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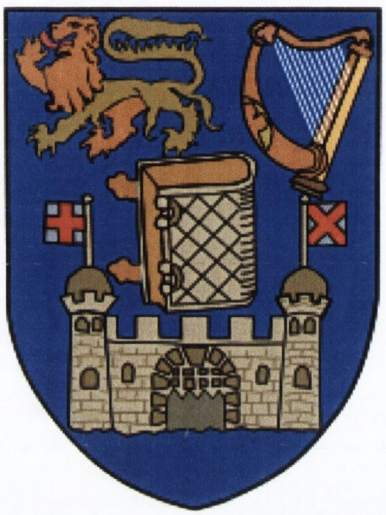
THE THERMO-HYGROMETRIC PROPERTIES OF MULTI-PURPOSE HISTORIC BUILDINGS



Niall Byrne BA BAI

A thesis submitted for the degree of Doctor of Philosophy to the University of Dublin, Trinity College.

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Niall Byrne

Executive Summary

The concept of sustainability is a multi-faceted one, with environmental, social and economic aspects all requiring consideration when assessing the sustainability at a micro or macro scale. Accordingly, when considering measures aimed to improve the sustainability of a building, town or city, improving the environmental performance of the area, although important, may not suffice in terms of making an area more sustainable. For example, on-going preservation of collection items in museums, libraries and archives will contribute to a city both socially and economically as it will be inherent in the culture of the area and will generate revenue from the resulting tourism.

This research project has been conducted in three related phases. Phase 1 involves developing the signature behaviours associated with a range of environmental stimuli. These were identified initially using a number of small-scale signature experiments in a test-room located in the basement of a mid-terraced Georgian building. The signatures associated with heat loading, moisture loading, increased infiltration due to a window being opened and the effect of occupancy (for occupants with both "dry" and "wet" clothing). These signatures were subsequently applied to a full-scale, multi-use (lecture theatres, library, administrative offices, museum), historic building (namely the Museum Building in Trinity College Dublin) dating from the mid-1800s. In general, the signatures defined in the small-scale experiment were applicable to the Museum Building, although some updates were required for the signatures, thus validating the signatures for use at a larger scale. Furthermore, three additional signatures were identified, namely the signature associated with solar gains, and hygroscopic materials such as a large volume of books.

Phase 2 involved applying the signatures that had been identified and validated in Phase 1 and applying it to the primary case-study building, namely, the Old Library in Trinity College Dublin (TCD) in order to determine the relevant stimuli that are dominating the thermo-hygrometric parameters in the building. Using recommendations made by the Smithsonian Institute and British Standards Institute (BSI) for suitable environmental conditions for the storage of collection items, it was found that, generally, thermo-hygrometric conditions in the building fell outside those defined by the Smithsonian Institute and temperature (T) and relative humidity (RH) variations in the building were found to exceed those specified by BSI as a result of the mechanical heating system as well as the presence of people in the building. Moreover, the environmental parameters fell significantly short of recommended comfort conditions during the winter period and seasonal variations were high. Despite this, the presence of a large volume of the books, contained in the space, is effective in regulating the

thermo-hygrometric properties in the space and, when the building is unoccupied and unheated, provide relatively stable environmental conditions in the building.

The final phase of the project involved using the Integrated Environmental Solutions <Virtual Environment> (IES <VE>) software to develop a model of the Old Library in order to model the environmental conditions in the Old Library. The effects of a range of retrofit options, involving both the building envelope and the upgrade and installation of plant within, could then be assessed in the software as a means of developing a strategy to improve the environmental conditions in the building. The model was calibrated using a sensitivity analysis and, although close calibration between the modelled and actual thermal conditions in the building was achieved, the difficulties associated with accurately simulating the effects of hygroscopic materials on the moisture conditions resulted in a disparity between the modelled and actual conditions. Upon simulating each individual retrofit option, it was determined that alterations to the building envelope, or the installation of plant alone would be insufficient to adequately improve environmental conditions in the building. Accordingly, four hybrid methodologies were developed and involved upgrading of the building fabric as well as the installation or upgrading of plant. The third methodology, which involved upgrading of windows, insulation of the roof and upgrading the heating to a continuous heating system had the potential to improve and stabilise environmental conditions in the building, although T values would still fall below those required for comfort during the winter season. This strategy was deemed to be most practical in terms of installation in the building as it did not require the installation of heating, ventilation and air conditioning (HVAC). The final strategy, involving insulating the Long Room from the Shop, upgrading the windows, insulating the attic and installing a HVAC system led to the largest improvement in environmental conditions in the Old Library as it improved comfort conditions and significantly reduced environmental fluctuations.

Acknowledgements

This PhD thesis represents the culmination of four years of work and would not have been possible without the help and assistance of a number of people. To my partner Angharad, without your help I would never have been able to complete this project. You were always there to help me enjoy the good times and get me through the bad times. Thank you for your ever-availability to go for a cup of coffee a walk, but most of all thank you for being my best friend throughout everything.

To my supervisor Dr. Roger West I would like to express my eternal gratitude. Through your ideas at the start-up stage of the project to your help in finding clarity in otherwise confusing data and your eye for detail in producing this document you have caused me to question everything about data trends and to rethink my writing style. This project would not have existed without your continuous input.

Special thanks must also be given to the Keeper of Preservation and Conservation, Ms. Susie Bioletti, without whom the study of the Old Library would not have been possible. Thanks you for your assistance in organising access to the building and your willingness to assist with sourcing documents and photographs used in this thesis. Further thanks must be given to the following TCD staff: the Architectural Services Officer, Mr. Michael Murray, the Services Co-ordinator Paul Bolger and the Engineering Services Manager Kieron McGovern for their input into this project. I would also like to thank the staff, past and present, in TrinityHaus as well as the staff and my fellow postgraduate students in the department of Civil Engineering, particularly Dr. Kevin Ryan, David McAulay, Eoin Dunne and Michael Harris for their continued willingness to advise and help me with technical issues that arose throughout the research.

To Dr. Ruth Kerrigan and, in particular Shane Campbell of IES I'd like to express my gratitude. Without your willingness to help and Shane's readiness to go above and beyond the call of duty and patience in training me to use the <VE> software , the modelling aspect of this research project would not have been possible.

Finally I would like to thank my parents, Des and Mary for their continued support, both moral and financial, throughout my education. Thank you for instilling in me a work ethic that has allowed me to complete my studies and for constantly supporting me throughout the entire process. I would also like to thank my brother, Colm and Sean, and my sister Sinead for their continued support.

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Nomenclature

A = Area, m^2

A = Constant/ Frequency factor

a, b = Coefficients

C = Coefficient depending on surface orientation depending on mean air speed

c = Specific heat capacity, J/kg.K

CO_2 = Carbon dioxide, t

c_p = Specific heat capacity of air at constant pressure, J/kg.K

D = Diffusion coefficient, m^2/s

d = Thickness, m

dA = Element of surface area, m^2

D_p = Depth percentage, mm

dW= Radiation flux, W/m^2

$d\omega$ = Element of solid angle

E = Modulus of elasticity

E_a = Activation energy

E_{st} = Rate of increase of energy stored within the body

F_1, F_2 = Fractional area of heat flow path

F_a , F_b = Fractional areas of bridged materials

f_f = Furniture mass factor

g = Room humidity ratio, kg/kg

h-w = Enthalpy (h) and humidity ratio (w) chart

H_{abs} = Absolute humidity, g/m^3

h_c = Convective heat transfer coefficient, W/m^2K

h_r = Surface heat transfer coefficient for exchange with the mean radiant temperature (MRT) node

i = Infiltration rate, ach (air changes per hour)

I_{beam} = Solar flux measured perpendicular to the beam, W/m^2

I_{dir} = Direct solar flux incident on the surface, W/m^2

$I_{g,diff}$ = Diffuse solar flux by ground, W/m^2

$I_{h,diff}$ = Diffuse sky solar flux on the horizontal plane, W/m^2

$I_{s,diff}$ = Diffuse sky solar flux incident on the surface, W/m^2

IAQ = Indoor Air Quality

IEQ = Indoor Environmnetal Quality

J = Diffusion flux, $mol/m^2.s$

k = Reaction rate

k = Thermal conductivity, W/mK

K, n = Coefficients.

L = Length, m

$L^*(\beta)$ = Net long-wave radiation gain, W/m^2

$L_g(\beta)$ = Long-wave radiation received from the ground, W/m^2

$L_{sky}(\beta)$ = Long-wave radiation received directly from the sky, W/m^2

m = Air mass flow rate, kg/s

M = Metabolic rate, W/m^2

MBV = Moisture buffer value, g/m^2 %RH

N = Air infiltration rate, ach (air changes per hour)

n = Exponent

n = Total number of time intervals

p = Vapour pressure, kPa

P_1, P_2 = Permanence rate, $years^{-1}$

P_f = Rate of fabric heat loss, W

PI = Preservation index, years

PI_n = PI measured at time interval n

P_T = Total heat loss, W

P_v = Rate of ventilation heat loss, W

Q = Net heat flow into the air mass, W

Q_i = Heat flux, W/m^2

q_x = Heat transfer rate by conduction, W

R = Combined radiative/convective resistance of the air gap

R = Gas constant

R = Resistance of a particular layer

R-value = Thermal resistance, m^2K/W

R_b = Thermal resistance of the bridged layer, m^2K/W

R_{ext} = External surface resistance, m^2K/W

RH = Relative humidity, %

RH_1, RH_2 = Relative humidity values

R_{int} = Internal surface resistance, m^2K/W

R_l = Lower resistance, m^2K/W

R_T = Total resistance, m^2K/W

R_u = Upper thermal resistance, m^2K/W

SVP = Saturated vapour pressure, Pa

T = Absolute temperature

T = Dry-bulb temperature of the ambient air, °C

T = Supply temperature of the air, °C

T = Temperature, °C

t = Time, s

T-w = Temperature (T) and humidity ratio (w) chart

T(x,y,z,t) = Temperature (°C) in the solid ar position (x,y,z) and time t

T_1, T_2 = Temperature values

T_1, T_2 = Temperatures at the air gap

T_a = Bulk air temperature, °C

$T_{a,\,out}$ = Outdoor air temperature, °C

T_{comf} = Indoor comfort temperature, °C

T_{MRT} = MRT of the enclosure

T_s = Mean surface temperature, °C

Ts_i = Temperature difference across the wall, K

T_T = Total temperature difference

TWPI = Time-Weighted Preservation Index

$TWPI_{n-1}$ = TWPI after time interval (n-1)

U-value = Thermal transmittance, W/m^2K

U_T = Total thermal transmittance, W/m^2K

V = Air volume, m^3

v = Wind speed, m/s

VHC = Volumetric heat capacity, kJ/m^3K

W = Heat flow across the gap

W'(x,y,z,t) = Heat flux vector (W/m^2) at position (x,y,z) and time t

W= Heat flux from air to surface, W/m^2

w_a = Net water vapour gain to the air, kg/s

x = Position, m

x', y' = Mean values of arrays

α = Solar altitude

α = Thermal diffusivity, m^2/s

α_t, α_{RH} = Thermal and moisture coefficients

β = Diffuse ground solar flux incident on the surface, W/m^2

$\delta^2x/\ \delta x^2=$

ΔH = Enthalpy of activation

ΔH_{abs} = Difference in absolute humidity, g/m^3

ΔH_{abs}/visitor = Absolute humidity per person, g/m^3/visitor

$\Delta T = |T_a - T_s|$

$\Delta T = |T_a - T_s|$

ΔT = Temperature difference across a particular layer, K

$\delta T/\ \delta t =$

$\Delta T/\Delta x$ = Temperature gradient

ε = Surface emissivity

ε_e = Emissivity of the external surface

ε_t, ε_{RH} = Thermal and moisture related strains

Θ = Absolute temperature of the surface, K

Θ = Angle of incidence

θ = Direction angle measured from the surface normal

Θ_e = Absolute temperature of the external surface, K

λ = Thermal conductivity, W/mK

ρ = Density, kg/m^3

ρ_a = Air density, kg/m^3

ρ_s = Solar reflectance of the ground (albedo)

σ = Stefan Boltzman constant, 5.6696×10^{-8}W/m^{2}K^4

σ_t, σ_{RH} = Thermal and moisture stresses

ϕ = Concentration, mol/m^3

1. Introduction

1.1. Context

Fundamentally, sustainability involves ensuring that the activities required for humans to meet their daily range of needs can be continued indefinitely by preventing these activities from causing irreversible damage to the environment and its assets (CIBSE, 2002a). Sustainability is increasingly becoming an issue of importance and practical significance for the construction sector as the environmental concerns related to buildings are rising amongst the public as well as amongst prospective buyers of buildings and facility managers (Anastaselos et al., 2009). In developed countries, buildings account for 40% of the total energy consumption (Vučićević et al., 2013). The idea behind *"sustainable construction"* is to minimise energy costs in the construction and maintenance of buildings (Pérez Gálvez et al., 2012). Today's ecological pressures, encourages a new approach to building, such that government agencies are moving rapidly to impose new mandatory standards on energy efficiency for both new buildings and for those under restoration. It is estimated that approximately 80% of buildings that are expected to be in use in the developed world in 2025 are currently occupied (English_Heritage, 2012). Moreover, at least 70% of the housing stock likely to exist in 2050 has already been built, with 75% of these having been constructed pre-1975. Accordingly, improving the energy efficiency of the built environment will primarily involve large-scale retrofitting schemes to reduce the energy demands of the existing building stock.

Although sustainable building is a multidimensional concept, attention to the issue often focuses solely on environmental indicators (such as energy and resource use, for example), ignoring the substantial importance of social, economic and cultural indicators (Mateus and Bragança, 2011). Historical buildings are a non-renewable resource and generally enrich the cultural heritage of an area. As such, many historic buildings are protected by law as their contribution to the economic, social and cultural sustainability are priceless and irreplaceable. As such, the continued use of this resource, through repair, conversion and conservation is therefore good practice in terms of sustainability (Urquhart, 2007).
Conservation, in terms of historic buildings, is the action taken to prevent decay and manage change dynamically and must preserve and, if possible, enhance the values of the cultural property (Feilden, 2003). The conservation of buildings can be justified on cultural, economic and environmental grounds, usually in combination (BSI, 1998). When they were first constructed and inhabited, all pre-industrial buildings were, by definition, sustainable

and made no use of fossil carbon in either their construction or use (English_Heritage, 2012). All construction materials were locally sourced and all energy to the building was supplied by local biomass. In recent decades, however, occupants of buildings have begun to expect and demand a higher level of thermal comfort, which is usually achieved by ensuring stable temperatures and little or no air movement. This has led to the perception that traditionally constructed buildings are cold and draughty as natural ventilation is core to a historic building's indoor environmental quality. Historic buildings disperse excess moisture and noxious airborne contaminants by ventilation. The growing expectations for thermal comfort have led designers to strive for higher levels of air-tightness in buildings with the implementation of mechanical ventilation, which has sometimes proved to be problematic and has led to a range of problems for occupants such as the prevalence of sick building syndrome amongst occupants of poorly designed buildings. Accordingly, the retention of older buildings, either in their entirety or simply by re-using components in-situ and allowing for their thermal upgrading, in benign and sympathetic ways, can provide excellent finished results that are fully in accordance with the principles of good building conservation and sustainability.

Over the course of their history, many historic and traditional buildings have served many purposes, from dwellings to offices and factories to schools. Presently, many historic buildings, throughout the world, are used to store and exhibit other items of cultural heritage. This application provides its own issues in terms of providing suitable environmental conditions, not only to prolong the lifetime of the building itself but also that of its contents, which need to be stored and maintained indefinitely. Given the highly individualistic characteristics of such buildings, provision of suitable environmental conditions provides a unique challenge to designers, who must balance the demands of prolonging the lifetime of the collection items while also providing a suitable level of comfort for the people who come to visit the collections while observing the principles of conservation of the building. The first step in achieving such goals is to identify not only the needs of the relevant stakeholders but also in understanding how the building behaves and identifying the primary stimuli that cause environmental changes to occur in the building. Previous research has indicated that the thermo-hygrometric properties (temperature and humidity) in a building are the single most damaging environmental condition to the lifetime of cultural collections. Furthermore, a number of studies have identified the presence of people, ineffective and inefficient plant, infiltration and lighting to be other factors that are significantly damaging to the cultural heritage in such buildings. An example of a building where this is suspected to be the case is the Old Library in Trinity College Dublin, which is the primary case study in this research project.

The Old Library was opened in 1732 to house the university's expanding collection of books that are today considered to be invaluable cultural heritage items. The Old Library was opened as a tourist attraction in the early 1990's and has evolved to become a major tourist attraction in Dublin. Accordingly, damage to the collection items has been observed to increase significantly over the last two decades and it is suspected that the large increase in traffic through the building, which now exceeds 500,000 people per annum, is responsible for this damage. Thus the primary aims of this thesis are outlined hereafter.

1.2. Objectives

The primary objectives of this PhD research project are as follows:

1. To develop an understanding of the primary influences that determine the thermo-hygrometric variations in historic buildings by means of developing environmental signatures
2. To develop sensible restorative strategies based on best historic building practice
3. To assess the adaptability of this to other buildings.

1.3. Thesis Composition

This PhD thesis comprises 8 individual chapters. The following is a brief description of the content of Chapters 2 to 8.

Chapter 2: Literature Review. This section provides a summary of the wide range of existing knowledge available and sets the background for the research conducted during this research project. Topics discussed in this chapter range from the features and performance of historic buildings to legislative 2mechanisms for buildings to aspects of indoor environmental quality to the health and comfort of building occupants.

Chapter 3: Methodology. Building on the knowledge gained in Chapter 2, this section defines the parameters for measurement, the instrumentation used and its calibration and the rationale behind the monitoring regimes and locations adopted during this research.

Chapter 4: Signature Tests. To investigate the effect of a number of environmental stimuli on the indoor environment, a number of small-scale signature tests were conducted. This chapter discusses the tests, their particular objectives and expected results, describes and

analyses the data obtained and identifies the causes of fluctuations and variations observed in the environment during the experiments.

Chapter 5: Museum Building. Although the small-scale tests were useful for developing an understanding of the effect of environmental stimuli on an environment, their application on a larger scale was essential. Accordingly, Chapter 5 describes the monitoring regime conducted in the Museum Building at Trinity College Dublin (TCD) and the analysis of data obtained with the purpose of determining whether the small-scale tests were applicable and transferrable to a full-size building. Additional stimuli and effects that had not been observed in the small-scale tests are also discussed where relevant.

Chapter 6: Old Library. Building on the knowledge gained from Chapters 2, 4 and 5, this section discusses the primary case study based in the Old Library in TCD, describing the major trends observed in the building during data acquisition, the key factors that contribute to the environmental conditions (in either a positive or negative manner) benchmarked against the behavioural signatures identified in previous chapters. A number of potential retrofit options, aimed specifically at providing greater stability to the internal environmental conditions are recommended.

Chapter 7: Computer Modelling and Simulation. This chapter introduces and describes the capabilities of the specified computer software used in this research. It discusses the process of constructing a model of the Old Library, its calibration with actual data and the various retrofit options that have been modelled, as suggested in Chapter 6, and their potential impact on the building's environment.

Chapter 8: Conclusions and Recommendations. A summary of the main features of the work conducted in this research project will be given. The key objectives of the research will be reiterated at this point as well as a discussion as to whether these have been achieved successfully. The key conclusions of the project will be summarised and recommendations for future research will also be suggested.

2. Literature Review

2.1. Building Performance

2.1.1. Historic Buildings

"Historic buildings are an integral part of our surroundings and contribute to give a sense of identity to our nation as a whole. Historic buildings are not fossils in a museum; most must earn their keep. They must change and adapt to retain their value and usefulness to people." (Changeworks, 2008)

The term *"history"* in English has been defined in two senses, namely *"the temporal progression of large-scale human events and actions or the discipline or inquiry in which knowledge of the human past is sought"* (new4old, 2009). Philosophy of history can be placed under either of these senses, and is termed *"speculative"* when examining progression or *"critical"* when searching for knowledge of the human past. The term *"historic"* is therefore not just considering a thing as being old, but rather as something that is significant as a source for the discipline of history, i.e. something that can be associated with a particular meaning and eventually value. Generally, one or more of the following criteria are used to determine significance: age, rarity, unique or unusual example, outstanding example, connected to a well-known person and associated with a historic event.

According to Feilden (2003) a historic building is one *"that gives us a sense of wonder and makes us want to know more about the people and culture that produced it. It has architectural, aesthetic, historic, documentary, archaeological, economic, social and even political and spiritual or symbolic values; but the first impact is always emotional for it is a part of our cultural identity and continuity – a part of our heritage".*

Generally, a building of historic interest is a notable example of a particular type or design of building, or of a specific style of construction. Alternatively, such a building may have some historic or architectural significance that contributes to the character of an area and provides a sense of *"place"* (Changeworks, 2008). It may also display examples of design, building techniques, or materials that continue to inform future developments. Many older buildings give a special interest and value to our culture: they are of architectural and/or historical importance and their materials and methods of construction are no longer in common use (CIBSE, 2002a, Urquhart, 2007). Their performance characteristics are different from those of modern buildings and are a non-renewable resource and should be treated as such.

Traditional buildings include not only buildings formally recognised for their architectural or historic interest, but all buildings that need to be approached in a manner that reflects the individual characteristics of their construction (CIBSE, 2002a). Traditionally constructed buildings can be of any size, shape or form. Construction materials are diverse, sometimes even in a single building. Walls are not only built of stone and brick but can be of earth (cob) or historic timber frames (often with thin render or weatherboard cladding, or with infill between the structural timbers).

Most modern buildings are made of hard, strong and impervious materials. To exclude moisture, they rely on physical barriers such as damp-proof courses and membranes, cavity walls and cladding. Historic and traditional buildings are completely different. Traditional buildings are constructed from locally sourced materials that are rarely used in the majority of buildings constructed today (Urquhart, 2007). Many have solid walls and most have porous fabric that both absorbs and readily allows the evaporation of moisture (CIBSE, 2002a, Changeworks, 2008). Although political, social and economic history have influenced the design, quality and layout of the built environment, the primary distinction between historic and modern buildings is derived from the fact that labour was comparatively cheap in the past and the transportation of materials difficult and expensive in comparison to today (Urquhart, 2007). Much of the practice of building in the past is now regarded as craftsmanship practiced by relatively few specialist contractors. With the exception of large commercial and public projects, modern building practice is largely standardised in its use of materials, many of which are typically transported over large distances.

The ventilation of many older buildings makes them less prone to condensation and its associated effects (Changeworks, 2008). The higher thermal mass of older solid walls retains heat better than modern cavity walls, which can help to regulate the temperature of a home, keeping it cool in summer and warm in winter (see Section 2.4.3).

Older buildings, however, can often be draughty and can leak heat unnecessarily. This can be accentuated by larger window sizes and a predominance of sash and case windows, which provide a greater area of low-efficiency glazing and more potential for draughts. Older buildings sometimes have larger rooms with higher ceilings that require more energy to keep them warm. These were built before modern Building Standards existed; typically without insulation (although a layer of deafening material was typically placed between floors). Many other components have lower levels of thermal efficiency than modern materials, leading to greater heat loss. Heating systems in traditional buildings tend to be inefficient compared to modern systems, using more energy and generating less heat.

Fig. 2-1 graphically illustrates the primary differences between the behaviour of modern and historic buildings. The differences between traditional and modern construction practice adds value to all historic buildings in terms of cultural heritage, and are an irreplaceable resource (Urquhart, 2007). Tangible elements that embody significance by association with specific events or persons, both on the exterior and interior, should, as far as possible, be preserved. The continued use of this resource through repair, conversion and conservation is, therefore, clearly good practice in terms of sustainability.

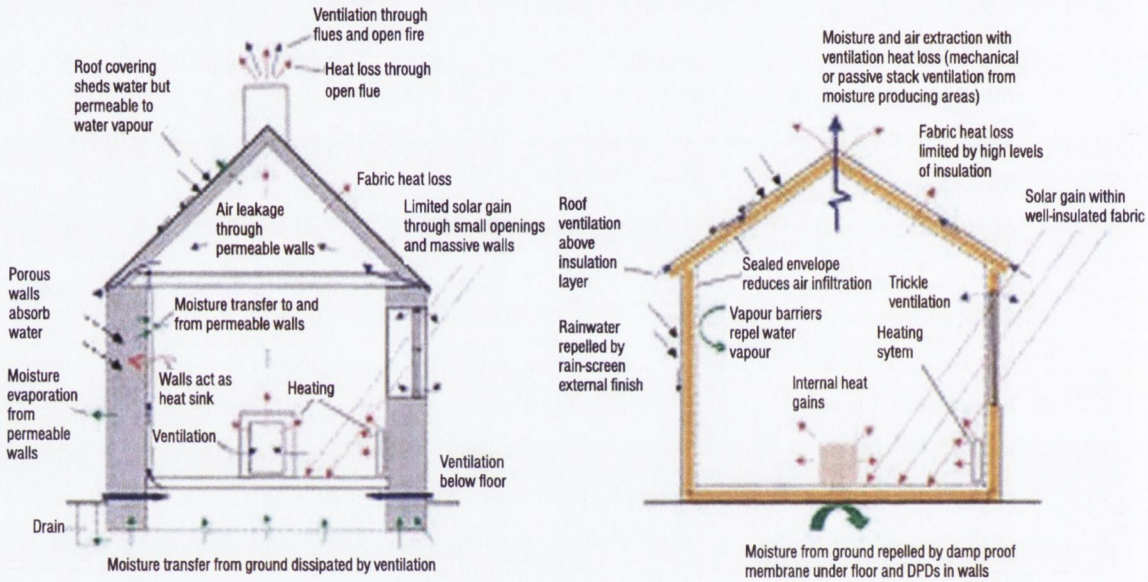


Fig. 2-1: Moisture, air movement and thermal behaviour of a traditional (left) and modern (right) building(Changeworks, 2008).

2.1.2. Conservation of Historic Buildings

Conservation, in terms of historic buildings, is the action taken to prevent decay and manage change dynamically (Feilden, 2003). The primary goal of conservation is to enliven cultural properties by evaluating their architectural, historical, environmental, visual and aesthetic characteristics (Ipekoglu, 2006). According to Clark (2001), Conservation *"is a process that seeks to question change and to reconcile modern needs with the significance of what we have inherited to safeguard the interests of future generations"*. BSI (1998) defines conservation as *"action to secure the survival or preservation of buildings, cultural artefacts, natural resources, energy or any other thing of acknowledged value for the future"*. The basis of historic building conservation is established by legislation through listing and scheduling buildings and ruins (see Section 2.2.2), through regular inspections and documentation and through town

planning and conservative action. Although the definition of conservation differs slightly from source to source, the common theme in all is the protection of heritage for the future.

Conservation must preserve and, if possible, enhance the messages and values of cultural property. These values (emotional values, such as wonder, identity, continuity and spiritual and symbolic; cultural values, such as documentary, historic, archaeological, age and scarcity, aesthetic and symbolic, architectural, townscape, landscape and ecological, technological and scientific; and use values, such as functional, economic, social, educational, political and ethnic) help systematically to set overall priorities in deciding proposed interventions, as well as to establish the extent and nature of the individual treatment. English_Heritage (2008) further describe four heritage values that may be attached to historical buildings and places. These are evidential value (the potential of a place to yield evidence about past human activity), historical value (the ways in which past people, events and aspects of life can be connected to a place in the present), aesthetic values (the ways in which people draw sensory and intellectual stimulation from a place) and communal value (the meaning of a place for the people who relate to it, or for whom it figures in their collective experience or memory).

The conservation of buildings can be justified on cultural, economic and environmental grounds, usually in combination (BSI, 1998). Well-researched analysis of the reasons for conservation will often help to resolve conflicting pressures, between which balances should be struck and good decision made.

Feilden (2003) defines a standard of ethics that should be rigorously adhered to when carrying out conservation work, as follows:

- the condition of the building must be recorded prior to any intervention,
- historic evidence must not be destroyed, falsified or removed,
- any intervention must be the minimum necessary,
- any intervention must be governed by unswerving respect for the aesthetic, historical and physical integrity of cultural property, and
- all methods and materials used during treatment must be fully documented.
- All interventions should be reversible.

Furthermore, any proposed interventions should (a) cause minimum intervention, (b) be reversible or repeatable if technically possible, or (c) at least not prejudice a future intervention whenever this may become necessary; (d) not hinder the possibility of later access to all evidence incorporated in the object; (e) allow the maximum amount of existing material to be retained; (f) be harmonious in colour, tone, texture, form and scale if

additions are necessary but should be less noticeable than the original material, while at the same time being identifiable; and (g) not be undertaken by conservators/restorers who are insufficiently trained or experienced unless they obtain competent advice (Feilden, 2003, CIBSE, 2002a, BSI, 1998).

English_Heritage (2004) state that effective conservation is only achievable if the conservation professionals *"understand"* the building fabric, a process that is termed *"informed conservation"*. In this context, understanding a building is the ability to *"read"* the fabric in order to analyse its construction, alteration and use through time, and then place it in a much wider context in order to assess its significance (Clark, 2001, English_Heritage, 2004). This is a multi-disciplinary skill that utilises historical research, architectural and landscape history, measured survey and the archaeological analysis of fabric (English_Heritage, 2004). Such analysis may incorporate the results of a range of specialist techniques, including but not limited to dendrochronology (the study of tree rings for dating purposes), technical research, architectural paint research, tree survey and ecology, archaeological evaluation, analysis of views and settings, remote sensing and keyhole investigation as well as stakeholder participation and understanding community values. Since there is no single word or academic discipline to describe the skill of analysing a building and landscape for conservation purposes, Clark (2001) coined the term Conservation-Based Research and Analysis (CoBRA), which refers to *"the research, analysis, survey and investigation needed to understand the significance of a building and its landscape and thus inform decisions about repair, alteration, use and management"*. CoBRA comprises five stages (see Fig. 2-2) dealing with all aspects of the conservation process from planning to on-going maintenance and management of the building.

Conservation used to be synonymous with preservation, however, conservation today is something much more dynamic and ranges from maintenance and repair, through to finding appropriate new uses when necessary. It is as much about facilitation and mediation as it is about regulation and is becoming increasingly positive and proactive, rather than negative and reactive (Clark, 2001). The minimum degree of intervention necessary and the techniques used depend upon the conditions of climate to which cultural property is likely to be subjected (Feilden, 2003). Interventions practically always involve some loss of *"value"* in cultural property but are justified in order to preserve the objects for the future.

Conservation involves making interventions at various scales and levels of intensity that are determined by the physical condition, causes of deterioration and anticipated future environment of the cultural property under treatment.

