Thermal Mass & Sustainable Building

Improving Energy Performance and Occupant Comfort

A practical guide for designers

Irish Concrete Federation

Set for life

Prepared by Rory Walsh, Paul Kenny and Vivienne Brophy
UCD Energy Research Group, University College Dublin.

Buildings shown on the front cover include, from left to right, BedZED: Wallington-UK, Hockerton Housing Project: Hockerton-UK, Limerick County Hall: Dooradoyle-IE and the Green Building: Templebar-IE.

Buildings shown on the back cover include, from left to right, Pantheon: Rome-IT, WIT Library: Waterford-Ireland, Elizabeth Fry Building: Norwich-UK and the James Ussher Library: College Green-IE.

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House at Doolin, Architect: Grafton Architects. Thermal mass captures free heat from the sun during the day, offsetting heating requirements for later that night.

Principles of Thermal Inertia

Introduction

In the coming years, the EU Energy Performance of Buildings Directive, or EPBD*, will raise the awareness of energy use in buildings and challenge current construction techniques. By providing a framework whereby all buildings will be required to have a certified energy rating, the EPBD will encourage prospective building owners to reduce their environmental impact by consciously choosing a building with good energy performance.

While the energy performance of a building can be improved at any stage in its life cycle, decisions made during the design phase are usually the most cost effective. There are a number of strategies that can be adopted in the design of a low energy building. One such strategy uses the mass of a building's structure to improve its thermal performance and enhance its internal comfort. This is often referred to as its thermal mass.

What is Thermal Mass

Thermal mass is a word used to describe the materials in a building's construction which can store and release large quantities of thermal energy. These materials are normally the dense structural elements that form part of the building's fabric. Materials such as concrete, brick and stone are particularly effective.

What is Thermal Inertia

The heat storing capacity of thermal mass has two effects on a building; it moderates internal temperatures by averaging diurnal (day/night) extremes and it delays the time at which peak temperatures occur. The temperatures experienced in a heavy-weight building will peak lower and later than those in a lightweight building and temperatures will not drop as much over the course of the night. This behaviour is commonly referred to as thermal inertia.

Benefits of Thermal Mass

Thermal mass offers building designers the opportunity to manage the thermal energy flows of a building to the advantage of its occupants, without the need for large amounts of high-grade energy.

Behaving like a thermal flywheel, the mass of a building can store thermal energy during times of surplus and release it back to the building during times of scarcity. By moderating internal temperatures, thermal mass can reduce the heating requirements of residential buildings and can offset the need for air conditioning in office buildings.

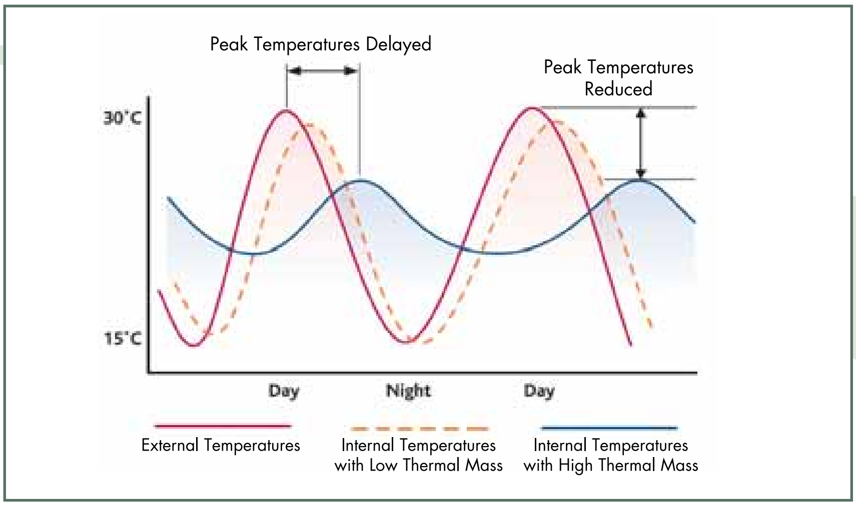
Residential Buildings

- Thermal mass can be used to store heat from the sun during the day in order to offset the need for plant heating later that night (Kisilewicz, 2005).
- Thermal mass can be used to curb the risk of overheating during warm sunny days (Energy Saving Trust, 2005).

Office Buildings

- Thermal mass reduces the peak air temperatures experienced in office buildings, resulting in a reduced cooling load (Givoni, 1998).
- Thermal mass delays the time at which peak temperatures occur. With enough thermal mass, peak temperatures can be delayed until after office hours. This reduces the length of time that a cooling plant is required to operate (Balaras, 1996).
- Adopting a night cooling strategy can enhance the performance of

The EU Energy Performance of Buildings Directive [2002/91/EC] was adopted on the 16th December 2002 and was legally transposed in Ireland by national legislation in January 2006.



Internal temperature profiles expected in buildings with high and low levels of therml mass. Source: The Concrete Centre.

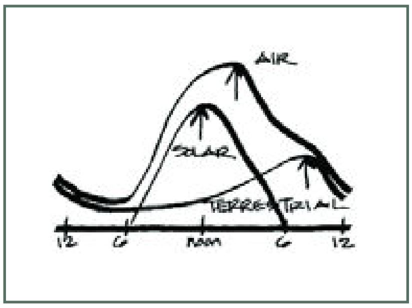
thermal mass. This strategy takes advantage of the free cooling which is available at night. Flushing an office building with cool night-time air can increase its capacity to deal with the following days' expected heat gains (Kolokotroni and Aronis, 1999).

Thermal Mass and the Earth

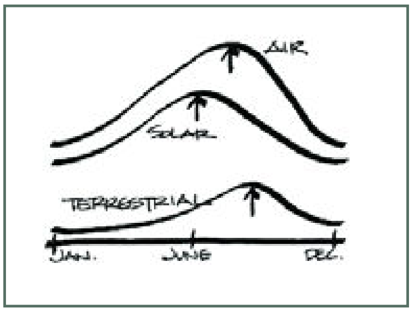
On a global scale the earth operates as the largest thermal mass we will encounter. Consisting of heavy heat storing materials like stone, clay and water, the earth has a significant influence on the ambient air temperatures that we experience throughout the year.

Were it not for the thermal mass of the earth the highest temperatures on a summer's day would occur at 12am, when the sun is highest in the sky. In reality, maximum air temperatures are generally not recorded until some time after 2pm.

In Ireland we receive the most amount of sunshine in June, yet the warmest temperatures recorded are generally in July. By absorbing a large portion of the incident solar radiation, the earth's thermal mass reduces and delays the peak ambient air temperatures that we experience. A key consequence of this is that the heat stored during the day is re-radiated back to the atmosphere at night. Were it not for the thermal mass of the earth, the night time temperatures we experience would be much lower.



Diurnal solar and terrestrial radiation combine to create a daily time lag of air temperature. Source: Bruce Haglund



Annual solar and terrestrial radiations combine to create a seasonal time lag of air temperature. Source: Bruce Haglund

Souterrains were used in Ireland up until the 12th century AD. Located underground, the stone structure and surrounding earth suppressed peak temperatures, making it possible to store food for longer. Source: www.burrebeo.com

Thermal Mass in Vernacular Architecture

In the Cappadoccia region of Turkey, soft volcanic rocks have been excavated to form thermally efficient homes. These dwellings possess ultimate levels of thermal mass and "earth coupling" which moderate the diurnal temperature extremes of the region. They are ventilated extremely well, employing stack ventilation in summer, while they store the heat from wood fires in winter. Source: Kevin Burke

The focal point of many traditional cottages in Ireland was the open fire. Recessed into a massive gable wall, heat generated by the fire is stored in the exposed walls and floor of the building. This stored heat is gently radiated back to the room long after the fire has gone out. Source: The Climatic Dwelling

The Trulli houses, which can be found in Apulia, in the South of Italy, use the thermal mass provided by thick masonry walls and corbelled dome roofs to ensure that the interior remains cool during hot summer days. Source: The Climatic Dwelling

Optimising Thermal Mass

The thermal mass of a building describes not just the presence of heavy heat storing elements in a building's construction, but also their location, configuration and the degree to which these elements are allowed to interact thermally with the internal environment.

Materials

In order for a material to operate successfully as a thermal mass it must be able to store large quantities of heat, but it must also be able to capture and release heat effectively within the diurnal cycle between day and night.

	Volumetric heat capacity @ 20°C kJ/m³.K
Air	1
Mineral insulation materials	90
Plastic insulation materials	100
Wood	187
Brick	1360
Rammed Earth	1673
Sandstone	1800
Concrete	**1940**
Glass	2184
Marble	2376
Water	4180

Volumetric heat capacity of different materials. Source: UCD ERG

The amount of heat a material can store is determined by is volumetric heat capacity. Heavy materials like stone, masonry, metal and water all have high volumetric heat capacities.

The ability of a thermal mass to charge and discharge effectively with a diurnal thermal cycle is largely determined by its conductivity. Because of their high conductivities, metals heat up and cool down too quickly to provide useful thermal mass in building applications. Wood has a low conductivity, and while it can store heat for long periods of time, it cannot store and release heat efficiently within a diurnal thermal cycle. Thermal energy is often rejected at the surface of wooden elements. This is because wood's low conductivity makes it difficult to transport thermal energy from the elements' surface to the elements' core.

Concrete, apart from having a high volumetric heat capacity, also has a suitable conductivity. This allows it to charge and discharge effectively during the course of a 24 hour period.

Effective Thickness

A limited thickness of thermal mass has been found to operate effectively within the diurnal cycle (Balcomb, 1984). Some general guidelines for high-density masonry (2,000–2,500 kg/m³) include:

- Performance variations for mass between 10 and 20cm are small. Mass thickness may be reduced to 10cm without incurring significant performance penalties.
- The range of mass thickness between 5 and 10cm can be considered as a transition region. In this region, the performance penalties for reduced thickness are becoming significant, but in some

cases may be considered acceptable as design cost trade-offs.

- For mass thickness below 5cm, performance falls off much more rapidly than in the transition region.
- Lower density masonry has a lower thermal conductivity and therefore, has a smaller effective thickness for diurnal heat storage. The same heat storage capacity must, therefore, be achieved with material spread over a larger area.

Surface Area

Of all the factors that contribute to the thermal mass of a building, it is the total area of exposed mass that provides the most influence. Per kilogram, mass in thin sections is more effective than mass in thick sections.

Increasing the surface area of exposed mass is the most effective way to increase the performance of thermal mass in a building.

Thermal Coupling

In order for thermal mass to perform effectively it must be allowed to interact thermally with the interior of a building. Linking thermal mass to the interior environment requires that consideration be given to all forms of heat transfer.

Conduction

Light finishes like carpets, plasterboard and ceiling tiles insulate the mass of a building's structure from the internal environment. Maximum performance can be achieved by exposing the internal surfaces of heavyweight construction elements. When this is not possible, a thermal link can be maintained by specifying a conductive surface finish like dense plaster or ceramic tiles.

In contrast, thermal mass needs to be isolated from the influence of external air temperatures. Thermal mass is most effective if it can be placed inside the insulated skin of the building's envelope.

Convection

Convective heat transfer can be improved by increasing the airflow over a mass surface, or by introducing turbulence into the air stream.

Radiation

Dark, matt or textured surfaces absorb and re-radiate more energy than light, smooth, reflective surfaces.

Admittance

Admittance, expressed in W/m^2K quantifies the (potential) thermal mass of a construction. It describes the ability of a material or construction to exchange heat with the internal environment when subjected to a simple cyclic variation in temperature (typically 24hrs for buildings). The key variables that determine admittance are heat capacity, conductivity, density and surface resistance. The typical rate of heat transfer from air to a thermal mass surface places an upper limit of $8.3 W/m^2K$ on its admittance. Improving the thermal coupling between the mass surface and the internal environment can increase this figure.

Construction	**Admittance W/m^2K**
External Walls	
105 mm brick, 50 mm EPS insulation, 100 mm dense concrete block, 13mm dense plaster	*5.75*
105 mm brick, 50 mm airspace, 19 mm plywood sheathing, 95 mm studding, 95 mm mineral fibre insulation between studs, 13 mm plasterboard	*0.86*
(Updating the constructions shown above to comply with existing building regulations can be achieved by specifying increased levels of insulation. Admittance values should not change significantly in doing so)	
Internal Partitions and Party Walls	
13 mm dense plaster, 215 mm dense concrete block, 13 mm dense plaster (Party Wall)	*5.81*
13 mm plaster, standard concrete block, 13 mm plaster	*4.29*
13 mm lightweight plaster, 105 mm brick, 13 mm lightweight plaster	*3.58*
12 mm plasterboard, timber studding, 12 mm plasterboard	*0.69*
Intermediate Floors	
50 mm screed, 150 mm cast concrete, 13 mm dense plaster	*5.09*
19 mm timber flooring or chipboard on 100 mm joists, 12 mm plasterboard ceiling	*1.89*
Ground Floors	
Vinyl floor covering, 75 mm screed, 50 mm extruded polystyrene insulation, 150 mm cast concrete	*3.58*

Admittance values for various constructions, higher values indicate better levels of thermal mass. Source: UCD ERG

Thermal Control

Providing for the thermal comfort of a building's occupants, whilst also conserving energy, requires that careful consideration be given to the control of a building's heating/cooling system. The control strategy employed needs to account for the building's thermal inertia and consideration should be given to control parameters like thermal response times, comfort zones and comfort set points.

Thermal Response

By virtue of its energy storing capacity, the thermal response of a thermally-massive building is slow. Where buildings are heated or cooled intermittently, this response needs to be taken into account. While thermally massive buildings do not cool down as quickly during a period of night setback, they do take longer to heat up the following morning. Achieving comfortable conditions at the start of occupancy can be achieved by including a period of preheating in the heating schedule. In large buildings a BMS (Building Management System) can be used to establish an optimum start up time.

Comfort Zones

Linking thermal mass to free sources of thermal energy (Passive Heating/Night Cooling) requires that the internal environment be influenced to some degree by the external climatic conditions. As the external temperature swings throughout the day, so too will the internal environment need to react accordingly.

Excluding the influence of ambient external conditions on the internal environment, and relying solely on heating and cooling systems to provide rigid comfort conditions, will render the energy saving capacity of thermal mass redundant.

The energy saving potential of thermal mass can be fully realised if the thermal comfort zone can be extended. This will allow the thermal mass to charge during warm periods and discharge during cooler periods. Extending the thermal comfort zone relies on an occupant's ability to adapt to temperature changes throughout the day.

Most residential buildings display large temperature changes throughout the day, yet occupants are able to adapt to maintain comfort. Simple adaptive measures include opening a window to cool down, or putting on a jumper to warm up. An extended comfort zone can be implemented if the occupant is provided with a number of adaptive opportunities. In an office situation, this can be achieved by providing measures such as access to an operable window, local radiator controls, or a more lenient dress code.

Comfort Set-points

An occupant's perception of temperature is determined not just by the surrounding air temperature, but also by the temperature of the surfaces present in a room. The mean radiant temperature is a temperature index, which accounts for radiation interchange between occupant and room surfaces, as well as the surrounding air temperature.

Thermal mass surfaces in south facing rooms will warm up during the day, increasing the radiant temperature in the room. When this occurs, the air temperature set point can be reduced accordingly. Occupants will have the same perception of warmth, even though the load on the heating system will have been reduced. Reducing a building's temperature set point by 1°C may save up to 10 percent of the energy it consumes.

Where night cooling has been implemented, and the thermal mass surfaces are cool, the air temperature can be allowed to increase accordingly without affecting the occupant's perception of coolness. This will reduce the load on a cooling system, providing additional energy savings.

Carton le Vert House, Architect: MacGabhann Architects. An internal wall, constructed using high density concrete blocks, is left exposed to provide a high degree of thermal mass.

Thermal Mass in Residential Buildings

The successful implementation of thermal mass in residential buildings relies strongly on the principles of passive solar heating. In Ireland's mild climate, the sun can make a substantial contribution to a building's space heating requirements. Passive heating relies on the form and fabric of the building to capture and store surplus solar heat during the day, which can be used to offset heating requirements later that night. Adopting passive solar strategies can reduce heating requirements in most new buildings by 20% and at its simplest level need involve no additional expenditure whatsoever.

A successful passive solar heating strategy requires that careful consideration be given to both passive solar collection and passive solar storage.

