ensure that the needs of occupants and maintenance personnel have been addressed and to allow further refinement for subsequent applications.

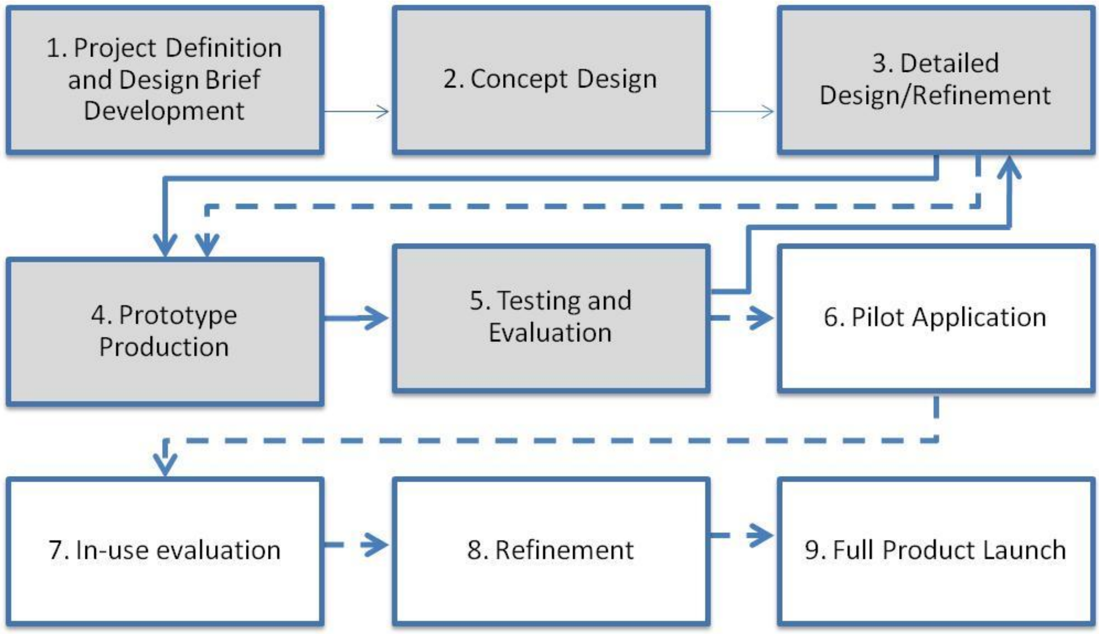

Figure 7.7 Product design stages – stages 1 to 5 have been completed within the thesis. Further work will return to stages 3 to 5 once more and then progress through to stage 6.

The key changes and requirements in the next development stage for the Double Facade can be summarised as:

- Bespoke profiles for increased structural efficiency;
- Evaluation of composite aluminium-timber unitised profile option;
- Improved profile U-values.

Those required for the Active Environmental System include:

- Integrated Heat exchanger and Active Beam;

- Increased capacity of the RSHP unit to serve two zones;
- Use of propane refrigerant.

There may also be potential to improve the glass energy performance. In Chapter 3, the relative performance of different glazing configurations was provided in terms of light transmission, solar energy transmission and U-value. Double glazing was specified over triple glazing as the light transmission was reduced and the weight increased, with little benefit in terms of reduction in U-value. However triple glazing using an intermediate film, instead of an additional pane of glass is starting to become available in the UK (www.albo.co.uk) with a U-value of 0.6W/m²K (glazing). This could provide an improved overall energy balance with its high light transmission and low U-value.

In the next development stage the design, location and facilities used, needs to bear in mind the larger size required and testing regime required in order to conduct and potentially be certified under CWCT standards. The Prototyping Hall being built at the University of Nottingham as part of the Energy Technologies Building should provide an improved environment and the potential to set up specialist equipment for CWCT standard tests.

7.3. CONCLUSION

An integrated passive and active Double Facade System has been successfully progressed to 'proof of concept' stage. It has integrated the functions of heating, cooling and fresh air in both a passive and active way to avoid the need for centralised plant and enable greater space efficiencies. Enhanced occupant comfort for inner-city medium to high rise offices has been provided by giving occupants maximised external views, daylight, natural ventilation and improved thermal control. Although not a full prefabricated 'super-component', it does offer greater levels of prefabrication than currently achieved with only three components installed on site and minimal site work. The energy and carbon dioxide emissions have been reduced by providing natural ventilation, a dynamic skin, reduced distribution losses, improved zonal control and low carbon heating, cooling and fresh air supply and delivery. Aesthetically the prototype can be progressed to a pleasing visual performance, adaptable to client and site specific requirements.

Further design development work to progress the prototype into a specifiable product has been identified and will form the basis for the next stage of research into the IPADFS, building on the body of work completed within this thesis.

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