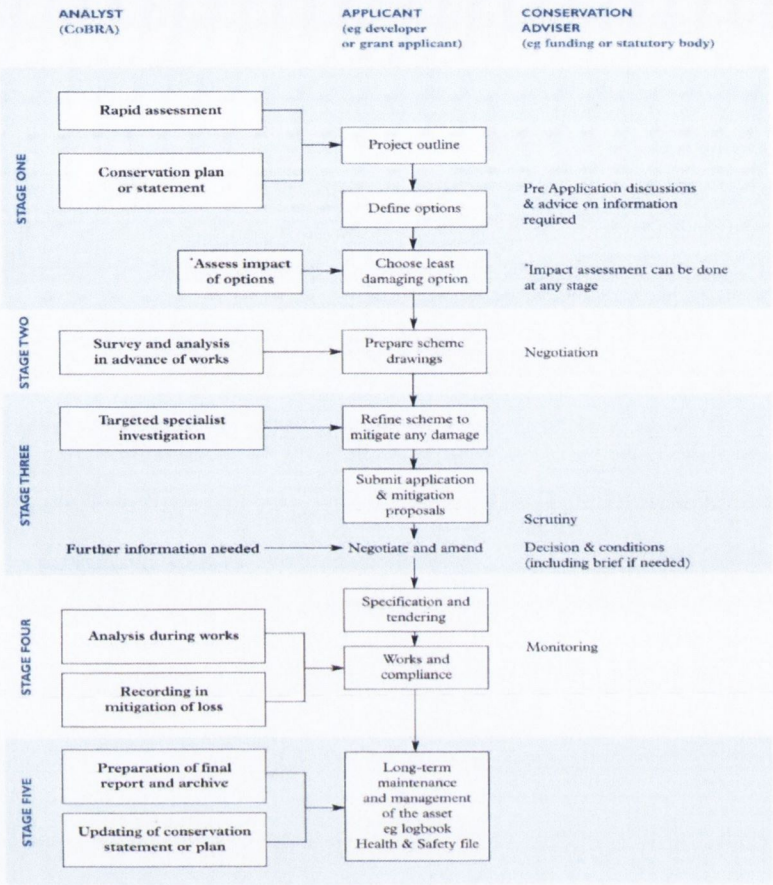


Fig. 2-2: The five stages of the CoBRA method of conservation (Clark, 2001, English_Heritage, 2004).

Feilden (2003) describes seven degrees of interventions that may be considered when conducting conservation works to a building as consolidation (direct conservation), prevention of deterioration (indirect conservation), preservation, restoration, rehabilitation, reproduction and reconstructions. Prevention and preservation are the most desirable of these interventions and may be achieved by on-going maintenance of the building fabric as well as monitoring and control of environmental conditions.

Further to the list of ethics for dealing with changes to historic buildings outlined previously by Feilden (2003), English_Heritage (2008) have published a list of principles for such work, which they describe as *"a comprehensive framework for the sustainable management of the historic environment"*. There are six principles as follows:

- The historic environment is a shared resource
- Everyone should be able to participate in sustaining the historic environment
- Understanding the significance of the place is vital
- Significant places should be managed to sustain their value
- Decisions about change must be reasonable, transparent and consistent

- Documenting and learning from decisions is essential.

These principles emphasise the point that the historic environment is an important resource in which there are several stakeholders. On-going management and recording are of fundamental importance to extending the working life of these buildings, while understanding the reasons for change and the behaviour and performance of the building is significant in ensuring that any conservation project is successful.

The process of converting a historic building to a new use, or a change in occupation has the potential to cause irreversible damage to the building, through loss of character, of archaeological information and of historic fabric if careful attention is not paid to the risks involved in both the design and construction process. Work that is not sympathetic to the nature of the building can, for example, dramatically alter the moisture balance within the fabric of the building and increase the moisture content of vulnerable materials. There is a greater attrition to historic buildings through dampness than any other mechanism, including fire (Urquhart, 2007).

2.1.3. Sustainability and Historic Buildings

"Put at its simplest, sustainability is about ensuring that the activities that we have to carry out to meet our range of needs can be continued indefinitely. To do this, we must ensure that these activities, whether they are power generation, farming, waste disposal or tourism, do not irreversibly damage the environment and its assets" (CIBSE, 2002a)

There are three different facets that comprise global sustainability, described individually as follows (CIBSE, 2002a):

- Environmental: conserving the environment, issues such as global warming, pollution, biodiversity;
- Social: ensuring that human needs are met, issues such as employment, self-government;
- Economic: ensuring that resources are available, issues such as funding, comparing schemes, developing self-sufficiency.

The aforementioned factors determining sustainability are not independent entities but interact to define true sustainable development, as illustrated in Fig. 2-3. It is recognised as a global priority to continue to use the existing building stock while improving its energy efficiency (CIBSE, 2002a). As the requirements for carbon reduction continuously increase in relevance, existing buildings and their associated energy use will come under closer

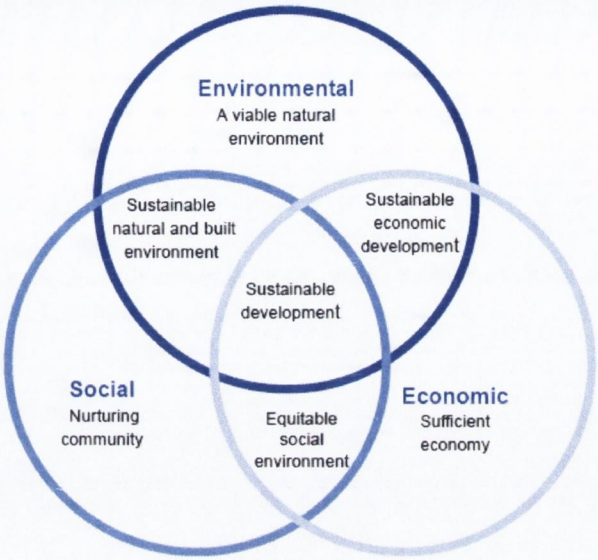


Fig. 2-3: The three primary components of sustainability

scrutiny as governments strive to achieve carbon reductions specified in the Kyoto Agreement, as well as various directives such as the EU 20-20-20 commitments.

When they were first built and inhabited, all pre-industrial buildings were, by definition, sustainable and made zero use of fossil carbon in both their construction and use (English_Heritage, 2012). The primary energy sources available for the conversion and transport of building materials were human and animal power, as well as the biomass of locally grown timber. Building, heating and cooking were almost entirely fuelled by sustainably sourced biomass and, where water and wind power were available, they could be used for the conversion of timber or the transport of materials by water. The retention of older buildings, either in their entirety or simply by re-using components in-situ and allowing for their thermal upgrading, in benign and sympathetic ways, can provide excellent finished results that are fully in accordance with the principles of building conservation and sustainability.

The four principal aims when seeking to improve the sustainability of existing building stock are listed by CIBSE (2002a) as follows:

- Preserve historic fabric: Adopt a respectful approach to the building and its fabric, understand how air and moisture moves in older buildings, avoid inappropriate and incompatible materials that will impair the ability of the building fabric to mitigate excess moisture.

- Extend the beneficial use of older buildings: Avoid building services that are expensive to run and maintain, seek to provide modern standards of accommodation, adapt existing buildings sympathetically and appropriately to modern demands and requirements.
- Reduce carbon dioxide emissions: Install efficient plant, use cleaner fuels, make higher health and comfort standards affordable without compromising the building or the environment, reduce fuel bills, improve the thermal performance of the building, but in ways that do not conflict with the historic features, the intended performance or the health of the occupants and users.
- Specify environmentally conscious materials: Assess the whole life costs of new and existing materials before making changes, assess the impact of new materials on the environment, assess the impact of new materials on the health of both those who install them and the users of the building.

Before implementing any energy conservation measures, the existing energy-efficient characteristics of a particular historic building should be assessed (Hensley and Aguilar, 2011). Buildings are more than the sum of their individual elements. The design, materials, construction type, size, shape, site orientation, surrounding landscape and climate all play a role in the performance of a building. Historic building construction methods and materials often maximised natural sources of heat, light and ventilation to respond to local climatic conditions. Moreover, the embodied energy (i.e. the energy related to the construction of the building) associated with historic buildings is no longer significant when compared to the operating energy (i.e. the energy associated with the use of the building), which is not necessarily the case with modern buildings (Curtis, 2008, Menzies, 2011). The key to a successful conservation (or upgrading) project is to understand and identify the existing energy efficient aspects of the historic building and how they function, as well as to understand and identify the character-defining features of the building and ensure they are preserved. Whether conservation for a new or continuing use, it is important to utilise the building's inherent sustainable qualities as they were intended to ensure that they function effectively together with any supplementary treatments added to improve energy efficiency.

Improving a building's sustainability typically involves a number of measures, either individually or as a combined strategy, aimed at reducing the energy consumption of the building. It is also important to identify how heat is lost from a building before undertaking a retrofit strategy. According to Changeworks (2008) and CIBSE (2002a), heat loss from a typical home can be broken down as shown in Fig. 2-4. These measures typically involve operational changes (i.e. user behaviour and optimising of current plant), upgrading equipment and appliances and upgrading building components (Hensley and Aguilar, 2011).

Older buildings are generally very complex structures, with a performance equilibrium that is highly sensitive to change (CIBSE, 2002a). Modern methods of insulation, draughtproofing and environmental control should only be introduced after careful consideration, based on an understanding of the building and the materials that are proposed.

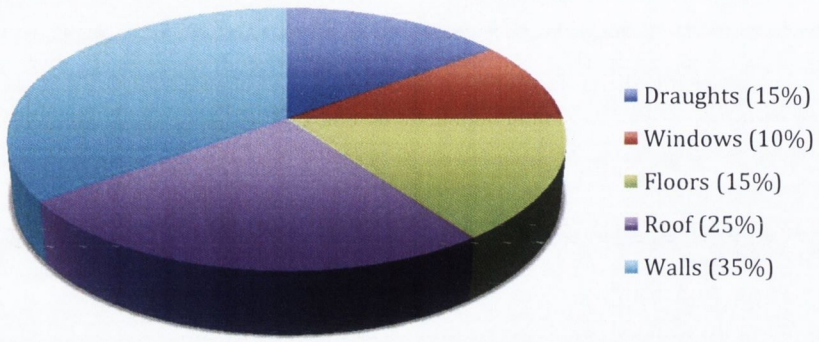


Fig. 2-4: Heat loss from a typical house

According to Hensley and Aguilar (2011), once the options of operational changes and equipment and appliance upgrading have been exhausted, reducing air leakage (infiltration and exfiltration) should be the next priority for any retrofit plan. Leakage of air into a building can account for between 5% and 40% of space-conditioning costs, which can be one of the largest operational costs for buildings. In addition, unwanted air leakage into and out of a building can lead to occupant comfort issues (see Section 2.3.2) from draughts (Hensley and Aguilar, 2011, CIBSE, 2002a). Cold external air that infiltrates the building envelope through holes in the fabric and through *"leaky"* windows, doors and cracks in the fabric causes the heating system to work harder to maintain comfort levels, consuming more energy accordingly (Hensley and Aguilar, 2011). In a multi-story building, cold air that enters the building at a lower level will travel up through the building and exit out unsealed windows and the attic as a result of temperature and pressure differentials. This pattern of air movement is known as the *"stack effect"* and contributes to heat loss from the building. A traditional building needs to be ventilated at a rate of 0.8 to 1.0 air changes per hour (ach) in order to remove excessive moisture and pollutants from the building, twice that of a modern building (Drewe, 2007). Since infiltration rates in many historic buildings exceed this value, draughtproofing (i.e. reducing air infiltration and exfiltration) is normally beneficial. Oversealing older buildings (i.e. reducing the ventilation rate below 0.8ach) however, can cause considerable problems in terms of condensation and other associated problems (Changeworks, 2008). Furthermore, in rooms where there is a gas or solid fuel-burning appliance it is a safety requirement that adequate ventilation be maintained (see Section

2.3.3). When reducing the air-infiltration rate it is imperative that the building fabric retains the ability to provide the building with an acceptable infiltration/exfiltration rate. Generally, sealing draughty gaps in a traditional building is unlikely to cause problems associated with oversealing, however, as the traditional building materials are porous.

From Fig. 2-4 it can be seen that heat loss through walls and roofs accounts for approximately 60% of the total heat lost from a typical house. Heat loss through such elements may be reduced through the installation of insulation, a practice that increases the thermal resistance of the wall or roof. In terms of retrofitting insulation to a historic building, the roof should be the starting point (Curtis, 2008). Insulating a traditional pitched-roof is a very simple and relatively cheap process, and the considerable savings result in a short payback period (Changeworks, 2008). In a traditional pitched roof, insulation is installed directly above the top floor ceiling, between the ceiling joists, and is generally referred to as loft insulation (Changeworks, 2008, Hensley and Aguilar, 2011) and at least 270mm of insulation is required to be effective (Curtis, 2008). Insulating roof spaces in historic buildings will have no adverse consequences on the roof itself, as long as the installation is carried out with due care and attention (Changeworks, 2008). The main conservation considerations surrounding this particular retrofit option relate to ensuring that adequate ventilation rates are maintained to facilitate moisture control. Warm air rising into the roof space carries relatively high moisture levels, which mayl condense on the underside of the roof and timbers, potentially leading to rot. By insulating the loft, the flow of warm air will reduce but the moisture will continue to enter. Accordingly, it is important to maintain ventilation levels to allow this moisture to disperse. The insulation of flat roofs is a more complex process, requiring considerable work to the roof and should be carried out by a professional installer (Changeworks, 2008).

By their very nature, walls in traditional and historic buildings are more difficult to insulate as compared to contemporary cavity walls (Changeworks, 2008). There are, however, two primary methods that can be used, namely external overcladding or internal dry lining. Generally, external overcladding is not a viable option for a historic building as it would change the appearance of the building and thus be unacceptable to many local planning authorities. Replacing the material and style of the building façade would also require realignment of the roof line and rainwater goods (gutters and downpipes), window reveals and sills and doorways and, as a result, would not be a cost-effective retrofit option.

Internal dry lining involves a significant amount of building work, as an extra layer is added to the wall (unless it is fitted during renovation works, in place of the existing plaster finish). Fittings such as windowsills and surrounds, skirting, decorative plasterwork, switches and

sockets and radiators also require repositioning during such work. In terms of building conservation, internal wall insulation is usually only a practical option when the original dry lining is not present or needs to be replaced. Furthermore, if a non-breathing material is added to an older, porous wall, its ability regulate moisture and air levels in the building is compromised. This may result in damp and structural damage where moisture is trapped inside the wall itself. Accordingly, the insulating material and installation method are critical for improving the thermal efficiency of walls. Insulating materials should be breathable and compatible with the other wall materials. Installation should be thorough to avoid any thermal bridging at junctions.

When selecting insulation materials for older buildings, a further degree of safety can be provided by using materials that are themselves hygroscopic, such as natural materials like cellulose fibre insulation, for example (CIBSE, 2002a). These can absorb some excess moisture without leading to condensation or decay and release it when conditions are more favourable. Care must be taken when introducing such systems, however, as the risk of interstitial condensation on the cold face of the material may be increased due to the absorption of moisture into the insulation.

Adding wall insulation must be evaluated as part of the overall goal to improve the thermal efficiency of a building and should only be considered after the insulation of the attic (and basement, if applicable) (Hensley and Aguilar, 2011). Can this goal be achieved without the use of wall insulation? Can insulation be added without causing significant loss of historic materials or accelerated deterioration of the wall assembly? Will it be cost-effective? These basic questions must be carefully considered before deciding on wall insulation.

Although windows only account for approximately 10% of heat loss from a building, they are typically targeted by building owners for improvement (Changeworks, 2008). The appearance of windows is a significant factor in shaping the overall character of the building and this can, to some extent, dictate the improvement options available for historic properties. A number of thermal improvement options available for historic buildings are listed in Table 2-1 as well as the corresponding U-value for each (Curtis, 2008).

Thermal properties of existing windows can be greatly improved through a number of simple measures such as fitting a blind, closing the shutters or fitting heavy lined curtains. Although effective in reducing the U-value of the windows, these measures are only practical at night and so alternate measures, such as installing secondary glazing, should be considered to improve the thermal properties of the windows. However, secondary glazing should complement the existing window so as to reduce the visual impact

Table 2-1: Low impact thermal improvement options available for windows in historic buildings with the thermal improvement (Curtis, 2008).

Action	U-Value (W/m^2K)
Single pane glass as existing (baseline)	5.2
Fitting a standard roller blind	3.2
Closing the shutters	2.2
Fitting heavy lined curtains	3.1
All 3 of the above	1.6
Fitting a modern honeycomb blind	2.8
Insulating the panels in the shutters	1.6
Fitting secondary glazing	1.6

(Changeworks, 2008). Window replacement can be avoided in the majority of cases by proactive window maintenance. If well maintained, a timber window could be viable for hundreds of years.

In addition to the retrofit options described previously, Humphreys et al. (2011) suggest another obvious option that would reduce heating costs. This technique would involve the use of more efficient heating systems, coupled with lower background indoor temperatures while maintaining user comfort (discussed in detail in Section 2.3.2), where needed, with local heaters. This approach, however, also requires a change in the understanding, perceptions, behaviours and expectations of the building occupants regarding how they achieve comfort in a particular building or area of the building, by wearing an extra layer of clothing rather than by changing the thermostat setting, for example. Using background heating and local supplementary warmth as a heating strategy does not imply an attempt to provide a uniform indoor temperature, but creates thermal microclimates when and where required, in a system in which occupants adapt, both to their building and themselves to stay comfortable. Humphreys et al. (2011) propose that the interior be maintained at a background temperature of 16°C and appropriate local supplementary heat-sources be provided, where and when desired, usually in the form of a radiant heater. With radiant heating, the volume of air in a space does not have to be warmed but rather the objects and surfaces in it. Convective heating acts primarily on the skin while radiant energy has a marked biochemical effect (Hobday, 2011). As well as acting on the surface of the body, it stimulates deeper-lying tissues and its influence extends to the internal organs, the central nervous system and enzymatic processes. Also with a radiant heat source, air temperatures can be kept lower than with convective systems, since the warmer the internal surfaces the cooler the air temperature can be, within reason. Occupants perceive indoor air quality to be

better at lower air temperatures (Hobday, 2011). As a result of the lower background temperature, it is possible to provide comfortable conditions while significantly lowering energy costs and related CO_2 emissions.

Although increasing the energy efficiency of the existing building stock is essential in improving the sustainability of the built environment, great care must be taken to prevent one set of problems being substituted for another, such as reduced levels of public health (Hobday, 2011). A delicate balance needs to be developed in retrofit and upgrade projects to ensure that energy reduction targets are realised, while maintaining the health and wellbeing of the occupants. Hobday (2011) contrasts two ways of making buildings energy efficient. Historically, local and natural materials were used and the layout of the building was orientated according to the local environment. In regions such as Ireland and the UK, this meant designing buildings to benefit from the winter sun and to prevent summer overheating. The fabric and internal spaces were arranged to allow cool air to circulate in summer and warm air in winter, with buildings having high levels of natural ventilation, natural light and a radiant heat source. These characteristics produced structures with a low environmental impact and healthy living conditions and, in some cases, the site was chosen for its health-giving properties. In contrast, the modern approach to reduce energy consumption involves making the building as airtight as possible and introducing a high level of insulation to the building.

Hobday (2011) cited Florence Nightingale, who set out how to create healthy, healing environments in the 1860s, by identifying the four essential features of a healthy dwelling as pure air, pure water, efficient drainage and light – sunlight in particular. Hobday (2011) also described the work of Sir Leonard Erskine Hill, the director of the Department of Applied Physiology of the National Institute for Medical Research in the UK in the 1920s, who reached similar conclusions to those of Ms. Nightingale. Hill also concluded that the human body needs the stimulus of constantly changing conditions to maintain health, and so a monotonous indoor environment was to be avoided. He favoured sunlight, fresh air and a radiant heat source.

Conversely, contemporary codes and regulations recommend sealed, highly insulated buildings that exclude the external environment rather than adapt to it. With this strategy, ventilation rates are low and heating is provided by convection rather than from a radiant source. As insulation levels increase, heat losses from ventilation assume greater importance. The aim is to make a highly insulated envelope airtight, while, at the same time, upholding indoor air quality. According to Hobday (2011), whether a healthy living environment can be provided by an airtight, highly insulated envelope remains to be seen.

Saving energy by increasing the airtightness of a building may concentrate moisture and any potentially toxic gasses given off by building materials and may also concentrate other pollutants (see Section 2.3.3). Air changes by ventilation are still a necessity.

Many traditional buildings were designed well in terms of providing a healthy environment for their occupants as they have high levels of natural ventilation, radiant heating and natural light. The challenge is refurbishing them to an energy efficient standard while maintaining their health benefits.

2.1.4. Increasing the Sustainability of Historic Buildings: Case Studies

Although it is true that no two historic buildings are identical and should not be treated as such, the issues, techniques and materials used and the methods of analysis may be similar between buildings. As a result, prior to commencing any refurbishment project, it is a useful exercise to examine previous studies involving similar buildings. The following section summarises a number of case studies carried out on historic buildings and the benefits achieved regarding energy efficiency and sustainability following completion of the works.

Changeworks (2008) carried out a range of energy efficiency improvement works to nine flats within one stairwell of a B-listed (see Section 2.2.2) Georgian tenement building in the heart of Edinburgh. The properties lie in the Old Town Conservation area and form part of the Old and New Towns of Edinburgh UNESCO World Heritage Site. The area was one where occupants were at the highest risk of fuel poverty, which has three contributory factors, namely poor building energy efficiency, low household income and the cost of fuel, in the city. A list of acceptable measures for improving the energy efficiency was devised and each potential measure was examined, in depth, under a number of key considerations. These were listed as follows: impact on the energy efficiency of the project, impact on the appearance of the property, impact on the fabric of the building, cost-benefit ratio, replicability on other homes and innovation. Floors, roofs and windows were the primary building aspects examined during the study, although heating systems and lighting as well as raising energy awareness amongst homeowners were also considerations. Combinations of the following energy efficient improvement measures were implemented in the nine flats: secondary glazing, floor insulation, draughtproofing, top-up loft insulation, shutter refurbishment, low-energy lighting, new "A" rated condensing boilers, smart monitors and home energy advice visits. Different combinations of measures were installed in each flat and these were determined by the location of the flat and the preferences of the householder.

The project reduced the annual energy costs of each flat by an average of £175, although in some cases the reduction was up to £400. The annual CO_2 emissions of each flat were reduced by an average of over 1 tonne and, in the best performing flats, this figure was up to 2.4 tonnes. The average energy consumption of each flat was reduced by an average of 5,000kWh, up to 12,000kWh in some cases, and the National Home Energy Rating (NEHR) of each flat was increased to an average of 8.9, with the largest increase of 1.5 in some of the flats.

A further study by the Energy Savings Trust, (EST) (2005b) on a Grade II listed (see Section 2.2.2), 17th century timber-framed cottage cited a cottage that was built in 1687 and has a thatch roof, render on the front walls of the building and weather-boarding at the rear. Despite containing a modern efficient gas condensing boiler and radiator system, draughts remained a problem, causing continuing discomfort. Moreover, unsuitable impervious cement renders and paints that had been applied to the envelope in the 1930s were having a detrimental effect on the underlying timber frame structure. Following an extensive study of the building and an associated schedule of upgrades to the plant and retrofitting to reduce air infiltration into the building the following achievements were noted as follows:

- A sensitive refurbishment based upon a thorough understanding of the building, its cultural value, condition and performance;
- The removal of the causes of damp and decay;
- The use of appropriate traditional methods and materials;
- The introduction of compatible and environmentally friendly modern materials to the existing fabric;
- Improvements in air-tightness that do not jeopardise the traditional air infiltration and exfiltration performance of the structure;
- Improvement in comfort levels for the occupants;
- A 50% reduction in fuel consumption and bills;
- A reduction in CO_2 emissions and
- Enhanced condition and serviceability of the building.

CIBSE (2002b) describe a similar study carried out on St Mary Abchurch, a Grade I listed (see Section 2.2.2) building that had mould bloom appearing on a painted dome. Upon monitoring of the building it was found that the mould bloom was due to rapid fluctuations in the temperature and moisture content of the plaster in the dome. These changes were attributed to an intermittent heating regime and the installation of natural insulation coupled with an upgraded condensing boiler, as well as an independent heating system to be

installed in the vestry, which would allow for low, continuous heating of the church was proposed to solve the mould issue. The retrofit options, in this particular case, performed successfully as environmental conditions were improved, thus protecting the fabric from accelerated deterioration, comfort conditions were improved and an estimated 20 tonnes of CO_2 per annum were saved.

In some historic buildings, such as the Grade I listed Rotherfield Park country house, alteration of the building fabric may not be possible (CIBSE, 2002b), although the sustainability of such buildings, however, may still be improved. In this particular case study, a 200kW wood-chip boiler with a $5m^3$ hopper was installed, a measure that reduced CO_2 emissions owing to the carbon neutral nature of timber as a fuel. Moreover, running costs were reduced and a better level of heat was supplied to the house, although figures to quantify any improvements were not provided by the authors.

Perhaps the most relevant case study in terms of this particular research project was, as described by CIBSE (2002c), the study of the restoration of the Wren Library in the Lincoln Cathedral, Trinity College Cambridge. Designed by Sir Christopher Wren, it was built between 1674 and 1677 to accommodate Wren's 5000 books and 1000 medieval manuscripts. The building contains a *"Long Room"* measuring 33.2metres in length, 5.2metres wide and 4.3metres high.

Restoration on the building began in the late 1980s as the floor was on the point of collapse, due to shrinkage. Humidity levels were monitored and deemed to be excessive (>70%) for the preservation of rare books, and there was an associated sensation of dankness. Two options were considered to improve the internal environmental condition, namely a *"high-tech"* option involving installation of a full environmental control system and a *"low-tech"* option of radiators and dehumidifiers. The simpler option was chosen because the alternative would have been expensive and visually intrusive. The new heat emitters were located beneath the windows and hidden from view by the original 19th century tables. Six cast-iron radiators were used in the system, as it was assumed that something similar would have existed in front of the windows, and so the look of the original library was recreated. Four dehumidifiers were also integrated into the system. The radiators function as a humidity-controlled conservation heating system and the temperature is allowed to modulate between 5°C and 18°C, in order to maintain relative humidity at between 55% and 65%. The dehumidifiers are used to control the humidity levels only when the temperature is above the maximum set point in the controller. Furthermore, sockets for electric heaters were installed to facilitate supplementary heating during evening lectures, which were also

held in the building. The system is controlled by four sensors located in bookshelves at a height of 1.8m to measure humidity and temperature levels among the books.

During the original repair, insulation was installed in the floor. Natural daylight was maximised as the library is shaded from direct sunlight by the adjoining cathedral. To protect the collection from degradation due to excessive sunlight exposure, two types of blind were fixed to each south-facing window to allow adjustments as required. These were conservative *"holland"* blinds, usually kept two-thirds down to exclude the majority of direct sunlight from penetrating the room and blackout blinds. This particular case study demonstrates the importance of adopting a holistic approach to historic buildings as the correct solution for this project (i.e. the *"low-tech"* option) was identified and executed. CO_2 emissions were reduced through the addition of floor insulation and the fabric and contents of the library were protected from degradation by the installation of the humidity control heating system.

The purpose of identifying the aforementioned case studies was to illustrate that even buildings with the most stringent legislative protection can be somewhat improved to increase the sustainability and energy efficiency of the building. A holistic approach to the entire building is required, however, if the alterations are to be effective in increasing the sustainability of the structure, a characteristic that is not solely adjudged to be achieved simply by improving the energy efficiency of the particular building. Although several options for energy improvement may be identified, the most suitable measure is always the one that is least damaging to the existing building fabric.

2.2. Legislation and Regulation

2.2.1. Background

As a result of the growing demand on global resources associated with increasing energy usage in the developed world and increasing industrialisation of developing nations, the associated damage to the environment due to greenhouse gas (GHG) emissions has long been a major issue for governments throughout the world. The importance of these issues was recognised as a governmental issue in 1997 with the adoption of the Kyoto Protocol. This agreement recognised that developed countries were the primary contributors to the high level of greenhouse gas emissions in the atmosphere following over 150 years of industrial activity and thus places a larger responsibility on developed nations under the principle of *"common but differentiated responsibilities"* (UNFCCC, 2013). As of 2006, the

Kyoto Protocol has been ratified by 162 countries, including the then 25 EU members, and is widely perceived as a first step in deeper and broader actions to cut greenhouse gas emissions in the future.

In response to the Kyoto Protocol, the EU defined its own targets for energy generation and usage, which are to be achieved throughout the union by 2020. These targets included a 20% reduction in GHG emissions compared to the benchmark year of 1990. Moreover, a target for energy from renewables of 20% was specified as well as a 20% increase in the energy efficiency of the built environment, the latter of which led to the introduction of the EU Energy Performance of Buildings Directive (EPBD) (EU, 2002). Ratified in 2002, the EPBD was implemented to *"promote the improvement of the energy performance of buildings within the community, taking into account outdoor and local conditions as well as indoor climate requirements and cost-effectiveness"*. The directive specifies a number of requirements regarding the establishment of a methodology for calculating the integrated environmental performance of buildings as well as specifying for the application of minimum energy performance of new buildings and large existing buildings that are subject to major renovations, energy certificates for buildings and regular HVAC inspections.

From an Irish legislative viewpoint, EPBD (EU, 2002) has been implemented initially in the form of the Statutory Instrument 666 (SI 666) (DoEHLG, 2006) and subsequently SI 243 (DoECLG, 2012) as well as alterations to Part L, Conservation of Fuel and Energy in Buildings, of the Building Regulations. It is through SI 666 that a Building Energy Rating (BER) certificate became a requirement for all new and existing buildings that are sold or leased after January 1st 2009 as well as before a new building is occupied for the first time. The BER certificate computes the energy usage associated with a *"standard"* family and occupancy rate of the building in question and, as such, provides a guidance of the actual energy performance of the house and, as a result, is rarely an accurate representation since actual energy use is dependent on how the building is occupied and the manner in which occupants use energy.

SI 243 also requires public bodies that operate from buildings with a floor area greater than 1000m^2 display a Display Energy Certificate (DEC) in a prominent position that is clearly visible to the public (SEAI, 2013). The *raison d'être* of the DEC is to persuade public authorities to adopt environmentally conscious and efficient energy usage within large buildings. The DEC, unlike the BER, calculates the energy rating of a building based on the operational energy used in a building that is occupied over a period of one year. As a result, the DEC is a more accurate representation of the actual energy rating of a building when compared to a BER.

It should be noted that SI 243 does not apply to all buildings and it is important to note the following exemptions, which are mentioned in Part 1 Section 4 of the SI 243 (DoECLG, 2012) regulations and also in Article 4 of the (EU, 2002):

- *"a national monument, for the purposes of the National Monument Act 1930 – 2004, including a recorded monument under the provisions of Section 12 of the National Monument (Amendment) Act 1994 or a registered historic monument under the provisions of Section 5 of the National Monuments (Amendment) Act 1987"*; or
- *"a protected structure within the meaning of the Planning and Development Acts 2000 – 2006"*; or
- *"a building used as a place of worship or for the religious activities of any religion".*

As both of the case study buildings used in this research project are protected structures and appear on the Record of Protected Structures (Section 2.2.2), they fall outside the bounds of such legislation and, accordingly, are not subjected to the conditions of SI 243 or Part L of the building Regulations.

2.2.2. Listed/Protected Status for Buildings

The term "Listed Structure" refers to buildings and scheduled ancient monuments that appear on the British Statutory List of Buildings of Special Architectural or Historic Interest or the Irish Record of Protected Structures (RPS). In the UK the level of protection afforded to a particular building is dependent on its grade (CIBSE, 2002). In England and Wales the grading system is as follows:

- Grade I: buildings of outstanding historical or architectural interest
- Grade II*: particularly important buildings
- Grade II: of special interest, warranting every effort to preserve them.