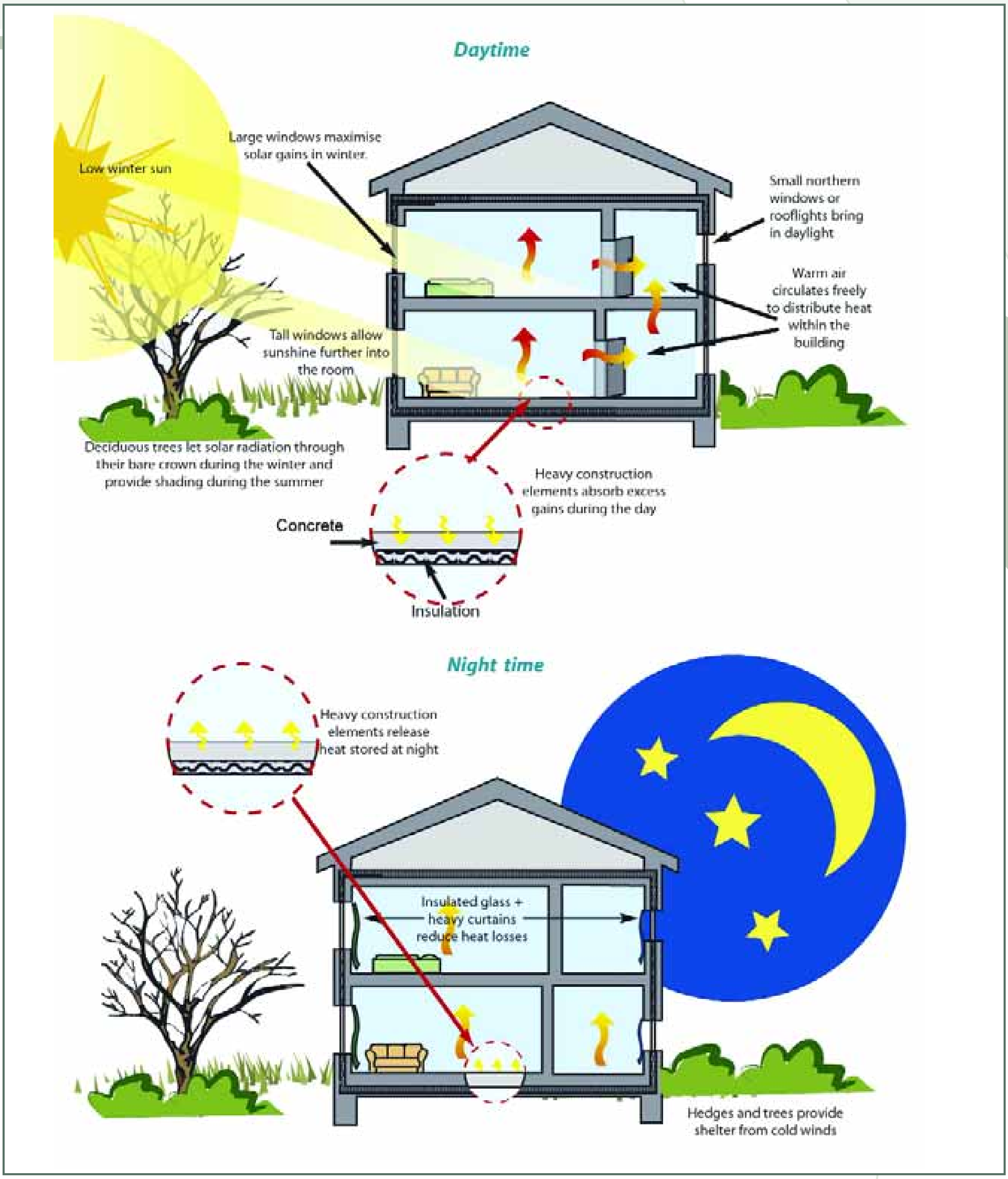
Passive Solar Collection

- Orientate the building so that the largest façade faces as close to south as possible.
- Locate the building so that it has good solar access. Consider the effects of neighbouring buildings and trees. Overshadowing will be most prevalent in winter when the solar angle is low.
- Integrate large windows into the south-facing façade. Vertical glazing is best because it allows low angle winter sun to penetrate into the building, while limiting the high angle summer sun, which can produce overheating.
- Tall windows will allow the sun to penetrate deeper into the building.
- Match the area of the windows to the thermal capacity of the room. When increasing the area of glazing, the area of exposed mass should be increased also; a mass to glass ratio of 6:1 is recommended (Balcomb, 1984).
- Windows with a high transmittance and a low-e coating will optimise the retention of solar heat gain.

Passive Solar Storage

Thermal mass can be integrated into a building's construction in a number of ways. Consideration can, in particular, be given to the building's envelope, the floor/ceiling slabs and the internal partition walls. In all cases the performance of thermal mass can be improved by considering the following guidelines:

Willem House, Architect: Jean Cosse. Using highly glazed south facing façades increases the solar heat gains which this building receives.



Diagrams illustrating how sunshine brings useful winter heating in a solar house. Source: SEI

- Locate thermal mass in rooms that receive generous amounts of sunlight.
- Although mass located in direct sunlight is perhaps 30% more effective than mass out of the sun, this should be considered secondary to distributing the mass over as large an area as practical within the room (Balcomb, 1984).
- High-density, masonry materials provide the most amount of thermal mass; a dense concrete block with a density of 1,850 kg/m^3 provides twice as much thermal mass as an aerated concrete block with a density of 500 kg/m^3 (Based on admittance values).
- The first 100mm of high-density masonry (2,000–2,500 kg/m^3) works best as a thermal mass. Additional thickness will provide diminishing performance benefits.

Perimeter Walls

- An externally insulated or cavity insulated masonry wall will provide thermal mass if its interior surface is left exposed. Avoid dry-lining and internal insulation.

- A fairfaced block work finish is optimum, but a light plaster skim can be applied to maintain the thermal link between the mass and the internal environment.

Ground Floor Slab

- The ground floor slab is the most convenient place to locate thermal mass; it is also the most effective, since it receives the most direct solar radiation over the course of a year.
- The ground floor slab will work effectively as a thermal mass, providing adequate levels of insulation have been installed both below and around the perimeter of the concrete slab.
- Raised floors and light finishes, like carpet or timber flooring, should be avoided, as they isolate the mass from the sun, and the interior environment.
- A polished concrete finish is optimum, but a ceramic, tiled or natural stone finish will also preserve the thermal link between the mass, the sun and the internal environment. Tiles should be attached to the slab with a mortar adhesive and grouted with complete contact to the slab.
- While it is inevitable that furnishings in a room will obstruct a portion of the incoming radiation, care should be taken to maximise the amount of sunlight which reaches the floor.
- Provision of an under-floor heating system in the ground floor slab can be beneficial, providing a boost to the slab's temperature in the morning before the sun can take over.

Ceilings

- Ceilings do not receive direct solar radiation, but they have a strong radiative link with the ground floor slab. This is because both surfaces face each other.
- The ceiling is also a good place to locate thermal mass, as it less likely to be obstructed and a large surface area can be presented to the room below.
- Thermal mass can be integrated into a room's ceiling, by constructing the upper floor using a concrete slab.
- In order to be most effective, the underside of this slab should be left exposed to the room air, or finished with a light plaster skim.

Internal Partition Walls

- Stud-wall partitions do not provide a lot of thermal mass, and a number of alternatives could be considered.
- Cast walls, poured at the same time as the ground floor slab, offer very high levels of thermal mass.
- Partition walls can also be built up using brickwork or block work.
- A fairfaced or light plaster finish should be specified to provide good thermal coupling.

Thermal Preservation

- Thermal mass is not a substitute for insulation. Materials such as concrete and brick will absorb heat, but this heat will only be stored and returned to the room when the concrete is insulated externally. Without good levels of insulation the benefits can be lost.
- Windows with low conductivity are especially important where large areas of glazing are to be included in a building's design.
- Thermal mass, which receives sunlight during the day, can radiate heat back to the sky through windows at night. This can be avoided by using thick curtains, shutters or night insulation.
- Infiltration heat losses can be reduced through careful detailing at the design stage and careful supervision of the building's construction. A heat recovery system can be used to reclaim up to 80% of the heat that would have been lost in providing adequate ventilation.

Willem House, Architect: Jean Cosse. A tiled floor can be used to maintain the thermal link between the ground floor slab and a room's internal environment for more information see case study seven.

Howth House, Architect: O'Donnell and Tuomey Architects. A cast in-situ floor slab provides effective thermal mass in a south facing room. Source: Denis Gilbert/View Pictures

Passive House, Architect: MosArt. Externally insulating the blockwork of this building with 325mm of rigid polystyrene (U-value 0.11W/m²/K), not only reduces heat losses, but also improves the effectiveness of the envelope's thermal mass.

Using thermal mass to control the thermal environment inside a building is not a new concept. It has been employed for centuries. Climate control is provided in the Pantheon in Rome using a massive stone and masonry structure. The oculus at the top of the roof facilitates passive night ventilation. Source: Paul Kenny

Thermal Mass in Office Buildings

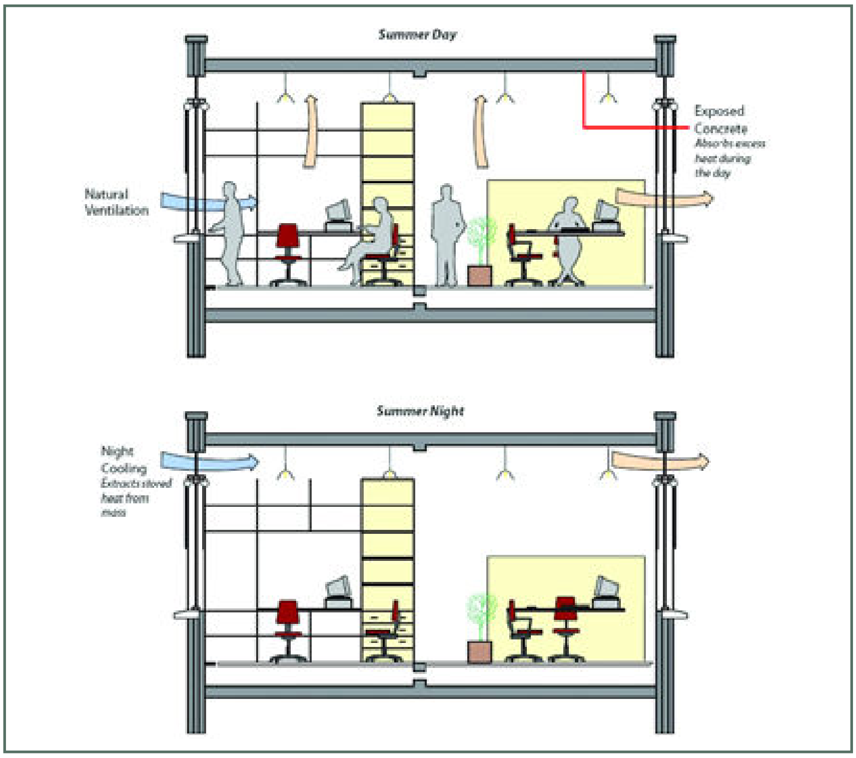
Providing a comfortable environment for the occupants of an office can be achieved in Ireland's mild climate without the need for energy intensive air conditioning. In general, cooling a building by 1°C, using air conditioning, requires three times more energy than heating a building by the same amount. Air conditioning can be avoided by integrating passive features into the building's design. Along with natural ventilation, night cooling and adequate shading, thermal mass can be employed to attenuate the impact of high internal heat gains, and to postpone the time at which peak temperatures occur. With sufficient thermal mass, the peak internal temperatures experienced inside an office building can be delayed until after office hours. Thermal mass in office buildings is commonly referred to as FES or Fabric Energy Storage.

Providing FES in office buildings can be achieved in much the same way as it is in residential buildings, with one exception. There is an increased reliance on the mass located in the ceilings of open-plan offices. The surface area provided by a ceiling in an open-plan office can be much greater than the combined surface area of the walls, which contain it. Avoiding the use of suspended ceilings allows the resulting exposed concrete soffit to operate as an effective thermal mass.

Night Cooling

FES can be used in office buildings to absorb a large portion of the heat gains, which are produced during a typical working day. These heat gains can be purged from the building by flushing it with cool night time air. This can be achieved by leaving windows open at night or by mechanically ventilating the building.

A typical naturally ventilated building, without FES will be able to offset heat



Night ventilation cycle in an office building. Source: UCD ERG gains of approximately 25W/m² from solar, lighting equipment and occupants (BRE, 1994). The addition of an exposed concrete soffit, when used in conjunction with an appropriate night cooling strategy can provide an additional 15–20W/m² of cooling capacity, provided the diurnal temperature swing is at least 5°C (BSRIA, 1996). This additional cooling capacity can typically reduce the peak temperatures experienced in an office by 3°C (BRE, 2001).

Managing Night Cooling

- The practical application of a night cooling strategy requires good management.
- If night cooling is not regularly applied, the building's temperature may steadily rise throughout the course of a working week.
- While the optimum rate of night cooling is building specific, an air change rate in the order of 2 to 5 ACH is typically employed. (BRECSU, 1995)
- Increasing the rate of night ventilation provides additional cooling, but with diminishing returns. As ventilation rates increase, fans consume more energy.
- Attention must be paid to room temperatures at the start of the occupied day. Over cooling must be avoided, as this can cause discomfort, or result in the unnecessary use of heating plant.
- Opening windows at night may compromise the security of ground floor offices. Hopper windows or vents can be used instead.

Thermal Mass Solutions

Using intermediate floor slabs to provide FES in office buildings can be achieved in a number of ways. A number of generic configurations are outlined below.

Plain Exposed Soffits with Natural Ventilation

Exposed Plain soffits can be used in conjunction with a passive night ventilation strategy. Windows are left open at night to provide cross flow, single-sided or stack ventilation, depending on the building's configuration. High-level windows or vents will encourage air to flow over the underside of the soffit, improving heat transfer. In larger buildings, the strategy can be implemented using mechanically actuated windows/vents that operate under the control of a BMS.

Removing false ceilings provides a number of additional benefits. The increased floor to ceiling height will provide better daylight penetration and improve cross flow ventilation.

Profiled Slabs

Profiled precast concrete slabs have been developed to fulfil a number of purposes. A profiled soffit has more surface area than a flat soffit, resulting in better heat transfer. An undulating soffit can be used to provide air flow passages through a building, allowing effective cross flow ventilation to be employed, while a light colour and an angled slab can be used to improve daylight penetration.

Void Ventilation

The void below a raised floor and above a suspended ceiling can be used to distribute air in office buildings. By mechanically ventilating air through these voids it is possible to indirectly link the thermal mass of the hidden slab to the office.

Mechanically Ventilated Hollow Core Slabs

A number of proprietary systems have been developed which exploit the thermal mass at the centre of a slab, in addition to that provided by its exposed soffit. This is achieved by mechanically ventilating air through cores that have been pre-cast into the concrete slab. Cooling these slabs is particularly efficient as the high velocity, turbulent airflow, improves the convective cooling of the slabs core. During the day incoming air is pre-cooled by the cores before it enters the office through ceiling diffusers.

Additional Considerations

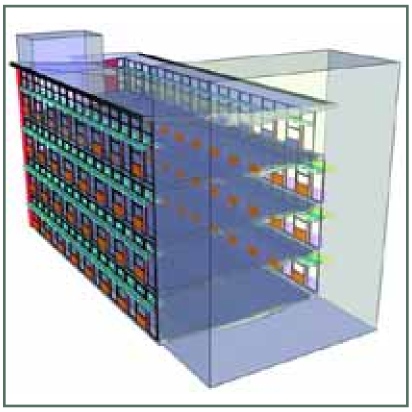
Routing Services

Omitting suspended ceilings will require that alternative service routings be developed. Raised floors can be used to distribute power and data

Plain exposed concrete soffits. Plain exposed soffits form part of the thermal mass strategy employed in the James Ussher Library; see case study six. Source: The Concrete Centre

Profiled concrete soffit and floor void ventilation. Wave-form soffits are employed in the BRE building, while raised floors are used in the WIT library building; see case studies three and five. Source: The Concrete Centre

Mechanically ventilated hollowcore slabs are employed in the Elizabeth Fry Building; see case study one. Source: The Concrete Centre



Computer model used in the analysis of Fingal County Hall. Source: John Carton cabling, while light fittings, fire detectors and sprinklers will need to be attached directly to the slab. Service runs to these fittings can be integrated into the slab during fabrication.

Acoustics

An acoustic consequence of providing large areas of exposed mass in open plan offices is that the reverberation time of sound can increase. Acoustic comfort can be regained by strategically placing sound absorbent panels and screens around the office. A thick carpet, provided along the main circulation routes in an office, will attenuate impact noise.