Similarly, A, B and C grades are used in Scotland and Northern Ireland. In the Republic of Ireland, however, this system of grading does not exist as is done Britain. Buildings or any specified part of a building or monument, which are placed on the RPS are considered to be a protected structure and obtain the same status as Grade I or A in Britain.

Under the Planning and Development Act 2000, it became the responsibility of Local Planning Authorities to create an RPS of buildings and monuments that were of special interest within their functional area (DoEHLG, 2004). This document must then be included

in the region's Development Plan along with objectives for the protection of structures appearing on the RPS. Additional structures, which may be included on the list, are decided on a case-by-case basis that occurs in three stages – identification, assessment and notification. For a building to be considered for protected status it must be of special interest under at least one of the following categories: architectural, historical, archaeological, artistic, cultural, scientific, technical or social.

The purpose of placing a structure onto the RPS is to ensure correct and close control and management of any future changes to the building. This places a higher level of responsibility onto the owners and occupants of the building to correctly maintain the building and also onto the local and planning authorities to ensure that the building is not endangered through neglect or future planning practices. In the event of the occupant wishing to carry out remedial work or otherwise which would materially alter the character of the building, planning permission from the local authority must be obtained. It is important to note that "protected status" applies not only to the exterior of the structure but also all land, interiors within its curtilage and other buildings within that curtilage, including interiors, and all fixtures and fittings which form part of the interior or exterior of all these structures (DoEHLG, 2004) and so planning permission must be sought for any alteration to the interior, exterior and other buildings associated with the listed structure.

2.2.3. Building Regulations

Published by the Department of the Environment, Heritage and Local Government, the Building Regulations are a collection of documents, which specify the minimum work standards and quality that are acceptable for construction projects in Ireland. The regulations are supplemented by a series of informative guidelines that cover all aspects of the design and construction process for any building project, from the structural issues (Part A) to Universal Design (Part M). As the matter of increasing the energy efficiency of the building stock becomes more relevant, and following on from the introduction of the EPBD, so too does the importance of designing according to Part L – Conservation of Fuel and Energy of the Building Regulations. The requirements of Part L (2008) are to design and construct a building *"so as to ensure that the energy performance of the building is such as to limit the amount of energy required for the operation of the building and the amount of CO_2 emissions associated with this energy insofar as is reasonably practical"*. In other words, to reduce and limit the use of non-renewable fuel energy and associated CO_2 emissions which result from the day-to-day operation of a building, while also maintaining acceptable levels of thermal comfort for the occupants.

Currently the Building Regulations apply only to new buildings or to new extensions of existing buildings. In cases where a building is undergoing a change of use or materials it may not be practical to implement the guidance in full. This is particularly relevant for buildings of architectural or historical significance. Such buildings are discussed in Section 0.6.1 of Part L (2008) as follows:

"Part L does not apply to works (including extensions) to an existing building which is a "protected structure" or a "proposed protected structure" within the meaning of the Planning and Development Act 2000 (No. 30 of 2000). Nevertheless, the application of this Part may pose particular difficulties for buildings which, although not protected structures or proposed protected structures, may be of architectural or historical interest...In specific cases, relaxation of the values proposed may be acceptable to the local building control authority, if it can be shown to be necessary in order to preserve the architectural integrity of the particular building".

The latter part of the above extract indicates that buildings which have not been granted "protected status" or "proposed protected status" but which are nevertheless of architectural or historical importance may still be subject to the full extent of Part L where a material change of use occurs based on the judgment of the local authority building officer. Unfortunately, in cases where the appropriate officer is ill-informed or does not fully understand the sources of CO_2 emissions within such a building or even the regulations themselves, such buildings can be exposed to alterations which are inappropriate and insensitive to the structure itself and lead to irreparable damage at later stages. Accordingly it is advisable, from a historic building viewpoint, to update the regulations so as to provide greater protection to buildings of architectural or historical significance.

2.3. Indoor Environment

2.3.1. Post Occupancy Evaluation

2.3.1.1. Background

Since the implementation of the Kyoto Protocol, the need to reduce energy consumption at a national and global scale has increased in relevance. Buildings account for 20-40% of the energy demands in the western world while the rate of new building construction in developing countries is accelerating (Birt and Newsham, 2009). Furthermore, occupants' expectations and demands of the comfort level provided within buildings have increased in

recent years. To reduce the impact that buildings have on the environment, the provision of satisfactory indoor environmental conditions using as little energy as possible is critical.

Post-occupancy evaluation (POE) is a method of evaluating the performance of buildings, in terms of energy use and indoor environmental quality (Riley et al., 2009). Although technical building evaluations are conducted routinely, including structural testing, mechanical systems performance checks etc., POE differs in that it addresses issues such as occupant performance, worker satisfaction and productivity (Preiser and Vischer, 2005). The rationale behind the process is to consider the extent to which a building or facility satisfies the needs of its occupants and to identify ways that design, performance and fitness-for-purpose can be improved (Turpin-Brooks and Viccars, 2006, Hashim et al., 2012). Zimmerman and Martin (2001) and Turpin-Brooks and Viccars (2006) both cite Zimring and Rizenstein in defining POE as *"examinations of the effectiveness for human users of occupied design environments"*. Zimmerman and Martin (2001) suggest that POE typically focuses on assessment of client satisfaction and functional *"fit"* with a specific space. Typically the criteria for judgement are the fulfilment of the functional and the occupants' needs (Turpin-Brooks and Viccars, 2006).

2.3.1.2. POE Methods

Currently, no single, defined approach to POE exists and the methods used to conduct a specific POE should be based on the objectives of the study, while also considering the unique aspect of the building (Riley et al., 2009). According to Leaman (2003) who cited Bruhns, over 150 POE techniques are available worldwide, with 50 available within the UK alone. The effectiveness of a POE method is dependent on the following (Riley et al., 2009) giving results that are comparable with previous studies, but where the time and patience of respondents are not encroached too much upon. It offers value in terms of quality and content and it is relevant in a given situation. It is reliable by giving similar results when used by different people within similar circumstances and addresses factors related to the need, activities and goals of the building users.

Daish et al. (1982) define the five essential elements that must be included in a workable POE programme, as follows:

- A need: a defined purpose, a clear and documented set of statements about the goals, anticipated benefits and standards required of a POE programme specific to the organisation.

- A system: the management of the resource (people, methods) allocated to supply the need within the time available.
- A process: the shared and agreed content of evaluation and methods for analyses and interpretation of recorded data.
- A product: the data gathered from evaluations, their recorded analyses and interpretation.
- A check: a capacity to change, the ability to review and assess the effectiveness of the programme, to continue investigating methods and to check and, where necessary, implement changes to the system, the process or the product to meet new needs or circumstances.

Table 2-2 provides a summary of the more common and widely used methods for conducting a POE (Riley et al, 2009). Depending on the purpose of the POE, any aspect of the construction process or the construction product can be assessed (Jaunzens et al., 2002). Methods employ a range of techniques, such as questionnaires, interviews, focus groups, measurement and observation. The relevance of a technique depends on a number of parameters, such as the level of detail required and the skill level of those undertaking the task.

Table 2-2: Summary of the most commonly used methods of POE (Riley et al, 2009)

Method	Format/techniques used	Focus
De Montfort method	• Forum • Walkthrough	Broadly covers the process review and functional performance
Overall Liking Score	• Questionnaire • 7-point scale	Occupant survey Diagnostic tool
PROBE	• Questionnaire/focus group/ visual survey • Energy assessment • Evaluation performance of systems	User satisfaction/occupant surveys System performance Benchmarks developed
BUS Occupant survey	• Building walkthrough • Questionnaire backed by focus groups	Occupant satisfaction productivity
Energy Assessment and Reporting Methodology	• Energy use survey • Data collection, e.g. from energy bills	Energy use and potential savings
Learning from experience	• Facilitated group discussions or interviews	Team learning from its experience.

Turpin-Brooks and Viccars (2006) suggest that the impact of sustainable strategies and technologies on the building occupant's experience in the workplace needs to be assessed and that a case study approach provides the most informative outcomes. Furthermore, the authors claim that, without case-studies, POE would lack a robust or real context, as this approach provides contextual information, a greater depth of qualitative data, opportunities for benchmarking performance and learning opportunities from each project for all stakeholders involved.

2.3.1.3. Benefits of POE and Barriers to its Implementation

Organisational effectiveness can be influenced either positively or negatively by conditions in a space (Zimmerman and Martin, 2001). If the functional fit of the client's organisation with the space is poor, the very functioning of the organisation can be affected. At its least disruptive, this will increase cost and reduce organisational competitiveness and, in extreme cases, could potentially cripple an organisation.

Benefits of POE can be divided into two distinct subsections, namely general and owner/developer specific. The primary and over-arching benefit from conducting a POE is the provision of valuable information that can be used to optimise energy usage or improve comfort and indoor environmental quality (Zimmerman and Martin, 2001, Riley et al., 2009). Traditionally, many decisions that are made in the programming or design stage of building projects are based on assumptions of how the organisation functions and how people use their spaces (Zimmerman and Martin, 2001). A proper POE will provide real information on which to base decisions, and this real information is fundamental to informing and improving later projects. In addition, POE studies lead to energy reduction (Claridge et al., 2002), thus aiding in reducing greenhouse gas emissions.

As well as the general benefits mentioned previously, which apply to the building community, POE can benefit the individual building owner or developer. Although Zimmerman and Martin (2001) outline in detail the advantages of a POE to an individual stakeholder in a particular building, the primary reasons for conducting such a study is to provide feedback to design to ensure that the building is functioning as it was designed and as was expected by the building owner and occupants. Once the suitability of the building to function is determined, it may be improved to, for example, enhance thermal comfort conditions for occupants or reduce energy costs associated with its operation or, in terms of specialised environments, such as a museum, ensure that suitable environmental conditions are continuously being provided to the building. A POE can then be implemented to assess

the effectiveness of any alterations that have been made to the building, facilitating further alterations and adjustments so that the positive impact of changes to the building can be optimised and the potential problems minimised or eliminated entirely.

Jaunzens et al (2002) suggest a number of additional benefits of POE as follows: staff time/efficiency gains through the provision of appropriate facilities, increase in staff comfort, increased staff motivation, an ability to prioritise facilities budgets more effectively and an ability to spot potential inefficiencies.

Despite the numerous benefits of POEs, their use remains sporadic and dependent on the will and interest of the owner/developer. Currently, a number of barriers exist to prevent large-scale implementation of POEs as part of the project delivery process, the primary one of which being that the implementation of a POE is not currently considered to be standard practice (Zimmerman and Martin, 2001). Furthermore, the distinction of what is considered to be *"a good building"* varies between professionals and organisations resulting in difficulties in defining an agreed performance indicator against which to assess a given building. Bordass and Leaman (2005) also cite bureaucracy and difficulties related to managing the knowledge gained (such as knowledge dissemination between organisations) as being barriers to the wider implementation of POE studies.

As well as these general obstacles to POE, Zimmerman and Martin (2001) suggest liability as the only owner/developer specific barrier. If the market does not provide adequate information on performance metrics because of a lack of suitable performance indicators, there is little incentive to do anything other than standard practice. POEs, because they are not standard practice, have difficulty overcoming this industry inertia. The major factor related to the construction industry's resistance to change is the perceived liability incurred through new knowledge of actual building conditions (Zimmerman and Martin, 2001). Many commercial building owners, especially with a fully let building, will be reluctant to undertake a POE as it could potentially uncover shortcomings in the performance of their building relative to comparable buildings. This could result in tenants moving out and consequent reduction in revenue or significant cost implications to eliminate a perceived problem.

2.3.1.4. Case Studies of Previous POE Research

To date, one of the largest POE studies, which was part funded by the British government and the Building Services Journal, is the Post-occupancy Review Of Buildings and their

Engineering (PROBE) which evaluated 16 buildings in two stages, PROBE 1 and PROBE 2 (Bordass et al., 2001a, Bordass et al., 2001b, Leaman and Bordass, 2001, Bordass et al., 2001c). These individual studies comprised seven office buildings, five educational buildings and four other buildings, all of which date from the early to mid-1990's. PROBE developed a method for carrying out a POE study that consisted of 10 stages as follows: seek and obtain access for first study, pre-visit questionnaire, first site visit, draft report, second site visit, occupant survey, energy survey, pressure test, report, PROBE article. Based on their analysis, the authors identified several generic issues that had not been identified previously (Bordass et al., 2001c). They also found that many buildings had recurrent problems, some of which were very minor and correctable, which significantly increased energy consumption or caused difficulties for management and occupants. Leaman and Bordass (2001) observed downward trends in thermal comfort, noise and perceived control. In addition, a disparity exists between the buildings now being produced and what occupants actually like. New techniques could have unintended consequences, leaving usability and manageability quality below standard (Bordass et al., 2001c).

Turpin-Brooks and Viccars (2006) carried out a POE on the Eden Project in the UK and concluded that a combined approach POE with more than one *"tool"* of assessment can enhance understanding of a building's performance and give a clear direction for further investigations of key relationships (e.g. energy usage/ventilation and familiarity with work environment/acoustic performance). Following this POE analysis, many more detailed energy and environmental data retrieval systems are now used at the site and further POEs are planned to cater for changing human capacity at a number of buildings on the site.

Paul and Taylor (2008) compared occupant comfort and satisfaction between a green and conventional building in two university buildings in Australia. The testing parameters for their study were aesthetics, serenity, lighting, acoustics, ventilation, temperature, humidity and overall satisfaction. The authors found no evidence to suggest that the green building provided greater comfort than conventional building. Occupants of the green building were more likely to perceive their work environment as warm. This, however, was due to a malfunction of the HVAC system at the time of the study. Similarly, Leaman et al (2007) conducted a Building Use Study (BUS) survey in 22 green and 23 conventional buildings in Australia. The study indicated that the users' ratings of the physical variables of temperature, air/ventilation, noise and lighting were lower in the green buildings compared to the conventional buildings. It was also noted that noise was often worse in the green buildings, but their occupants tend to be more tolerant of their environment if items that they like are present or if they have an understanding of how controls and facilities are meant to work.

Jiboye (2012) carried out a POE of residential satisfaction in an indicative estate of standard Nigerian houses in Lagos, Nigeria, with the aim of assessing residents' attitude towards aspects of their environment. The purpose of the study was to attain knowledge about aspects of housing design that warrant replication or improvement in any future residential development. He found that a large proportion of occupants in the study area were generally satisfied with their dwellings and neighbourhood and that the quality of housing was, predominantly, high. The study also indicated the relationships between users' responses on residential satisfaction and the physical characteristics of their dwellings.

These case studies indicate that a POE is an effective technique in assessing and improving issues related to comfort, energy and environmental conditions in a building and can inform the most effective method for improving the performance of buildings. In terms of traditional buildings, conducting a POE is essential before, during and after any alterations or upgrades to the building to ensure that the building fabric, as well as occupant comfort and indoor environmentally quality are not negatively impacted by any alteration.

2.3.2. Thermal Comfort

2.3.2.1. An Introduction to Thermal Comfort

The principal objective of the study of thermal comfort conditions is generally to determine the conditions necessary for achieving human internal thermal neutrality with minimal power consumption (Orosa, 2009). Hensen (1991) describes comfort as *"a state in which there are no driving impulses to correct the environment by behaviour"*. The most commonly cited definition of thermal comfort is described by ASHRAE (2004), Humphreys and Nicol (2006) and NSAI (2006) as *"the condition of the mind in which satisfaction is expressed with the thermal environment"*. Considering both of these definitions suggests that comfort is influenced by a range of factors that vary from individual to individual such as personal, difference in mood, culture and other individual and social factors (Djongyang et al., 2010, Indraganti and Rao, 2010). Neither definition describes what is meant by *"the condition of mind"* or *"satisfaction"*, but emphasizes that judgement of comfort is a cognitive process, involving many inputs and is influenced by physical, physiological, psychological and other factors (new4old, 2009, Djongyang et al., 2010). True comfort is more than providing a particular air temperature as is often assumed (Bordass, 1996). By convention, thermal sensation is treated as an objective sensation, while thermal discomfort is a subjective condition (Hensen, 1991).

There is no absolute standard for assessing thermal comfort (Djongyang et al., 2010). Generally comfort is achieved when body temperatures are maintained within a narrow range, skin moisture is low and the physiological effort of regulation is minimised. Comfort also depends on behavioural actions such as altering clothing or activity, changing position or location, changing the thermostat setting, opening a window or leaving a space.

The manner in which humans perceive their surroundings has an effect on the way that they perform their daily tasks and also in the manner in which they interact with plant and controls within a building (Corgnati et al., 2007). Thermal comfort standards determine the energy consumption by a building's environmental systems and are, therefore, important in determining a building's sustainability (Djongyang et al., 2010). Thermal comfort is also a key parameter for a healthy and productive workplace.

Six factors influence thermal sensation, four physical (air temperature, air velocity, relative humidity and mean radiant temperature) and two personal variables (clothing insulation and metabolic rate, i.e. activity level) (ASHRAE, 2004, Humphreys and Nicol, 2006, Oughton and Hodkinson, 2008). In order to determine appropriate thermal conditions, designers typically refer to standards that define temperature ranges that should result in thermal satisfaction for at least 80% of occupants in a given space.

At present, two alternative approaches for the definition of thermal comfort coexist, namely the rational or heat-balance approach and the adaptive model (Djongyang et al., 2010). The rational approach uses data obtained experimentally from climate chamber studies and is best described by the works of Fanger (1970). Conversely, the adaptive approach uses data from field studies of people in buildings.

2.3.2.2. The Rational or Heat-Balance Approach

When humans are involved in near-sedentary activity and steady-state conditions, cold discomfort is correlated strongly to the mean skin temperature, while warmth discomfort is directly related to the skin wettedness resulting from skin secretions (Djongyang et al., 2010). According to Hensen (1991), thermal dissatisfaction can result from the entire body being too warm or cold, or by unwanted heating or cooling (such as a draught, for example) of a particular part of the body, which is known as local discomfort.

Djongyang et al. (2010) describes the work carried out by Fanger in developing the heat-balance approach to thermal comfort, whose model incorporates all six factors, as

mentioned previously. The first of Fanger's experiments involved a total of 1296 students who were dressed in standardised clothing and completed standardised activities while exposed to a variety of thermal environments in a climate chamber. Participants were required to record how hot or cold they felt using the ASHRAE 7-point thermal sensation scale, which ranges from cold (-3) to hot (+3) as follows: cold (-3), cool (-2), slightly cool (-1), neutral (0), slightly warm (+1), warm (+2), hot (+3). In supplemental experiments, participants were presented with the opportunity to control the environment themselves by adjusting the temperature until they felt thermally *"neutral"*.

Fanger's model combines the theory of heat balance with the physiology of thermoregulation to determine a range of temperatures that building occupant's will find comfortable. According to these theories, the human body employs physiological processes (i.e. sweating, shivering, regulating blood flow to the skin) in order to maintain a balance between the heat produced by metabolism and the heat lost from the body. Maintaining this heat balance is the primary requirement for achieving a neutral thermal sensation.

Upon developing his thermal comfort model, Fanger conducted further experiments with the aim of predicting the conditions at which thermal neutrality could be achieved. By studying the body's physiological processes when close to neutral, he determined that the only physiological processes actively influencing heat balance were sweat rate and mean skin temperature, both of which are a function of activity level. Using data from a study involving 183 college-age participants who were exposed to different thermal constraints while wearing standardised clothing, Fanger developed a linear relationship between activity level and skin wettedness. Supplementary experiments facilitated the derivation of a linear relationship between activity level and mean-skin temperature. Substitutions of these two relationships into heat balance equations yielded a *"comfort equation"*. When data obtained during the initial experiment, involving 1296 participants, was used to expand the comfort equation, the resulting formula described thermal comfort as "*the imbalance between heat flow from the body in a given thermal environment and the actual heat flow required for optimum (neutral) comfort for a given activity*" (Djongyang et al., 2010). When this equation was related back to the ASHRAE thermal sensation scale it became known as the Predicted Mean Vote (PMV) and was subsequently incorporated into a descriptive index known as the Predicted Percentage Dissatisfied (PPD).

The PMV is an index that predicts the mean value of the votes of a large group of occupants on the 7-point ASHRAE sensation scale based on the heat balance of the human body (NSAI, 2006). Thermal balance is achieved when the internal heat production of the body is equal to the loss of heat to the environment. In a moderate environment, the human

thermoregulatory system will automatically attempt to modify skin temperature and sweat secretion to maintain heat balance. PMV is calculated using Equations (2-1) as follows (NSAI, 2006):

$$PMV = [0.303e^{-0.036M} + 0.028]E_{st} \qquad (2\text{-}1)$$

where M is the metabolic rate (W/m^2) and E_{st} is the rate of increase of energy stored within the body, i.e. E_{st} = metabolic rate - mechanical power - skin difference loss - sweat loss - latent respiration loss - dry respiration loss - radiative heat loss - convective heat loss. For the equations required to solve these individual parameters, the reader is referred to IS EN ISO 7730, 2006 (NSAI, 2006).

The PPD is an index that establishes a quantitive prediction of the percentage of thermally dissatisfied people who feel too cool or too warm (NSAI, 2006). Thermally dissatisfied people are those who responded ±2 or ±3 on the ASHRAE thermal sensation scale. The relationship between PPD and PMV is given by Equation (2-2) and displayed in Fig. 2-5.

$$PPD = 100 - 95e^{[-(0.03353PMV^4 + 0.2179PMV^2)]} \qquad (2\text{-}2)$$

It can be seen in Fig. 2-5 that, even when PMV is 0, there are some individual cases of dissatisfaction with the level of temperature, despite all occupants undertaking similar activity and being dressed in a similar way (Djongyang et al., 2010). This is a consequence of the differences in approach in the evaluation for thermal comfort from person to person. Accordingly, a PMV of 0 corresponds to a minimum PPD value of 5%.

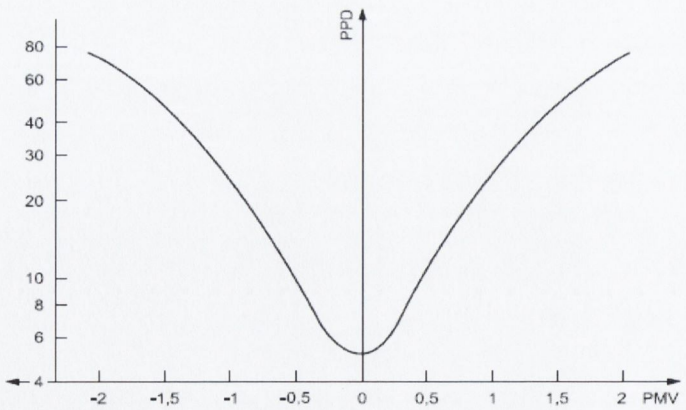


Fig. 2-5: Relationship between PMV (x-axis) and PPD (y-axis) (NSAI, 2006)

Although the rational model of thermal comfort is an effective and useful tool for providing thermal conditions, it is not without its flaws. Research carried out by Oseland (1995) found appreciable divergence between calculated PMV and the reported actual mean vote obtained in actual building environments when compared to those reported in a climate chamber. Oseland (1995) concluded that the discrepancies in values were due to contextual and adaption issues. As a result, field studies may be a more accurate method of assessing comfort conditions.

2.3.2.3. *The Adaptive Approach to Model Thermal Comfort*

The adaptive approach to thermal comfort has gained unprecedented exposure and rising status recently among the thermal comfort community at the apparent expense of the heat balance approach for the evaluation of thermal comfort in naturally ventilated buildings (Halawa and van Hoof, 2012). The adaptive model for analysing thermal comfort utilises field studies to determine the actual acceptability of the thermal environment (Djongyang et al., 2010). Nicol and Humphreys (2002) pioneered an equation that expressed indoor comfort temperature, T_{comf}, as a function of outdoor air temperature, $T_{a,out}$, as follows:

$$T_{comf} = A \times T_{a,out} + B \qquad (2\text{-}3)$$

where A and B are constants.

This relationship is valid and was originally intended for free-running (i.e. naturally ventilated) buildings as a similar relationship for heat and air conditioned buildings is *"more complex and less stable"* (Nicol and Humphreys, 2002). This expression differs fundamentally from the heat balance approach described previously because Nicol and Humphreys (2002) argued that some parameters, such as clothing insulation, could be ignored as they are related to the external temperatures. ASHRAE (2004) acknowledged the relationship between internal comfort and external temperatures and published a chart for naturally ventilated buildings as presented in Fig. 2-6.

De Dear (1997) describes the fundamental principle on which the adaptive approach is based, namely that factors beyond the basic physics and physiology considerations interact with thermal perception. These factors include, but are not limited to, demographics (gender, age, economic status), context (building design, building function, climatic, semantics, social conditioning) and cognition (attitude, preference, expectations). These issues are irrelevant in terms of climate chamber experiments but may not be ignored in terms of actual building environments.

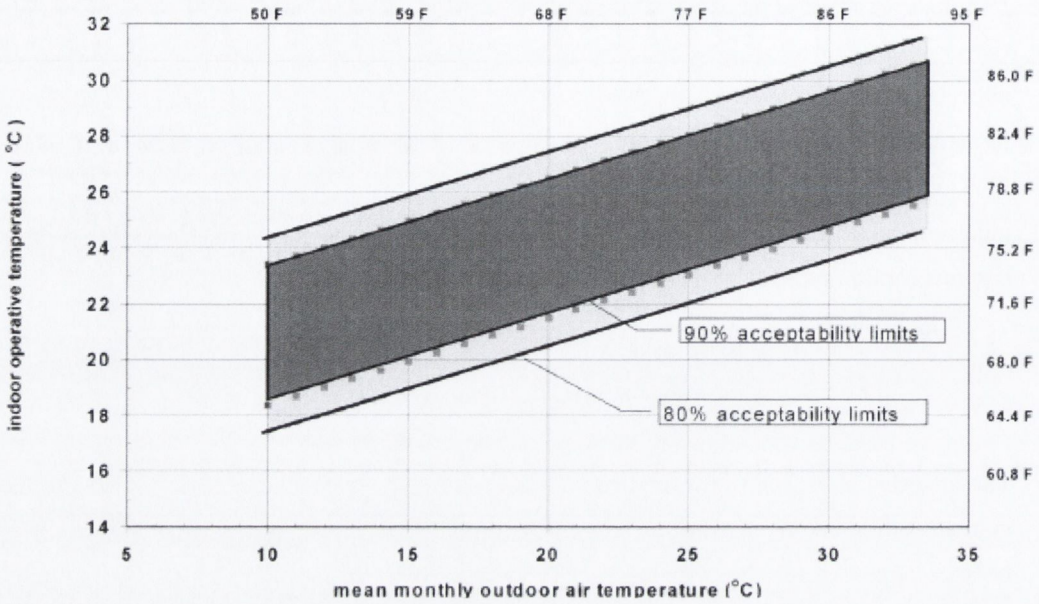


Fig. 2-6: The ASHRAE comfort chart illustrating recommended indoor comfort temperatures for external temperature conditions (ASHRAE, 2004).

The term *"adaption"* refers to *"all physiological mechanisms of acclimatization, plus all behavioural and psychological processes which building occupants undergo in order to improve the fit of the indoor climate to their personal or collective requirements"* (De Dear et al., 1997). This definition encompasses three categories of adaption, namely behavioural adjustment, which includes all modifications a person might consciously or unconsciously make to modify the heat and mass fluxes determining the body's thermal balance, physiological adaption, that refers to the physiological response arising from exposure to thermal environmental factors that lead to a gradual alleviation in the strain induced by such exposure and, finally, psychological adaption, describing the altered perception of, and reaction to, sensory information and is dependent on one's experiences and expectations of the indoor environment. A flow chart of the adaptive model of thermal comfort is presented in Fig. 2-7 (Djongyang et al., 2010).

Although a large volume of research has been conducted into the application of the adaptive model of thermal comfort to different applications and building types, in the context of this project, only research relating to traditional buildings and classroom environments will be considered. The main appeal of the adaptive approach in terms of traditional and naturally ventilated buildings lies in its simplicity, whereby the comfort temperature is expressed as a function of the outdoor temperature (Halawa and van Hoof, 2012). Eilawa et al. (2001) investigated thermal comfort within both modern and traditional buildings in the Ghadames oasis of Libya. Measurements of PMV in modern air-conditioned buildings provided acceptable comfort conditions, however, the corresponding values in traditional buildings

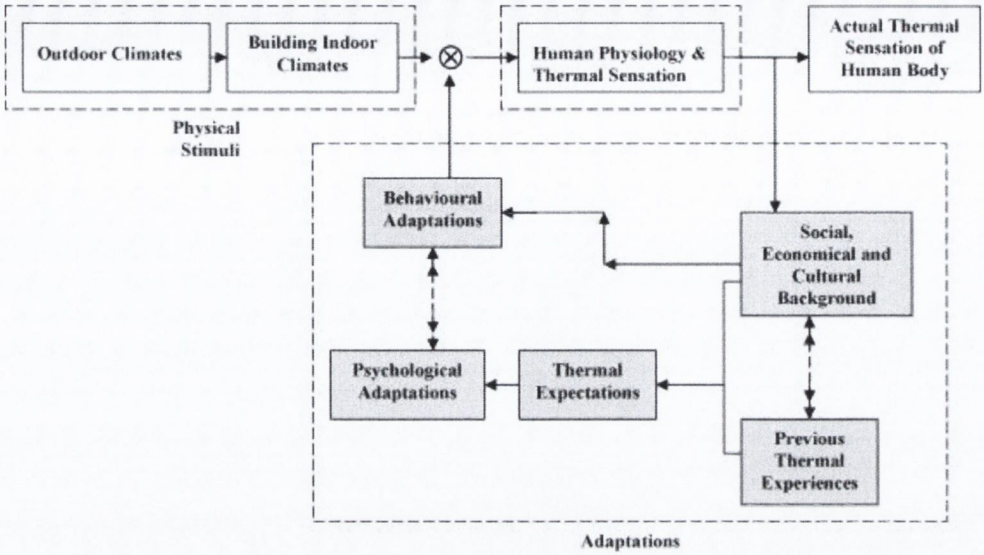


Fig. 2-7: The adaptive model of thermal comfort (Djongyang et al., 2010)

indicated discomfort due to heat, unsurprisingly. Despite this, occupants in the traditional buildings expressed satisfaction with the indoor comfort conditions and, in general, a higher standard of comfort was reported in these buildings compared to the modern equivalents.

Dili et al. (2010) conducted a thermal comfort analysis of traditional and modern buildings using occupant surveys in India. Based on these surveys, they found that a high percentage of occupants in traditional buildings expressed satisfaction with their thermal environment stating that they found the environment *"very comfortable"*. The vast majority of the remaining participants perceived the environment as *"comfortable"* and the remainder saying they were *"slightly uncomfortable"*. This is in stark contrast to the results in the modern buildings where 70% of participants described the thermal environment as *"very uncomfortable"*. Furthermore, Dili et al. (2010) were able to identify the factors causing discomfort from their data.

Brager and de Dear (1998) identified a clear distinction between the responses of occupants in naturally ventilated buildings as opposed to air-conditioned buildings. They postulated that the most likely reason for these differences is the contextual influences of thermal history and their effect on expectations, i.e. past thermal experiences in a building create a benchmark for expectations of future thermal performance. In naturally ventilated and traditional buildings, indoor temperatures more closely match the diurnal and seasonal variations in outdoor temperatures. As a result, occupants recognise this and reduce their expectations and, not only become more tolerant of the varied environment, but often prefer having a closer connection with weather and seasonal changes. Conversely, in air-conditioned buildings, thermal history comprises consistently cool, constant and uniform

conditions, hence creating more rigid comfort criteria while biasing expectations towards constant HVAC set points as opposed to daily or seasonal fluctuations. Accordingly, occupants typically base their expectations on their own perception of what HVAC should achieve rather than on what it actually provides.

Cognati et al. (2007) performed field studies in four Italian high schools and four typical medium-sized university class rooms during the heating season, measuring PMV values while also asking students to participate in a subjective survey on thermal environmental perception. Based on their findings, they concluded that students preferred a thermal environment that was judged to be slightly warm, although neutral or warm environments were acceptable. In a further study, Corgnati et al. (2009a) examined thermal comfort in a number of classrooms in Turin. This study expanded on the previous research carried out during the heating season and involved monitoring of the indoor environment to facilitate calculation of PMV. Students were also required to fill in a subjective survey on the thermal environment. On the basis of the results, a trend was found for the thermal preference from slightly warm in the winter period to neutral in the temperate season, suggesting that thermal preference may be a function of the season.

Despite being considered as a more accurate representation of thermal comfort, Halawa and van Hoof (2012) review the adaptive process in a more critical manner and compare it to the rational method. The ASHRAE comfort chart (Fig. 2-6) presents an overly simplified approach, and the assumptions used in its computation are hidden from the reader. Conversely the heat-balance approach can be altered to take into account several factors that influence thermal comfort. Furthermore, Fig. 2-6 is only applicable within a range of outdoor temperatures (from 10°C to 33°C) and so may not be used when monthly mean temperatures do not lie within this gap. In addition a number of adaptive models exist and have been derived by different researchers. As a result, calculated comfort temperatures differ depending on the model used and, in free-running buildings in moderate climate zones, the range in calculated temperatures can reach 3°C (Halawa and van Hoof, 2012). Although the adaptive approach may have widened the range of acceptable comfort temperatures and in turn reduced energy consumption, in the long run it may prove unsustainable, as a large number of green buildings are considered *"much colder in winter and much warmer in summer"*.

2.3.3. Indoor Environmental Quality

Indoor environmental quality (IEQ) and indoor air quality (IAQ) are terms referring to the environmental qualities within a building, used especially in relation to the health and comfort of building occupants (Hobday, 2011). IEQ generally encompasses factors such as temperature, humidity, ventilation, daylighting and lighting quality, thermal comfort, access to views and IAQ. IAQ can be affected by a number of factors that include but are not limited to microbial contaminants (including mould and bacteria), gases (including carbon monoxide, carbon dioxide, radon and volatile organic compounds) and particulates, or any mass (e.g. smoke, fumes, bacteria, spores, gases, vapours) or energy (e.g. sound, vibrations, light) stressor that can induce adverse health conditions. Sometimes IAQ can be taken to encompass temperature, humidity and ventilation.

During the last 50 years, concern has been growing about levels of indoor air pollution in developed countries (Berry et al., 1996, Jones, 1999). Changes in building design devised to improve energy efficiency have resulted in buildings that are typically more airtight than traditionally constructed structures (Jones, 1999). Furthermore, advances in construction technology have resulted in the greater use of synthetic building materials. Although these improvements have resulted in more comfortable buildings and lower running costs, they also provide indoor environments in which contaminants are readily produced and may build up to significantly higher concentrations than those observed externally (Berry et al., 1996, Jones, 1999).

IEQ is an important issue from both a social and economic viewpoint (Straube and deGraauw, 2001). In industrialised countries, most people spend more than 90% of their lives indoors (Straube and deGraauw, 2001, Apter et al., 1994). During this time, the nature of the enclosed environment directly affects the health, quality of life and productivity of the occupants. Modern buildings have a problem providing a healthy environment with 30% of new and renovated buildings having serious IEQ problems (Straube and deGraauw, 2001). IEQ is currently the most prevalent environmental problem (Roodman and Lenssen, 1995) in the United States and direct health costs due to poor IEQ is estimated to be $30 billion per annum, with a further $100 billion lost due to sick leave and productivity losses (Fisk and Rosenfeld, 1997). The sick building syndrome (SBS) has been the subject of serious scientific inquiry over the last 30 years or so (Apter et al., 1994). It is commonly accepted to represent eye, nose and throat irritation, headaches, lethargy, difficulty concentrating and sometimes dizziness, nausea and chest tightness. These symptoms may typically be attributed to indoor air pollutants.

Typical modern buildings contain a wide range of chemicals (Straube and deGraauw, 2001) although identification of single toxic materials within a more complex cocktail of products and materials as well as their contribution to a hostile indoor climate is difficult to determine (Halliday, 2009). Some of the principal factors known to have an impact on indoor health are listed as follows (Halliday, 2009, Berry et al., 1996, Ucci et al., 2004, Koskinen et al., 1999, Howieson et al., 2003, Jones, 1999): Volatile Organic Compounds (VOCs), Aldehydes, Lead, Carbon Dioxide, Carbon Monoxide, NO_x, Particulate Matter, Damp and Condensation, Dust Mites, Mould and Bacteria and Radon.

Factors such as building location, materials, finishes and furnishings and the provision of adequate ventilation, how a building is operated and the state of repair have an influence on the occupants' exposure to potential pollutants There is evidence to suggest that there is a greater incidence of damp in traditional buildings, although the state of repair will clearly be a factor. Damp also occurs in modern buildings due to poor quality of construction and can occur anywhere due to inadequate cleaning and maintenance regimes. Condensation can occur anywhere that there is a high relative humidity and a lack of uniformity of surface temperatures and is discussed in greater detail in Section 2.5.2. Careful consideration needs to be given to aspects of a minority of traditional buildings that can pose a significant and severe health risk if disturbed, such as where lead-based paint or asbestos is found, for example.

2.3.4. Mitigation of Indoor Air Pollutants

It is more desirable to prevent indoor contamination problems than to mitigate them once they have occurred (Godish, 2001). Three primary strategies are available to designers to improve IEQ that can be affected by design decisions at every stage of project development (Levin, 2001). Design strategies should address the major determinants of IEQ and include pollutant source control, ventilation and air cleaning and occupant and building management activity modifications.

Pollutant sources fall into four general categories, namely outdoors, building, building contents and occupants. The major sources of indoor air pollutants in the built environment are outdoor air, soil and water, the building envelope, building equipment, finishes and furnishings, machines and appliances, occupant activities and maintenance and cleaning (Levin, 2001). It is easier, in theory, and more cost-effective, to control a contaminant at its source before it becomes airborne or causes significant indoor contamination than by any other means (Levin, 2001, Godish, 2001). Rough estimates of the effectiveness of source

control indicate that it is at least 4 times less costly than dilution by ventilation to achieve a comparable IEQ (Levin, 2001).

Pollutant source control includes a variety of principles and applications based on individual contaminants and the nature of contamination problems (Godish, 2001). These include (1) measures that prevent or exclude the use of contaminant-producing materials, furnishings, equipment, etc. in indoor environments, (2) elements of building design, operation and maintenance that prevent or minimise contamination, (3) treatment or modification of sources directly or indirectly to reduce contaminant production and/or release, (4) removal of the source and replacement with materials with low or no contaminant production, (5) measures that prevent infestation of indoor environments by biological organisms and (6) removal of surface contaminants using cleaning measures.

Despite the design quality, some pollutant sources, such as people and their activities, are simply unavoidable (Levin, 2001). Dilution of contaminant concentrations with outdoor air is the most common approach to indoor air quality control, although effective air cleaners, capable of removing many indoor pollutants, and recirculation are also used in highly sensitive environments such as museums. When source control by design is impractical, impossible or of limited effectiveness, designers can reduce concentrations of unavoidable pollutants through dilution ventilation or cleaned, recirculated indoor air.

Designers can improve IEQ by their, potentially large, impact on construction practices as well as the operation and use characteristics of a building (Levin, 2001). Building material installation procedures, cleaning, maintenance and product use are all forms of behaviour that can be influenced by the design professional. By specifying proper product installation procedures with appropriate ventilation, significant reductions in pollutant concentrations can be achieved during the early life of a product or material where strong offgassing occurs. During the entire period of a building material or product's life, the largest emissions may originate from chemicals used for its cleaning, maintenance and repair, refinishing and, ultimately, removal. Assessing the products, not only for their own potential contaminant emissions but also for those of the products necessary for the use of the product over its entire life, can result in selection of products with significantly lower lifetime emissions.

Halliday (2009) and Feilden (2003) describe relative humidity as a further factor that requires careful consideration when contemplating mitigation factors of indoor air pollution. The effect of high and low relative humidity on IEQ is discussed in detail in Sections 2.5 and 2.6 of this thesis.

Reducing the exposure to certain indoor pollutants can be readily achieved through informed material selection and is an important mitigation strategy in buildings of all ages (Halliday, 2009). Providing adequate ventilation and moisture management is more complex and requires an informed and individual response. Only when the lead designer of a particular project takes an aggressive position on IEQ is the achievement of "good" IEQ likely (Levin, 2001).

2.4. Thermal Considerations in Buildings

2.4.1. Heat Transfer within a Building

There are three distinct modes of heat transfer from a source to a receiver, namely conduction, convection and radiation (Oughton and Hodkinson, 2008). An additional process is that of evaporation, however in the context of transfer in buildings this is negligible.

Conduction results from molecular interactions within an object. Molecules at a high temperature region in an object vibrate around their equilibrium position with greater amplitude than normal. This greater vibration causes the molecules to collide with their nearest neighbours, causing them to vibrate more. As a result, these molecules interact with their nearest neighbours passing on this energy as kinetic energy of vibration, thus transferring their energy to the molecules with less energy in a cooler part of the object. The net result of the vibrations is a transfer of thermal energy through a solid. The energy is therefore conductively transferred from a higher temperature region to a lower temperature region resulting in a reduction in the temperature difference. In general, a solid is a better conductor than a liquid or a gas because its molecules are very closely packed, meaning that the energy transfer between the molecules is faster (Ghoshdastidar, 2004).

The rate equation for steady state conduction is given by Fourier's law of heat conduction, as displayed in Equation (2-1) (Holman, 2010, Ghoshdastidar, 2004).

$$q_x = -kA\frac{\Delta T}{\Delta x} \qquad (2\text{-}1)$$

where q_x is the heat transfer rate (W), k, is the thermal conductivity of the material (W/mK), A is the surface area (m^2) and $\Delta T/\Delta x$ is the temperature gradient in the direction of the heat flow. The minus sign is present so that q is positive. It is measured in units of W/mK.

Boundary conditions, however, are a dynamic entity that are continually changing. Since heat is stored when the temperature rises and is released when the temperature decreases,

the temperature distribution and the heat flow in a structure depend not only on the instantaneous values but also on previous values. The influence of these values diminishes with time and, furthermore, variation near the boundary are larger in magnitude than those that occur deeper in the material, although this factor is dependent on the thermal conductivity. This phenomenon is known as transient heat conduction and can be described in Equation (2-2) as follows:

$$\frac{\partial T}{\partial t} = a\frac{\partial^2 T}{\partial x^2} \qquad (2\text{-}2)$$

where a is the thermal diffusivity as described by Equation (2-3).

$$a = \frac{\lambda}{\rho c} \qquad (2\text{-}3)$$

where λ is the thermal conductivity (W/mK), ρ is the density (kg/m^3) and c is the specific heat capacity (J/kgK).

Convection is a mechanism of heat transfer that involves the movement of a fluid (liquid or gas) medium to convey energy, often where the particles have typically obtained heat by conduction with a hot surface (Oughton and Hodkinson, 2008). An everyday example of this phenomenon is that of air surrounding a radiator. As the radiator gains heat, the air immediately in contact with the surface becomes hot and consequently expands with a reduction in density. As a result this warm air begins to rise and an upward current is formed immediately above the radiator. The rising air can lead to the occurrence of stratification in a room. This refers to the layering of air into distinct strata due to the different densities resulting from the range of temperatures that are observed in the rising air as it cools. Stratification is most likely to occur in leaky buildings during warm up when a fast responding heat source is used. The significance of stratification in buildings is its relationship with local thermal discomfort, which occurs when there is unwanted heating or cooling of one particular part of the body (NSAI, 2006). Although draughts are the most common cause of this, a large vertical temperature difference between the head and feet due to stratification is also a significant source of local thermal discomfort.

Radiation may refer to either light or heat, but, in the present context, describes the transfer of heat energy by an electromagnetic process at wavelengths that are within the infrared range (10^{-6} to 10^{-4} m). The radiation from any surface is proportional to its area and increases very rapidly with its temperature (Bordass, 1996). Heat transfer from the sun to the earth is the most important example of heat transfer by radiation (Isačenko et al., 1980).

2.4.2. Thermal Mass

2.4.2.1. What is Thermal Mass?

Buildings that have been constructed using traditional methods typically utilise thermal mass to regulate internal thermal conditions. The term "Thermal Mass" is used to describe not only the extent to which the materials used to construct a building can store and release thermal energy but also their location, configuration and the degree to which these elements are allowed to interact thermally with the internal environment (Walsh et al., 2006). Thermal mass can be extremely beneficial as it offers the ability to manage the thermal energy flows within a building to the advantage of the occupants, while reducing the need for large amounts of expensive high-grade energy. Historic buildings typically have a large thermal mass owing to the large thickness and dense materials used to construct the external walls.

The heat storing capacity associated with thermal mass influences a building in two ways. It moderates internal temperatures by averaging diurnal extremes while also delaying the time at which peak temperatures occur. A building constructed using heavyweight materials will observe lower diurnal peak temperatures later in the day when compared to lightweight constructions. Given that the heavyweight materials take a longer time and more energy to heat up, they also release energy at a slow rate; internal temperatures will not drop to the same extent over the course of a night when compared to a lightweight building. This type of behaviour is known as thermal inertia and is illustrated in Fig. 2-8.

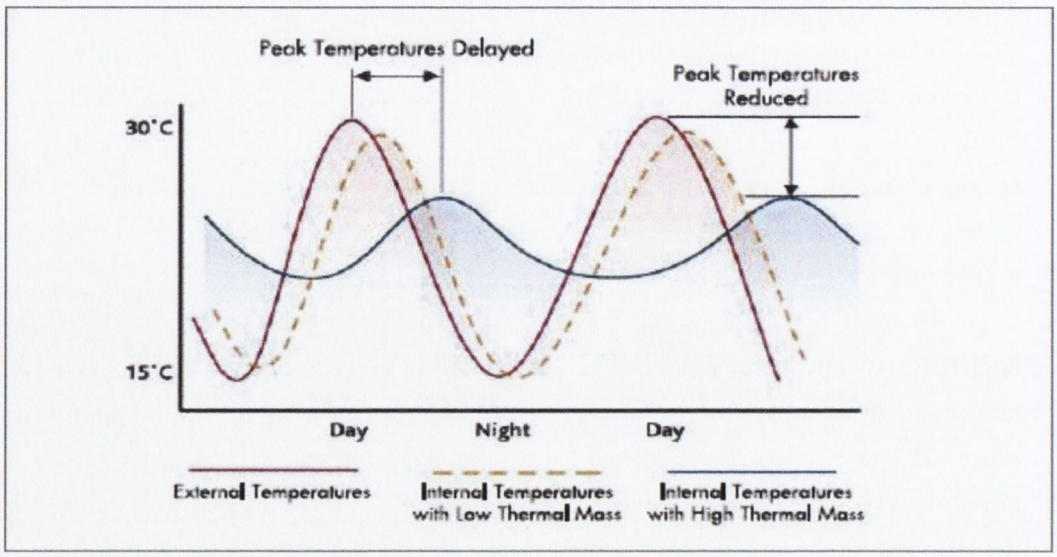


Fig. 2-8: Internal temperature profiles expected in buildings with high and low levels of thermal mass (De Saulles, 2005).

By regulating internal temperatures, thermal mass can reduce the heating requirements of residential buildings and can offset the need for air-conditioning in office buildings (Walsh et al., 2006). In residential buildings, heat from the sun is stored in the thermal mass and then released when the temperatures drop at night. It may also reduce the chance of overheating on sunny days, as excess heat is absorbed by and stored in the dense materials (EST, 2005a). In office buildings, thermal mass reduces the peak temperature load and, accordingly, reduces the need for air-conditioning (Givoni, 1998). Furthermore, if implemented correctly, thermal mass can be used to delay the internal peak temperatures until after office hours (Balaras, 1996).

2.4.2.2. Optimising Thermal Mass

In order for a material to effectively provide thermal mass in a building it must not only be capable of storing large amounts of heat, but also be able to effectively capture and release heat within the typical diurnal cycle. Optimisation of thermal mass depends on building material properties, building orientation for its location and distribution, thermal insulation, ventilation, climatic conditions and the use of auxiliary cooling systems and occupancy patterns (Balaras, 1996). The amount of heat that a material can store is determined by its volumetric heat capacity. Materials, such as stone, masonry and metals all have relatively high volumetric heat capacities.

The location and distribution of thermal mass within a building is an important factor in determining its effectiveness (Balaras, 1996). Thermal mass obtains energy by direct (i.e. solar) radiation, and indirect (i.e. infrared) radiation and room air convection, means. Direct heat gains are observed in the outer building envelope and by the interior surfaces that may absorb incident solar radiation as it enters through the building's openings. Indirect heat gains are recorded at opaque elements inside the building and occur as a result of the transfer of energy internally from direct gain surfaces. Direct locations provide thermal mass much more effectively than indirect locations. The distribution of thermal mass within a building should be designed to ensure a desirable time lag in energy transfer depending on the orientation of the building. North and east orientations do not require a time lag whereas south and west orientations would benefit from an 8 hour lag, which would delay heat transfer from midday to the evening hours.

For a material to effectively store heat, it must exhibit a suitable density, high thermal capacity and a high thermal conductivity (Balaras, 1996). A material's conductivity determines its ability to charge and discharge effectively with a thermal cycle. Although

materials such as metals have a high volumetric heat capacity, their high conductivities mean that they heat up and cool down too quickly to provide useful thermal mass in building applications. Materials with low conductivities, such as timber, are also unsuitable because, although it can store heat for a long period of time, timber is unable to store and release heat efficiently within a diurnal cycle. Concrete, brick and stone, for example, are most effective in providing thermal mass owing to their high volumetric heat capacity and suitable conductivity values. Table 2-3 shows the density, volumetric heat capacity and conductivity of some materials.

Table 2-3: Density, volumetric heat capacity and thermal conductivity values for a range of building and other materials (Walsh et al., 2006, McMullan, 2007)

Material	Density (kg/m^3)	Volumetric Heat Capacity (kJ/m^3K)(at 20°C)	Thermal Conductivity (W/mK)
Air	1.2	1	0.03
Mineral Insulation	12	90	0.04
Wood (hardwood)	700	187	0.18
Brick	1700	1360	0.77
Sandstone	2600	1800	2.60
Concrete	2400	1940	2.00
Glass	2560	2184	1.02
Water	1000	4180	0.58

The potential thermal mass of an element may be quantified using the admittance, which is expressed in Watts per metre squared Kelvin (W/m^2K). This parameter describes the ability of a material in a structural element to exchange heat with the internal environment when subjected to a simple cyclic variation (typically 24 hours for a building) (Walsh et al., 2006, McMullan, 2007). The heat capacity, conductivity, density and surface resistance of a material directly influence admittance. The typical rate of heat transfer from air to a thermal mass surface imposes an upper limit of 8.3 W/m^2K on its admittance, a value that may be increased by improving thermal coupling between the mass surface and the internal environment.

Thermal coupling refers to the way in which the thermal mass is linked to the internal environment. Maximum performance can be achieved by exposing the internal surfaces of heavyweight construction elements. In cases where this is not possible, a thermal link can be maintained by specifying a conductive surface finish such as dense plaster or ceramic tiles. It

is also important to isolate thermal mass from the influence of external temperatures and, as a result, it is most effective when placed inside the insulated skin of the building's envelope.

Ventilation plays an important role in preventing overheating due to excessive stored energy being present in the thermal mass. During the summer, outdoor night temperatures are typically lower than those indoors, which facilitates cooling of the building by natural night ventilation (Balaras, 1996). Ventilated air increases convective heat losses from mass elements and dissipates the released heat to the lower temperature outdoor heat sink, effectively purging the mass of its stored energy. At the beginning of the next day, the now cooled mass is utilized as a heat sink. Part of the cooling load will be passively covered by the building mass, provided that the building is well insulated and not ventilated during the daytime. As a result, in air-conditioned buildings, the operating time of HVAC plant is reduced and accordingly the energy consumption. For naturally ventilated buildings it is possible to achieve longer periods within comfort conditions.

Building occupants determine the practical efficacy of any building system, including thermal mass (Balaras, 1996). By changing the use of internal surfaces and spaces, the effectiveness of thermal storage can be greatly reduced. Consequently it is necessary to carefully consider the final use of the space when making calculations of the cooling load and incorporating the true potential savings from thermal mass effects.

Other factors that influence the effectiveness of thermal mass are the effective thickness and the surface area of the thermal mass element (Walsh et al., 2006). A limited thickness of thermal mass has been found to operate effectively within the diurnal cycle and some guidelines for high-density masonry (2000 – 2500 kg/m^3) include:

- Performance variations for mass between 10cm and 20cm are small. Mass thicknesses may be reduced to 10cm without incurring performance penalties. No notable improvement in performance is observed for elements of thermal mass that are thicker than 20cm.
- The range of mass thickness between 5cm and 10cm can be considered as a transition region. In this region, the performance penalties for reduced thicknesses become significant, however, in some cases these 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.

The total surface area of exposed mass is the most important property that contributes to the thermal mass of a building. Per kilogram, mass in narrow sections is much 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.

2.4.3. Heat Loss

The sources of heat loss in a typical pre-1960s building are displayed in Fig. 2-9. Although there are several factors that affect the rate of heat loss, the most important are as follows (McMullan, 2007):

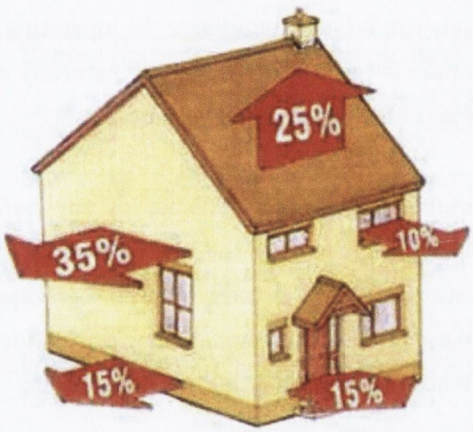


Fig. 2-9: Heat losses from apres-1960's building (Holmes_Insulation, 2012).

- Insulation of the building shell: As the insulation quality of the building envelope improves, the heat loss from the building decreases. Most attention should be given to the parts of the structure surrounding occupied areas, however, in terms of maximizing energy savings, all heated areas of the building should be insulated. Poor workmanship in installing insulation in a building, however, can result in significant thermal bridging, although this phenomenon can occur even in well insulated buildings. A thermal bridge is *"a portion of the structure with higher thermal conductivity that increases heat flow and lowers the overall thermal insulation of the structure"* (McMullan, 2007).
- Area of the shell: The greater the area of external surfaces compared to the internal volume the greater the rate of heat loss from the building.
- Temperature difference: A large difference between the T inside and outside of the building increases the rate of heat loss by conduction and ventilation.
- Air change rate: When warm air leaves a building it carries with it heat that is wasted and must be replaced by incoming air, which is usually cooler. Air leakage, or air

permeability as it is also called, in a building may be caused by intentional ventilation or unintentional 'infiltration' through windows, doors, gaps in construction and flues.

- Exposure to climate: The rate of heat transfer through an element increases when a wind blows across a wall or roof surface. This factor in determining the effective insulation can be included when calculating U-values by varying the value of external surface resistance, which are available for three different exposure classes, namely sheltered, normal and severe.
- Efficiency of services: There is usually some wastage of heat energy used for water and space heating, and the design of services can minimize, or make use of, this waste heat.
- Patterns of use: The number of hours per day and the days per year that a building is used has a large effect on its energy consumption. Many buildings that are unoccupied at times, such as nights, need to be re-heated before occupancy each morning.

Various methods exist for calculating the rate at which heat is lost from a building and the quantity of heat lost in a given time (McMullan, 2007). Although it is very difficult to compute heat losses for cyclic or unsteady conditions involving fluctuating temperatures, certain simplified calculations, such as the one outlined below, can be used to give good approximations.

During steady state conditions, the temperatures inside and outside the building do not change with time and the various heat flows occur at constant rates. By assuming steady state conditions, heat losses from a building can be classed as either fabric loss or ventilation loss. When intermittent heating exists, such as that given by electric storage heaters or by solar radiation, non-steady state conditions exist and the thermal capacity of the structure becomes significant and needs to be considered in calculations.
Fabric heat loss refers to heat loss caused by the transmission of heat through the materials in the building envelope. Equation (2-4) is used to calculate fabric heat loss under steady state conditions (McMullan, 2007).

$$P_f = UA\Delta t \qquad (2\text{-}4)$$

where P_f is the rate of fabric heat loss (W), U is the U-value of the element considered (W/m^2K), A is the area of that element (m^2) and Δt is the difference between the internal and external temperatures (°C).

Ventilation heat loss is caused by the loss of warm air and its replacement by air that is colder and has to be heated as calculated using Equation (2-5).

$$P_v = 0.33\, NV\Delta t \qquad (2\text{-}5)$$

where P_v is the rate of ventilation heat loss (W), N is the air infiltration rate for the room (air changes per hour, ach), V is the volume of the room (m^3) and Δt is the temperature difference between the inside and outside environments (°C).

The total heat loss for steady state conditions is the sum of the fabric and ventilation heat loss.

$$P_T = P_f + P_v \qquad (2\text{-}6)$$

To calculate daily heat losses as opposed to instantaneous losses, appropriate temperatures would be the mean internal air temperature and the mean external air temperature, both averaged over 24 hours. For the calculation of maximum heat losses, for example when choosing the size of heating equipment, it is appropriate to assume a lowest design temperature for external air, such as -1°C (McMullan, 2007).

It is also possible to calculate the T differences within a multi-layered structure, such as a cavity wall, resulting from heat flow due to a T gradient between the two sides of the wall (McMullan, 2007). A multi-layered structure will have varying T gradients between inside and out with the steepest gradients occurring in the layers with the lowest thermal conductivities, since the best insulators must have the greatest T differences between their surfaces. The ratio of the changes in T within a structure is proportional to the ratio of the thermal resistances as illustrated in Equation (2-7).

$$\frac{\Delta T}{T_T} = \frac{R}{R_T} \qquad (2\text{-}7)$$

where ΔT is the temperature difference across a particular layer, R is the resistance of that layer, T_T is the total temperature difference across the structure and R_T is the total resistance of the structure, where heat flow is given by Equation (2-2).

2.4.4. Thermal Transmittance (U-Values)

According to Part L of the Irish Building Regulations (2011), the thermal transmittance or U-value is a measure of the rate at which heat passes through a particular building component or structure when a unit temperature difference is maintained between the ambient air temperatures on each side. It is expressed in terms of Watts per square metre per degree difference in temperature (W/m^2K). The U-value is a convenient way of combining all mechanisms of heat transfer through an element of a building in a single parameter that describes the air-to-air behaviour of a particular element (McMullan, 2007).

Before discussing the calculation process for the thermal transmittance, it is first necessary to define the thermal conductivity (λ-value) of a material. This λ-value quantifies the rate at which heat is conducted through a particular material, when unit temperature difference is maintained between its inner and outer face. The unit of measurement is the Watt per metre per degree (W/mK). A list of common construction materials along with their thermal conductivity values are displayed in Table 2-4.

Table 2-4: Densities and Thermal Conductivity values for a range of commonly used building and insulating materials (DoEHLG, 2011).

Material	Density (kg/m^3)	Thermal Conductivity (W/mK)
Clay Brickwork (outer leaf)	1700	0.77
Clay Brickwork (inner leaf)	1700	0.56
Concrete Block (heavyweight)	2000	1.33
Concrete Block (medium weight)	1400	0.57
Cast Concrete (high density)	2400	2.00
Cast Concrete (medium density)	1800	1.15
Mortar (protected)	1750	0.88
Mortar (exposed)	1750	0.94
External Rendering	1300	0.57
Plaster (Gypsum)	1200	0.43
Plaster Board	900	0.25
Natural Slate	2500	2.20
Timber (softwood)	500	0.13
Timber (hardwood)	700	0.18
Expanded Polystyrene Slab	25	0.035
Extruded Polystyrene	30	0.029
Mineral Fibre/wool quilt	12	0.044
Mineral Fibre /wool batt	25	0.037
Polyurethane Board (unfaced)	30	0.021

U-values are a function of the thermal resistances of the various components that make up a particular construction. These different elements and surfaces all oppose heat transmission,

albeit at different rates and the thermal resistance (R-value) is a measure of the opposition, of a particular component in a building element, to heat transfer (McMullan, 2007).

To calculate the thermal resistance of a given structural element it is necessary to determine the material, surface and airspace resistances. Material resistances of each layer in an element are a function of the thermal conductivity and are calculated based on the assumption that the material being considered is homogeneous. The equation for thermal resistance of a single component is as follows:

$$R = \frac{d}{\lambda} \qquad (2\text{-}8)$$

where R is the thermal resistance of the component (m^2K/W), d is the thickness of the material (m) and λ is the thermal conductivity of the material (W/mK).

Surface resistances of an open surface depend upon the conduction, convection and radiation processes at that surface. Heat flow is opposed at the surface by a stationary layer formed by the air that is in contact with the surface and can be obtained by consulting standard values that have been computed by careful measurement and advanced calculation (McMullan, 2007). The surface resistances are influenced by the direction of heat flow, climatic effects (sheltered or exposed) and surface properties (such as normal building materials with high emissivity or polished metal with low emissivity).

Airspace resistances refer to the thermal resistance of an empty cavity or airspace within an element, such as a cavity wall, and depend on the nature of any conduction, convection or radiation processes occurring in the cavity. As is the case for the surface resistances, values for airspace resistances are generally found by consulting standard airspace value tables. Airspace resistances are affected by three primary factors, namely the thickness of the airspace, the flow of air in the airspace (ventilated or unventilated) and the lining of the cavity (normal surfaces or reflective surfaces of low emissivity).