Winter Performance

While the enhanced comfort provided by thermally massive buildings in summer is well established, some research suggests that there is an attendant increase in heating requirements during the winter. This could be because of the slow thermal response of heavyweight structures following a period of night setback. Minimising heat losses at night can be achieved by ensuring the buildings envelope is both airtight and well insulated. Where a façade is highly glazed, windows with a low U-value should be specified.

Heat Gains

Designing heat gains out of office buildings is one of the best ways to ensure that passive cooling strategies can be adopted in favour of mechanical cooling. The following measures can be considered.

- Proper sizing and design of glazing systems with respect to orientation.
- External shading is more effective than internal shading.
- Natural daylighting can be exploited to reduce the reliance on electrical lighting. Where artificial lighting is required, high efficiency luminaries produce less heat.
- Heat producing equipment can be located in a separate room from the main office. A local mechanical extract can be installed in this room.
- High efficiency equipment is preferable. Standard computer monitors produce almost twice the heat that flat screen monitors do.
- Minimising the heat gains from these sources will preserve the cool energy stored in the thermal mass of a building, following a period of night cooling, allowing the building to remain cooler for longer.

Thermal Modelling

Up until recently, a building's performance has been established using relatively simple calculation procedures. These procedures, which have sometimes been required for energy rating purposes, have relied on steady-state methods to determine a building's heating or cooling requirements. While steady-state methods have been used with good success to size heating and cooling plant in the past, they do not provide much insight into the thermal behaviour of the building and do not account for the benefits of thermal mass in a building's construction.

Determining the performance of a passive cooling/heating strategy requires that the complex relationship between a buildings form, fabric and operation be reconciled with the weather conditions in which it is expected to operate. Dynamic modelling soft-ware allows designers to observe the transient thermal behaviour of virtual buildings under the influence of realistic weather conditions.

The development of a passive feature/strategy can be informed to a great extent by the analytical output that a dynamic model can provide. The impact of different envelope constructions can be investigated, the relationship between thermal capacity and glazing ratios can be explored, while appropriate control strategies can be developed, to ensure that the installed heating, cooling and ventilation systems work effectively together.

Simulation can be conducted for a number of design days to investigate the comfort conditions provided inside the building at different times of the year, or a full year's simulation can be executed to predict the buildings annual energy performance.

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Exterior view of the Elizabeth Fry Building.
Source: John Miller and Partners

Case Studies

In this section a selection of case studies are used to exemplify the thermal mass strategies outlined in the first half of this manual. The buildings have been selected to illustrate a range of typical thermal mass solutions, as applied in a number of different building types, including office, educational and residential buildings.

In each case, thermal mass was adopted as a key component of the building's environmental control strategy from the earliest stages of the design process, and as such has been consciously and sensitively integrated into the design of the whole building. Each building illustrates a unique thermal mass solution, both in terms of how thermal mass was physically integrated into the building's structure, and in terms of the control strategies and modes of operation which were developed to optimise its effectiveness.

The buildings chosen are not the only examples of particular thermal mass strategies from around Ireland and the UK, nor are they necessarily 'Best Practice' examples. They have been chosen because they are generally perceived as being good examples of recent buildings designed to provide pleasant internal environments through the integration of thermal mass into good design.

1. Elizabeth Fry Building

Client
University of East Anglia

Architect
John Miller and Partners

Building Services Engineering
Fulcrum Consulting

Outline of Thermal Mass Strategy

Where a high degree of insulation and air tightness has been specified to reduce heat losses during cool periods, the buildings hollow core slabs are mechanically ventilated at night in order to offset the attendant risk of overheating during warm periods.

Project Description

The building, which was commissioned to house the school of social work at the University of East Anglia, was designed to minimise the use of heating and air conditioning, whilst making the best possible use of natural daylight. The low energy strategy employed uses high insulation and an airtight envelope to minimise heat losses and a heavy internal structure to attenuate and control heat gains. Ventilating incoming air through hollowcore slabs provides the building with more thermal mass than would be provided using standard solid slabs, while controlling the number of cores that are ventilated at any one time makes it possible to modulate the influence of thermal mass on the internal environment.

The clients' brief called for a building with a lecture theatre, a seminar room and a number of teaching rooms, as well as offices to facilitate a maximum occupancy of 1,100 people. The building was completed in 1995, at which point the BRE conducted an extensive monitoring survey which revealed that the Elizabeth Fry Building consumes less than half the energy required by a conventional university building of this type based on DETR energy benchmarks.

A post occupancy survey conducted by the Probe team concluded that this building was amongst the most comfortable buildings that had been monitored at that time.

Building Form and Layout

Built into a gently sloping site on the University's main campus, the Elizabeth Fry Building contains 50 cellular offices on its first and second floors with lecture theatres and seminar rooms located on the ground and lower ground floors.

Interior view of building showing triple height atrium and tiled floor slab. Source: John Miller and Partners

The building is narrow in plan with most offices being less than 6m deep. This provides access to high levels of natural daylight, a link with the external environment, as well as the opportunity to include operable windows as part of a mixed mode ventilation strategy.

Thermal Mass in the Building

Thermal mass is provided using a proprietary concrete slab which uses hollow cores within the slab as the final part of the air supply ducting. The soffits of these slabs are exposed to the offices/teaching rooms below, allowing them to act as a heat sink for heat gains during the day. During the summer, the hollow cores are mechanically ventilated at night to provide an efficient and effective method of purging heat from the slab.

An additional benefit of mechanically ventilating these slabs is that the degree to which the incoming air interacts with the slab can be regulated. Incoming air typically passes through three hollow cores before being diffused into the room, providing maximum use of thermal mass. In certain circumstances, a faster thermal response, which requires less thermal mass is preferable, especially on cold winter mornings. This can be achieved by manipulating the incoming ventilation route, so that air only makes one pass through the hollowcore slab instead of three.

In addition to the hollowcore slabs, which are used on all floors including the top floor, the internal partitions are constructed from a combination of painted fairfaced and plastered concrete block walls, 100mm and 140mm thick.

The high thermal capacity of the internal structure results in a building with a very long time constant, where a temperature drop of less than 1°C has been recorded over the course of a cold winter weekend after the heating system had been turned off.

Envelope Insulation and Air tightness

The Elizabeth Fry building is insulated to meet Scandinavian best practice standards with a double skin block work wall containing 200mm of insulation. The windows are triple glazed with a low-e coating and argon filling, while the construction achieves an air tightness of one ACH at 50pa under the BRE fan pressure test.

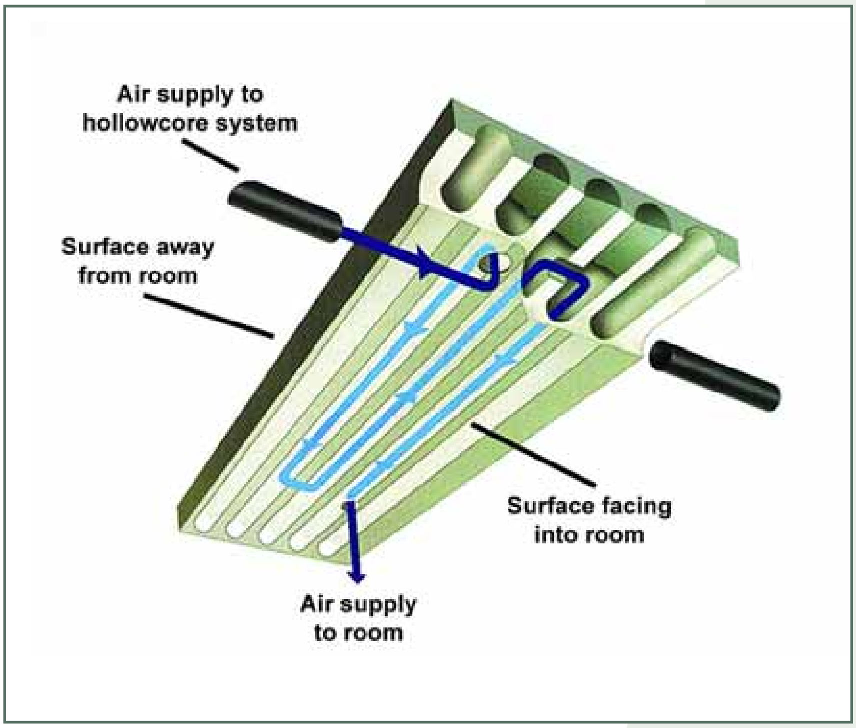
Achieving such a well-sealed building was achieved through careful planning at the design stage and rigorous supervision during construction. An air tightness requirement was written into the building contract with a stipulation that this was to be independently verified prior to handover. These stipulations did not incur additional construction expense, but did result in more careful detailing, and more regular and thorough inspections being carried out during the building's construction.

Where these thermal preservation measures combine to provide a designed heat loss of only 15W/m^2, the addition of an 85% efficient heat recovery system ensures that the building remains comfortably warm for most of the year without the need for any heating plant. The occupants and the office equipment generate most of the heat required in the building.

Cooling the Building

The building is night cooled by mechanically ventilating air through the hollowcore slabs. Convective heat transfer from the cool night time air to the slabs core is very high due to the fast flowing turbulent nature of the airflow in the cores. Incoming air passes through the hollow cores three times before being discharged through ceiling mounted diffusers into the offices below.

A survey of the operation of this night cooling system has found that the coefficient of performance is 5.8, which means that, for every one kilowatt of fan energy used, 5.8 kilowatts of heat is removed from the building.



Operation of the proprietary hollow core ventilation system used in the Elizabeth Fry Building. Source: TermoDeck

Where heat gains were expected to be higher in the lecture rooms, an innovative ventilation system was employed. Incoming air is circulated through a labyrinth of ducts located in the ground floor slab. Where external air temperature increases quickly during the day, the temperature of the ground, by virtue of its own thermal inertia, remains relatively cool. Circulating air through the ground floor slab can reduce the air supply temperatures by a number of degrees.

Thermal Control of the Building

Where high inertia buildings respond slowly to thermal stimuli it can be difficult to recover comfortable conditions quickly when discomfort has been reported. In order to avoid this situation, a trend BMS system was installed to fine tune and simplify the environmental control of the building.

During the winter and the summer the BMS aims to maintain a core temperature set point of 22°C. During occupied hours, the variable speed air-handling units operate to provide fresh air requirements, based on CO_2 sensor readings from the return air.

After 10pm the building is assumed to be unoccupied and night ventilation commences if two conditions are satisfied; the core temperatures must be above 23°C and the external air temperature should be 2°C less than the core temperatures at that time.

Comfort is provided to occupants using a 0.5°C air temperature dead band below 22°C for heating and a 1°C dead band above 22°C for cooling. The different modes of operation are outlined below.

Summer Night

Cool night time air is mechanically ventilated through the hollowcore slabs, providing a cool store for the following days' expected heat gains. Night cooling is successful in maintaining internal temperatures below 25°C even on the hottest of summer days.

The system also has the advantage of using cheap off-peak electricity rates to operate the AHU's.

Summer Day

Having cooled the slabs down the previous night, occupant comfort is achieved on a warm day in two ways. The underside of the slab provides radiant cooling to the occupants below, while incoming air is pre-cooled in the slabs hollow cores before being discharged into the room. Where this system provides base levels of cooling, the occupants are free to manually operate perimeter windows to regulate further their own local environment.

Winter Night

Sealing the building at night conserves the previous day's heat gains. In cold weather, heating activates at 8pm to provide comfort at the start of the working day. If the building begins to cool down while unoccupied, the plant is called upon to start by the temperature sensors in the slabs and is set to run on recirculation only. There is no fresh air ventilation provided to the building when it is unoccupied.

Winter Day

During cold winter periods the airtight and highly insulated envelope retains most of the heat from the building. Heat produced by the occupants is radiated to the hollowcore slabs and recovered from the extract air, which is then passed back through the slabs into the rooms.

Overall Performance

The Elizabeth Fry Building has achieved the comfort criteria specified in the original brief without the need for air conditioning. During one hot week in June 1996 when external temperatures reached 30°C, the temperatures in the south facing offices were maintained below 25°C.

Two occupant surveys were completed in the spring and autumn of 1996. Occupants involved in the survey included office staff, lecturers and students. Seventy percent of the office staff were satisfied with the conditions in the building while only 7% reported dissatisfaction. Occupants also felt that on average their productivity had increased by 7% as a result of their new surroundings.

Internal temperatures were maintained at 20°C during the winter and most occupants reported wintertime conditions as being comfortable, being neither too hot nor too cold. While the conditions provided in the building appear to be very good, the survey highlighted that the users felt they had very little control over the heating of their local environment; with the exception of perimeter windows and doors, there was very few adaptive opportunities/controls provided to the occupants.

The Elizabeth Fry building consumes 102kWh/m², which is less than half the energy required by a conventional university building of this type. Heating and lighting accounts for 45% and 25% of the total energy consumption respectively, while the fans in the AHU's consume 18kWh/m² annually, despite the high number of slab cooling hours.

In the early days of occupation, monitoring revealed that there was a poor relationship between daylight and energy use for artificial lighting. A memo was circulated to the occupants of the building providing information on how to optimise the use of natural daylighting. This initiative has reduced lighting energy significantly with monitored results showing a lighting energy use that was 20% below the good practice figure for academic buildings.

Although high quality finishes were used throughout the buildings construction, costs did not exceed those of a conventionally constructed building. The cost of construction was estimated to be £820 sterling per meter square of gross floor area at 1995 prices. This cost is equivalent to a naturally-ventilated office and significantly less than an air-conditioned building, where services make up a large portion of the capital costs. Offsetting the requirement for additional mechanical and electrical servicing produced cost savings, which helped to pay for the additional expenditure incurred in providing a high performance envelope.

Achieving such high levels of occupant comfort and energy performance has been as much to do with the management of the building as the expertise that was invested in its original design. Supervision from the client, the design team and the contractor ensured that the pioneering design was not compromised during construction, while the building's handover took place over two years, during which time the monitoring campaign informed an optimized control regime. An uncompromising commitment to the low energy brief at every stage of the building's development has ensured that performance targets drawn up at the design stage have been achieved in practice.

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Exterior view of the National Maritime College. Source: BDP, Photo: David Barbour

2. The National Maritime College

Client

Dept of Education/Focus Education

Architect

BDP

Building Services Engineer

BDP

Outline of Thermal Mass Strategy

Thermal mass is employed as a climate moderating device in zones within the building that experience high internal heat gains. This has been achieved by using exposed blockwork and deeply troughed concrete ceiling soffits. Additionally, night cooling is provided using mechanically actuated windows and vents.

Project Description

Completed in 2004 the National Maritime College was procured by the Department of Education via a Public Private Partnership with Focus Education Ltd, a division of Bovis Lend Lease. Conceived and commissioned to provide a world class teaching facility to be used jointly by the Cork Institute of Technology and the Irish Navy, the building is designed to facilitate 750 students in their seafaring studies.

As well as classrooms, labs, computer suites and a library, the college was required to include a broad range of specialist facilities for hands-on training, including two state-of-the-art simulators for teaching navigation skills. The simulators are mock-ups of actual ship bridges and use 360° projection screens to simulate the main waterways and harbours of the world. In addition, a 5m deep survival training pool, equipped with a wave generator, rain simulator and large fans, was to be provided as well as several heavy engineering workshops, including welding rooms, machine rooms, electrical motor test rigs and an engine room.

The training pool, located in the engineering block. Source: BDP, Photo: David Barbour

The provision of such a well-equipped facility had consequences for the environmental control of the building. Such a high density of heat producing equipment would typically have necessitated that full air conditioning be employed. This, however, was not an option, as the design brief called for a building that offered an exceptionally low energy usage. The brief set an energy usage target of 112kWh/m^2/yr and under the PPP agreement, the provider is required to accept the risk on the volume of energy consumed by the building for the first twenty-five years of its operation.

To this end, BDP were engaged by Focus Education in 2002 to provide an integrated, fully multi-disciplinary design service. The BDP team included building service engineers, structural engineers and architects. Developing a low energy servicing strategy was aided by the ability to enrol representatives from all three disciplines at the design development stage.

Building Form and Layout

Situated in Ringaskiddy, 16 kilometres from Cork City, the site is partially located on reclaimed land, which was created using debris that had been dredged from the harbour channel.

The building is organised into three distinct blocks: to the east is the facilities block, in the centre is the simulator block and to the west is the engineering block. A lateral three-storey circulation route links these blocks.

The design team knew there would be large heat gains produced by the PC-based systems, projectors and electrical equipment that the simulators used and, since most of the simulators required total blackout conditions, it was decided that this equipment and its attendant heat gains would be best isolated in a self contained inner block. Rooms with a lighter load, which would benefit from natural ventilation and daylighting, such as classrooms and labs, were wrapped around the outside of the simulator block.