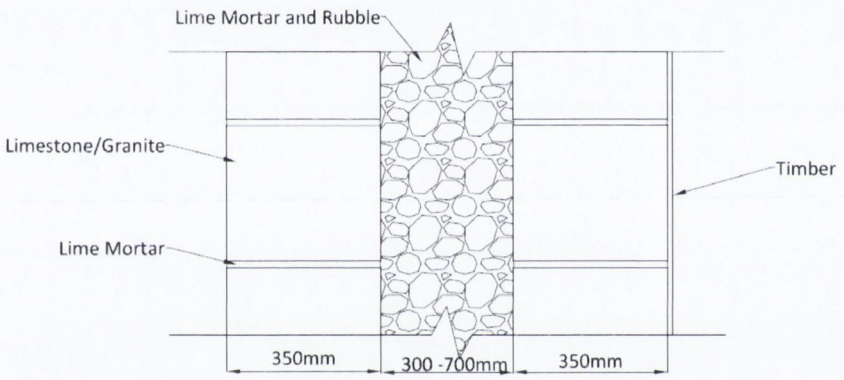
The three types of thermal resistance discussed above combine to give the total thermal resistance (R_T).

$$R_T = \sum_i R_i \qquad (2\text{-}9)$$

There are a number of methods that can be used to calculate the thermal transmittance (U-values) for particular building elements, depending on the condition and type of building element, but fundamentally the thermal transmittance is the inverse of the total thermal resistances of the element.

$$U = \frac{1}{R_T} \qquad (2\text{-}10)$$

In most wall configurations, particularly in modern buildings, there may be a number of layers. An example of such a construction detail can be seen in Fig. 2-10, which considers a limestone block construction with a cavity that has been filled with limestone rubble and mortar. A 10mm sheet of oak timber is placed on the inner face of the wall and there is no rendering applied to the outer face. The method outlined in this example considers a building component consisting of homogeneous layers and thus ignores any influence of thermal bridges on the properties of the element.



	d(mm)	λ (W/mK)	R (m^2K/W)
Limestone	700	1.5	0.466
Lime Mortar	300	0.7	0.428
Timber	10	0.16	0.0625
Internal Surface			0.130
External Surface			0.020
		Σ =	1.109

$$U = \frac{1}{R} = \frac{1}{1.109} = 0.904 W/m^2K$$

Fig. 2-10: Sample U-value calculation using the unbridged method (DoEHLG, 2011).

As mentioned previously, a thermal bridge is a section of a structure than has a higher thermal conductivity that in turn increases the rate of heat flow through that section of the construction, thus lowering the overall thermal insulation of the structure. This phenomenon typically occurs around structural details such as doors, junctions and openings where the continuity of the insulation material may be compromised and the section is then considered "bridged" (McMullan, 2007). Given the high levels of thermal insulation that current building designers aim to achieve, the relevance of thermal bridging has become of much greater importance in recent times. One distinctive type of thermal bridge, such as an uninsulated lintel above a window, is observed to conduct heat away at a

higher rate than surrounding areas, which results in lower surface temperatures on the interior side of the bridge. This type of bridge increases the risk of condensation and mould growth on the internal surfaces on and around the bridge and this is discussed in more detail in Section 2.5.2.

The thermal transmittance of a construction that is bridged can be calculated using the proportional method as described in Part L of the Building Regulations (DoEHLG, 2011). The total thermal resistance is calculated in three steps, as follows (DoEHLG, 2011):

- *"the upper thermal resistance is based on the assumption that heat flows through the component in straight lines perpendicular to the element's surface. To calculate this parameter, all possible heat flow paths are identified, for each path the resistances of all layers are combined in series to give the total resistance for the path, and the resistances of all paths are then combined in parallel to give the upper resistance of the element.*
- *the lower thermal resistance is based on the assumption that all planes parallel to the surfaces of the component are isothermal surfaces. To calculate it, the resistances of all components of each thermally bridged layer are combined in parallel to give the effective resistances for the layer, and the resistances of all layers are then combined in series to give the lower resistance of the element.*
- the total thermal resistance is the mean of the upper and lower resistances."

The upper thermal resistance (R_u) is computed using Equation (2-11):

$$R_u = \frac{1}{\frac{F_1}{R_1} + \frac{F_2}{R_2}} \qquad (2\text{-}11)$$

where F_1 and F_2 are the fractional areas of the heat flow paths and R_1 and R_2 are the resistances of these paths.

The thermal resistance of the bridged layer (R_b) is calculated using Equation (2-12):

$$R_b = \frac{1}{\frac{F_a}{R_a} + \frac{F_b}{R_b}} \qquad (2\text{-}12)$$

where F_a and F_b are the fractional areas of the bridged materials and R_a and R_b are their resistances. For example, in a timber frame wall with one insulating layer bridge *"a"* would refer to the insulation and *"b"* would refer to the timber studs. The resistances of all layers are then summed to give the lower resistance, R_l.

The total resistance, R_T is then calculated using Equation (2-13):

$$R_T = \frac{R_u + R_l}{2} \qquad (2\text{-}13)$$

The onsite measurement of thermal transmittance values is becoming increasingly relevant in determining the actual U-values of a building element. The method of in situ measurement has been developed by Dr. Paul Baker (2008) and used specifically on historic masonry buildings. Baker's apparatus consists of Campbell Scientific CR1000 data loggers that are equipped with heat flux and temperature sensors. These sensors were applied to the surfaces of the structural element in question and internal and external temperatures were recorded. Given the non-steady state nature of the monitoring conditions, a minimum recording period of 2 weeks was specified to ensure sufficient data was collected to compute the U-value of the construction. Baker then used the following equation to calculate the thermal transmittance:

$$U_t = \frac{1}{\frac{\Sigma \Delta T s_i}{\Sigma Q_i} + R_{int} + R_{ext}} \qquad (2\text{-}14)$$

where Q_i is the heat flux, Ts_i is the temperature difference across the wall, R_{int} refers to the internal surface resistance and R_{ext} is the external surface resistance. A correction is also applied to account for the thermal resistance of the heat flux sensor ($<6.25 \times 10^{3} m^2K/W$) and overall the uncertainty of the U-value estimates is ±10%. Baker found that, in general, in situ values for thermal transmittance were lower than those that were calculated using standard thermal conductivity values for "stone".

Rye (2010) examined the difference between U-values in traditionally constructed walls recorded on site using the techniques set out by Baker (2008) compared to those calculated using the BuildDesk software. Significant differences between the calculated and recorded values were observed, with the computer software overestimating U-values in almost 80% of the cases while underestimating the thermal performance of the walls. This is a significant finding given that BuildDesk is the basis for much building energy assessment and legislation and, in terms of historic buildings, may lead to the implementation of unnecessary and potentially harmful energy savings interventions. Rye (2010) concluded that, given the difficulties in defining the precise material properties of traditionally constructed walls, an insitu figure will be more representative of actual thermal performance than a calculated one.

2.5. Moisture Considerations in a Building

2.5.1. Humidity

Humidity is the term given to describe the amount of water vapour present in the air. Although it is only approximately 5%, by mass, of the total gases contained in the air, this water vapour creates significant global effects, such as the weather systems, water supplies and the ability of humans to grow their own food (McMullan, 2007). Humidity also influences the heat balance and comfort of the human body, the durability of building materials and the rate at which materials dry, while also causing the formation of condensation in buildings hence leading to building envelope and indoor environmental quality issues that will be discussed further later in this section. The concentration of water vapour in the air can be quantified by vapour pressure, mixing ratio, absolute humidity, relative humidity, dew point depression, saturation level or wet and dry – bulb temperature (Stull, 2000).

2.5.1.1. Saturation

Before discussing saturation it is important to first define vapour pressure. Air comprises of a mixture of gases, all of which contribute to the total pressure of the air (Stull, 2000). The pressure associated with any one gas in a mixture of gases is known as the partial pressure. As water vapour is a gas, its partial pressure in the air is known as the vapour pressure.

McMullan (2007) describes the state of saturation using the example of a volume of liquid water contained within an enclosed space. The vapour pressure of the air in the enclosed space increases as water molecules evaporate from the surface of the liquid water and collect in the air. Some molecules continually return to the liquid state and eventually the number of molecules evaporating is equal to the number of molecules condensing. At this point the air in the space is said to be saturated, which describes the state where the air contains the maximum amount of water vapour possible, at that particular temperature. At saturation, the vapour pressure reaches a steady value known as the saturated vapour pressure (SVP).

SVP is defined as the vapour pressure of the water vapour in a pocket of air that contains the maximum volume of vapour possible at that temperature. SVP is found to increase with increasing temperature and the relationship between the two, which is exponential-like in nature, is illustrated in Fig. 2-11. The curve includes temperatures below 0°C since

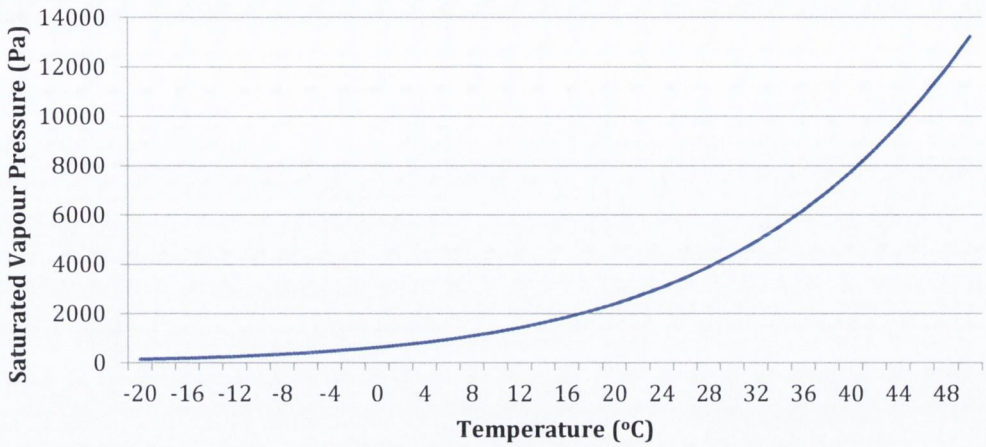


Fig. 2-11: Graphic representation of the relationship between temperature and SVP for a range of temperature values.

supercooled or unfrozen liquid water is known to exist between temperatures of 0°C and -40°C and therefore saturation can still occur (Stull, 2000).

The vapour pressure is an indication of the moisture content of the air at constant temperature. As the moisture content of the air increases, in conditions of constant temperature, the vapour pressure of the water vapour increases until SVP is achieved. Accordingly the saturation of a fixed sample of air is delayed if the temperature of the air is increased as more water vapour is required for saturation to be achieved as a result of the increase in temperature. It is this property that gives rise to the principle that warm air can support more moisture than cold air (BSI, 2011).

2.5.1.2. Quantification of Humidity

As mentioned previously, the concentration of water vapour in the air can be quantified using a variety of properties. For the purposes of this research, however, it is sufficient to discuss dew point, absolute humidity and relative humidity.

If an unsaturated parcel of air is cooled, it will become saturated at a particular temperature known as the dewpoint (Stull, 2000, McMullan, 2007). A sample of air, which has a fixed moisture content, has a constant dew point that is independent of the air temperature. Should the air become cooled to temperatures below this dew point temperature, the water vapour condenses to liquid in the form of condensation, a phenomenon that will be discussed in greater detail at a later stage.

The term "absolute humidity" (H_{abs}) refers to the concentration of the water vapour in the air and is defined in units of grams of water vapour per metre cubed of air (g/m^3) (Stull, 2000). In other words, it is the mass of water vapour in a given volume of air and is independent of temperature.

Relative humidity (RH) on the other hand is defined as the ratio of the air's actual water vapour pressure to the air's total capacity for water vapour pressure, i.e. its SVP (McMullan, 2007, Arundel et al., 1986, Chamberlain and Dougherty, 2006, Stull, 2000) BSI (2011) defines RH as the term that *"is used to describe the amount of water vapour the air contains relative to that which would produce saturation at a given temperature".*

$$Relative\ Humidity = \frac{Actual\ Vapour\ Pressure}{Saturation\ Vapour\ Pressure} \times 100\% \qquad (2\text{-}15)$$

RH could also be considered as an indication of the potential net evaporation into the air from hygroscopic materials as well as plants, people and soil (Stull, 2000). When RH equals 100%, no further net evaporation can occur since the air is now saturated, while lower RH values facilitate greater evaporation from hygroscopic materials. Along with the dewpoint, RH is paramount in determining whether condensation occurs (BSI, 2011), a point that is discussed further in Section 2.5.2.

McMullan (2007) also considers the RH in terms of SVP as described in Equation (2-16)

$$Relative\ Humidity = \frac{SVP\ at\ Dew\ Point}{SVP\ at\ Room\ Temperature} \times 100\% \qquad (2\text{-}16)$$

As discussed previously the SVP varies with temperature. As the air temperature in a space is increased, the denominator of Equation (2-16) is found to increase and, accordingly, the RH decreases. Hence it is observed that by increasing the temperature in a room, the RH decreases and by decreasing the temperature a corresponding increase in RH is observed, assuming that the absolute humidity remains constant throughout and the temperature does not fall below the dewpoint.

The RH of the ambient air determines the moisture content of hygroscopic materials (BSI, 2011). When RH conditions are lowered, moisture that is contained in these hygroscopic materials may be released into the atmosphere once more, however, should the RH remain

high, moisture is retained and absorbed into these materials, resulting in an increased risk of mould growth on surfaces, which is a health concern, and the decay of materials.

Dew point depression describes the difference between the ambient air temperature and the dew point temperature at a certain altitude in the atmosphere. This particular parameter is widely used for meteorological purposes such as the formation of cloud bases or thunderstorms and is also an important indicator in agricultural and forest meteorology, particularly in predicting wildfires. The magnitude of the difference between ambient air temperature and dew point temperature is an indication of the moisture in the air. The smaller the difference, the more moisture is present and the higher the RH and the chance of saturation or condensation occurring is high. Large differences on the other hand lead to drier air and so the potential for the occurrence of saturation or condensation is low.

The mixing ratio, which is also known as the humidity ratio, is similar to the absolute humidity and is the amount of water vapour that is in the air. It is the number of grams of vapour per kilogram of dry air (g/kg). Although not computed in this research, given that it is a fundamental parameter used to compute the ASHRAE psychrometric chart (Section 2.5.1.3) it is defined for completeness.

2.5.1.3. The Psychrometric Chart

Developed by Hyland and Wexler, on behalf of the American Society of Heating and Air Conditioning Engineers (ASHRAE), a Psychrometric chart (Fig. 2-12) provides a graphical representation of many of the thermodynamic properties of moist air (Wang, 2000). These charts have become useful in the design of air conditioning cycles as they illustrate the relationship between an array of variables that specify humidity.

There are two different coordinate types used for these charts, h-w charts, which use enthalpy (h), which is a thermodynamic property used to express the total heat content/energy of a system, and humidity ratio (w) and T-w charts that comprise temperature (T) and humidity ratio coordinates (w). Large air conditioning manufacturers most commonly use T-w charts whereas h-w charts are published by ASHRAE and CIBSE.

For the purposes of this research, only temperature, RH and H_{abs} are of concern and so the complete psychometric chart was considered to be overly complex and an alternative was found that illustrates T, RH and H_{abs} only and is displayed in Fig. 2-13. McMullan (2007) describes the method for using the psychrometric chart. The temperature and moisture

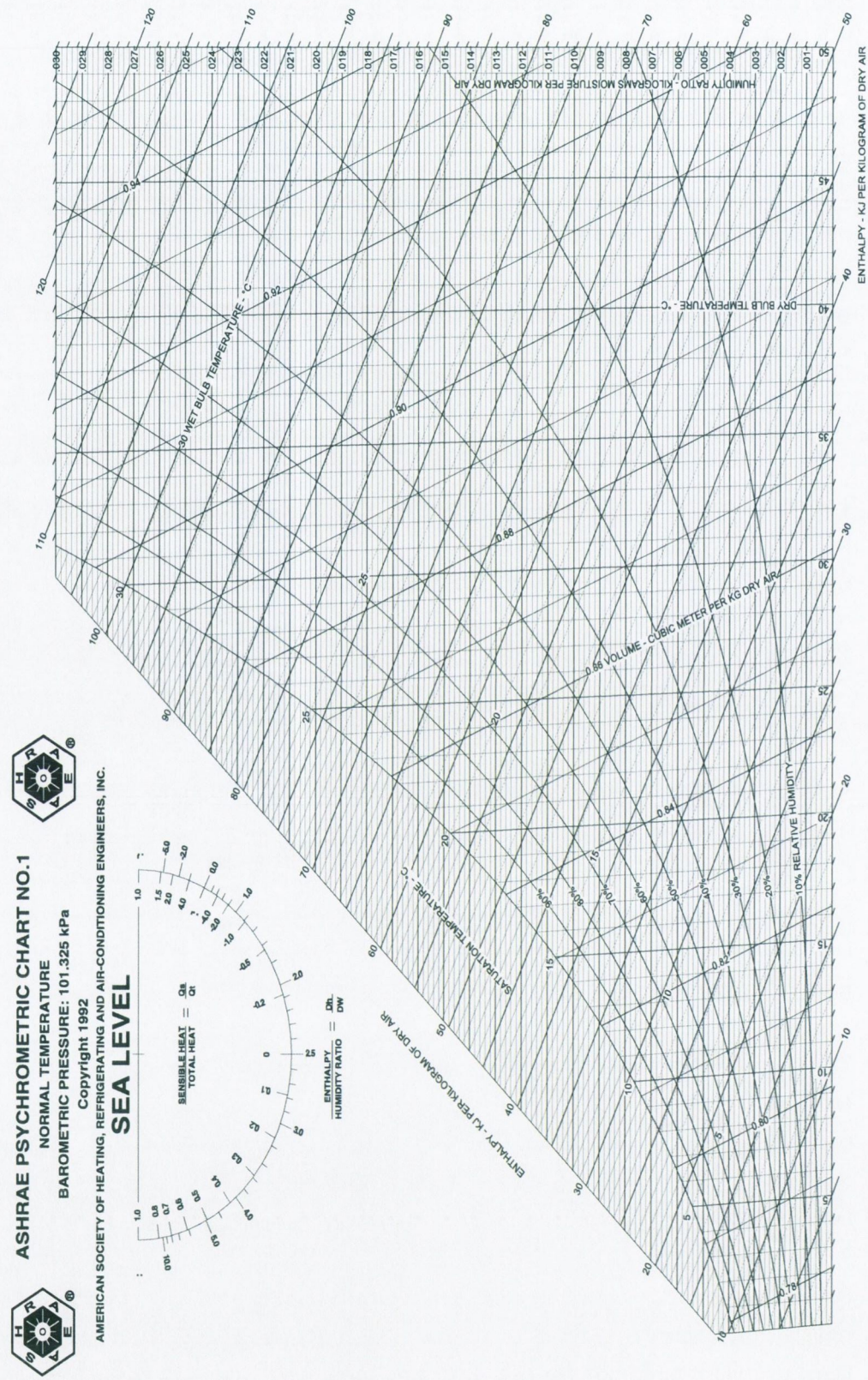


Fig. 2-12: ASHRAE Psychrometric Chart at sea level (ASHRAE, 2009)

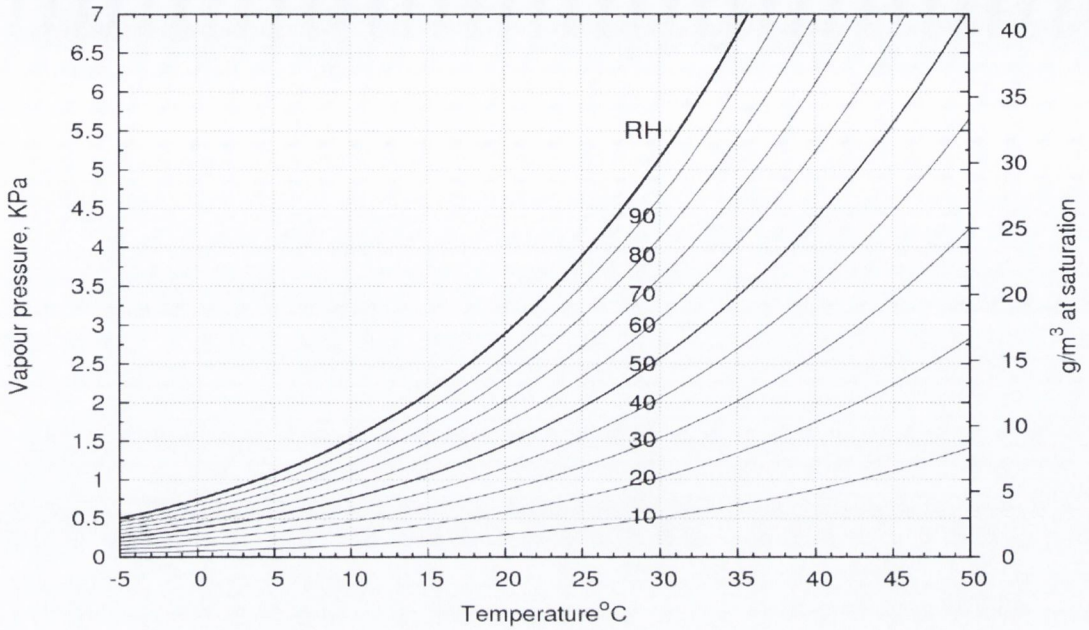


Fig. 2-13 Psychrometric chart displaying the relevant parameters used in this research (www.conservationphysics.org, First Accessed 04/10/2011). Absolute humidity is charted on the right hand axis.

content (humidity ratio or absolute humidity, for example) of a particular sample of air is described using a pair of values. These two values act as coordinates on the chart and define a single *"state point"* for the air. Moving to any other state point on the chart represents a change in the condition of the air. The direction of movement on the chart also represents specific types of air-conditioning change. For example, horizontal movements mean that the moisture content of the air remains constant, as is the case when air is simply heated without humidification. The RH, however, does change during horizontal movements. Similarly, vertical movements signify a gain in moisture content at constant temperature.

BSI (2011), Sanders (2006) and Gorham Schaffler (2011) describe a numerical solution for determining a number of the properties of moist air that corresponds to values obtained using psychrometric charts, including SVP, vapour pressure, dewpoint and absolute humidity using dry bulb temperature and RH. In order to compute the absolute humidity (H_{abs}), it is first necessary to calculate the SVP followed by the vapour pressure. The equations are as follows:

$$SVP = 0.6105e^{\frac{17.269T}{237.3+T}} \quad (for\ T \geq 0°C) \qquad (2\text{-}17)$$

$$SVP = 0.6105\, e^{\frac{21.875T}{265.5+T}} \quad (for\ T < 0°C) \qquad (2\text{-}18)$$

where T is the dry-bulb temperature of the ambient air (°C). BSI (2011) also states that the figure 237.3 in Equation (2-17) is not to be confused with the value 273.3, which is used to convert degrees Celsius to Kelvin. Stull (2000) offers an explanation for the differing terms used in Equations (2-17) and (2-18) (237.3 compared with 265.5 respectively). He considers the latent heat of vaporisation of air travelling across both ice and water. When the temperature is greater than 0°C, the latent heat of vaporisation is used, resulting in the constant of 237.7, compared to 265.5 when the vaporisation of ice is used for temperatures below 0°C.

Upon computation of the SVP values it is then necessary to calculate the vapour pressure, p (kPa), using Equation (2-19):

$$p = SVP \times \frac{RH}{100} \qquad (2\text{-}19)$$

The vapour pressure is then used to calculate the absolute humidity (H_{abs}) using Equation (2-20):

$$H_{abs} = \frac{2170 \times p}{T + 273.3} \qquad (2\text{-}20)$$

where p is the computed vapour pressure (kPa) and T is the dry-bulb temperature of the ambient air (°C).

2.5.1.4. Moisture Movement within a Building

Before discussing the various mechanisms that transport moisture throughout the internal environment of a building, it may be beneficial to first identify the major sources of moisture in a building. Typically, moisture loads in buildings are generated by the activities, such as cooking, cleaning, bathing, etc. or by the metabolic processes of the occupants (respiration, perspiration) (Berge, 2009). McMullan (2007) states that *"an average family produces 10 to 20kg of moisture per day by the activities of normal breathing, cooking and washing"*. The effect of these activities on the moisture conditions in a building is quantified in Table 2-5, which describes the moisture loads associated with a range of typical household activities.

As can be seen from Table 2-5, the presence of people in a building or room, particularly in relatively large numbers, such as in a lecture theatre or museum, for example, can induce a major moisture load in that room or space. For example, the presence of 50 people in a lecture theatre for a period of 1 hour will induce a moisture load in that space of 3.5kg during the residency time. This large load, if untreated, will result in an increase in the

moisture load and greater potential for condensation and mould development in the room as well as other undesirable effects associated with high humidity levels (Sections 2.5.3 and 2.6.2). The metabolic processes of humans are a function of activity level, generate moisture and this is noted in the figures displayed in Table 2-5, where the moisture generation rate for a person increases as activity levels increases (lowest for a sleeping person to highest for manual labour). People, by their presence in a building, may also be responsible for additional moisture loads, for example when entering a building having been out in the rain and, as a result, carrying additional moisture into the building on their wet clothes and belongings.

Table 2-5: Typical moisture generation rates for typical household activities (BSI, 2011)

Household Activity	**Moisture Generation Rates**
People	
asleep	40g/h.person
seated, office work	70g/h.person
standing, housework	90g/h.person
moderate manual work	300g/h.person
Cooking	
electricity	2000g/day
gas	3000g/day
Dishwashing	400g/day
Bathing/washing	200g/day
Shower (15mins)	600g/day
Washing clothes	500g/day
Drying Clothes indoors	1500g/day
Washing floors	200g/day
Plants	20g/day.plant

Water vapour within a building is transported through the processes of air movement, vapour pressure differences and diffusion, which refer to transfer of H_{abs} via a moisture gradient. (BSI, 2011). The rate of transfer by air movement and vapour pressure differences are significantly greater, sometimes as much as by an order of magnitude, than that of diffusion (Sanders, 2006).

When wind acts on a building, a negative pressure zone is produced on the leeward side that acts in such a way that it draws air from the building through any gaps and openings in the building envelope. The moisture gradient typically facilitates moisture removal from inside a

building as human activity usually results in a greater H_{abs} value than observed in the external ambient air (McMullan, 2007). In cases where the external H_{abs} conditions are higher in magnitude than internally, this air infiltration will lead to moisture infiltration into the building. In periods of cold weather, the higher internal temperatures increase the air pressure at high levels within the building relative to the outside, as the hot air rises, thus driving air through the structure. The volume of water vapour that is removed, or that enters a building, by such air movement depends on the size and location of these gaps and openings.

Water vapour also diffuses through the majority of building materials from areas of high to low vapour concentrations, the rate of which is dependent on the difference in vapour pressures between inside and outside and also the vapour resistance of each layer in the construction. Diffusion describes the movement of molecules, through random motion, from regions of high concentration to regions of low concentration and is governed by Fick's First and Second Laws. Fick's first law relates the diffusive flux, the rate of movement of molecules across a unit area, to the concentration of a substance as follows:

$$J = -D\frac{\delta\phi}{\delta x} \qquad (2\text{-}21)$$

where J is the "diffusion flux" or amount of substance per unit area per unit time [mol/m^2.s], D is the diffusion coefficient or diffusivity, [m^2/s], ϕ is the concentration [mol/m^3] and x is the position [m].

Fick's second law describes the change in concentration of a substance with time as a result of diffusion and states:

$$\frac{\delta\phi}{\delta t} = D\frac{\delta^2\phi}{\delta x^2} \qquad (2\text{-}22)$$

where ϕ is the concentration [mol/m^3], t is time [s], D is the diffusion coefficient [m^2/s] and x is the position [m].

Although not necessarily a form of moisture movement, the influence of hygroscopic materials on the internal moisture conditions in a building warrants discussion. The effect of hygroscopic materials on the internal environment is akin to the behaviour of thermal mass in regulating thermal conditions. Hygroscopic material, such as untreated timber for example, adsorb moisture during periods of high humidity and then release it back to the

environment when the humidity is low (Berge, 2009). This interaction between the indoor air and the hygroscopic materials, generally improves indoor humidity conditions (Simonson et al., 2002).

The moisture buffer value (MBV) is one parameter used to express the ability of a material to regulate moisture. According to Berge (2009), the MBV *"indicates the amount of water that is transported in or out of a material per unit open surface area, during a certain period, when it is subjected to variations in relative humidity in the surrounding air"* and is expressed in units of grams per metre-squared percentage RH ($g/m^2\%RH$). Table 2-6 displays the MBV as well as the actual penetration depth per 1% change in RH over 24 hours (D_p) for a number of common hygroscopic building materials. Unsurprisingly, timber has the highest MBV value indicating it has high potential for regulating humidity conditions. Cellular concrete, due to its permeability, also performs well in terms of its MBV value indicating its potential for use as a hygroscopic material.

Table 2-6: MBV and D_p values for a number of common hygroscopic building materials

Building Material	MBV ($g/m^2\%RH$)	D_p 1% RH for 24hrs (mm)
Concrete	0.35 – 0.42	6
Cellular Concrete (aerated)	0.96 – 1.11	52
Gypsum	0.57 – 0.69	33
Brick	0.39 – 0.69	104
Spruce Boards	1.15 – 1.22	16
Birch Panels	0.91 – 1.03	14

Paper and books, being constructed of organic fibres, are a further example of a hydroscopic material and is particularly relevant to this research (Derluyn et al., 2007). According to Waters (1993), *"manuscripts and books dated earlier than 1840 sill, generally, absorb water to an average of 80% of their original weight, although some will absorb as much as 200% of their original weight"*. For modern books (other than those with brittle paper) this value reduces to, on average, 60% of their original weight. Although effective in reducing fluctuations in the humidity parameters, the fact that paper absorbs moisture at different rates depending on a variety of factors, such as age, composition and condition, fluctuating humidity parameters will have a detrimental effect on collection items if exposed to excessive variations (Waters, 1993), a matter that is discussed in detail in Section 2.6.2.

When considering the effect of hygroscopic materials, it is also important to mention the Equilibrium Moisture Content (EMC). EMC is a parameter that is used to describe the amount of moisture that is a material contains when it has reached equilibrium with its

environment and is expressed as a percentage (IPI, 2014). EMC is determined by the inherent properties of the material and the temperature and relative humidity of the surrounding environment. The IPI calculates the %EMC for a block of average wood at a given T and RH and this EMC value is then used to provide an insight into how other hygroscopic materials would behave in such a climate. Accordingly this facilitates characterisation of the environmental quality.

Moisture transfer between the air of the environment, the perimeter of an object and its core is a dynamic process. The moisture is transferred in the form of water vapour and by the process of diffusion and is driven by differences in moisture content. When hygroscopic materials are exposed to fluctuating humidity conditions, the moisture content of the material is no longer in equilibrium with the environment and, as a result, the material will absorb or desorb moisture until equilibrium is achieved once more.

Fig. 2-14 displays typical EMC values for the components of photographic materials. From the chart it can be clearly seen that as the RH increases, so too does the EMC. Furthermore, the effect of fluctuating RH on the EMC varies significantly between materials. Both gelatin and paper appear to undergo large variations in EMC (7% for gelatin and 6% for paper) over a 55% RH range. Materials with a plastic film base are less responsive to RH fluctuations, unsurprisingly.

The response times of materials to fluctuating RH is not instantaneous but depends on a number of variables, including the inherent properties of the object, the hygroscopic nature of the material, the dimensional characteristics and the surface exposure to the environment. Table 2-7 illustrates the response time, in days, for a number of various library items that have not been placed in enclosures, to reach 50% equilibrium at 20°C. The values in the table indicate the slow response times for several materials and, accordingly, it may be concluded that short term variations in RH about a stable baseline may not alter the moisture content of materials significantly.

The effectiveness of using absorbent materials to stabilise the moisture conditions in museums and archives was studies by Padfield and Jensen (2011). They evaluated unfired clay brick, wood and cellular concrete as RH buffers and compared them using a novel unit *"buf"*. The *"buf"* was defined as *"the quantity of water vapour exchanged with the material, expressed as a volume of space, which will experience the same change in amount of water vapour when exposed to the same RH cycle"*. Upon subjecting the three materials to a cyclic RH variation between 50 and 60%, Padfield and Jensen (2011) found that well ventilated, unfired perforated brick, 5cm thick, was the most effective in buffering humidity variations

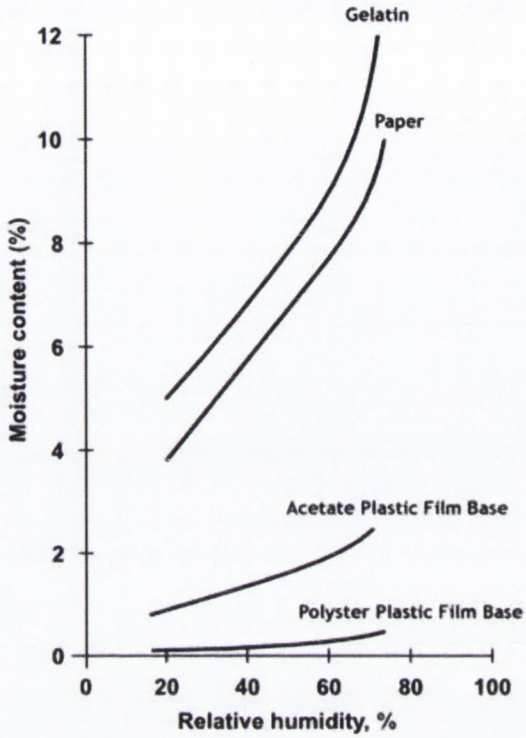


Fig. 2-14: Typical EMC curves for the components of photographic materials (IPI, 2014)

Table 2-7: Time (in days) to reach 50% moisture equilibrium at 20°C for various materials without enclosures exposed to (1) a one-time RH change from 20% to 50% and (2) a one-time RH change from 50% to 20% (IPI, 2014).

Material	Format	Absorbtion (days)	Desorbtion (days)
Photograph	Stack of 15 window-mat mounted 8" x 10" silver gelatin prints	12-15	14-15
Paper	Stack of 250 8" x 10" Office Paper	-	2-3
Book	Hardcover Book	2	3-3.5
	Hardcover Book in the middle of a group of 5	2.5-4.5	5-6

in a building. This material had a buffering capacity of $27m^3$ per square meter of surface for a daily RH cycle. In buildings that are used as stores or archives, humidity buffering gives real benefit in providing stability to the hygric environment and reducing the peak load on dehumidifiers.

Air flow and vapour pressure differences are the primary mechanisms that transport moisture throughout a room or building. Diffusion in air, while occurring, is not a significant transport mechanism relative to air flow and vapour pressure differences, although diffusion is significant when considering moisture movement through a building mechanism. in terms of humidity control in a building, the presence of hygroscopically active materials are effective in regulating moisture loads and thus preventing the problems associated with excessive humidity such as condensation and mould growth, for example, although it could be argued that high absorption of moisture could aid mould growth in historic elements if suspended for a prolonged period of time.

2.5.2. Condensation and Building Envelope Damage

2.5.2.1. Description and Causes of Condensation

The term condensation refers to a form of dampness in buildings, resulting typically in misting of windows, formation of beads of water on non-absorbent surfaces, dampness of absorbent materials and mould growth (McMullan, 2007). When considered during the design process, condensation will not normally be considered a problem as its formation can be facilitated, for example, the presence of impermeable tiles in a kitchen or bathroom or through natural or forced ventilation. However, when not designed for, condensation can pose serious problems, causing unhealthy living conditions, damage to materials and structures and concern to occupants in general.

The prevalence of condensation is a relatively recent concern and has particularly manifested itself due to modern building techniques that aim to eliminate energy inefficient draughts. As a result, natural ventilation through a building is effectively eliminated and alternative mechanisms for moisture removal must be considered. Historically, sufficient fresh air for the building occupants and their activities was provided by air leakage through gaps and cracks in the building envelope, which functioned so as to remove any excess water vapour which the air supported (BSI, 2011). Generally in modern building this air leakage is unacceptable, as it is perceived as reducing thermal comfort levels within the building as well as facilitating energy wastage due to higher heat losses through the envelope. If the ventilation system provided in the building is not sufficient to remove excess water vapour, condensation is more likely to occur.

Condensation can be classified depending on where in the building it occurs. There are two primary types, interstitial condensation and surface condensation. When water vapour,

moving through a particular multi-layered structure such as a wall, comes into contact with a material that is at or below the dewpoint of the vapour, condensate is deposited on the material (BSI, 2011, McMullan, 2007). This phenomenon is known as interstitial condensation. Although such condensation is most likely to occur on the surface of a material, it can also form within the body of a material if that is where the dewpoint lies. In multilayer construction, condensate may also be deposited on more than one plane as moisture evaporates from one surface and recondenses on a colder one. The dampness caused by interstitial condensation is a problem as it can result not only in staining and odour problems (Bellia and Minichiello, 2003), but also in significant damage and deterioration to structural materials through corrosion, rot and decay (Wyrwał and Marynowicz, 2002). It can also reduce the effectiveness of insulating materials by decreasing their thermal resistance, thus leading to decreased energy efficiency of the building as a whole.

Surface condensation occurs when warm, humid air within a building becomes cooled by contact with cold, non-absorbent materials such as window glass, uninsulated pipework and cisterns and cold joints at thermal bridges (BSI, 2011). Once the air is cooled below the dewpoint, excess moisture will be deposited on these surfaces as condensate. The effect of different magnitudes of condensate on non-absorbent surfaces is displayed in Table 2-8.

Table 2-8: Effect of condensate on impermeable surfaces (BSI, 2011)

Amount of Condensate (g/m^2)	**Effect**
<30	A fine mist that does not run or drip
30 – 50	Droplets form and begin to run down vertical surfaces
51 – 250	Large drops form and begin to run down sloping surfaces: • $70g/m^2$ will run down a 45^0 slope • $150g/m^2$ will run down a 23^0 slope
>250	Drops form and drip from horizontal surfaces

Although condensate may cause no damage to the impervious surface on which it forms, if sufficient accumulations occur, the water will run or drip onto other materials with the possibility of causing secondary damage. Absorbent surfaces may not exhibit condensation at first, although persistent condensation will eventually cause dampness leading to mould growth (see Sections 2.5.3 and 2.6.2).

According to BS EN ISO 13788 (BSI, 2002), "*the process of moisture transfer through a particular structure is a complex issue and a knowledge of moisture transfer mechanisms,*

initial conditions and boundary conditions is often insufficient, inadequate or underdeveloped", however the reader is referred to BS EN ISO 13788 for guidance on the calculation procedure for determining the likelihood of condensation occurring in a structural element. The two requirements for condensation to form in buildings are moist air and cold surfaces (McMullan, 2007). Furthermore, there are four primary factors that influence the production of condensation, as follows:

- Moisture Sources: Refers to the origin of the water in the air, typically from either the weather or human activity within a building.
- Temperatures: As mentioned previously, warm air can "*hold*" more water than cold air. The extra moisture contained in warm air is likely to cause condensation once the air is cooled. The rate at which structures change temperature may also influence whether or not condensation will occur. For example, heavyweight construction, with a high thermal capacity, will take a longer time to heat up than a lightweight construction and thus condensation may occur as it is heating up.
- Ventilation: The use of ventilation, either natural or forced, is effective in assisting with the extraction of moist air that may condense if cooled. This mitigation strategy is most effective when used near the source of the moisture, for example, an extractor fan in a bathroom.
- Use of Buildings: Modern building practices and modern living have resulted in higher occupant demands regarding thermal comfort conditions and these changes have increased the likelihood of condensation occurring in buildings. Modern heating systems require low levels of air movement and accordingly more draught-proofing and higher levels of insulation have been introduced to housing, resulting in lower levels of natural ventilation. Moreover, many dwellings are only occupied during the evening and so moisture-making activities such as cooking and washing are often compressed into a short period of time when the windows are generally closed. Moisture removal through ventilation in this case is ineffective as there is minimal air movement through the building.

2.5.2.2. Prevention and Removal of Condensation

The most effective manner in which condensation related problems can be prevented is by correct and comprehensive building design to avoid the occurrence of condensation (BSI, 2002). Designers need to fully account for both the moisture loads created during the construction phase and also the moisture loads generated by typical occupant activities. BSI

(2002) describes a series of methods for assessing the risk of surface and interstitial condensation as well as mould growth, all of which relate to three core criteria:

1. The structure and the heating system should be designed so as to ensure that the RH limit for mould growth of 80%, at the surface of the material, is not exceeded during the coldest month of the year.
2. Any interstitial condensation that may occur should evaporate during the following summer thus preventing a year on year accumulation of moisture.
3. The risk of degradation of materials should be assessed in terms of the maximum level of condensate that might occur.

Given the effects of condensation on building materials and occupant comfort, it is essential to determine a method to prevent and remove the condensate. Persistent surface condensation can be remedied using a combination of ventilation, heating and insulation (Sanders, 2006, McMullan, 2007).

Ventilation reduces condensation by removing moist air from the building that may otherwise condense when cooled, and is most effective when used near the source of moisture. It is of particular importance in historical buildings that are typically uninsulated. Moreover, the building envelope of such buildings is typically permeable and ventilation is utilised to remove excess moisture. As a result of the high level of ventilation in traditional buildings, condensation is generally not observed in such buildings unless incompatible retrofitting measures are installed, such as replacing windows with double glazing or using impermeable insulation materials without provision for ventilation. Heating and insulation work in tandem to prevent the formation of condensation. Heat is necessary to maintain an air temperature higher than the dewpoint, while also allowing the air to support more moisture, which can then be removed more efficiently by ventilation. Thermal insulation then prevents the heat loss associated with some forms of ventilation, preventing surfaces from cooling down sufficiently to fall below the dewpoint. When considering the prevention of condensation, the heating regime of the building is of importance. Generally, long periods of low temperature heating are more effective than short periods of high temperature heating. By providing a base heating level and using effective insulation, the ambient air temperature, as well as the surface temperatures within the building, can be maintained at a level that is higher than the dew point. Furthermore, it is important to keep the RH conditions at the surfaces of cold materials in a building below 70% to further minimise the risk of condensation.

As mentioned previously, interstitial condensation is a relatively recent design concern and, given the issues associated with its formation, it is important to prevent the occurrence of this condensation. Sanders (2006) lists a number of steps that may be implemented so as to eliminate moisture problems within the building envelope. These are as follows:

1. Obtain low vapour pressures by ventilation and/or reduced moisture input to the building.
2. Seal any gaps to limit air movement from the warm side into the structure as condensation will occur should this warm air cool to the dew-point temperature.
3. Use materials of high vapour resistance near to the warmer side of the construction to minimise the volume of water vapour entering the cold side of the construction.
4. Use materials of low vapour resistance, or provide ventilated cavities, near the colder side of the construction.
5. Use materials of low thermal resistance near to the warmer side of the construction.
6. Use materials of high thermal resistance near to the colder side of the construction.

2.5.3. Health Concerns associated with Low and High Humidity Conditions

Arundel et al (1986) carried out a review of the influence of RH on human health and divided the effects into two distinct categories – direct and indirect health effects. Direct health effects occur in both very low and very high RH conditions and refer to physical discomfort due to altered temperature perception. Conditions of extremely low RH (below 20%) result in irritation of the eye, a phenomenon that is discussed in greater detail below. Conversely, high RH values have been found to reduce the severity of symptoms among asthma sufferers (Strauss et al., 1978). Combining high RH conditions with high temperatures have been shown to have an important adverse effect on health. These particular environmental conditions reduce the rate of evaporative cooling of the body and can cause considerable discomfort and, in extreme cases, can result in heat stroke, exhaustion and even death (Arundel et al., 1986). Indirect health effects refer to the impact of RH on the population growth and survival of infectious or allergenic organisms, particularly fungi, protozoans, mites, bacteria and viruses, all of which can lead to increased instances of respiratory illnesses and allergies amongst people vulnerable to these conditions. Brundrett et al. (2006) state that buildings that are subjected to prolonged high air humidities (>70%) are likely to experience problems associated with the aforementioned allergenic organisms. The growth of these organisms can also be a by-product of artificial humidification of an indoor space. Moreover, RH can influence the concentration of noxious chemicals in the air by altering the rate of noxious gas emissions that occur from building materials, for example formaldehyde, and the reactions of water vapour with chemicals in

the air. The indirect health effects do not vary uniformly with RH and the humidity range that minimises the majority of adverse effects lies between 40 and 60%, as illustrated in Fig. 2-15.

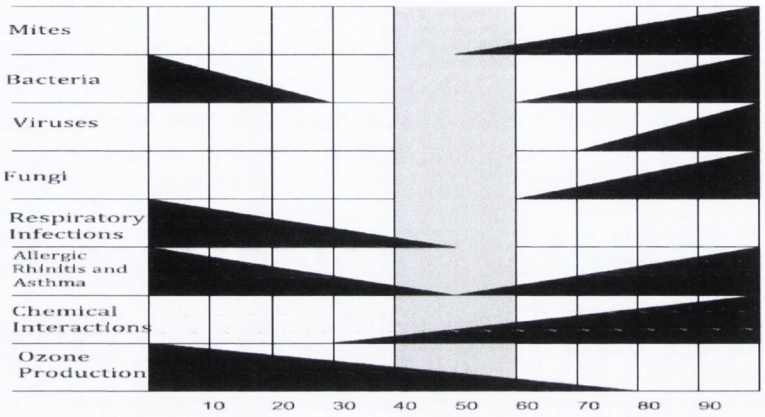


Fig. 2-15: Optimum range (highlighted in grey) of RH for minimising adverse health effects. RH values are indicated on the X-axis (Arundel et al., 1986).

Arundel et al (1986) summarise a large number of studies that aimed to establish a definitive link between low RH conditions and absenteeism from school or work. Generally it was found that low RH conditions lead to a higher level of absenteeism due to respiratory illnesses. One such study was carried out by Sale (1972) who found that the absenteeism rate for children subjected to no form of humidified environment was 7.1% per week, while children attending a humidified school had an absenteeism rate of 3.9%, which improved to 1.3% for children with humidification at school and in the home.

Melia et al (1982) compared the incidence of respiratory illnesses such as colds, wheezing and bronchitis amongst a number of English schoolchildren. By monitoring the RH conditions in the home of each child, it was found that 55% RH conditions were exceeded in almost three quarters of homes and that respiratory conditions were more likely to develop amongst children who were regularly subjected to RH values higher than 75% compared to children from homes with mean relative humidity conditions below 55%. No statistically significant relationship was found between the incidence of respiratory infections and the children's age, sex, class, home temperature, or parent's smoking habits indicating that it was the high humidity levels that resulted in the increased incidence of respiratory illness.

Leitte et al (2009) investigated the associations between chronic obstructive pulmonary disease, asthma and chronic bronchitis and total suspended particles, sulphur dioxide and nitrogen oxide present in the air using models. These models considered time patterns and

weather effects and the delayed effects for up to seven days were analysed. The study found that an increase in total suspended particles of 10μg/m^3 was related to an increase in hospital admissions for chronic bronchitis of 3.3%. The time lag for this influence was between one and four days. The results indicated that lower humidities aggravated symptoms in individuals suffering from respiratory illnesses. On the other hand in high RH conditions there are a reduced number of particles present in the air, as the particles, many of which are inorganic salts, absorb moisture and change to the liquid phase under a process known as deliquescence. When this phenomenon occurs, the number of total suspended particles in the atmosphere is reduced.

The tests carried out by Sale (1972), Melia et al (1982) and Leitte et al (2009) illustrate that both low and high humidity conditions may be damaging to human health. These somewhat validate Fig. 2-15 and indicate that the optimum RH range for human health lies between 40 and 60%.

Wolkoff (2008) examined the effect of RH on the eye and in particular the precorneal tear film (PTF), which is the field covering the anterior surface of the cornea. The PTF is essential for the maintenance of vision as well as the health of the cornea (Chopra et al., 1985). Thinning of the outer layer of the PTF over the course of the working day results in a lower break-up time, which refers to the elapsed time from the latest blink to the occurrence of the first dry spot in the PTF or a thinning of the PTF(Wolkoff and Kjærgaard, 2007). Over time, this can result in an increase of dry-eye related symptoms and diseases.

Wolkoff and Kjaergaard (2007) describes how a number of epidemiological studies in offices have developed a link between low RH values (from 5% to 30%) and an increased occurrence of perceived dry air and sensory irritation of the eyes and upper airways. This is a result of the desiccation of the mucous membranes over time initially in the eye and followed by the nasal cavity. RH significantly impacts water evaporation from the PTF, irrespective of the presence of dry eye disease. The water loss is caused partly by the difference in water vapour pressure between the ocular surface and the environment.

The substantial evaporation induced at low RH conditions is compatible with reporting of dry and irritated eyes as typically encountered in office-like environments where the symptoms listed in Table 2-9 are frequently reported particularly amongst wearers of contact lenses. In order to prevent damage to the PTF, the RH should be maintained at approximately 45% or higher as the PTF appears to stabilize against dessication, sensory irritants and other indoor pollutants at this minimum level.

Table 2-9: Symptoms, signs and perceptions reported in epidemiological and clinical studies of indoor environments (Wolkoff, 2008)

Ache	Ocular/visual fatigue
Blurred (near) vision that improves with blinking	Oppressive eyelids
Burning	Pain/painful
Discomfort (increased awareness)	Sandy/gravel
Dryness (desiccation	Scratching/scratchiness
Foreign Body Sensation	Smarting
Gritty	Sore
Itching	Stinging
Inflamed	Strained
Irritation	Tiredness (Fatigue)
	Lacrimation (excess tearing)

As well as causing complaints of dryness amongst occupants, low humidity levels may also increase the effects of certain pollutants (Brundrett et al., 2006). By lowering the humidity in a building, the occupants report an increased perception of smells as well as the irritation of cigarette smoke because it enables fine particles to remain suspended in the air for a longer period of time, hence prolonging the nuisance.

2.6. Indoor Environmental Quality in Libraries and Museums

2.6.1. Relevant Environmental Parameters in Libraries and Museums

Cultural heritage refers to the "*legacy of physical artefacts and intangible attributes of a group or society that are inherited from past generations, maintained in the present and bestowed for the benefit of future generations*" (UNESCO, 2012). According to ASHRAE (2011) "*the importance of cultural heritage ranges from national to regional, or even local, but retains symbolic, cultural, social, historical and monetary value that is frequently impossible to estimate*". As a result, the conservation and preservation of such artefacts is important, worthwhile and, in some cases, legally mandated. Over the course of the last decade, museum exhibition facilities and storage areas have been shown to be the most crucial environments concerning the preservation of collections and artefacts (Pavlogeorgatos, 2003). Corgnati et al. (2009b) state that the need to monitor variations in the thermo-hygrometric environment over time is fundamental in museums and defining the actual microclimatic quality level when compared to the expected quality based on the artefacts' preservation requirements is essential. Generally speaking, any environmental perturbation

contributes to the deterioration process of works of cultural significance. It should also be noted, however, that steady but inappropriate microclimatic conditions can cause damage to artefacts. Chemical pollution, humidity, temperature and lighting can all damage or even destroy the material cultural goods that are kept, protected and displayed in museum collections (BSI, 2012, Pavlogeorgatos, 2003, La Gennusa et al., 2005, Michalski, 2003). The specific effects of temperature and relative humidity will be discussed in Section 2.6.2.

Although critical for enhancing access to collections, all sources of light, whether natural or artificial, can cause extensive and irreversible damage to collection materials (BSI, 2012) and may present the most extensive threat to museum collections (ASHRAE, 2011). These items can undergo chemical changes, for example, inks, dyes and pigments will discolour, or physical changes, such as, mechanical strength, can be lost or glossy materials become matt. Materials can range from non-sensitive to high sensitivity to light and, in general, organic materials are more sensitive than inorganic materials.

As the wavelength of light radiation decreases, the rate of photochemical damage generally increases (BSI, 2012). Within the spectrum of visible light, damage increases from red to violet, and ultraviolet radiation is yet more damaging still than violet light. Radiant heat from light sources can also cause damage to collections, as it can lead to uneven distribution of heat or moisture within collection items or produce a desiccating environment. Intensive illumination can also lead to accumulation of heat and heat-related stress of collection items. Light and ultraviolet radiation damage is cumulative and proportional to exposure and can be minimised by reducing either the illuminance or the duration of exposure, or both. Since objects are generally seen better in brighter light, the specification of illuminance is always a compromise between preserving the collection and making it clearly visible.

Pavlogeorgatos (2003) and Schieweck and Salthammer (2011) state that atmospheric pollution is the most significant threat to the preservation of museum collections. Gaseous atmospheric pollutants such as sulphur and nitrogen oxides, ozone, particulates and other combinations that are unique to a location can penetrate most building types, which is an issue of global and local concern (BSI, 2012, Pavlogeorgatos, 2003, Schieweck and Salthammer, 2011, ASHRAE, 2011). Pollutants, even in very low concentrations, can adversely affect the condition of collections (ASHRAE, 2011). Some particulates, especially soot in urban and industrial areas, are not removed fully by many coarse particle filters and are typically deposited on collection items. This can result in damage to intricate details on museum exhibits, an increase in the possibility of the development of microorganisms, traces of chemical pollution on the surface of exhibits and a sense of neglectfulness due to accumulation on collection items. In the presence of humidity, sulphur and nitrogen oxides

can transform into sulphuric acid and nitric acid respectively, resulting in chemical and mechanical deterioration of a wide range of cultural items. As well as particulates and sulphur and nitrogen oxides, Schieweck and Salthammer (2011) also identify volatile organic compounds, semi-volatile organic compounds, formaldehyde, formic acid and acetic acid as air pollutants that are commonly found in museum and library environments and, by their corrosive nature, are damaging to museum exhibits and library collection items.

In addition to the factors mentioned previously, ASHRAE (2011) also propose that the following factors influence damage to cultural artefacts, as follows: pest infestation, natural emergencies, building and mechanical plant malfunctions, theft and vandalism. Although these considerations are of concern to curators and librarians, they are beyond the scope of this thesis, which is to examine the thermo-hygrometric environment in historic buildings, and will not be discussed further.

2.6.2. The Effect of Temperature and Relative Humidity on Collection Items

Adequate control of the thermo-hygrometric properties in museums, libraries and archives is of fundamental importance for preserving organic hygroscopic materials, such as books. Magnitudes and fluctuations of temperature and relative humidity in the indoor environment of such buildings are two of the most important causes of deterioration (Camuffo et al., 2001, Krüger and Diniz, 2011, Kozlowski et al., 2011, Jakiela et al., 2008). ASHRAE (2011) state that of all indoor environmental parameters that may be controlled by HVAC, high humidity is the most important factor from a conservation viewpoint.

The conventional (late twentieth century) approach to specification of environmental conditions for museums has typically involved the specification of a single "ideal" environment and, failing that, to specify *"compromise"* or *"relaxed"* conditions (Michalski, 2007). The belief was that the larger the deviation from the ideal conditions the greater the damage to the cultural items. Recognising that stringent specification of environmental conditions in museums, libraries and archives may be impractical and, in the case of museums contained in historic buildings unfeasible, Michalski, through his contributions to ASHRAE (2011), introduced the concept of environmental classification for museums, libraries and archives, a system that has since been somewhat adopted by the Canadian Council of Archival Materials (Michalski, 2003), who continue to specify optimal RH conditions as 45% ±10% with a temperature of 18-20°C.

ASHRAE (2011) suggest 5 different environmental classifications of varying rigorousness, namely AA, A, B, C and D. The environmental set-points specified by each classification is specified in Table 2-10. From the Table it can be seen that the optimum classification for museums is Classification A, which aims to reduce seasonal fluctuations significantly and limit and variations in the thermo-hygrometric environment to short-term ones. This, however, may not be feasible in historic museums and so, an environmental classification of A might be the best that can be achieved.

Table 2-10: Environmental classifications for Museums, Libraries and Archives as specified by ASHRAE (2011).

Classification	Allowable Temperature Fluctuations	Acceptable Relative Humidity Fluctuations	Notes
AA	±2k	±5%	Most stringent and energy intensive solution
A	±10%	±5k	Optimal for Museums. Fluctuations are short term only
B	±10%	±5k	Precision Control may be required
C	T < 25°C	25% - 75%	Most likely in historic museums
D	-	<75%	Control of dampness is the only environmental issue

Michalski (2007) also proposed the notion of proofed fluctuation in RH or temperature conditions in museums, libraries and archives. This describes the largest T or RH variation to which the cultural object has been exposed to in the past. Michalski (2007) argues that the risk of further mechanical damage (beyond that already accumulated) from fluctuations that are smaller than the proofed value is very low. Considering museums, libraries and archives that are situated in historic buildings and have poor environmental control, such as the Old Library in TCD, this concept may not be a suitable strategy for the preservation of the cultural heritage within. The influence of climate change on the environmental conditions in historic museums, libraries and archives is of serious concern to conservationists (Staniforth, 2007) and the concept of proofed fluctuations is likely to require an increased level of environmental control in such building if it is to be a successful conservation strategy.

Depending on the type of material to be stored in a given museum, library or archive, an object can undergo degradation, in three different manners: change in dimensions, chemical reactions and biological degradation (Alten, 1999, Krüger and Diniz, 2011, Mecklenburg and Tumosa, 1999). Very low or fluctuating RH or temperature can lead to mechanical damage of objects, fundamentally as a result of expansion and contraction, or swelling and shrinkage, combined with some form of internal or external restraint (Krüger and Diniz, 2011, ASHRAE,

2011). When the RH increases, hygroscopic materials adsorb water vapour molecules, increasing their equilibrium moisture content, augment their size with dimensional changes that are not identical in the three dimensions and generate internal stress (Alten, 1999, Camuffo et al., 2001, Camuffo et al., 2004, Corgnati et al., 2009b, Pavlogeorgatos, 2003, Steeman et al., 2010). When the RH level drops, the equilibrium moisture content of the hygroscopic artefact also decreases through evaporation, resulting in shrinkage. Cycles in dimensional changes are, in the long term, damaging due to their cumulative effect and can accelerate physical deformations in a process known as "creep" (Bogaard and Whitmore, 2002, ASHRAE (2011)), Kruger and Diniz (2011) and Mecklenburg and Tumosa (1999) also considered the effect of high and low RH on physical properties of organic materials. In general, low RH conditions tend to stiffen materials making them brittle, while high RH conditions make them more flexible. Varying thermal conditions result in expansion and contraction of objects, which, over time, leads to mechanical damage to the object.

Fluctuations in ambient RH bring about dimensional changes in wooden cultural objects, which can cause high stresses within the material and significant damage (Bratasz et al., 2005). If a dry wooden item is restrained from swelling when RH increases, it can experience crushing of the internal structure and buckling. Similarly, if the wet timber object is restrained from shrinkage on return to low RH, it will experience stretching and eventual cracking. The structural restraint is a result of two-fold higher moisture related dimensional change in the tangential direction than in the radial one. Therefore, in all wooden objects in which the curvature of the growth rings is significant (i.e. objects of a cylindrical symmetry), the large tangential shrinkage or swelling will not be accommodated by the corresponding radial change. This would result in internal stresses in the material even for slow, quasi-static changes in RH producing no gradient of moisture content in bulk wood. After carrying out a monitoring scheme on environmental induced strains in wooden cultural items, Bratasz et al. (2005) plotted the tangential and radial strains versus the EMC (see Fig. 2-16) and found that wooden elements are particularly endangered by mechanical damage. This is due to dynamic restraint generated by a gradient of the dimensional change across the material when the exterior (tangential strain) responded more quickly to an RH change than the interior (radial strain). This is reflected by the higher slope for the tangential strain than the radial which implies that changes in RH induce larger strains in the tangential direction compared to the radial. Similar conclusions were reached by Jakiela et al. (2008) who used numerical modelling to assess the evolution of the moisture content gradient and the stress field resulting from the restrained differential dimensional response across lime wood samples, in response to variations in temperature and RH. The allowable RH variations, below which mechanical damage would not occur, were derived as functions of the amplitude, time period and starting RH level of the variation. Lime wood can endure step RH

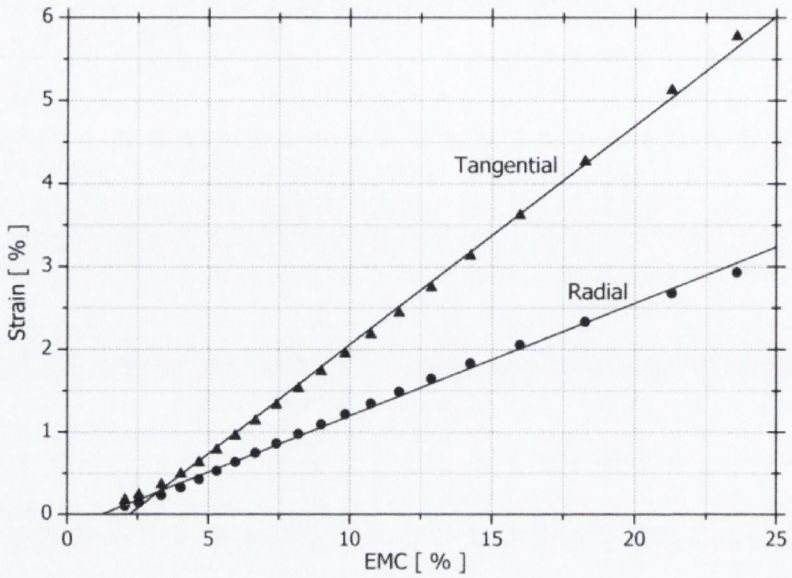


Fig. 2-16: Strain of lime wood in the radial and tangential directions plotted versus EMS(Bratasz et al., 2005)

variations of up to 15%, but the allowable domain narrows when RH levels shift from the middle range. The allowable amplitude of the variations increases when time allowed for the change increases.

The stresses and strains induced in an object as a result of temperature and RH fluctuations may be calculated directly using the following equations (Mecklenburg and Tumosa, 1999):

$$\varepsilon_t = \alpha_t \Delta T \qquad (2\text{-}23)$$

$$\sigma_t = E\alpha_t \Delta T \qquad (2\text{-}24)$$

$$\varepsilon_{RH} = \alpha_{RH} \Delta RH \qquad (2\text{-}25)$$

$$\sigma_{RH} = E\alpha_{RH} \Delta RH \qquad (2\text{-}26)$$

where ε_t and ε_{RH} are thermal and moisture related strains, α_t and α_{RH} are the thermal and moisture expansion coefficients, σ_t and σ_{RH} are the thermal and moisture stresses and E is the equilibrium modulus of elasticity for the material at the given temperature or RH. These equations can be used to develop diagrams and calculate the mechanical strains developed when a specimen is restrained and the environment changed. Fig. 2-17 is one such diagram that has been generated by Mecklenburg and Tumosa (1999) for the strains versus the RH for a sample of 350- year old Scotch pine timber that is restrained about its perimeter.