The facilities' block occupies the eastern portion of the site and contains the canteen, learning resource centre, administration offices and a lecture theatre, while the engineering block accommodates the technical workshops and training pool.

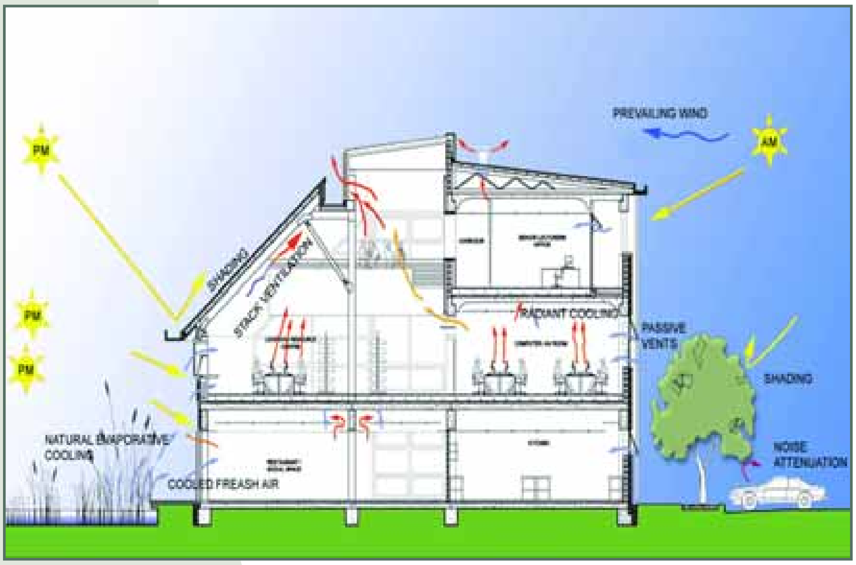
Thermal Mass in the Building

Thermal mass is used judiciously throughout the building with special treatment being given to areas where high heat gains were expected. The facilities block and simulator block were constructed using dense block work, which was consciously left exposed to the interior.

In the simulator block, the installation of suspended ceilings has been avoided to expose the structure, with services being carried through a raised floor void instead.

Other areas of the building utilise exposed concrete soffits also, including the classrooms, laboratories and the computer suites. A pre-cast slab with deep profiled troughs was used to provide the increased surface area required for optimum heat transfer.

Thermal mass is employed as a climate-moderating device in the building. By using it to even out diurnal temperature swings, thermal mass is expected to reduce peak temperatures during the summer and heating loads during the winter.



Passive ventilation strategy employed in the NMC building. Source: BDP

The Library has been designed to fully exploit natural day lighting and passive ventilation. Source: BDP, Photo: David Barbour

Deeply troughed ceiling soffits provide thermal mass in the buildings computer suites. Source: BDP, Photo: David Barbour

Night Ventilation

The cooling capacity of thermal mass in the computer rooms and the library is enhanced using a night ventilation strategy, which operates using motorised windows and vents. Controlled by the BMS the vents are opened at night for a period, which is determined using temperature readings provided by sensors located inside the building.

Fresh air enters the zone through motorised grilles at low level; is drawn into the library stack where it is finally exhausted through high-level vents. Much of the air movement through this part of the building is completely passive, relying on the natural buoyancy forces created inside the library stack.

Heating the Building

Space heating is provided using two fully condensing boilers, which were configured to operate in condensing mode as much as possible. This was achieved by adopting two measures, both of which were intended to reduce the temperature at which the circulating water returned to the boiler.

Traditional heating systems produce water at 82°C and reduce this temperature subsequently, using a mixing valve to meet the required heating load. The system installed in NMC avoided the need for a mixing valve by outputting boiler water at the lowest temperature required to heat the building with the actual external temperatures. The system's efficiency was further enhanced by over sizing the building's radiators. This allowed the same amount of heat to be distributed to the building using water at a lower temperature. Adopting both measures is expected to improve the efficiency of the system by some 10%.

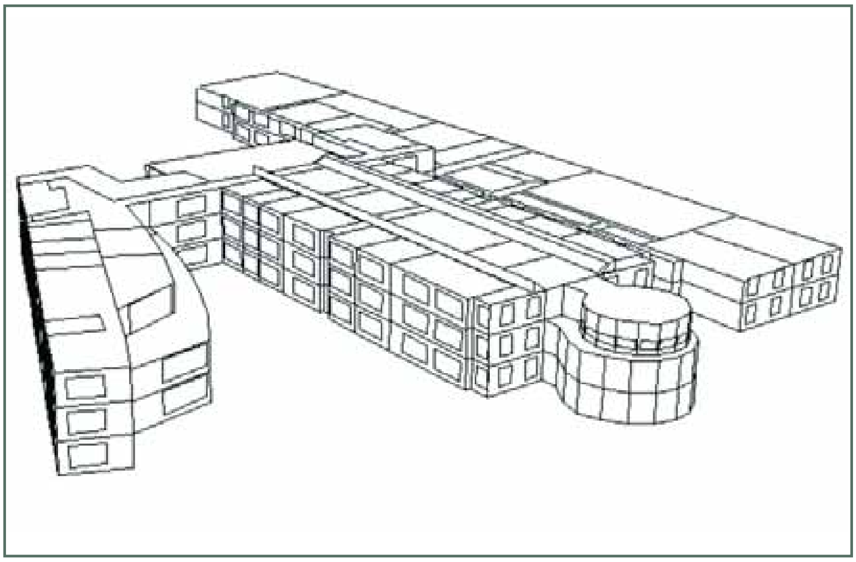
Thermal Control

The BMS controls the main energy systems in the building and is designed to provide a minimum internal temperature of 21°C during the winter while summer time temperatures are only permitted to increase beyond 25°C for 5% of the occupied period.

The BMS achieves these targets using a host of control strategies including optimum start, weather compensation, frost control, time scheduling, and a night cooling facility, which is initiated using the trigger temperature method.

The night cooling strategy proceeds under the dictates of the following control logic.

At 11pm the temperatures inside the building are sampled. If the internal temperatures are above 18°C, then night cooling is initiated, providing the following conditions are both met; the external temperature must be below the internal temperature and the internal temperature must have peaked above 24°C at some point during the previous day. Night cooling continues either until 8am the following morning, or until the internal air temperatures drop below 18°C.



Computer model of NMC building, used during its dynamic thermal analysis. Source: BDP

Certain measures have been taken to improve the amount of control that occupants in the classrooms and labs have over their own local environment. Windows in these areas can be opened manually, automatic lighting controls can be overridden and thermostatic valves have been provided on many of the building's radiators.

Integrated Design Process

An integrated, fully multi-disciplinary design team composed of professionals from different departments within BDP including Architecture, Mechanical & Electrical Engineering, Civil & Structural Engineering, Landscape Architecture, and Interior Design met on a regular basis from the earliest stages of the design process. In particular, BDP's engineers were involved in the early development of the building's form and façade to ensure that the structure worked as an integral part of the environmental control strategy.

This approach allowed the implications of a number of secondary design issues to be fully investigated and assessed prior to construction. The decision to avoid suspended ceilings required that a new solution be developed to distribute the building's power and data cabling. Using the corridors as the main service arteries, a raised floor was provided, while final service runs were cast into the concrete structure.

Designers felt that service distribution in a building with exposed slabs was not difficult, but that special care had to be taken during the installation to avoid damaging the services. This was particularly crucial in the NMC where a large volume of construction traffic was experienced in the corridors, but was resolved using temporary coverings and walkways where required.

Another consequence of exposing large areas of concrete is that the hard surfaces often increase the reverberation time of sound within an open space. This concern was addressed early in the design process when BDP's acoustic engineers determined that satisfactory reverberation times and noise levels could be achieved using a deeply troughed/ profiled slab.

Overall Performance

Having agreed to accept the risk on the volume of energy consumed by the building for the first twenty-five years of its operation, it was important that BDP produced a building which was capable of meeting the specified energy target of 112kWh/m^2/yr. Where passive measures like natural ventilation and night cooling were required to improve the building's energy performance, simulation studies were conducted to asses if these strategies would provide sufficient levels of indoor air quality and thermal comfort. In working towards an optimum building design, the outputs provided by the simulation studies were used to inform the design team's decision-making process and to provide confidence in the long term performance of the resulting design.

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Exterior view of BRE building. Source: Fielden Clegg Architects

3. BRE Environmental Building

Client
BRE

Architect
Fielden Clegg Architects

Building Services Engineer
Max Fordham Consulting

> **Outline of Thermal Mass Strategy**
>
> Thermal mass is provided by highly engineered profiled floor slabs, which have been holistically designed to fulfil a number of functions. The mass of these slabs is used in conjunction with passive and active heating/cooling strategies to moderate internal temperature swings, whilst also providing airflow routes through the office spaces.

Project Description

Initiated in 1991 under the UK government's Energy Efficiency Best Practice Programme, the Environmental Building is the product of a collaborative effort between the BRE and eleven different construction and energy agencies.

The objective for the project was to demonstrate that low energy and environmentally-sensitive design can provide a viable, comfortable and healthy alternative to the energy intensive, heavy servicing that is required in many office buildings. While the buildings final specification includes technologically advanced features like automated, light sensitive external shading, and infrared user controls, it is design principles that have been established for centuries that are exploited as the primary modifiers of the internal climate. Thermal mass is used to provide a more stable thermal environment, reducing peak temperatures, while passive ventilation provides both indoor air quality and cooling opportunities where required.

The building was completed in 1996 and was awarded 39 credits out of a possible 42 credits under the BREEAM (REFERENCE) environmental assessment scheme; at the time, this was the highest number of credits that any building had been awarded. Today the building is still considered to be a landmark building and a replicable example of cutting edge environmental design.

Building Form and Layout

Located near Garston in Hertfordshire the building was designed to accommodate 100 of BRE's staff, as well as providing seminar and conference room facilities.

The offices are located on three floors and account for 1,300m^2 of the 2,100m^2 total floor area, with a conference room designed to accommodate 100 people and two smaller seminar rooms making up the difference.

L-shaped in form, the building's long axis has been orientated close to east-west, perpendicular to the prevailing wind direction, in order to encourage cross flow ventilation across the building's shallow floor plate (13.5m^2). Constructed using recycled material where possible, the walls are faced using 80,000 reclaimed London stock bricks and 90% of the in-situ concrete contains recycled aggregates. High levels of insulation were designed into the building's envelope, while the double-glazing, which makes up 50% of the south facing façade, has argon filling and a low emissivity coating.

Thermal Mass in the Building

One of the key innovations used in the BRE building is the waveform concrete floor slab construction. Where partitioning in open-plan offices can compromise the effectiveness of a cross flow ventilation strategy, the waveform ceiling soffit was initially conceived as a means of providing effective air paths through the building. A happy consequence of this form is that the area of exposed thermal mass presented to the office below is increased significantly.

The exposed waveform ceiling soffit is constructed as a 75mm thick precast sinusoidal shell, which is filled with concrete on-site to produce a structural floor slab. The final construction provides an integral air channel in the lower section of the slabs waveform, while the topside includes a repeating series of accessible service voids, which alternate with sections of screed into which under floor piping is cast.

The undersides of the slabs have been left exposed and painted white to improve daylight penetration within the building.

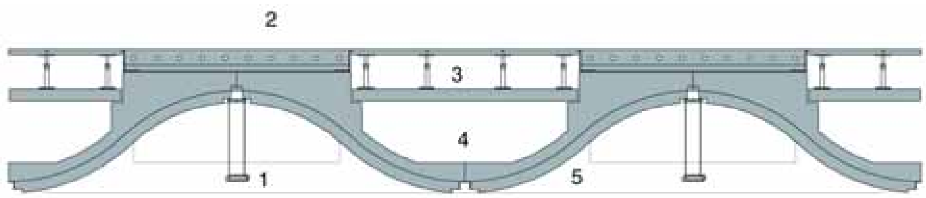
Cooling the Building

Night ventilation is employed as the primary method of cooling the building, and is achieved using a collection of mechanically actuated windows/vents on the building's north and south façade. High level windows open automatically at night providing airflow through the offices and over the underside of the floor soffit. Inter-floor vents also open directly into the hollow channels inside the waveform slab, providing additional cooling to the core of the slabs. During still windless nights, mechanical fans located in the building's chimneystacks activate to exhaust warm air from the building and draw cooler air in.

Although seldom used, a secondary cooling system was included as a fail safe in the building's environmental control strategy. It was determined at the design stage that the conference room required to accommodate 100+ people would need some form of supplementary cooling. Instead of re-sorting to full mechanical refrigeration, the designers decided to use a lower energy ground water cooling system. Water at 10–12°C, sourced from a 70m bore hole is fed at 1.5l/s through a series of steel heat exchangers. Water which circulates in a secondary loop through a network of pipes embedded in the floor slabs is cooled using the heat exchanger, providing approximately 35 kW of cooling to the building and shaving 2°C off the peak internal temperatures.

While the performance of the ground water cooling system does not rely on the thermal inertia of the building itself, the ground from which the water is sourced provides a temperature time lag of approximately five months. This results in the coolest water being available to the system, during the summer months when it is required the most.

Sinusoidal Slabs used in the BRE building. Source: Fielden Clegg Architects



Cross-section through the sinusoidal floor slab used in the BRE building. Source: Fielden Clegg Architects

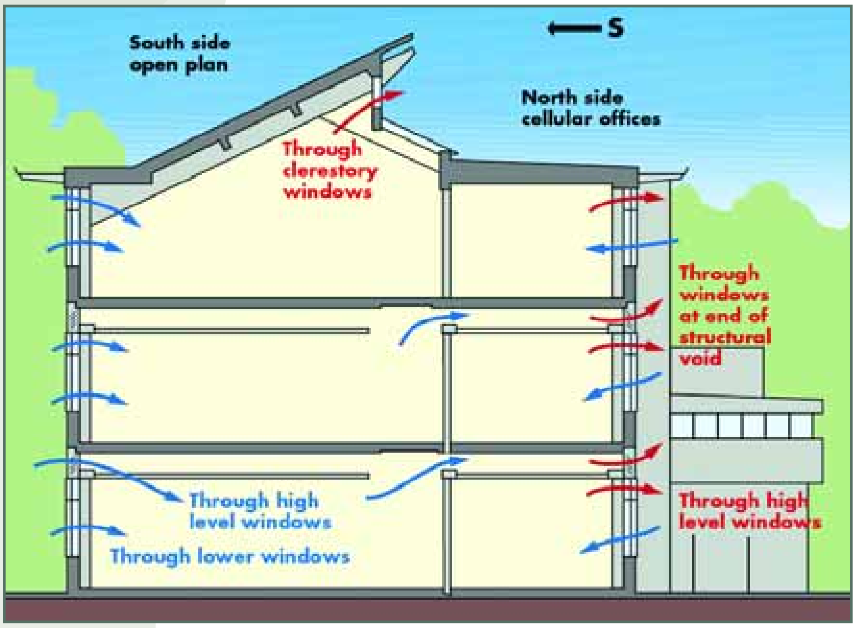
Control Strategy

A well considered control strategy is employed in the BRE building, using a building management system, which operates all of the building systems on one network. Employing a common network allows the BMS to coordinate the provision of ventilation, heating, cooling, external shading and lighting simultaneously with minimal cross over. The heating system has standard optimization software, with a self-learning facility, which determines the most efficient operating schedule.

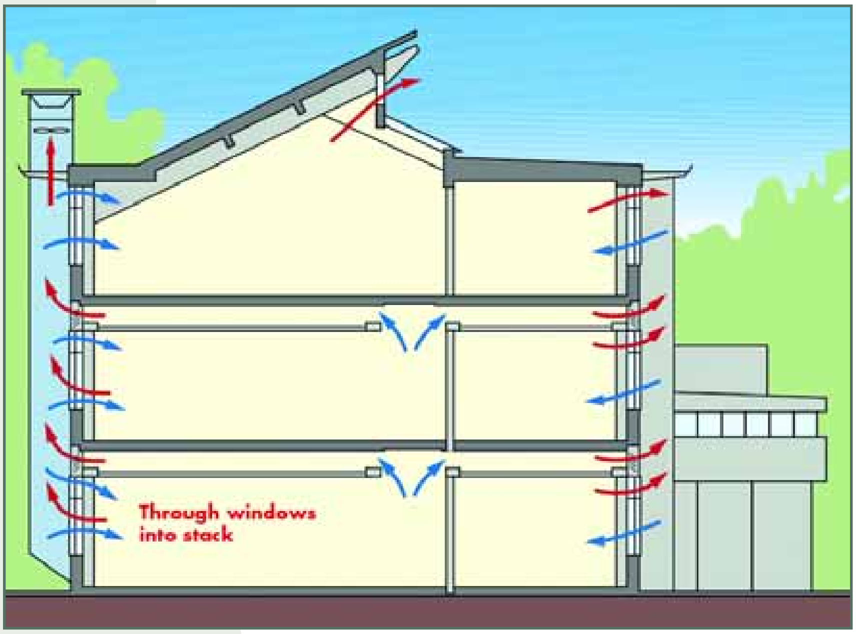
The BMS control strategy is designed to ensure that temperatures do not rise above 28°C for more than 1% of the working hours or increase beyond 25°C for more than 5% of the annual hours of operation. An 18°C set point temperature is used for heating purposes. These temperatures are achieved using four primary control algorithms.

Winter Day

Transporting air from outside through the ventilation ducts in the waveform slabs provides minimum fresh air requirements. Incoming air is pre-heated in this way, reducing the requirement for heating which operates to maintain a minimum temperature of 18°C. While the heating coils cast into the slab provide more efficient heating than the perimeter radiators, the radiators are used on occasion to provide a faster thermal response when required.



On warm windy days cross ventilation is possible in the BRE building. Source: BRE



On warm still days stack ventilation is possible in the BRE building. Source: BRE

Winter Night

No ventilation is required and only enough heat is supplied to prevent frost.

Summer Day

Minimum ventilation is provided unless the internal temperature is above its summer set point temperature. Once the internal temperature rises above the set point, the windows open to provide cooling and the borehole cooling system operates, if required. When additional cooling is still required, the stack fans switch on to increase the ventilation.

Summer Night

Night ventilation is activated, provided the external air temperature has dropped below the air temperature in the building. When the opening of windows does not provide enough airflow through the building, the stack fans operate to exhaust hot air from the building, drawing cool night time air in. When external air temperatures cannot provide enough cooling, the borehole cooling system operates.

Adaptive Opportunities

Providing occupants with control over their local environment has been achieved by ensuring that every control system is capable of being overridden manually. Using infrared remote controls, all occupants are able to control the systems which influence their own local environment. With the exception of the manually operated windows, these systems include thermo-statically controlled radiators, external shading devices and artificial lighting. Adjustments made to the systems by the occupants are re-set everyday at midnight by the BMS, providing a balance between energy efficiency and occupant comfort.

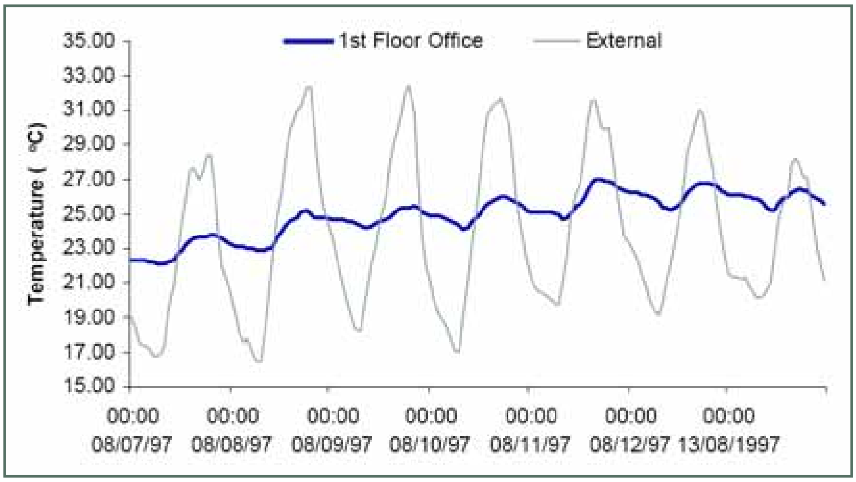
Reducing Heat Gains in the Building

Having chosen a highly glazed (50% glazing) south façade to maximise natural daylighting, an external shading system was required to reduce solar heat gains.

A rotating shading system was developed using fritted glass louvers. The louvers are treated with a white ceramic coating on one side, and a reflective surface finish on the opposite side. This gives the louvers a 40% light transmission factor and a 50% reflectance factor respectively. The louvers are designed to cut out all direct sunlight during the summer without limiting the availability of diffuse daylight. When the external lighting level is low, the louvers open past their horizontal position, so that they act as external light shelves, reflecting daylight into the offices. By dynamically reacting to solar intensity, the louvers are designed to reduce solar heat gains, whilst also improving the amount of daylight available to the offices by 15% over the course of a year. Moving no more than once every 15 minutes, the louvers cycle time provides optimum performance without becoming a source of distraction to the occupants of the building.

While the building has been designed to maximise the use of natural daylighting, high efficiency lighting has been installed in the building to reduce energy consumption and internal heat gains. The offices are lit with high frequency fluorescent lamps to a relatively low general light level of 300 lux, with task lights being used to provide 500–600 lux locally. As the daylighting levels in the offices increases, the output from the luminaries is reduced accordingly. There is a facility to reduce artificial lighting level gradually so that changes in lighting are almost imperceptible to the occupants of the office. As internal daylight rises from 300 lux to 400 lux, the output of the luminaries will be reduced from 100% to 0%. Lights are switched off when an office becomes unoccupied, while occupants can manually override the BMS settings using their infrared controls. These measures combined are intended to reduce the peak summer temperatures by 0.5–1.0° C.

Mechanically actuated louvers, installed on the buildings south facade. Source: Denis Gilbert



Hourly average temperatures recorded during a peak of warm weather in 1997. Source: BRE

Thermal Performance and Occupant Comfort

The BRE building has been monitored over the course of three years from 1997 to 1999, during which time the thermal comfort provided in the building has exceeded expectation. Stable temperatures were achieved in all the office spaces even during the last week of August when external temperature reached a summer high of 33°C. The thermal performance criteria set out in the brief were met, with the exception of one area of the top floor, which exceeded 25°C for 11% of the total monitoring period.

Borehole cooling was not often needed, but when it was activated it delivered 8.6kWh of cooling energy for every 1kWh of electrical pump energy, making it an extremely efficient method of summer cooling. From the occupants standpoint, the building has been a success with surveys showing that 80% of the building's occupants are happy with their new facility, where only 30% had been happy in their previous building.

Overall Performance

The BRE building uses half the energy required by a typical air-conditioned office, based on the benchmarks outlined in the Energy Consumption Guide 19. Despite this, the energy performance of the building in its first year of operation fell short of the initial energy target by 60%, requiring 144kWh/m^2 compared to the target of 83kWh/m^2. In 1997, as performance results were beginning to accumulate, it became clear that heating energy consumption was excessive and an air leakage audit was commissioned immediately. The audit identified that the air leakage into the office areas was 60% higher than expected, while air leakage for the building as a whole exceeded original targets by 100%.

The high infiltration rates resulted in excessive heating energy consumption until remedial action was completed in 1999. This intervention immediately reduced the heating energy demand in the offices by 22%. Although an air leakage rate of $7.5m^3hr/m^2$ had been discussed at the design stage, all members of the design team agree that a specific air leakage rate requirement should be specified in the contract prior to construction in future projects.
Employing a combination of proven low energy design principles and technologically advanced concepts, the BRE building achieves high levels of thermal comfort without the need for air-conditioning. Using passive strategies by default, active systems are relied upon only during peak periods; moreover, a particularly robust control system has been developed where the provision of comfort does not rely on one system, but on the collective contribution of a number of well managed environmental controls.

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Exterior view of Limerick County Hall. Source: Brian Murphy

4. Limerick County Hall

Client
Limerick County Council

Architects
Bucholz McEvoy

Building Services Engineers
Buro Happold

Outline of Thermal Mass Strategy

Vaulted concrete soffits are employed as the main components of the thermal mass strategy; while night cooling is exercised extensively throughout the building using BMS controlled, mechanically actuated windows.

Project Description

In 1998 Architects Bucholz McEvoy were awarded the commission to design Limerick County Hall. Their project brief was to design a new headquarters to accommodate and enhance the public services offered by the council and to provide office space for 260 employees.

The performance targets for Limerick County Council's headquarters were adopted from BRECSU report 30's 'Energy Efficient Office of the Future' (EOF) best practice guidance. The building is designed not to exceed a daily temperature of 28°C for more than 1% of the year and not to exceed 25°C for more than 5% of the year. Air velocities within the building are to be maintained below 0.8m/s. The building was developed as a low energy building from the outset and Buro Happold were employed to design/integrate the necessary energy saving features into the building's design.

Building Form and Layout

Located in Dooradoyle, Co. Limerick, the building is organised into two distinct blocks. The main five-storey block provides 7,100m² of floor area within the confines of a 12.7m floor plate. Its southwest elevation is dominated by a large common atrium into which the top four levels of office accommodation open. A smaller three-storey finger block intersects the main

A high quality surface finish is achieved on the slab's undersides and lighting fixtures have been carefully integrated into the ceiling system. Source: Brian Murphy

Internal view of the south facing atrium showing the degree to which the external Brise Soleil shades the interior. Source: Michael Moran

building's southwest façade and has been designed to accommodate the council chamber, a restaurant, as well as the main public entrance. The building is strategically split into zones, with the functional requirements of each zone dictating the environmental control strategy used. Passive ventilation is employed in the offices; mechanical extract ventilation is used in the kitchens and toilets, while comfort cooling has been provided in the council chambers.

Thermal Mass in the Building

The building is composed of predominantly pre-cast elements, including a post and beam structural frame, concrete floor slabs and heavy internal partitions. It has been estimated that the building contains 300 cubic metres of concrete, most of which has been left exposed to the interior. Vaulted concrete soffits are provided in all the office areas. These six metre long slabs were cast in fibreglass moulds that had been fabricated by a boat builder, allowing an elegant form and high quality surface finish to be achieved.

Passive Ventilation

The outline form of the Limerick County Hall has been developed to support a passive ventilation strategy. Orientated to face directly into the prevailing south-westerly winds, the building's shallow floor plate supports a cross ventilation strategy. On warm windless days the four story atrium generates air movement via the stack effect, drawing air through the offices before expelling it through high level vents.

Air enters and leaves the building through approximately 90 mechanically actuated windows and vents. These windows operate under the control of the BMS, but they are also equipped with a manual override facility. When wind or rain precludes the opening of windows, a mechanical extract fan, located in the atriums roof, draws air through the offices from louvered ventilators located in the building's façade. Careful consideration has also been given to the internal layout of the offices. Low internal partitioning has been provided in all of the open plan offices, in order to encourage airflow and improve daylight penetration. Private offices with full height partitioning have been located so that they do not compromise the ability to cross ventilate. The impact that future partitioning will have on the ventilation strategy has also been considered, using a series of computational design studies. A simple set of recommendations were drawn up so that Limerick County Council can reconfigure office space in the future, without compromising the air flows through the building.

Night Ventilation Strategy

Night time cooling is enabled during summer months and non-occupied periods by the BMS. Night cooling is initiated based on feedback from temperature sensors located throughout the building. Each zone is provided with at least two averaging air temperature sensors and one slab temperature sensor; in addition, the external conditions are assessed using a roof top weather station, which collects temperature, wind speed, wind direction and rainfall. Night ventilation is initiated in each zone, independently, under the following control regime.

Automated windows/louvers open to 100% if the following conditions are met:

- The building is in a non-occupied period (6pm to 8am), during summer months.
- The average external temperature between 12am to 5pm exceeded 18°C.
- The average zone temperature exceeded 22°C and/or the zone slab temperature exceeded 22°C.
- The average internal air temperature exceeds the external temperature.

The windows/louvers remain open through the non occupied period provided that

- The average internal air temperature exceeds external air temperatures.
- The wind speed does not exceed a preset level.
- It is not raining

- The average internal air temperature exceeds the heating low limit set-point, set at 12°C.

When the lower set point temperature is achieved, windows/louvers close. Windows will generally open again as the temperatures inside the building are expected to increase steadily as remaining heat stored in the fabric and furniture radiates to the interior. The windows will modulate between open and closed in this way until the preheating period is reached. The BMS calculates this as the time at which the windows/louvers must be shut in order that the passive heating from the fabric, furniture and fittings of the zone can heat the space to the passive heating set point of 19°C by the start of the occupation period.

The BMS carries out a further calculation after the start of the pre-heat period to assess if the building will reach the passive heating set point by the start up of occupation. If it is calculated that the set point will not be reached, then the heating plant will be enabled under the dictates of the optimum start routine.

Reducing Solar Gains

Buro Happold conducted design studies at various stages in the building's development. Using TAS, Thermal Analysis Software, it was possible to determine what specific measures could be adopted to ensure that the comfort targets outlined in the brief could be achieved.

TAS was used to investigate the influence that solar gains would have on internal temperatures.

Early morning sun, streaming in through the office elevation, was found to be of sufficient intensity to cancel out the effects of the previous night's cooling strategy. This observation led to the specification of solar control glass with a 60% shading coefficient. The Brise Soleil, which was required to shade the atriums glazed façade, was also modelled, allowing the effectiveness of different louver configurations to be investigated. This study produced a set of recommendations, which were used in its final design. Instead of adopting a conventional louvered configuration, RFR, the façade engineers were given the freedom to create a saw-toothed form, which was intended to intercept both midday and evening solar gains.

Reducing Internal Gains

By maximising natural daylighting, the requirement for artificial lighting has been reduced and the associated heat gains have been avoided. Daylighting through the north east façade is enhanced using specially configured floor slabs which protrude through the building's envelope to act as light shelves. The vaulted ceiling soffits rise from the centre of each office towards the perimeter windows, improving daylight penetration and distribution within the building.

Internal blinds have been omitted in favour of local shading devices. Each occupant is provided with a movable shading device, which can be used to intercept glare without compromising the overall day lighting strategy.

Luminaries are configured to provide 300–500 lux on the working plane, through a combination of up-lighting of the concrete soffit and down-lighting. To achieve the lowest possible energy use, a lighting control system modulates in accordance with the amount of natural daylight that is available.

Overall Performance

The target energy performance for this building is predicted to be 76.4kwh/m^2/yr. This figure represents an 80% saving on the energy used by a typical air-conditioned building (based on ECON benchmarking). Using passive strategies to obviate the need for air conditioning, the building is expected to save 400 tones of CO_2 emissions per year.

The external façade showing the manually operated ventilator casing and the internal light shelf. The vaulted concrete soffit has been designed to taper up, to maximise the amount of daylight which enters the room. Source: Michael Moran

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Exterior view of WIT library. Source: A &D Wejchert Architects

5. WIT Library

Client

WIT

Architects

A & D Wejchert Architects

Building Services

J.V. Tierney and Co.

Energy Consultants

UCD Energy Research Group

Outline Thermal Mass Strategy

Thermal mass is provided using a range of elements including exposed blockwork and plain exposed concrete soffits. In addition, the thermal mass available in the floor slabs is utilised by mechanically ventilating the void formed below the raised floor. The building can be flushed with cold air at night using both the mechanical ventilation system and the passive airflows which can be generated in the north facing atrium.

Project Description

As part of the overall campus expansion, the new library was completed in 2,000 to cater for the needs of 1,200 of WIT's students. Apart from containing a traditional library, the building also accommodates a number of seminar rooms, a lecture theatre, an electronic learning centre, as well as reading rooms and a bookshop.

High internal heat gains were expected in the building, as a function of high occupancy and I.T. equipment densities. Despite this, the design team was asked to develop a low energy solution to provide a comfortable environment inside the building. Achieving this required that passive environmental strategies be adopted to alleviate the requirement for full air conditioning. The resulting design was awarded the sustainable building of the year in the education and healthcare category of the construction excellence awards in 2000.

Building Form and Layout

Passive environmental control is one of the generating forces behind the linear nature of the building. Organised along an east west axis, the shallow floor plate of the two-storey building ensures maximum use can be made of daylighting and natural ventilation. The library is organised around three staggered floors which all open into a large atrium on the north elevation of the building. Smaller seminar rooms and computer suites are located along the building's south elevation.

Thermal Mass in the Building

The decision to create a heavy structure to minimise temperature fluctuations within the building has been astutely executed. Thermal mass has been provided using all the elements of the building's structure, including the external envelope, internal partitions, floor slabs and ceiling soffits.