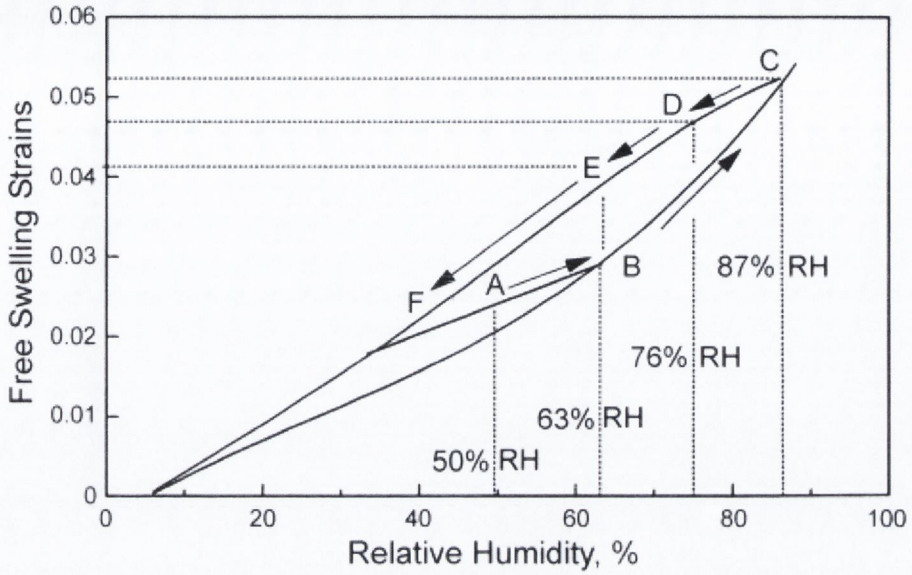


Fig. 2-17: A simplified free swelling diagram for strains versus RH for a sample of 350-year-old Scotch pine that is restrained about its perimeter (Mecklenburg and Tumosa, 1999).

As the RH rises from 50% (Point A) to 63% (Point B), the wood increases in compressive strain to approximately 0.03. It begins to make the transition from elastic to plastic behaviour. As the RH continues to rise from 63% (Point B) to 87% (Point C), the timber, if it does not buckle, experiences full plastic strain (permanent deformation), and the stresses due to expansion of the material are fairly constant. From Point C, if the RH is forced to drop by the environmental conditions until the specimen reaches 76% (Point D) where it unloads all elastic compressive strain and is stress free once again. At this point the specimen has experienced *"compressive set"* and has completely reinitialized its equilibrium position (stress equals zero). If the RH continues to decrease, tensile stress builds and at Point E (63% RH), the specimen yields in tension. From this point on, further desiccation causes plastic deformation in tension until Point F (40% RH) where the sample cracks. If the timber had not been subjected to the large RH incursion, it could have equilibrated to low RH levels without cracking.

Chemical deterioration, sometimes called *"natural aging"*, refers to the occurrence of a chemical reaction, resulting in damage to an object (Alten, 1999). Higher temperatures and moderate amounts of adsorbed moisture lead to more rapid decay in chemically unstable artefacts, especially paper based and other archival materials (BSI, 2012, ASHRAE, 2011). The most important factor in chemical damage to modern records is hydrolysis, which refers to the breakdown of a chemical due to reaction with water, which affects papers, photographic negatives and analogue magnetic media.

Pavlogeorgatos (2003) and Krüger and Diniz (2011) state that there are four major categories of chemical reactions that lead to the deterioration or destruction of materials in a museum, namely the commencement or acceleration of metal corrosion, the fading of dye materials, the decrease of paper and cloth resistance and the deterioration of some glass materials. The rates of chemical reactions were discussed briefly by Mecklenburg and Tumosa (1999) who quoted Svante Arrhenius' equation as follows:

$$k = Ae^{\left(\frac{-E_a}{RT}\right)} \qquad (2\text{-}27)$$

where k is the reaction rate, A is a constant, often called the frequency factor, E_a is the activation energy, which in general increases as the rate of degradation decreases, R is the gas constant and T is the absolute temperature.

This equation states that the chemical reaction rate increases with increasing temperature and vice versa (Mecklenburg and Tumosa, 1999). Another important aspect of this effect is related to the activation energies of cultural materials. If the activation energy for a process is lower in Material A than in Material B, then Material A will degrade faster than Material B in the same environment. Higher temperatures will markedly accelerate chemical degradation of both materials but at different rates.

Biological deterioration is damage caused by living organisms such as insects, bacteria and mould (Alten, 1999). RH and temperature levels determine whether these organisms flourish or exist at all. Pavlogeorgatos (2003) suggests that mould development is favoured in RH conditions above 79%, especially in hot environments with static air. ASHRAE (2011) state a lower limit for the prevention of mould growth on any surface as below 60% at the material's surface. A list of material damage and deteriorations and the associated risks for materials that may be commonly found in a library or archive can be found in Table 2-11 (BSI, 2012).

Based on the information outlined in the table, recommended environmental conditions for the preservation of a heritage collection in a library or archive can be determined. For example, if the collection contains a substantial quantity of leather bound books, an RH range between 35% and 60% is recommended to prevent the leather from becoming overly dry, leading to physical damage of the material while also preventing mould formation. Furthermore, a temperature below 20°C should be maintained to slow the rate of chemical-induced degradation.

Table 2-11: Material damage and risks associated with T and RH (BSI, 2012)

Material	Damage and Deterioration	Risk
Ink: iron gall	• Data suggests iron gall inks are susceptible to both oxidation and hydrolysis. The latter is especially significantly accelerated by high RH and high temperature. Long-term preservation is achievable by cooled storage or cold storage similar to those for rosin-sized acidic papers. The present level of knowledge suggests limits of ±10% RH and ±5°C in any time interval.	• Ink corrosion ultimitely leads to loss of material support, which results in loss of areas with ink application and loss of information. In earlier stages of deterioration, ink lines are prone to cracking during handling.
Leather	• **High Temperature:** above 20°C, increase in the rate of chemical-induced degradation; oxidation of protein and tannins leading to loss of stability; and hardening. • **Low RH:** below 35%, dessication leading to breaks and other physical changes occur. **High RH:** above 60% mould can develop and shrinkage occurs, leading to embrittlement.	• Structural deterioration and loss of protein structure; staining and discolouration due to moulsd growth; loss of intrinsic value
Paper	• **High RH:** above 65%, increased risk of bio-deterioration. Acid hydrolysis significantly accelerates with RH. • Acidic paper and paper containing iron gall ink generally degrade at 10 times the rate of rag and alkaline/pseudo-alkaline sized papers, and require lower T and/or RH for long-term preservation. • Fluctuations of ±10% RH and ±5°C are considered acceptable	• Brittleness due to hydrolysis or oxidations. Discolouration due to chemical degradation or photo-induced degradation. Stiffness of bindings if RH below 25%. • Mechanical damage leading to loss of organic material, information and intrincic value.
Parchment	• Setting environmental conditions depends upon the proportion of collagen and gelatine in the parchment. • **High T:** causes structural changes in collagen and predisposes parchment to gelatinization. • **Low T:** T below 0°C will induce structural changes in collagen. Effects on historic parchment have yet to be investigated. • **Fluctuating RH:** increased cockling and distortion leading to separation of paint and ink layers from support. • **High RH:** above 65% there is an increased risk of biodegradation. • 38% to 45% produces a water content of approximately 14%, which reduces internal stress. • **Low RH:** RH below 30% increases stiffness of bindings.	• Inappropriate conditions will cause permanent distortion leading to loss of the collection item.

Similarly, for paper items, RH values should be kept above 25% to prevent stiffness of bindings and below 65% to reduce the risk of bio-degradation due to mould formation. Moreover, environmental fluctuations should not exceed ±10% RH or ±5°C in a room containing paper heritage items, which correspond to ASHRAE classifications A or B as illustrated in Table 2-10. This range of acceptable RH values is smaller where the storage of parchment is concerned, as the recommended environmental limits are 38% and 45% respectively.

Based on the information outlined in Table 2-11, it can be deduced that, for a typical library or archive that contains a volume of historic books and manuscripts, environmental limits of 15°C to 20°C and 38% RH to 45% RH are acceptable.

Further to the information presented in the table, Mecklenburg (2007) states that the current environmental guidelines specified by the Smithsonian Institute are 45%RH ±8% and 21°C ±2°C. Therefore, environmental limits for RH and T are 37%RH to 53%RH and 19°C to 23°C respectively, although the impact of conditions falling outside this band depends on the duration of the change as well as the rate of moisture absorption of the materials as those with a higher rate will be affected more by the change in environmental conditions. These specifications are generally in line with those indicated in Table 2-11, although, where more delicate materials, such as parchment or leather are located, they may need some refinement in order to preserve the entire collection.

Fig. 2-18 illustrates the detremental effect of unsuitable environmental conditions on collections items, in this case books (provided by The Board of Trinity College Dublin) which are stored in the Long Room in the Old Library in TCD. Referring back to Table 2-10, environmental conditions in the building could be currently classed in Environmental Classification C, which is proving to be unsuitable for the storage of these collection items.

Of the samples displayed in Fig. 2-18, (a) exhibits "foxing stains" that are a result of high humidity. Samples (b) and (c) illustrate fracture damage to the binding of a parchment book resulting from a combination of light damage and excessive cycling of temperature and humidity conditions. The remaining two samples, (d) and (e) display mould damage to the books resulting from high humidity. Accordingly, the importance of regulating the thermo-hygrometric conditions in a building that is used to store collection items is reinforced as irreversible damage to precious heritage items can be caused as a result of unsuitable environmental conditions. In the case of the Old Library in TCD, this will involve improving the environmental conditions in the building from an ASHRAE classification of C, which is its current value, to a B or A rating. The control required to achieve an A-classification may not



(a) *(b)* *(c)*

(d) *(e)*

Fig. 2-18: Examples of books that have been damaged by unsuitable environmental conditions.

be possible in the Old Library, however, owing to the sensitive nature of the building as well as its size. These two factors would make it unfeasible to upgrade the building to this level and so, classification B would be recommended. This corresponds to the conditions specified by BSI (2012).

2.6.3. Quantifying the Effect of the Museum/Library Environment on the Life Expectancy of Collection Items

Quantification of the effect, on collection items, of altering temperature and RH conditions in a museum or library environment is an important consideration for museum curators and librarians. Increasing temperature and RH unduly can significantly shorten the life span, or permanence, of artefacts while decreasing environmental parameters can reduce the rate of chemical deterioration (Sebera, 1994). Two different tools for illustrating the preservation consequences of allowing wider swings in T and RH values in a museum building currently exist, namely the Isoperm method and the Time Weighted Preservation Index.

The isoperm method is largely restricted to strength loss associated with the chemical reactions of cellulose hydrolysis and oxidation, which are the mechanisms that account for at least 90% of paper deterioration (Sebera, 1994). This approach arises from a single idea that the rate of deterioration of hygroscopic materials, such as paper, is influenced by the T and RH of its surrounding environment, that is, the rate of chemically induced degradation increases with increasing T and RH. Moreover the concept of isoperms deals with relative rather than absolute rates of deterioration and can, therefore, be used to illustrate the relative rate of degradation observed when environmental conditions are altered. Suppose that a change in T and RH resulted in a deterioration rate, r_1, dropping to r_2 such that $r_2/r_1 = 0.5$. This would signify that this environmental change halved the rate of degradation of a hygroscopic material, thus doubling its permanence. To mathematically determine the relative permanence of paper that has been subjected to environmental change, Sebera (1994) proposes Equation (2-28) as follows:

$$\frac{P_2}{P_1} = \left(\frac{RH_1}{RH_2}\right)\left(\frac{T_1 + 460}{T_2 + 460}\right) 10^{+394\Delta H\left(\frac{1}{T_2+460} - \frac{1}{T_1+460}\right)} \qquad (2\text{-}28)$$

where P_1 and P_2 are the permanence rates (years^{-1}), RH_1 and RH_2 are the relative humidity values, T_1 and T_2 are the temperature values and ΔH is the enthalpy of activation. The latter is a thermodynamic function that quantifies the sensitivity of a specific reaction to temperature change and ranges from 20-35Kcal, with a value of 30-35Kcal providing a very good approximation. Algebraic computations involving Equation (2-28) would be time consuming and so the isoperm chart, such as the one displayed in Fig. 2-19, is a useful graphical form of the mathematical equation.

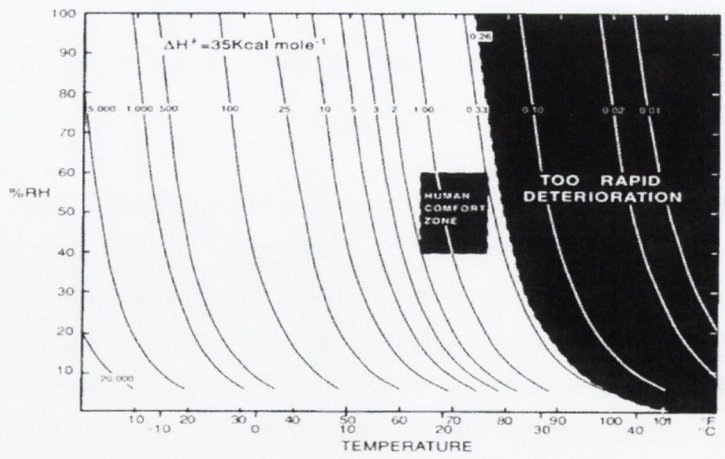


Fig. 2-19: Percentage relative humidity vs. temperature Isoperm diagram for an activation energy of 35Kcal. Optimum conditions for thermal comfort are also displayed on the chart (Sebera, 1994)

The theoretical basis for Fig. 2-19 is as follows. Consider a paper sample at equilibrium with initial T and RH values that determine its permanence and deterioration rate. If the RH is increased and T is unchanged, the rate of deterioration will increase. However, if the T is reduced by exactly the right amount, the resulting decrease in the rate of degradation associated with the change in T will compensate exactly for the RH induced increase. Accordingly, the overall deterioration rate and permanence will remain unchanged. An infinite set of such paired T and RH conditions exist that are all associated with the same permanence value and when these values are plotted, a line of constant permanence (isopermanence) is generated (see Fig. 2-19). This line is defined as an isoperm. This isoperm chart can then be used to inform curators and librarians of the consequences of moving collection items into unsuitable storage conditions on their permanence.

The human comfort zone is also illustrated on Fig. 2-19 and from this illustration it can be seen that optimum conditions for providing human thermal comfort are not compatable with those that would be most suitable for preservation of the collection. The human comfort zone lies between the isoperms labelled 0.33 and 2 indicating that such an environment is unsuitable for long term preservation of collection items. This issue is discussed further in Section 2.6.4.

The Time-Weighted Preservation Index (TWPI) is an evolution of the isoperm method of assessing the influence of environmental parameters on the permanence of hygroscopic cultural artefacts (Reilly et al., 1995). It measures the combined effect of T and RH on the preservation quality of a storage environment and is a general measure that is applicable to all organic materials, not just to paper. The most important difference between the TWPI and the isoperm method is that the TWPI facilitates the measurement of the preservation quality of dynamic environments, allowing whole periods of changing conditions to be characterised by a single value. The approach defined by Reilly et al. (1995) requires the calculation of the preservation index (PI) and then the TWPI. The PI evaluates the effect of particular combinations of static and unchanging T and RH conditions on the rate of chemical deterioration in collections and has units of years. PI values for a given combination of T and RH values are obtained using PI definition tables such as that displayed in Table 2-12. Although chemical decay is the most significant threat to library and archive collections, consideration of biological damage is also of importance. PI is meant to supplement and not replace consideration of these other important environmental issues.

Environmental parameters are dynamic by nature and can change markedly, resulting in a changing deterioration rate for collection items (La Gennusa et al., 2005). The cumulative effect of PI values over a given period of time is given by the TWPI (Krüger and Diniz, 2011).

Table 2-12: Definition table of PI values showing predicted lifetime, in years, of short-lived organic materials at various combinations of T (X-axis) and RH (Y-axis) (Reilly et al., 1995)

		Temperature (°C)											
		0.0	2.3	5.5	8.3	11.1	13.9	16.7	19.5	22.4	25.2	28.0	30.8	33.6
% RH	5	2634	1731	1147	767	516	350	250	165	114	80	56	40	28
	10	2234	1473	979	656	443	302	207	143	99	70	49	35	25
	15	1897	1255	837	562	381	260	179	124	86	61	43	30	22
	20	1613	1070	716	482	328	224	155	107	75	53	37	27	19
	25	1373	914	613	414	282	194	134	93	65	46	33	23	17
	30	1170	781	525	356	243	168	116	81	57	40	29	21	15
	35	998	668	451	307	210	145	101	71	50	35	25	18	13
	40	852	572	387	264	182	126	88	62	43	31	22	16	12
	45	729	491	333	228	157	109	76	54	38	27	19	14	10
	50	624	421	287	197	136	95	66	47	33	24	17	12	9
	55	535	362	247	170	118	82	58	41	29	21	15	11	8
	60	459	312	213	147	102	72	51	36	26	18	13	10	7
	65	394	269	184	128	89	62	44	31	22	16	12	9	6
	70	339	232	160	111	77	54	39	28	20	14	10	8	6
	75	292	200	138	96	67	48	34	24	17	13	9	7	5
	80	251	173	120	84	59	42	30	21	15	11	8	6	4
	85	217	150	104	73	51	36	26	19	14	10	7	5	4
	90	187	130	91	63	45	32	23	16	12	9	6	5	3
	95	162	112	79	55	39	28	20	15	11	8	6	4	3
		PI Values, in Years												

Reilly et al. (1995) explain that taking the average PI values in order to assess the effect of different environmental conditions on a collection does not yield a reasonable estimate concerning its preservation. For example, if an item spends six months of the year in very cold and dry storage, its permanence is 2000 years. If the item is brought out of the cold storage conditions and placed on display in a much warmer environment, its life expectancy would reduce significantly to, for example, 50 years. Using the simple average of PI values to compute the combined life expectancy gives a PI value of 1025 years, which is incorrect given that if the item is stored in the hot environment for six months of the year, its expected life span would elapse after 100 years. A more accurate method of estimating the expected life span is to take the average of the reciprocals of each PI value (0.01025 in this case) and invert it to determine the collection's overall lifespan, which in this example would be 98 years. This simple example, which used two distinct time intervals, illustrates the principles behind TWPI. When dealing with a large number of time intervals, Equation (2-29) can be used to mathematically calculate the TWPI (Reilly et al., 1995, Krüger and Diniz, 2011).

$$TWPI_n = \frac{nTWPI_{n-1} + PI_n}{PI_n(n-1) + TWPI_{n-1}} \qquad (2\text{-}29)$$

where n is the total number of time intervals, $TWPI_{n-1}$ is the TWPI after time interval (n-1) and PI_n is the PI measured at time interval n.

TWPI is one way to evaluate the overall impact that changing T and RH will have on the chemical lifetime of organic materials in collections (Reilly et al., 1995).

2.6.4. The Contradiction between Thermal Comfort and Optimum Environmental Conditions for Preservation of Cultural Artefacts

Collections are vulnerable to many threats (ASHRAE, 2011). As they must be preserved indefinitely, the steps taken to protect cultural artefacts are sometimes extraordinary. Most threats can be addressed by properly maintained housing and professional support. The level of acceptable risk is a compromise between the theoretically ideal environment and the practical. It is possible to slow deterioration notably, but doing so may conflict with the ultimate function of museums, libraries and archives: not only to preserve, but also to allow public and scholarly access (Steeman et al., 2010, ASHRAE, 2011, La Gennusa et al., 2008). Additionally, extremely high control over all environmental parameters can help to ensure an object's survival but at a price that no cultural institution can justify or is willing to pay. Accordingly, indoor environmental conditions typically involve a compromise between the comfort of occupants, the economy of operation of plant and the collections' requirements (ASHRAE, 2011).

One such compromise is pointed out by Steeman et al. (2010) who considers the impact of RH on both thermal comfort parameters and the preservation of organic hygroscopic materials. In terms of thermal comfort, conditions of low RH may dry the membranes in the eyes and nose too quickly, resulting in irritation of the eyes and breathing discomfort. High RH values, on the other hand, cause a feeling of discomfort by increasing the friction between skin and clothing fibres. Accordingly, RH values ranging from 40% to 60% are recommended in providing human comfort with no specifications on diurnal or seasonal variations, which, according to Table 2-12, yields a PI of between 36 and 62 years at a temperature of 19.5°C. In contrast, the impact of RH on the preservation of hygroscopic objects is more significant. A stable RH is essential to prevent the artefacts from changes in size or shape or to avoid the introduction of chemical reactions. Furthermore, if the RH is too high, particularly at the surface of the material, condensation and mould growth may occur while low RH values may induce cracks in porous materials. Precise indoor climate specifications concerning temperature and RH exist for the preservation of valuable books and artworks: the RH must be kept stable and diurnal and seasonal/yearly fluctuations should be minimised. In many cases, the comfort requirements have had dramatic consequences on artwork preserved in churches, mostly managed by people who fail to grasp the implications of heating on the preservation of artwork (Camuffo et al., 1999).

It is worth mentioning at this point that, generally, in museums and libraries, the microclimate is designed and controlled for the well-being of the visitors during visiting times only, disregarding the needs of conservation that requires a relatively constant climate

by day and by night (Camuffo et al., 2001, La Gennusa et al., 2008, Steeman et al., 2010). During their research into the microclimate in four European museums, Camuffo et al. (2001) discussed the negative impact of mass tourism on the environmental quality of museums, noting that visitors are responsible for pollutants, emissions of water vapour, CO_2 and heat, typically causing unacceptable diurnal variations in temperature and RH. When visitor numbers are high, HVAC may be required to provide satisfactory conditions in the building. The presence of these systems, however, may increase the risk of pollution damage to objects as more pollution is brought into the building from outside. A different study of an historical building containing frescoes enabled researchers to quantify the effect of people on the temperature and moisture conditions in an area of the building known as the Giant Hall (Camuffo et al., 2004). When the Giant Hall was occupied during a concert, both the temperature and mixing ratio of the air were observed to rise by 1-3°C for the temperature and 1-2.5g/kg for the mixing ratio. The majority of this additional moisture (approximately 50-60%) was subsequently lost to the external environment or absorbed (by the frescoes, ceiling, floor, furniture, etc.), however, the fluctuations in temperature and RH were unacceptable for conservation.

Krüger and Diniz (2011) examined the relationship between the TWPI and thermal comfort calculated using the PMV method in three Brazilian archives. The archives used in the study were situated in three different climatic regions, namely subtropical humid (Climate A), tropical altitude (Climate B) and tropical Atlantic (Climate C). All three climate types exhibited large daily and seasonal fluctuation in environmental conditions, however Climate A was characterised by a mean annual temperature of 16.5°C and average summer and winter RH of 82% and 76% respectively. These values were 21°C with a summer and winter RH of 79% and 65% for Climate B and 24°C with a summer and winter RH of 80% and 77% in the case of Climate C. The HVAC systems in each archive are also different with no air conditioning in the archive in Climate A, pre-programmed forced ventilation in Climate B and a central air-conditioning system in Climate C. By calculating TWPI and PMV values for the three archives, Krüger and Diniz (2011) found that the archive located in Climate C provided the best conditions for preservation of the books while the remaining two archives were unsuitable for storing hygroscopic materials. In terms of thermal comfort measurements, PMV calculations indicated that the archive in Climate C had the lowest comfort value as virtually all hours experienced "cold" conditions. Krüger and Diniz (2011) concluded that the comfort analysis is contradictory to the preservation quality of a particular archive as it had the highest TWPI and lowest corresponding PMV value.

2.6.5. Environmental Monitoring in Libraries and Museums

Since a monitoring program in a museum can support decisions and actions aimed at preventing the deterioration of vulnerable objects, the need to observe the environmental parameter status over time is of primary importance (Corgnati et al., 2009b). It is essential to define the actual microclimatic quality level, in comparison to the expected quality, on the basis of the artefacts' preservation requirements.

Maekawa et al. (2007) measured the RH, temperature and CO_2 variations in the Our Lord in the Attic Church, which is now a museum located in a historic house in Amsterdam. The museum has seen its annual visitor numbers increase from 36,000 in 1990 to 75,000 in 2005, a trend that is continuing exponentially, with between 100 and 650 people visiting on a daily basis. The owners of the building had expressed serious concerns regarding the impact of the visitors on the environmental conditions in the building. Maekawa et al. (2007) found that the central heating system in the building may have caused the majority of the damage to the collection. They also concluded that people, while having a direct impact on the temperature, RH and CO_2, particularly when the building opened each morning, did not cause the environmental conditions to fluctuate sufficiently to result in damage to the collection. The authors recommended that 600 people in winter and 1200 in summer, well-distributed over the building's opening hours, could be accommodated if the entrance door and a window in the attic were opened to increase natural ventilation.

Bernardi and Camuffo (1995) carried out a monitoring programme in a museum housed in a historic building in Vicenza. They found that the heating system was excessive and discontinuous and was resulting in large thermal and RH gradients that were causing damage to collection items. Using this knowledge they implemented a number of passive changes to the building, including comprehensive roof and wall insulation and blocking of solar radiation. Once these works had been completed, T and RH values were significantly improved and were barely influenced by large gradients between the microclimate in the environment and external environmental conditions.

Bernardi et al. (2000) conducted microclimatic monitoring following interventions on a church intended to preserve frescoes located therein. Results of the study indicated that the interventions, while well intended, were poorly implemented and led to heavy weathering of the frescoes, particularly those on internal walls. By subsequently replacing poorly fitted windows and doors they reduced the hygrothermal gradients that were causing the majority of the damage and provided a much more favourable environment for preservation.

During a study of the Royal Museum of Fine Arts in Antwerp, Belgium, Gysels et al. (2004) concluded that the microclimates in the exhibition rooms were negatively influenced by poorly balanced heating and air conditioning, free-standing humidifiers, ventilating and lighting systems and the daily flux of visitors. When combined, these factors produced rapid changes and marked thermo-hygrometric gradients, which reduced the life expectancy of collection items displayed in this museum. Based on this, the authors suggested improvements that could be made to the heating and air-conditioning system. A similar study by Camuffo et al. (1999) involving micro mapping the environmental conditions in the Correr Museum in Italy, which found that the HVAC system that was installed in recent years, was responsible for poor preservation conditions within the building. By implementing a new heating and air-conditioning regime as well as installing new windows, diurnal fluctuations in T and RH were reduced. This study also concluded that the carpet has a negative impact on the indoor environmental quality as it retains particles and bacteria that are then re-suspended each time people walk on it. A further study by Camuffo et al. (2004) successfully identified the parameters that resulted in damage to a Great Hall located in a historic building. Four major issues regarding conservation with the hall were reported, namely the impact of heating, lighting and people, racks formed on oak panels on the ceiling, soiling on frescoes by dust and soot particles and soiling on the stained glass windows. Microclimatic monitoring and analysis proved that the impact of the lamps on the ceiling, the penetration of external air in the room, the heat and moisture released by people, the impact of sunshine through windows and the daily cycles in T and RH were the factors that were causing the problems in the building.

Microclimatic analysis of a semi-confined environment, in which heritage materials were contained, by Becherini et al. (2010) found that the thermo-hygrometric conditions in the environment were unsuitable for the conservation of organic materials. The environment being tested contained a wooden coffin that was orientated such that it was deteriorating at different rates depending on the surface being tested. Having identified the orientation as the principal reason for the different damage features of the two sides of the coffin, the authors implemented change, by means of placing the artefact in a sealed glass case, ensuring that further damage would be minimised.

The studies outlined above indicate the wealth of knowledge that may be gained through environmental monitoring of museum and library building. By carrying out a comprehensive microclimatic monitoring scheme, museum curators and librarians can make informed decisions regarding building upgrades and heating and air-conditioning scheduling so as to provide the optimum conditions for preservation of priceless artefacts.

2.7. Conclusions

The key findings from the literature that will help determine the methodology for this research are as follows:

- Historic buildings are unique, non-renewable resources and alterations or updates to them demands an in-depth understanding of how they function. By their nature, historic properties require a holistic approach when making alterations to improve energy efficiency, reduce draughts or accommodate a change of use and any interventions should be reversible and use compatible materials and methods.
- Evaluation of building performance by a POE regime is an effective process in analysing the current IEQ and energy use of a building. Furthermore, a POE can identify the stimuli that cause environmental perturbations and is effective in providing guidance on potential upgrades, as well as monitoring the actual impact of such changes.
- The majority of heat loss from a building is through the walls (typically 35%) and roof (25%). Retrofit options to improve the thermal performance of walls are generally problematic in historic and traditional building. Installation of loft insulation, however, is a relatively straightforward process and should be among the first considered when performing upgrades to a traditional building. Furthermore, education and behavioural change of occupants and close control of heating systems can lead to further reductions in energy consumption while having little effect on the building fabric.
- Traditional buildings contain a large quantity of thermal mass, which is very effective in modulating diurnal temperature fluctuations.
- IEQ is a key parameter in determining occupant comfort. Adequate ventilation is essential for mitigating the several gaseous and microbial contaminants. Close control of temperature and relative humidity, within particular values, however, can also be effective in controlling several issues relating to IAQ.
- The preservation of cultural heritage has important economic and social ramifications. In terms of IEQ, fluctuating thermo-hygrometric parameters are the most damaging to organic-hygroscopic materials in museums and libraries. Furthermore, based on existing case studies of IEQ in historic museums that are used to house cultural collections, the presence of people, ineffective plant, infiltration and lighting are the factors that have the most damaging effect on the environment and, as a direct consequence, the collection.

- Generally, the primary objective when designing plant systems is to provide occupants with an acceptable level of thermal comfort. This is generally achieved by providing a pre-defined standard temperature while eliminating draughts and other sources of local discomfort. This strategy typically suffices in terms of the provision of adequate IEQ. However, when the building is used to store cultural items, the indoor environment should be designed to stringently control the humidity conditions as well as the thermal conditions, which are somewhat less critical in terms of conservation. Although this may lead to discomfort, the preservation of cultural items should be of paramount importance, however, given the multiple uses of these buildings, compromise is necessary but this should not cause long-term damage to the cultural heritage.
- The Smithsonian Institute recommend environmental conditions for the conservation of collection items in the temperature and relative humidity range of 19°C to 23°C and 37% to 53% respectively. BSI (2012) specify that fluctuations should not exceed ±5°C for temperature and ±10% for relative humidity. This is the equivalent to an ASHRAE environmental classification of "B".

As will be discussed in Chapters 3 and 6, the primary case study for this research project is the Old Library in Trinity College Dublin (TCD), which opened in 1732 with the purpose to *"provide storage, reading and tutorial spaces for the growing college collection, staff and student"* (Ruhland et al., 2009). In recent years, however, additional risks to the collection that would have been unforeseen at the time of construction have been identified. These include an elevation in external pollution levels, the effects of continued exposure of the collection to natural light, the development of the building into a major tourist attraction and the effect of a dynamic thermo-hygrometric environment on the collection. The latter of these issues was identified in the literature to be the most damaging environmental condition to collection items.

Upon meeting some staff members in the conservation and preservation department in TCD, it became apparent that a monitoring regime for the analysis of pollution levels in the Old Library, as well as a parallel research project on the deposition of dust on the collection, are currently being undertaken. The temperature and relative humidity data that the department are recording, despite their significance in terms of collection preservation, is not necessarily being critically analysed, although relatively large variations in both were reported. Furthermore, the placement of data loggers for the purpose of monitoring the thermo-hygrometric properties in the building was not carried out in a manner that would take engineering considerations into account.