A crucial element in thermal mass strategy was the provision and configuration of a 215mm cast in-situ

Internal view of north facing zone, showing generous levels of natural daylighting. Source: A & D Wejchert Architects

Exposed concrete floor soffit. Source: A & D Wejchert Architects concrete slab. The thermal mass of this slab was fully realised with an exposed soffit providing a thermal link to the environment below and a ventilated raised floor allowing convective heat transfer to occur between the slab and the air destined for the room above. Although hollow blocks have been used to construct the building's external walls, maintaining a fairfaced finish to the interior has enhanced the thermal mass they provide.

All these measures combine to produce a situation where thermal mass is provided by all six-component surfaces in many rooms.

Cooling the Building

The requirement for a quiet environment inside the library required that windows on the south façade be sealed to reduce the impact of traffic noise from the busy Cork road outside. This required that ventilation requirements be provided using some form of mechanical ventilation. A number of different systems were considered, but the mechanical ventilation of the raised floor was chosen, as it allowed the hidden mass of the slab below to be utilized. The 335mm deep void created between the concrete floor slab and the raised floor is used as a plenum to distribute air throughout the building. Air from the void passes to each zone via a system of grilled inlet diffusers embedded in the floor. The air is then extracted from the zone by return fans, which are connected to high-level outlets in the rooms.

There is a reduced requirement for mechanical ventilation in the north-facing zone where buoyancy-driven airflow is generated in the triple height space. Airflow develops naturally from low level inlets located along the atriums perimeter to high level outlets integrated into the highest point of the atrium's façade.

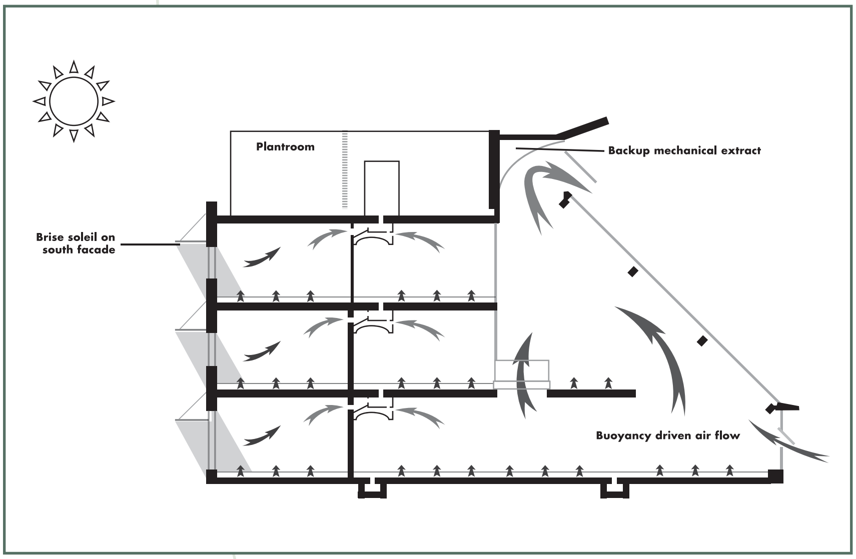
Both mechanical and passive ventilation is utilised in the building's night cooling strategy. During the night, air dampers are automatically opened to provide a direct route for outdoor air into the supply air fans. The reduced friction in the system causes an increase in airflow rate from four to eight air changes per hour. The return fan continues to operate at night, exhausting air to outside at six air changes per hour, with the high level atrium vents being opened to exhaust the remaining two air changes per hour.

Heating the Building

In addition to a heat recovery system, heat is provided to the building by three high efficiency gas fired boilers, with a condensing boiler taking the lead load, while the atrium is heated using a ground coupled heat pump, which uses water pumped from a borehole drilled 160m below ground level as its heat source.

Thermal Control

Year round comfort is provided in the building using the following control strategies.



Cross section illustrating different zones in the building and the ventilation strategy. Source: A & D Wejchert Architects

Daytime Operation

- The overall objective of the control strategy is to provide a minimum supply air temperature of 18°C to avoid discomfort from the floor discharge grilles and a return air temperature set point of 20°C.
- When external air temperatures are below 18°C, the heat recovery system operates to elevate incoming air temperatures. Should additional heating be required, the lead gas-condensing boiler provides heat to the AHU's.
- When internal air temperatures approach 20°C, cooling is provided by increasing the introduction of full fresh air to a maximum of six air changes per hour.

Night time Operation

- The overall objective of the night ventilation system is to achieve an indoor air temperature of 19°C at the beginning of occupancy the following day.
- At 10pm the library doors close and the air handling units are switched off.
- A period between 10pm and 12pm is provided to allow the temperatures within the building to stabilize and also to provide a window of opportunity for cleaning within the library to be conducted before the night cooling process commences.
- At twelve midnight the night cooling cycle commences and the indoor air temperature is sampled. Ventilation begins if the indoor temperature is above 22°C, and there exists at least a 4°C temperature difference between internal and external air.
- This procedure is programmed to repeat itself at 2.30am and 4.30am, with night cooling continuing through these periods, if the criteria outlined above are satisfied.
- The night cooling system is required to switch off at 6am to allow early occupancy within the building for maintenance and cleaning. This period has also been provided to allow the internal temperatures to

stabilise at 19°C, before the start of occupancy at 8am

- A low temperature limit of 13°C has been provided, to preserve the building's book collection and equipment.

Dynamic Simulation

The building has been simulated extensively at different stages during its development. At the design stage Vesol was asked to conduct a number of design studies to assess the expected thermal behaviour of the building, and to establish under what circumstances overheating could become an issue. The study investigated the thermal conditions in different parts of the building under the influence of increasing levels of internal heat gains and provided the following results and recommendations.

- Under peak cooling conditions the exposed under floor slab can cool the supply air down by up to 3.7°C.
- The computer suite, which contained 43 terminals, was shown to run the highest risk of overheating. Initial simulation showed that the heat gains associated with a conventional computer suite would have resulted in summertime peak temperatures of 30.9°C. Reducing internal heat gains from 102 W/m^2 to 36W/m^2, which was to be achieved using high efficiency peripherals and flat panel monitors, was expected to reduce the worst-case peak summer temperatures to 27.6°C. This information proved invaluable at the design stage, resulting in flat panel monitors being specified in the computer suites' eventual fit out.

A masters student in UCD carried out further simulation. His research focused on the performance of the night cooling strategy in the same computer suite. His research produced the following insights.

- The effects of increasing the thermal mass of the materials used in the room's construction were investigated. The external walls in this zone were converted from the original 215mm hollow blocks to a heavy weight 0.5m thick construction. The internal walls were converted from a single cavity block, of thickness 0.14m to heavy 0.3m solid concrete blocks, while the thickness of the ceiling slab was increased from 0.25m to 0.3m. These modifications increased the available thermal mass in the zone from 887kg per m^2 floor area to 1567 kg per m^2 floor area. The combined influence of this additional thermal mass was predicted to reduce the peak internal temperatures by a further 2°C, and a three-hour delay in peak temperatures was observed.
- The night ventilation procedure employed in the library is predicted to reduce peak temperatures by up to 1.6°C and mean daytime temperatures by up to 1.7°C.
- The risk of overcooling the building was found to be negligible in the cases studied; it was found that cooling the building below 18°C did not result in uncomfortable conditions at the beginning of occupancy the following day. Resultant temperatures inside the building were observed to rapidly increase as soon as night ventilation finished.
- Increasing the night ventilation rates inside the building from 4 ACH to 20ACH reduced peak next day temperatures by 0.4°C, but the increased fan energy consumed in providing these air change rates was not investigated.

Overall Performance

The thermal environment inside the computer suite was monitored during the summer of 2003.

Air and fabric temperatures inside the building at night were observed to drop to 17.5°C and 19°C respectively when night ventilation was employed and peak daytime temperatures were not observed to increase beyond 21°C. The monitoring programme established that the night cooling strategy was capable of maintaining internal temperatures within comfort limits and that it does so using very little energy.

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Slit windows have been incorporated into the library's south façade to reduce solar heat gain. Source: Brian Murphy

6. James Ussher Library

Client

Trinity College Dublin

Architect

McCullough Mulvin Architects and KMD Architecture

Building Services Engineer

Homan O'Brien Associates

Outline of Thermal Mass Strategy

Plain exposed concrete soffits, exposed blockwork, floor void ventilation and fin shaped up-stand beams all contribute to this building's thermal mass. Passive cooling and ventilation strategies operate by default with active systems being employed during peak periods. The ability to operate predominantly using passive measures is facilitated to a large degree by the temperature moderating influence of thermal mass in the building.

Project Description

Formally opened in 2003, the James Ussher library is the result of a limited competition, to design a building, which would accommodate Trinity College's growing student population. Developed as a collaborative project between McCullough Mulvin and KMD Architecture, the main functional requirements for the library included 750 additional reader spaces, space for 350,000 additional volumes on open access and the provision of fast information access using extensive IT networking. Later additions to the brief included the Glucksman map library, Irelands largest map collection and a special book conservation unit.

Building Form and Layout

Located on campus, and visible from Nassau Street, the building nestles between and physically links the pre-existing Berkeley Library to the north and the Arts Building to the west. Rising eight storeys from a basement located two and a half storeys below ground; the building is split into two distinct blocks by a narrow glazed atrium orientated along a north south axis. The taller western block is dedicated to book storage, while reader spaces are provided in the eastern block.

Thermal Mass in the Building

Providing a thermally massive building has been achieved by exploiting all elements of the building's structure, including walls, floors, and ceilings. A fairfaced finish has been maintained on the block work of most internal walls, while the west façade, which is constructed using reinforced concrete panels, is also exposed to the interior. The thermal mass available in the intermediate floor is fully realised with both the upper and lower surfaces of the concrete slab being utilised. An exposed profiled soffit is provided to the slab's underside while the upper side is thermally linked to the space above by mechanically ventilating air

The atrium provides both natural daylight and fresh air to the core of the building. Source: Christian Richters between the slab and the raised floor. In addition, the structural up-stand beams used in the library are fin shaped in cross section to maximise the surface area of exposed mass that they provide.

Cooling the Building

A combination of passive and mechanical ventilation is employed in the building. The primary generator of passive ventilation is the eight-storey atrium located centrally in the building. Air moves up through the atrium under the influence of a combination of wind and buoyancy driven currents, providing a facility where vitiated air from all levels of the building can be expelled through vents located in the atriums roof.

Additional ventilation is provided in the readers' block in a number of ways. Air is introduced directly into the space using a combination of manually operated windows and mechanically actuated ventilators.

Operable windows have been provided on all levels apart from the ground floor, where security was of primary concern. The mechanically actuated ventilators, which are located at high levels in the external façade, are particularly effective in providing night cooling, as they promote air movement over the underside of the exposed concrete soffits. An additional 3ACH is provided using a low capacity mechanical ventilation system. Air drawn through vents in the external façade is circulated inside the void below the raised floor, before finally entering the space through an array of low velocity floor outlets.

An air chiller is provided as a fail-safe system to trim 3°C off peak temperatures. The peak temperatures experienced in the building generally only occur in the run up to college exams, when the library is operating at full capacity.

Overall Performance

The James Ussher library has been monitored as part of a joint energy saving initiative between UCD, DIT, TCD and DCU. A special energy management bureau called e3 was set up in 2003 to carry out the work. Apart from being one of the most efficient buildings monitored, with an energy rating of 214 kWh/m^2, the building's energy consumption is approximately half that of a typical air-conditioned building, based on the benchmarks outlined in the DETR, 'Energy Consumption Guide 19'.

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Interior view of the library's narrow atrium. Source: Christian Richters

Interior view showing the exposed concrete soffits and the fin shaped up stand posts. Source: Christian Richters

Exterior view of Hockerton Housing Development. Copyright of Hockerton Housing Project

7. Hockerton Housing Project

Architects

Brenda and Robert Vale

Outline of Thermal Mass Strategy

The thermal mass provided by the concrete slab construction serves as the crucial element which allows such a highly insulated building to adopt a passive solar collection strategy without over-heating.

By insulating the slabs externally and exposing them internally, the full potential of the buildings storage has been realised, resulting in a degree of inter-seasonal heat storage, and a nominal annual requirement for active space heating.

Project Description

The Hockerton housing project was designed to provide five families with the opportunity to live in an ecologically sensitive way where they would be self sufficient in food, water and energy. Apart from requiring the scheme to be built within the budget of a typical residential scheme, the client also requested that the building should be CO_2 neutral and pollution free in operation.

The combined provision of a highly insulated envelope with a thermally massive internal structure has allowed the building to utilise passive solar heating year round to provide comfort conditions, without the need for supplementary heating.

Designed by Brenda and Robert Vale, the Hockerton housing project is located just outside the village of Hockerton in rural Nottinghamshire. Located on a ten hectare site, the terrace of five houses is built into a gentle south-facing slope. The five hundred tons of earth that was excavated from the slope was used to cover the roofs of the buildings providing shelter and additional thermal mass. The earth sheltering also provided the terrace of houses with an unobtrusive appearance, which aided the acquisition of planning permission in this rural setting.

A common conservatory, which spans the south façade of all five houses, serves as both a recreational amenity and the primary means of passively heating the buildings. Internally the plan is designed as a repeating series of structural bays, 3 meters wide and 6 meters deep, with a 3 meter high roof on the south façade, sloping to 2.3 meters at the rear of the building.

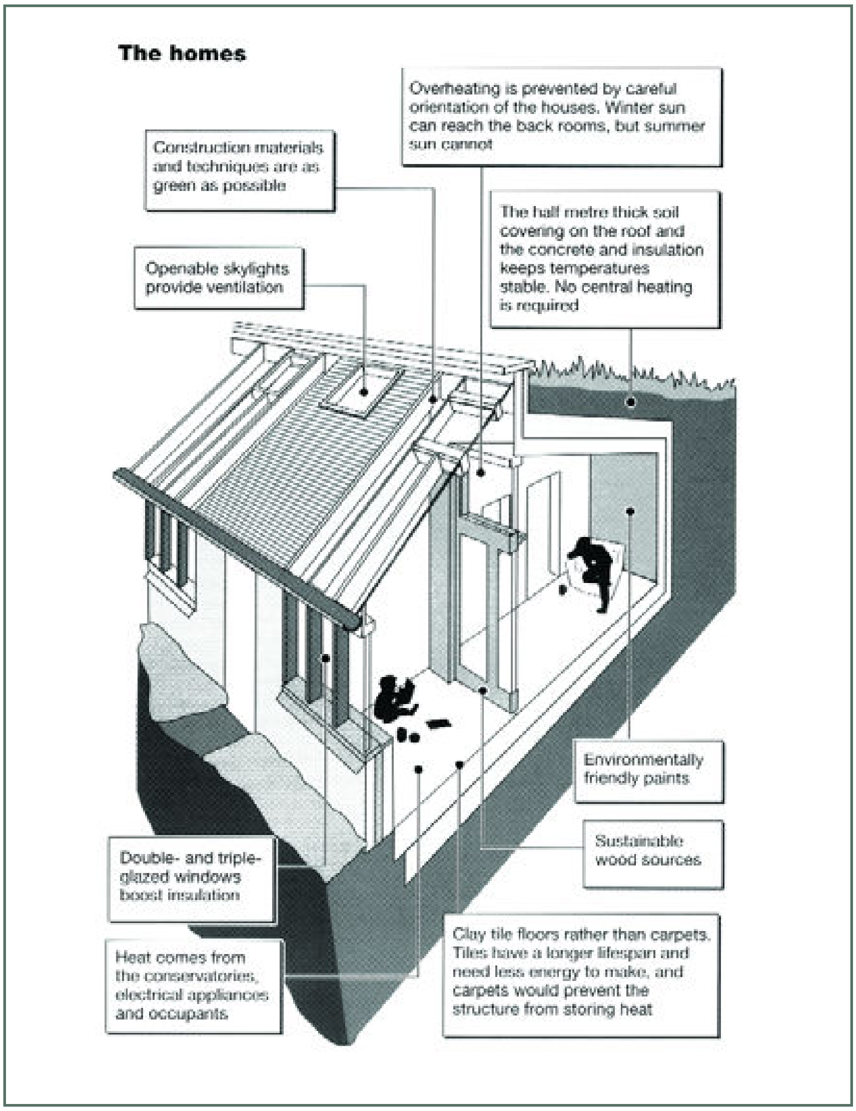
South facing conservatory acts as a large suntrap. Copyright: Hockerton Housing Project

The slab construction is left exposed internally in this room, allowing the walls and ceilings to contribute thermal mass. Additional thermal mass is provided by the tiled floor, which creates a thermal link to the ground floor slab. Copyright: Hockerton Housing Project

Thermal Mass in the Building

Constructed using an assembly of concrete slabs the resulting structure contains 2.3 tonnes of concrete per meter squared of floor area. The roof is constructed with a 300mm reinforced concrete slab while the slab, which forms the back wall, is 450mm thick. By externally insulating the envelope, the designers have ensured that the entire concrete structure is permitted to operate as a thermal mass. All surfaces remain exposed internally including the 200mm internal load-bearing walls.

The massive structure is intended to provide the buildings with some degree of seasonal storage, allowing heat gains collected during the summer to offset heating requirements during the winter.



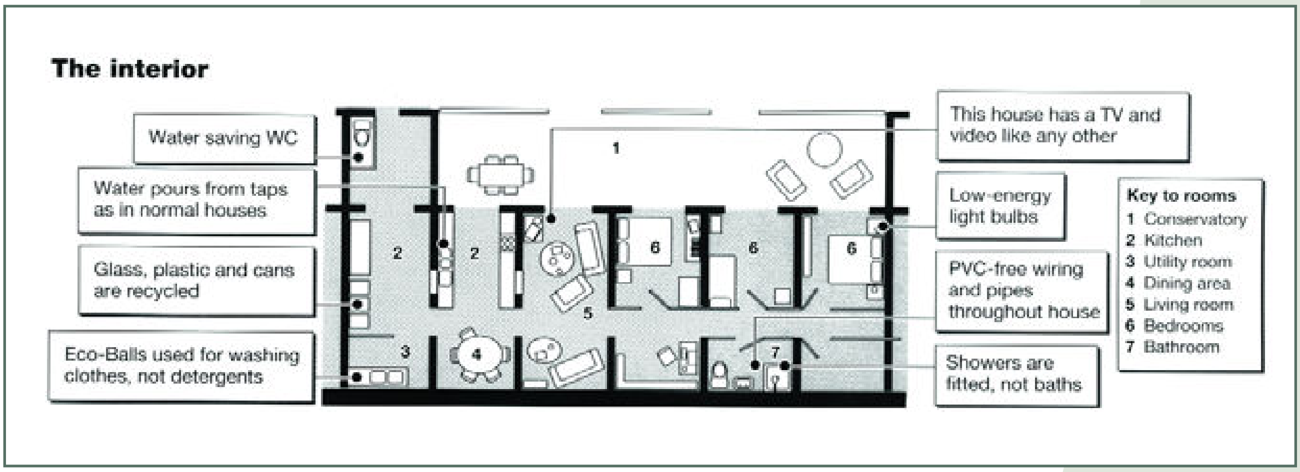
Component parts of the Hockerton buildings. Copyright: Hockerton Housing Project

Thermal Preservation

The concrete structure of the Hockerton houses is insulated externally using 300mm of expanded polystyrene, providing the walls, roof and floor with a U-value of .11W m²/K. The windows, which open into the conservatory, are triple glazed, while the glazing used in the conservatory itself is double-glazed.

Arranging the houses in a long terrace has proved effective in minimising heat loss, as it reduces the number of gable ends from which transmission losses can occur from ten to two.

Using mechanical ventilation and heat recovery obviates infiltration heat losses. An air management system is installed, which recovers heat from stale air, which is mechanically extracted from wet areas, toilets, bathrooms and kitchens, while introducing the equivalent volume of preheated filtered air to the main living areas of the buildings. Operating continuously at low speeds, this system recovers up to 70% of the heat from the exhaust air.



Internal Layout of the Hockerton dwellings. Copyright: Hockerton Housing Project

Passive Solar Heating

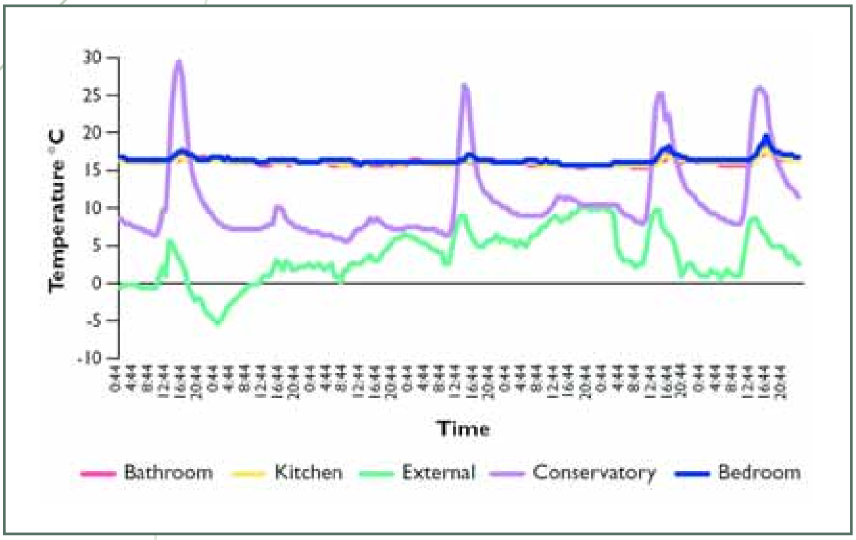
The conservatory, which is orientated to face south, functions as a large solar collector. Heat transfer from the conservatory to the interior rooms can be achieved by opening the three metre high intermediate windows. This free thermal energy is absorbed by the internal structure during the day, with heat being released back to the internal environment at night, when the air temperature drops below that of the concrete surfaces.

The internal partition walls are particularly effective at absorbing solar radiation as, apart from being aligned to receive direct solar radiation in the morning and evening, each wall also presents two surfaces with which to charge and discharge.

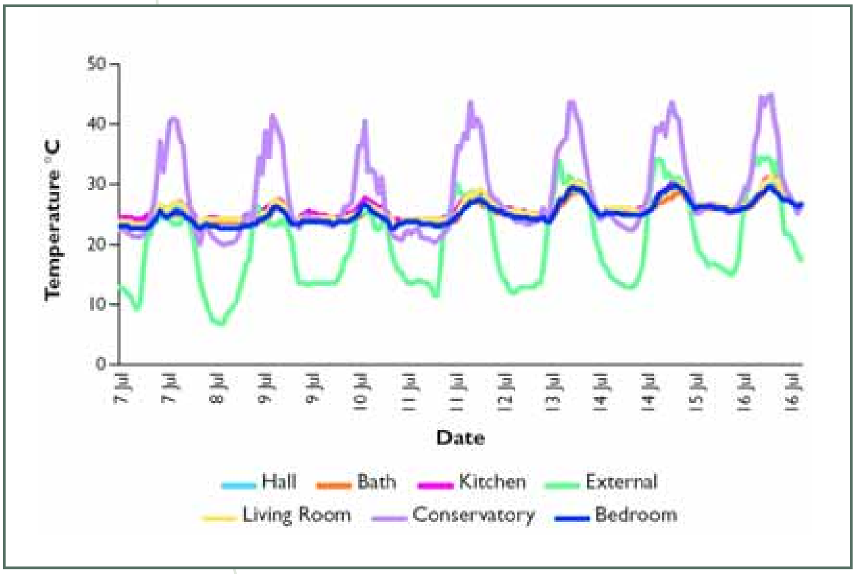
Avoiding Overheating

Integrating a high degree of south facing glazing into a well insulated building elevates the risk of overheating. While thermal mass provides a passive solar building with the opportunity to store heat for future use, it also serves to attenuate instantaneous solar heat gains providing a measure of control against overheating.

A combination of passive and mechanical ventilation is used to provide supplementary comfort cooling. Opening windows and doors into the conservatory allows warm air from the building's interior to be exhausted through high-level Velux windows in the conservatory's roof. During particularly warm spells a degree of night cooling can be achieved by opening windows at night while blinds can be drawn in the conservatory to curtail heat gain during the day.



Air Temperatures record inside a home during a cold winter week. Information courtesy of the Energy Saving Trust



Temperatures recorded inside a home during a warm summer week. Information courtesy of the Energy Saving Trust

Overall Performance

A monitoring campaign on one of the Hockerton Houses has determined that these houses require 75% less energy than a typical residential home. The daily consumption is around 25% lower in the summer than in the winter as there is a reduced requirement for artificial lighting. While the annual energy consumption is only 43kWhr/m² the study revealed that this figure could be reduced by a further 33% by replacing the freezer with a more efficient model, and by installing an air to water heat exchanger to provide domestic hot water.

The thermal performance of the houses has been monitored independently as part of BRECSU's "Energy Efficiency Best Practice Programme". Recording results on a half hourly basis throughout the year, the survey shows the temperatures in the buildings to be very stable with changes in external temperatures not being reflected inside the houses for several weeks.

During the summer months, typical temperatures inside the building remained at 24°C, while the temperature in the conservatory often rose to over 30°C. The coldest week in the winter of 1998–99 saw external temperatures drop to below 5°C, while the temperatures inside the buildings remained stable at 17°C for most of the week.

The occupants reported that the houses did not feel cold during the winter, although there was occasional use of supplementary heating provided by small electric convectors. Where all the occupants in the scheme were enrolled and familiar with the development's low energy intentions, the occupants may have found it easier to adapt to the relatively low winter temperatures.

Where typical residence cool down at night the stable diurnal temperatures provided inside the Hockerton houses caused some occupants to feel too warm at night.

A three-pronged approach, involving passive solar collection, storage and preservation is evidenced in the conservatory, the massive internal structure and the exterior insulation, respectively. Where these elements have combined to produce energy efficient buildings, the success of this project as a whole has relied to a large extent on the common desire amongst the residents of the scheme to live in an ecologically sustainable way.

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Exterior view of the Green Building. Source: Bill Hastings, ARC Digital Photo Graphics

View towards the atriums skylight, showing the specially commissioned ducting that is used to transport fresh air down to the lower levels of the building. Source: Bill Hastings, ARC Digital Photo Graphics

8. The Green Building

Client
Temple Bar Properties

Architects
Murray O'Laoire Architects

Building Services Engineers
Homan O'Brien Associates

Outline of Thermal Mass Strategy

A heavy concrete skeleton composed primarily of dense blockwork and plain exposed soffits has been provided to moderate the internal climate in this mixed use development. Insulated externally and exposed internally the thermal mass of the structure is capable of directly intervening to dampen temperature fluctuations within the different zones of the building.

Project Description

The Green Building located in Temple Bar is a mixed-use development, which provides a high-profile demonstration of environmentally conscious design. Daylighting, fan-assisted natural ventilation and passive solar heating are employed within a thermally massive structure to provide an environmentally sound building with considerable potential for replication.

The decision to employ passive ventilation or passive solar strategies has often been dismissed in city centre locations where air pollution and overshadowing are both concerns. Avoiding the use of heavy servicing in the Green Building required that the design team develop effective solutions to surmount the limitations presented by a less than ideal site. A large tapering atrium distributes light deep into the core of the building, while air is filtered at basement level before entering the building's central courtyard.

Completed in September 1994, the building has been described as "a globally unique role model for environmentally responsible urban renewal and living", and has attracted widespread coverage in the media and the press. The added value that a "Green" project can generate is evidenced in the fact that all apartments were sold within minutes of being put on the market, with some 15,000 members of the public having visited the building in its opening three weeks.

Building Form and Layout

Located on a 26m x 11m site the building has façades, which look onto Temple Street to the west and Crow Street to the east. The building is laid out around a six storey central courtyard, with eight apartments on the top three floors, offices on the first floor, and retail space at ground and basement levels.

Thermal Mass in the Building

Thermal mass has been provided in the

Green Building by purposely using heavy construction materials throughout. The entire structure has been constructed using dense 215mm concrete blocks. These blocks are insulated externally with mineral fibre insulation to form the external envelope and are plastered to form the partition walls inside the building. A cast in situ construction was used to form the intermediate floor slabs.

Special efforts have been made to expose all concrete surfaces internally, with plastered concrete soffits being provided in both the offices and the apartments. Achieving such a high degree of exposed mass required that the services, which would typically have been routed behind plasterboard or above a suspended ceiling, be boxed out and distributed along the underside of the soffits.

Passive Strategies

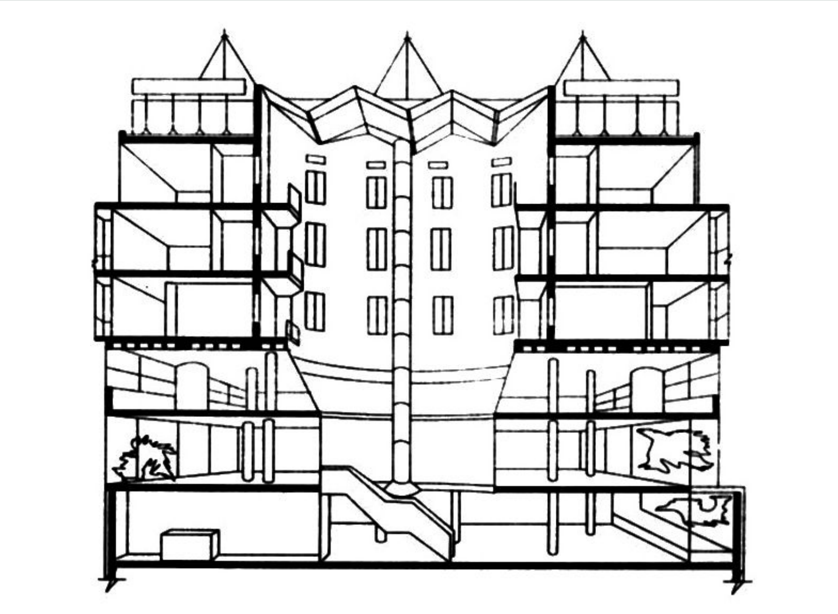
Passive ventilation is employed by default with fan assistance being used when the CO_2 level in the atrium exceeds a preset limit. In summer, air is sourced at street level and passes through basement planters to be cleaned and humidified before entering the central courtyard. Natural buoyancy drives the air up through the atrium providing adequate ventilation to the offices and apartments on each floor. In winter the heat from air trapped at the top of the atrium is recovered and used to heat incoming air, which is fan assisted through vents in the atriums roof into a specially designed duct which transports the air down to lower levels.

Apart from introducing generous amounts of daylight into the core of the building, the atrium also operates as a suntrap to some degree. A large glazed rooflight at the top of the atrium collects sunlight, the light coloured walls and tapering cross-section of the atrium distributes light down to the ground floor where dark surface finishes have been specified on heavy construction materials to improve solar absorption.

Renewable Systems

While the fabric and form of the building has been exploited as the primary components in the low energy strategy, a number of renewable technologies have been included to further reduce primary energy consumption. A bank of 24 heavy-duty lead-acid batteries are charged by 76 roof-mounted (50W peak) photovoltaic panels, and three (1.5kW peak) wind generators. This array provided 100% of the building's energy requirements during its initial test period. Water heating is provided by 40 evacuated tube solar collectors, which are also mounted at roof level, while space heating is supplemented using an under floor distribution system which extracts heat from a 150m borehole using a high efficiency heat exchanger.

Solar-thermal collectors provide the building with hot water while photo-voltaic panels and wind turbines provide off-grid electricity. Source: Bill Hastings, ARC Digital Photo Graphics



Cross section through the building, showing the centrally located atrium. Source: Murray O'Laoire Architects

This ventilation shoot was specially commissioned to transport fresh incoming air from the top of the atrium down to the offices on the ground floor. Source: Bill Hastings, ARC Digital Photo Graphics

Overall Performance

Tim Cooper, who was director of buildings in TCD at the time, has monitored the building as part of the EU Thermie programme. Teething problems were experienced during the building's commissioning but feedback provided by the monitoring campaign allowed the individual building systems to be fine-tuned.

Total net consumption of energy is as follows: cooling, 2 GJ/year; heating, 39 GJ/year; hot water, 8 GJ/year; motors, 22 GJ/year. The PV panels provide all the electricity requirements for artificial lighting.

Total energy consumed is thus 71 GJ/year, compared with 519 GJ/year for a typical conventional building of the same size.

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Bedroom showing exposed concrete ceiling soffit. Source: Raf Makda/ View Pictures

Exterior view of the BedZED development. Source: Raf Makda/ View Pictures

9. BedZED

Clients

Peabody Trust

Architects

Bill Dunster Architects

Building Service Engineers

Arup Associates

Outline of Thermal Mass Strategy

Thermal mass, provided by heavy-weight walls, exposed slab soffits and tiled floors serves to increase the amount of passive solar heating that can be utilised on an annual basis. Where heat losses have been minimised using high levels of insulation and a heat recovery system, thermal mass also allows the risk of overheating during warm summer periods to be offset.

Project Description

Completed in 2002, the Beddington Zero Energy Development is the UK's first urban, carbon neutral development. Appointed by the Peabody Trust in 1999, Bill Dunster Architects and Arup Associates were asked to design a low energy housing scheme that would provide people with the opportunity to live in a sustainable way without having to sacrifice a modern, urban and mobile lifestyle.

The combination of super insulation, a wind driven ventilation system and the provision of a high degree of thermal mass to store solar gains, reduces the need for both electricity and heat to a point where a 135kW wood fuelled CHP plant can meet the energy requirements for a community of around 240 residents and 200 workers.

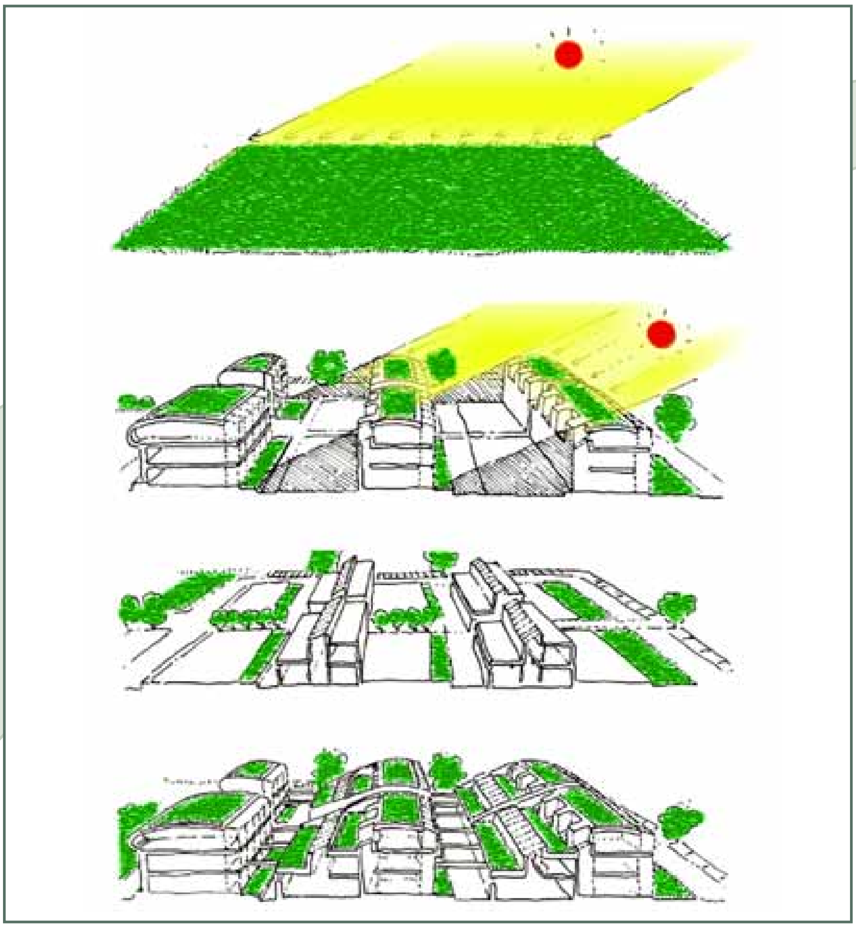
Bedzed won an award for sustainability in RIBA's housing design awards 2000 and an energy globe award in 2002.

Building Form and Layout

The development is located on what was a dis-used brown field site in Wallington South London where a mixture of 82 housing types are organised in a parallel series of south facing terraces. The profiled form of the buildings is a function of the desire to reconcile high density urban planning with the provision of solar access to all of the dwellings. Sloping from three stories on the south to two on the north the terraces are composed of a mixture of flats, maisonettes, offices and townhouses.

Thermal Mass in the Building

Using a combination of bricks, blocks, cast concrete and precast floor planks to produce a heavy weight structure, the designers have furnished this build with a high degree of thermal mass. Uncompromising in their pursuit of thermal mass, the designers have left the heavy block work and pre-cast floor planks exposed throughout, requiring services, that could otherwise have been concealed behind a sheet of plasterboard, to be routed in steel



Passive solar layout ensures all building receive optimum levels of sunlight. Source: Zedfactory.com

pipes which are mounted directly onto the internal walls and ceilings. Where the living rooms are designed to receive the most amount of direct solar radiation, a tiled floor finish has been employed to provide thermal coupling between the slab and the internal environment. Passive solar gains are predicted to contribute 1100 kWhrs/yr to the space heating of each dwelling.

Thermal Preservation

Externally insulating the structure with 300mm of expanded polystyrene ensures that the thermal mass of the structure is capable of interacting with the internal environment, whilst also reducing the risk of thermal bridging. Where large areas of glazing can be a source of heat loss during the winter, the designers have specified triple glazed, argon filled windows with a low emissivity glass and wooden frames. The buildings are well sealed, achieving an air tightness of 2 air changes per hour at 50 Pa.

Passive Solar Design

Both the layout and form of the terraces in Bedzed are optimised to provide the maximum amount of solar access to all

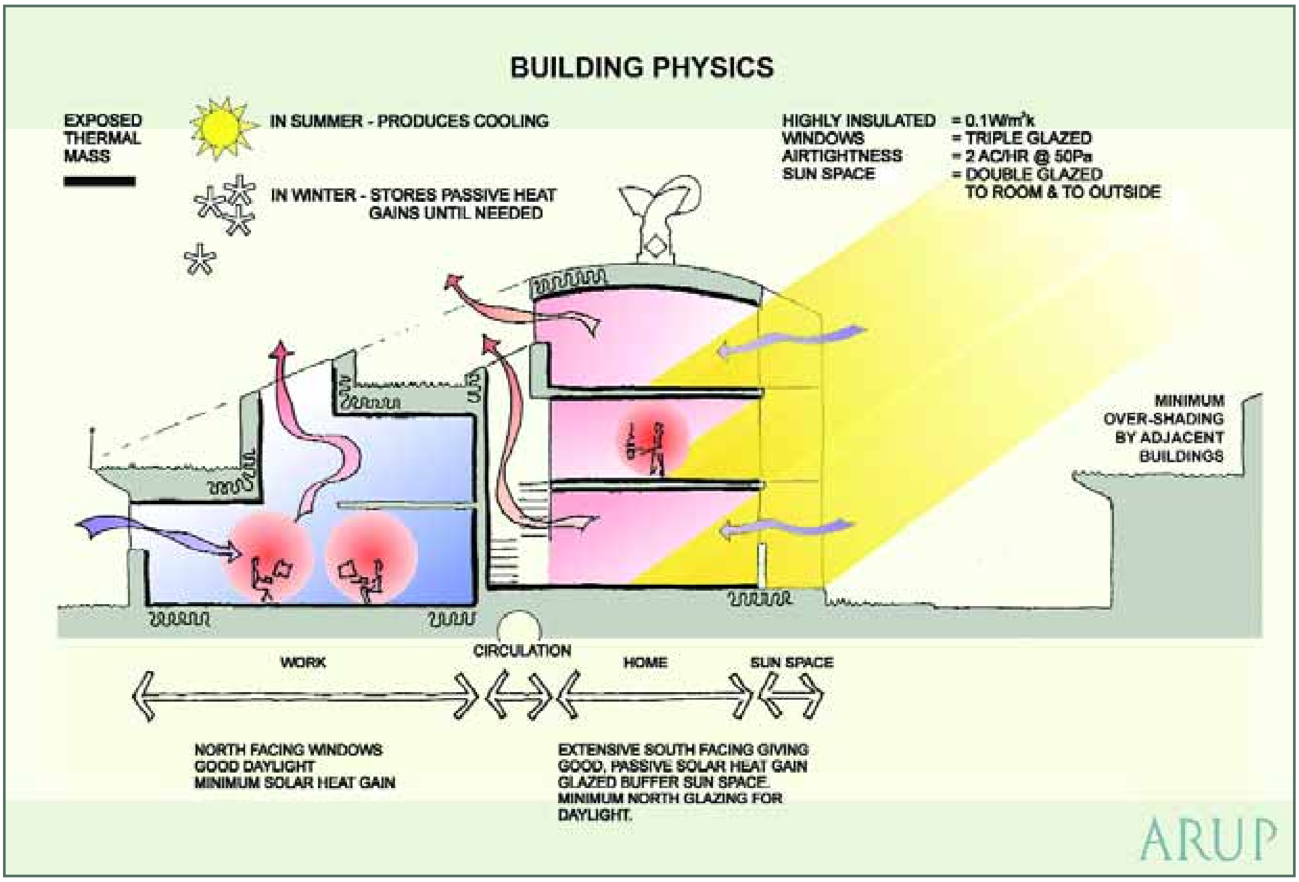


Diagram illustrating the passive strategies that have been employed in BedZED. Source: Arup Associates

The trademark wind cowls, serve as a crucial element in the developments ventilation strategy. Source: Zedfactory.com

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of the dwellings in the scheme. The sloping roof of the buildings, from three stories on the south façade to two on the north, provides all of the terraces with good solar access without compromising the high-density urban layout. The ground floor levels of northern blocks have been raised by 700–2,000mm, reducing the over-shadowing of ground floor windows. Most of the glazing has a south facing aspect, with balconies strategically integrated into the façade to intercept high angle summer sun.

Where the development was designed to accommodate both living and office space, careful consideration of the divergent requirements prompted the designers to locate living spaces to the south and office spaces to the north. Where solar gains can result in over-heating in densely occupied offices with high internal heat gains, the decision to locate offices to the north of the terraces obviated the need for mechanical cooling, especially where a high degree of thermal mass affords the occupants the opportunity to implement a night cooling strategy.

Ventilation

Developed specifically for the project, the signature wind cowls that define the roofs at BedZED use both positive and negative wind pressure to deliver supply air and extract vitiated air respectively. This system provides the buildings with adequate base level of ventilation; allowing trickle vents and ventilation fans to be omitted. In addition a 70% efficient heat recovery system has been integrated into the wind cowl systems to reduce the heat losses that infiltration would have introduced.

Overheating can be controlled in summer by opening large windows and doors into the south facing sun-spaces. The ability to open roof lights and windows on the north elevation affords occupants the opportunity to cross ventilate their buildings.

Dynamic Simulation

The final BedZED development represents the culmination of a series of design iterations, which evolved using dynamic simulation. Using real weather data, engineers were able to quantify the contribution which solar gain could make, while the additional heating provided by incidental occupant gains was also included in the model. By evolving the buildings form and fabric, the engineers were able to arrive at a building specific-ation that was so thermally efficient that no heating systems would be required. Some insights, which the programme of simulations provided, include:

- Thermal inertia is an integral part of the winter heating strategy, as it provides thermal stability in buildings that are subject to highly fluctuating solar and occupant heat gains.
- The necessity for shading on the extensive south facing glazing could be offset if enough thermal mass was provided in the building's interior.

Overall Performance

Monitoring results from Bedzed's first year of occupation show that space heating requirements are 88% less than those expected in conventional UK dwellings.

The success of Bedzed is borne out by the market demand for the properties in south London. Commanding a sig-nificant premium above market rates, it is the modern green lifestyle that has attracted most people to the properties. The development and success of Bedzed represents an encouraging step for sustainability into large high-density developments, where the success of some of its design features may be replicated in future mainstream developments.

Exterior view of the Passive House. Source: MosArt

10. Wiclow Passive House

Client
Tomás Ó'Leary

Architect
MosART Architects

Energy Consultants
UCD Energy Research Group

Outline of Thermal Mass Strategy

Thermal mass has been provided using a heavy concrete construction composed of a single leaf, externally insulated, blockwork envelope, a concrete intermediate floor and exposed internal surfaces throughout. Functioning as an integral element in the building's passive solar heating strategy, the mass is expected to curtail the risk of overheating which would have been an issue in such a highly insulated and airtight building.

Project Description

Designed to "Passive House" standards, Tomás Ó'Leary's new house in Wicklow is expected to provide comfortable indoor conditions without the need for a conventional heating system. The two-story building provides 350m^2 of floor area within a compact south facing form. The ground floor accommodates a large open living space, as well as a sitting room, playroom and a self-contained garage. Four bedrooms and an office are provided on the building's first floor.

Features like super insulation, high performance glazing, and a mechanical ventilation system with heat recovery are expected to reduce the building's annual space heating requirements to 15kWhrs/m^2.

Passive solar principles have been adopted to provide much of this heat, while occupancy and equipment gains are expected to make up the deficit during most of the year. Tomás has installed a small wood pellet stove as a failsafe to provide additional space heating during the coldest periods of the year. Designed by MosART architects, the project is being supported by SEI, assessed by the Passive House Institute and monitored by the UCD Energy Research Group.

Thermal Mass in the Building

Although "Passive Houses" constructed on mainland Europe are generally built using a lightweight framed construction, Tomás Ó'Leary has opted for a heavy masonry structure. The 215mm thick inner leaf of the perimeter walls is constructed using a high-density concrete block, laid on the flat. High levels of external insulation ensure that maximum use can be made of this thermal mass. Internal partitions on the ground floor are constructed using standard block work, while precast concrete planks are used to construct the first floor. The thermal link to the ground floor slab has been maintained, by using a tiled floor finish instead of a lighter alternative.

A ceramic tiled floor ensures that the transmitted solar radiation can be absorbed and stored in the building ground floor concrete slab. Source: MosArt

Thermal Preservation

The building's external envelope provides an overall U-value of 0.1 W/m²K; this has achieved in a number of ways. The perimeter walls are externally insulated with 325mm of rigid polystyrene. Blocks of polystyrene have been glued directly onto the exterior of the building, before a final skin of acrylic plaster was applied. The roof is insulated with 40–50cm of cellulose insulation while triple glazed windows have been used throughout. The frames of the Austrian windows are thermally broken to reduce conduction heat losses while an argon filling is provided to limit convection heat transfer from one pane to the next. One drawback of producing such a well insulated home is that the risk of overheating in summer increases. This is especially the case where a southerly façade has been exploited to maximise solar heat gains. The heavy internal structure used in the Wicklow house is expected to alleviate a large portion of the overheating risk. Storing solar energy during the day will reduce peak temperatures, while night ventilation can be employed to further reduce internal temperatures when required.

325mm of rigid polystyrene is used to form the external skin of the Passive House. Source: Brian Murphy

Mechanical Ventilation

Air infiltration through unsealed gaps in the building's envelope can account for a significant proportion of a conventional building's total heat loss. Passive Houses are required to achieve an air-tightness of 0.6 air changes per hour at 50pa and while heat losses are minimised in this way the limited airflow can compromise the building's indoor air quality. For this reason, ventilation requirements are met in most passive houses using a mechanical ventilation system. Using this system, fresh outside air is mechanically ventilated through ducts to the living areas, while vitiated air is extracted from wet rooms and kitchens. This system is employed in the passive house in Wicklow with the addition of an air-to-air heat exchanger, which recovers 80% of the heat from the building's exhaust air to pre-heat the incoming fresh air. Apart from providing a controlled supply of fresh air the system also serves to equalize room temperatures throughout the building. Surplus heat, which can often be collected in south facing rooms, will be distributed via the ducting network to cooler north facing rooms, where the thermal mass of these rooms can provide additional heat storage.

Passive Solar Heating

The house in Wicklow has a good southerly aspect, with large tall windows provided on the south façade to maximise solar heat gains. Natural daylighting is provided through windows on the north façade, but the glazed area on this façade has been reduced to minimise heat losses in winter. The kitchen is located on the east corner of the building to capture the benefits of early morning sun, while the evening sun sets behind deciduous trees which border the neighbouring road. The deciduous trees provide welcome shade in summer, without greatly reducing the availability of sunlight in winter. In addition, using a 750mm roof overhang on the building's south elevation has provided an element of solar control.

Model generated for computational analysis.

Dynamic Modelling

The Energy Research Group, using dynamic simulation, has conducted a computational analysis of the Passive House. One aspect of this study investigated the influence that thermal mass has on the thermal behaviour of the building. The thermal mass provided in the passive house is expected to reduce annual energy consumption by 6% and reduce peak internal temperatures by 1.5°C, compared to a comparable lightweight construction. Employing a night cooling strategy could reduce peak temperatures further.

Overall Performance

Achieving an annual energy consumption of 42kWh/m² will make this home in Wicklow one of the most energy efficient buildings in Ireland.

Tomás has designed the building to achieve the "Passive House" standard without sacrificing the comfort and charm afforded to his family. It has been estimated that adopting such a high performance construction has added 10% to the building's construction costs, but the money that would have been spent on a heating system has covered the cost of the mechanical ventilation system. Tomás has concluded that the main benefits of his house are the comfortable living spaces, low CO_2 emissions, and the fact that he does not expect to receive a heating bill any time soon.

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