Although monitoring of the thermo-hygrometric parameters is an important process, using the data to inform on alterations to the building with a view to providing more suitable conditions for conservation requires an understanding of the factors that cause variations in temperature and humidity. Following a review of the literature, a description of the thermo-hygrometric signatures associated with a range of environmental stimuli (such as a heat load, a change in infiltration rate or the presence of people) was not found. Accordingly, before conducting a survey of the Old Library to determine the factors that are causing the fluctuating thermo-hygrometric environment, it is first necessary to determine the signatures associated with potential environmental stimuli in the building experimentally on a small scale and then apply this knowledge to a large historic building to both validate and add to the observations and conclusions made from such experiments. Thereafter, a more informed analysis of the environmental conditions in the Old Library can be conducted and the relevant issues addressed with a view of improving the environment for the collection.

The significant shortage of literature on the signatures associated with a number of major environmental stimuli coupled with the importance of the thermo-hygrometric properties in terms of collection conservation have helped to define the research objectives of this project. Although these objectives are defined in Section 1.3 they are reiterated as follows:

1. To develop an understanding of the primary influences that determine the thermo-hygrometric variations in historic buildings by means of developing environmental signatures
2. To develop sensible restorative strategies based on best historic building practice
3. To assess the adaptability of this to other buildings.

Chapter 3 will now outline the steps that were taken to achieve these objectives.

3. Methodology

3.1. Introduction

The following chapter describes the instrumentation and methodologies used to complete this research. At an early stage it was decided that the project would follow a POE style evaluation, however, the exact methodologies evolved throughout the project. This research was completed in six various and interdependent stages as follows:

1. Determination of the case study buildings and monitoring parameters
2. Selection of instrumentation
3. Small-scale signature tests
4. Application of small-scale tests to a full sized historic building
5. Monitoring and analysis of the primary case study building and
6. Computer modelling of the case study building.

The first of these stages involved a desk study of existing literature with a view to developing a strong background knowledge of the subject matter, while identifying the key parameters and considerations in terms of historic buildings. While this study was on-going, a number of stakeholder meetings with members of the college community took place to establish a variety of buildings on the TCD campus that would be suitable for use as case-studies. At this stage, two disparate buildings were identified, namely the Museum Building and the Old Library. After careful consideration of the properties of the buildings choices, the Museum Building, which is a mixed use building (containing offices of varying occupancy, lecture theatres, a museum and a library) and the Old Library, a building used to house the college's most precious book and manuscript collections, were chosen for testing.

Once the Old Library was identified as a potential case study, the Keeper of Preservation and Conservation, Ms. Susie Bioletti was approached with a view to identifying the building performance issues regarding the preservation of the collection and the comfort of visitors and staff in the building. During this meeting it became apparent that, the thermo-hygrometric conditions in the building were causing damage to the collection, a situation that was to be expected considering the general conclusions of the literature review. This was primarily a result of the large seasonal, and in some areas of the building diurnal, variations observed in both temperature and relative humidity. Furthermore, the presence of significant numbers of visitors was believed to be causing unacceptable fluctuations to the IEQ in the Old Library in TCD and, as a result, causing structural and aesthetic deterioration to the collection. Bioletti also expressed concern at the level of air infiltration into the

building from the external environment that was leading to increased levels of contaminant pollution and dust formation. A study of the deposition of particulate matter as well as some gaseous contaminants associated with poor IAQ were on-going in the Old Library although the findings of these studies have yet to be published. The decision to measure the thermo-hygrometric properties of the building was made since studies of dust deposition and pollutants were already underway in the building. Moreover, although temperature and relative humidity were being measured in the building, this limited data had to be supplemented by new sensors, given that the literature identified fluctuations in the thermo-hygrometric environment to be the most damaging to the collection, a structured monitoring programme for temperature and relative humidity parameters in the building was designed to assess the effect of people and air infiltration on the IEQ of the building. After a number of initial environmental tests, however, the relative humidity was not found to be a very good indicator of moisture movement owing to its dependence on temperature. As a result, it was decided that an additional parameter, namely the absolute humidity, which could be calculated from these two base parameters (see Section 2.5), would also be observed during this research, as is commonplace in building physics.

Given that the temperature and relative humidity were recognised in the literature as the primary factors causing damage to collection items, this choice of parameters for study was consistent with previous research in the area. Moreover, the sensitive nature of the Old Library, in terms of its architectural importance coupled with the invaluable artefacts contained within, was a major contributing factor in the choice of instrumentation (Section 3.2) for this project because access to the relevant areas of the building would be somewhat limited.

3.2. Selection of Instrumentation

Owing to the heritage and cultural value of the building, as well as the collection it houses, the use of devices that would require cables or even minor alterations to the building, or that could be seen by the general public were deemed unacceptable. Furthermore, given the scale of the building, it would not have been efficient or practical to use devices such as thermocouples and their associated data loggers for an on-going monitoring regime. As a result, it was decided that a small, discrete and wireless temperature and relative humidity sensor, with its capacity to log a large amount of data, was the most suitable device for on-going thermo-hygrometric monitoring over the course of this project.

After researching a range of temperature and relative humidity sensors on the market, the OM-EL-USB-2-PLUS (referred to as EL-2 hereafter), supplied by OMEGA Engineering was selected. This particular device was chosen as it offered the highest accuracy of reading available amongst such devices on the market (see Table 3-1) while being relatively small in size (dimensions are displayed in Fig. 3-1). Furthermore, this standalone data-logger had a long battery-life and relatively large storage capacity (16,279 relative humidity and temperature readings). Moreover, the device could be pre-set to commence recording at a designated time and date, meaning that several sensors could be set to record at the same time, and had a customisable sampling period, varying from 10 seconds to 12 hours. The time constant is much less than the typical sampling period used during data collection. A software package was also supplied with the EL-2 that had functionality with the Microsoft Excel programme, thus allowing exportation of collected data directly into spreadsheets for further analysis.

Table 3-1: Specifications of the EL-2

	Temperature	Relative Humidity
Range	-35 - 80°C	0 - 100%
Resolution	0.5°C	0.5%
Accuracy	±0.3°C	±2.0%

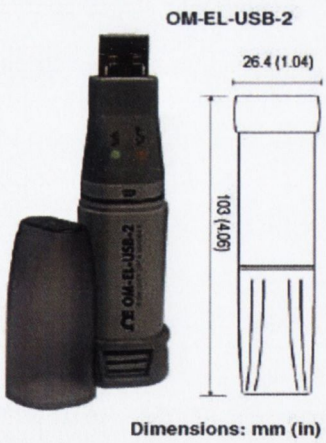


Fig. 3-1: Image of the EL-2 device with physical dimensions in mm(in)

In order to quantify the number of sensors required to adequately monitor and obtain a suitable amount of data to gain an appreciation of how the case study buildings behave from an environmental viewpoint, a desk study of building plans as well as a number of visits to each building were conducted. Based on these, the potential zones and rooms that would be monitored in each building were identified.

Upon completion of this process, it was determined that a total of 20 sensors were required for the study, of which, 19 would be placed in specific locations in each building and the remaining device would be used to monitor the external environment. The rationale in doing this was to enable comparison of external environmental conditions with those in each building and the relationship between both. The location of each sensor during the various monitoring phases is discussed in Sections 3.4 and 3.5 respectively.

Given the number of different sensors used in this research and the need for accurate comparison of thermo-hygrometric properties of different zones in each case study building, it was deemed essential to carry out a comparison test on the sensors to ensure that the data collected would be comparable. Accordingly a simple comparison test was designed and carried out before each monitoring regime.

The sensor comparison test involved placing each sensor that was to be used in a particular test, into a particular microclimate for a period of time before removing them and extracting the data from the sensors. Typically, the data loggers were set to record at 1-minute intervals and left in an empty drawer in the author's office for a period of one day. Data was then extracted from each data logger and placed into individual spreadsheets. Thereafter, the data for both temperature and RH for each sensor is accumulated in two excel spreadsheets, one for all temperature data and the other for all relative humidity data.

Since variation in environmental parameters is a dynamic process, the comparison test and associated analysis of data was required to examine two important issues. Firstly, are the trends observed in each sensor suitably comparable and, secondly, are the values themselves comparable. As all sensors had been placed in an identical microclimate, it was expected that each sensor would yield the same trends and magnitudes for the parameters observed.

To test the overall trends recorded by each sensor, a correlation coefficient between each sensor was computed. This was completed using the *"correl"* function in Excel for MAC (Microsoft, 2011), which uses Equation (3-1) to compute this value. If the correlation coefficient between individual sensors was greater than 0.95 (i.e. (95% correlation) the sensors were adjudged to be acceptable. However, in the event that the correlation coefficient fell below this value, either the sensor was not used for the monitoring period (in the case of the small scale tests discussed in Section 3.3 and Chapter 4) or alternatively the battery of the logger was changed and the test was carried out again. Results from the most recent comparison test for temperature are displayed in Table 3-2 for illustrative purposes.

$$Correl(X,Y) = \frac{\sum(x-x')(y-y')}{\sqrt{\sum(x-x')^2 \sum(y-y')^2}} \quad (3\text{-}1)$$

where x' and y' are the mean values of the arrays.

Table 3-2: Correlation coefficients calculated for the temperature values recorded during a comparison test.

	B	D	E	G	J	P	R
B	1.00						
D	0.97	1.00					
E	0.99	0.96	1.00				
G	0.98	0.99	0.97	1.00			
J	0.96	0.96	0.97	0.96	1.00		
P	0.98	0.96	0.98	0.97	0.98	1.00	
R	0.95	0.97	0.95	0.96	0.96	0.95	1.00

It was important to assess the precision and accuracy of the values recorded at each device as accurate analysis and comparison of temperature and relative humidity data that was recorded in different areas of a building and on different data loggers would not be possible if precision and/or accuracy were poor. Accordingly, upon computation of the correlation coefficient, the mean temperature and relative humidity at each individual time period, calculated from the individual values at each sensor as well as the standard deviation, for the microenvironment were computed. The standard deviation values were then averaged to obtain a single value of standard deviation for the course of the comparison test. Data recorded during one such comparison test for temperature values is illustrated in Table 3-3.

The data displayed in Table 3-3 is indicative of the data typically collected during a comparison test. In general it was found, particularly during the first number of monitoring phases, that good accuracy and precision was observed between each sensor, illustrated by the low magnitude of the standard deviation and coefficient of variation. From Table 3-1, it can be seen that the accuracy and resolution of the device in terms of temperature is 0.3°C and 0.5°C respectively and, when the standard deviation values in Table 3-3 are compared to the specifications of the device it can be seen that the standard deviation calculated for each time interval does not exceed the specified accuracy and resolution of the device.

Table 3-3: Temperature data observed during a sensor comparison test. Mean, standard deviation and the coefficeint of variation for each time interval are also indicated in the table

Time	B (°C)	D (°C)	E (°C)	G (°C)	J (°C)	P (°C)	R (°C)	Mean	St Dev	Cov (%)
12:45	16.5	17.0	17.0	17.0	17.0	16.5	17.0	16.9	0.24	1.45
13:00	16.5	17.0	17.0	17.0	17.0	17.0	17.0	16.9	0.19	1.12
13.15	17.0	17.5	17.5	17.5	17.0	17.0	17.0	17.2	0.27	1.55
13:30	17.5	18.0	18.0	18.0	17.5	17.5	18.0	17.8	0.27	1.50
13:45	18.5	18.5	19.0	18.5	18.5	18.5	18.5	18.6	0.19	1.02
14:00	18.5	18.5	19.0	19.0	18.5	18.5	18.5	18.6	0.24	1.31
14:15	18.5	19.0	19.0	19.0	18.5	18.5	18.5	18.7	0.27	1.43
14:30	18.5	19.0	19.0	19.0	18.5	18.5	18.5	18.7	0.27	1.43
14:45	18.5	19.0	19.0	19.0	18.5	18.5	18.5	18.7	0.27	1.43
15:00	18.5	19.0	19.0	19.0	18.5	18.5	19.0	18.8	0.27	1.43
15:15	18.5	19.0	19.0	19.0	19.0	19.0	19.0	18.8	0.19	1.00

This observation coupled with the low coefficient of variation means that no alteration to values is necessary, however, no trends will be inferred in differences of 0.5°C between sensors. As time passed and the sensors were used more, however, the data recorded between sensors tended to differ slightly more than recorded initially, which was attributed to drift in the accuracy of the device and wearing of the batteries, and the comparison adjustments became more important in ensuring comparable results.

3.3. Small-scale Signature Tests

Once the key parameters for measurement were defined and a comprehensive review of the relevant literature completed, it was necessary to conduct a number of preliminary experiments to attempt to identify the response of the thermo-hygrometric environment to a range of stimuli that may be commonplace in the case study buildings. Given the limited amount of research on the signatures associated with a number of environmental stimuli, a total of four tests, as well as a baseline test, were designed to obtain a better understanding of the changes in environmental conditions. The specific stimuli were heat loads, moisture loads, increasing the infiltration rate in a room by opening a window and occupancy. The

signature tests involved inducing individual loading scenarios to an internal environment and then monitoring the change in thermo-hygrometric parameters associated with that load. With the exception of the heat loading test, the same room (discussed momentarily) was used for each experiment and the baseline conditions in the room were monitored prior to each test to ensure that stable environmental conditions were present in the room.

Once the individual tests were defined it was necessary to identify a suitable area in which to conduct the tests. After conducting an initial environmental monitoring regime in a number of potential sites, a basement room in a typical terraced Georgian building on the TCD campus was chosen as it provided the most stable background conditions and was not susceptible to solar gains. Furthermore, potential losses from this particular site were relatively low compared to other sites, owing to the presence of secondary glazing, which was retrofitted to the windows in the room, a feature that was not present in the other sites considered for this testing regime. The presence of this secondary glazing reduced heat losses and infiltration into the room from the external environment and, as a result, contributed to relatively stable baseline environmental conditions in the room. Two weeks prior to the commencement of the small-scale signature tests, mechanical heat sources in the room were deactivated to allow the room to reach a natural equilibrium. A further monitoring session, lasting 2 days, was carried out before the first test, which functioned to establish the baseline conditions in the room before any environmentally stimuli would be introduced.

Although the individual tests are described in detail in Chapter 4, a brief summary of the rationale for each test will be provided as follows:

- Heat Loading Test: Although it is accepted that an inverse relationship between temperature and relative humidity exists, in the absence of ad- and desorption of moisture, during initial environmental tests, this relationship did not necessarily appear to hold true. As a result, the heat-loading test was conducted to determine whether any additional effect that may distort or influence the expected environmental behaviour could be identified.
- Moisture Loading Test: In this case the purpose of the experiment is to discern the relationship between the humidity parameters (relative humidity and absolute humidity) when a moisture load was induced in a room during a period when thermal conditions were relatively constant.
- Open Window Test: This test was conducted to examine the effect of opening a window or door in a room, or, in other words, to determine the result of significantly increasing the infiltration rate on the environmental conditions in a space.

- Occupancy Test: From the literature and also conversations with stakeholders, the effect of people on the indoor environment is a major issue in the preservation of cultural artefacts. A minimum amount of literature on the exact effect of people on the internal environmental conditions could be found (although information regarding the moisture load due to the average person was studied), an occupancy test was deemed necessary. This particular experiment was conducted in two phases, the first of which examined the effect of *"dry"* occupants and the second the influence of *"wet"* occupants (those who had been exposed to rainfall) to assess the effect, if any, of people on an environment and whether this effect was magnified when these people had been subjected to pre-wetting.

During all tests, the data loggers were placed at a height of 1.2m above ground level, corresponding to head height when seated. This value was also used for sensor placement during the monitoring phase for the case study buildings. By conducting these tests, it was envisaged that the signatures associated with each individual environmental stimulus could be identifiable and the outcomes of the small-scale experiments would be applicable to a large-scale historic building.

3.4. Application of Signature Tests to a full-sized Historic Building

Upon completion of the small-scale signature tests it was necessary to acquire data from the first large-scale case study building to determine whether the signatures observed during the tests were identifiable in a large historic building. As mentioned previously, the Museum Building was chosen for this process. Owing to the range of room sizes, orientation of the building and its multi-functional nature, the Museum Building offered a useful platform on which to build from the knowledge gained during the signature tests. For a full description of the characteristics of the building as well as the full discussion of the findings from the data collection process, refer to Chapter 5.

Monitoring was carried out in two phases. The purpose of the first phase was to obtain an appreciation of the factors that are driving the internal environmental conditions in the building and to validate and build on the knowledge gained from the small-scale signature tests. As discussed previously, the individual signature tests were designed such that only one environmental variable was altered. In full scale historic building, however, the environmental stimuli are not reflected individually in the data and so, applying the signatures to a full scale building was necessary to ensure that the trends observed in the small-scale experiments could be identified in a full-scale building with a dynamic

environment and disparate environmental stimuli that are influencing environmental condition simultaneously. In total, four lecture theatres (the DO, the GLT, M4 and M17) were identified for monitoring as well as five offices, the Civil Engineering Library and the Atrium. These rooms were chosen to examine the influence of different environmental stimuli and room characteristics (north or south facing, effect of thermal mass, high and low occupancy, stratification, and heat losses) and a full description of the various rooms, and their relevant features, is provided in Section 5.2.

The second phase was conducted to examine the thermo-hygrometric properties of the lecture theatres during the Christmas period when no mechanical heating or occupancy is present in the building. This would allow comparison between the theatres when the building was unoccupied and unheated, unoccupied and heated and occupied and heated. Only the theatres were identified for supplementary monitoring as they were subjected to the highest occupancy levels and were also consistently used on weekends, which meant that their baseline environmental properties were difficult to determine from existing data. Furthermore, this phase provided indications as to the behaviour of the building as a whole when loads due to mechanical heating or occupancy were not present in the building. The purpose of Phase 2 of the monitoring in this building was to define, and gain an understanding of, the natural equilibrium in the theatres, assess the influence of alternative stimuli (such as solar gains and infiltration) and to investigate the effect of large occupancy on a room compared to the baseline conditions. Only the lecture theatres were monitored during this phase as they are used on the weekends, meaning that the thermo-hygrometric environment in these spaces did not stabilise sufficiently to observe the baseline conditions during Phase 1 of data collection. Conversely, the offices are only in use from Monday to Friday and, as a result, baseline environmental data from the offices had been collected on the weekends during Phase 1 of monitoring.

As well as monitoring the rooms described presently, the Atrium (Fig. 3-2) and Foyer (Fig. 3-3) of the building were monitored. This was to assess the effect of stratification on the thermal environment in the building as well as the effect of the main entrance door, which was frequently opened and closed, on the thermal and moisture conditions in this area of the building. Furthermore, as the Atrium is linked to the majority of the offices and lecture theatres, monitoring the environmental conditions in this area would allow examination of heat and moisture movement from the relevant space into the Atrium and allow greater insight into the boundary conditions in each room.



Fig. 3-2: Image of the east end of the Atrium of the Museum Building taken from ground floor level.



Fig. 3-3: Image of the Atrium as taken from the Foyer (left photo) and of the Foyer as viewed from the Atrium (right photo)

In terms of lecture theatres, rooms at three disparate levels were identified (basement, first and second levels). Two first floor lecture theatres were included in the study with one on the north side of the building (the GLT) and the other on the south (M17). This would enable examination of the effects of solar gains on a room. The theatre on the second floor (the DO) would also facilitate such a comparison, owing to the relatively large glazed area in the roof - the purpose of monitoring this room was to examine whether heat loss rates were higher in this space compared to other rooms owing to its location beneath the roof space.

A basement theatre (M4) was chosen to investigate whether environmental conditions in this area were more stable compared to other levels as a result of the large level of thermal mass, due to the surrounding soil outside the external walls. Furthermore, the different levels on which the lecture theatres were located allowed examination of the degree of thermal stratification in the building. A fully annotated set of floor plans of the Museum Building are presented in Appendix A.

A method for obtaining accurate occupant numbers during Phase 1 of monitoring was also implemented. This involved placing a tabulated sheet in the room, which had the lecture time and date pre-printed on it. The system required lecturers to count and note the number of students attending their lecture at the beginning of the lecture. Unfortunately, the majority of lecturers did not fill out the form as requested and, as a result, only a small amount of information on the actual number of occupants in the lecture theatres was collected.

Similarly, the offices were carefully chosen to examine the differences in environmental conditions due to a variety of environmental stimuli. Although a basement office was monitored during Phase 1, the data obtained was erratic due to a malfunction of the logger and was discarded accordingly. Of the remaining offices, all four are located on the first level of the building, although Office 02 is on a mezzanine level.

Offices 02 and 03 are south facing and generally occupied by a single person. Office 03 is an administrative office and the door is generally left open, during working hours, while Office 02 is a personal office and the door is mostly closed. Conversely, Offices 01 and 04 are north facing. Office 01 has varying occupancy, up to a maximum of 8 and the door generally remains closed. Office 04, like Office 03 is an administrative office where the door is typically left open during working hours. Two people generally occupy this particular office. These offices were chosen to examine the difference between north and south facing rooms and the effect of an open door versus a closed door, with occupancy numbers as a minor factor.

The final room that was monitored during Phase 1 was the Civil Engineering Library, which is located on a mezzanine level directly above Office 04. It shares the same footprint and envelope properties as the office and is heated solely by infiltration from the room beneath. This particular location was chosen with the primary case study in mind. The purpose of monitoring the library was to ascertain whether a large volume of books has a discernible effect on the thermo-hygrometric properties of a space, a factor that was expected to be a significant contributor to the environmental conditions in the Old Library, particularly the Long Room.

The location of each sensor during both phases is described in Table 3-4 supplemented in Appendix A by a visual description of the location of each room and where each sensor was placed. As with the signature tests, each sensor was placed at a height of 1.2m above the ground and fixed in position using blu-tac, with the exception of the Atrium where sensors were placed equidistant along the wall, in 2 metre increments, in the vertical direction. From Table 3-4, it can be seen that the same sensor was used in specific areas during the two monitoring phases where possible. By collecting data in this method, and in conjunction with the comparison testing described previously, the margin for variation between different areas of the building due to instrumentation inaccuracies, were minimised to the greatest degree possible.

Table 3-4: Location of EL-2s during both the monitoring phases in the Museum Building. Refer to Appendix A for floor plans that indicate each location

Sensor	Phase 1 Location	Phase 2 Location
A	Foyer beside main door	N/A
B	DO Central Compartment	DO Central Compartment
C	DO Front Compartment	DO Front Compartment
D	GLT Front	GLT Front
E	GLT Rear	GLT Rear
F	Single Occupancy Basement Office	GLT Centre
G	M17 Rear	M17 South East Corner
H	M17 Front	M17 South West Corner
I	Office 02	N/A
J	External	External
K	Office 04	DO Rear Compartment
L	Civil Engineering Library	N/A
M	Office 03	N/A
N	M4 Front	M4 Front
O	M4 Rear	M4 Rear
P	Office 01	N/A
Q	DO Rear Compartment	DO Rear Compartment
R	Atrium Top Level	M17 North West Corner
S	Atrium Middle Level	M17 North East Corner
T	Atrium Bottom Level	N/A

Phase 1 of data collection was conducted over a four-month period, between February and May. The sensors were removed and the data downloaded from them twice during this period. In both cases, the process took place over a two hour period, i.e. the sensors were removed, the information extracted and the sensors quickly replaced, to minimise the amount of downtime in the data collection process. Phase 2 was carried out over a three-week interval at the Christmas vacation. Once the data was collected, the absolute humidity was calculated using a predesigned macro that was developed by the author in Excel, which was based on the calculation method outlined in Section 2.5. Data was then categorised into monthly, weekly and daily charts and compared and contrasted for similar trends and

differences in environmental behaviour. When the most interesting data trends were identified, the data for a number of locations was collated onto single graphs to be examined in greater detail to isolate the various signatures for comparison with those identified during the small-scale tests.

3.5. Monitoring and Analysis of the Primary Case study Building

Similar to the monitoring regime conducted in the Museum Building, data collection in the Old Library was carried out in two phases. The first of these took place over a five-month period (from September to January) while the second occurred over a three-week period in July. As well as monitoring conditions within the building, a sensor was also placed externally on the north face of the external at a height of approximately 5 metres above ground level and adjacent to a window at first-floor level in the Long Room. This location was chosen as the data would not be distorted by solar effects while fulfilling the potentially conflicting requirements of security and ease of access.

Although a comprehensive description of the building is provided in Chapter 6 (and floor plans are presented in Appendix B) a brief outline of the geometry of the building will be presented here. Construction of the building was completed in 1732 and the characteristics features of historic buildings are visible in the Old Library. The external walls are constructed of stone and range in thickness from 1 to 1.5m. The windows are relatively tall and the building is orientated to obtain maximum benefit from solar gains. The building currently retains its primary purpose as a functioning library containing more than 300,000 books, however, in relatively recent times it has developed into one of Dublin's major tourist attractions due to the presence of the Book of Kells as well as the Long Room (see Fig. 3-4).

In terms of geometry, the Old Library comprises three areas, namely the East Pavilion, West Pavilion and the central area in which the majority of the tourist facilities are located. The majority of the pavilions are currently used to provide facilities for readers and students that use the building as well as office space for a small number of staff and meeting areas, as well as for the storage of additional collection items. The central area of the building comprises two floors, of which the ground floor is divided into two compartments. The western compartment is used as a storage area for manuscripts and is referred to as the Colonnades. The remainder of the ground floor area contains a visitor shop and two interconnected exhibition spaces, the first of which is used for general exhibitions and is henceforth referred to as the Exhibition Space and the second which is used to house the Book of Kells and will be called BOKE hereafter.

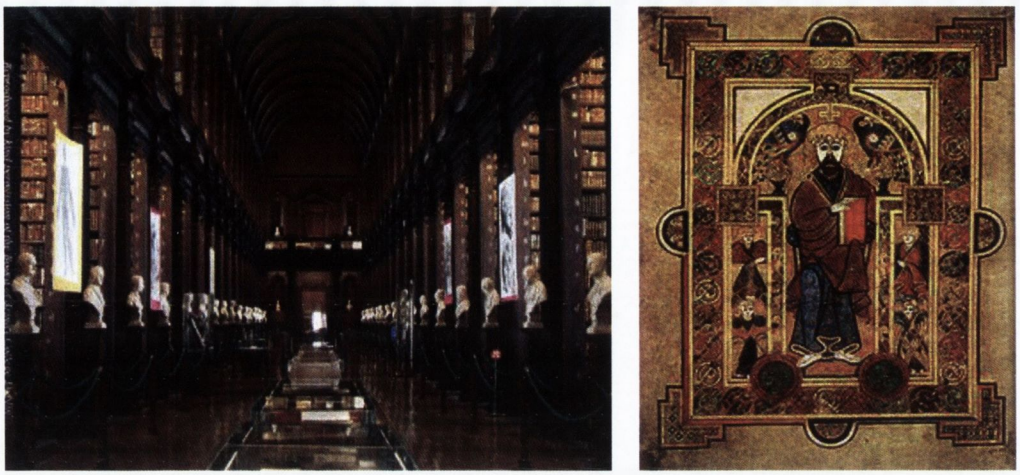


Fig. 3-4: Image of the Long Room as viewed from floor level (UCD, 2012) and a page from the Book of Kells showing "Christ enthroned" (Wikimedia, 2013)

The first-floor level of the central compartment of the building is known as the Long Room and is used to house approximately 200,000 ancient books. This space is the largest in the building and measures approximately 61m in length and is approximately 12m wide and 15m high. The room is split into two levels, namely the floor level from where visitors to the space view the Long Room, and the gallery level, which is located at a width of approximately 4 metres around the perimeter of the room and is off limits to the general public. The barrel-vaulted ceiling of the Long Room is a famous characteristic of the space and above this ceiling, the attic space is an unoccupied area that is divided into three compartments with a walkway running the length of the attic directly above the central spine of the attic.

The purpose of the first phase of data collection was to obtain a general understanding of the thermo-hygrometric behaviours of the building as a whole. Sensors were placed throughout the building, as described in Table 3-5 and Appendix B, focused on the areas that were open to the public, though two areas that were used to store delicate collection items and required stable environmental conditions as a result were also examined.

Phase 1 also incorporated the Christmas period, which, after the study on the Museum Building, was identified as crucial in obtaining a comprehensive understanding of how the building behaved when not subjected to mechanical or occupant loading, and the associated cool down and heating up period associated with the removal and reapplication of such loads. The rationale behind conducting a second phase of data collection was to examine the environmental impact of high occupancy levels on the building in the absence of mechanical heating. Based on historical visitor statistics, July was identified as the busiest month in terms of visitor numbers. For this phase, it was not necessary to monitor unoccupied rooms

Table 3-5: Location of EL-2s during both monitoring phases in the Old Library Building. Refer to Appendix B for a visual description of the location of each room and sensor

Sensor	Phase 1 Location	Phase 2 Location
A	Attic West Compartment	Attic West Compartment
B	Attic Central Compartment	Attic Central Compartment
C	Attic East Compartment	N/A
D	Long Room SW Gallery	Long Room SW Gallery
E	Long Room S Central Gallery	Long Room S Central Gallery
F	Long Room SE Gallery	Long Room SE Gallery
G	Long Room SW Ground	Long Room SW Ground
H	Long Room S Central Ground	Long Room S Central Ground
I	Long Room SE Ground	Long Room SE Ground
J	External	External
K	Locked Colonnade	Long Room N Central Ground
L	Shop beside Stairs	Shop beside Stairs
M	Shop beside Ticket Attendant	Shop beside Ticket Attendant
N	Exhibition Area	Exhibition Area
O	Passageway 1 (see Appendix B)	Passageway 1 (see Appendix B)
P	Upper Colonnade	Passageway 2 (see Appendix B)
Q	Treasury	Shack
R	Fagle Room (Book Storage)	Long Room N Central Ground
S	Book of Kells' Exhibition (BoKE)	BoKE
T	BoKE	Long Room NE Ground

and thus additional sensors were placed in the Exhibition Area and the Long Room to track the environmental conditions from the entrance point at the shop, through the Exhibition Area and into the Long Room.

Where possible, data loggers were placed in the same location as in Phase 1 and sensors that were used in the other zones of the building during the first monitoring sessions were distributed at suitable locations throughout the Exhibition Space and also on the north side of the Long Room.

Sensors were again placed at a height of 1.2m above ground level, however, given the sensitive nature of the building, they were not fixed in place with blu-tac where possible, such as in the book stacks. Typically, the data-loggers were left in place for a period of six-weeks before collection, although Phase 2 of data collection was conducted over a three-week period. Due to restrictions on access to the building (anyone researching in the Old Library must be accompanied by a member of staff at all times), the period between sensor collection and replacement was generally 24 to 48 hours.

Prior to conducting the monitoring schedule for the Old Library, a large number of suitable locations for sensors were identified. Following a survey of the building in situ, this number was reduced to the 19 locations used during the first data collection period. For Phase 1, it

was decided that the data-loggers would be primarily located along the route that visitors take through the building, with some supplementary sensors placed in unoccupied rooms and the attic.

Visitors enter the building through the ground floor shop, purchase their ticket and then pass through a short, narrow passageway into the Exhibition Space and subsequently onto the BoKE area. Thereafter, visitors go to the first floor level of the building and into the Long Room before returning to the shop and exiting through the same door in the shop. The route is designed as a one-way system to start and finish in the shop and once they enter the exhibition space, visitors must complete the circuit before exiting the building.

Accordingly, data-loggers were placed at the ticket desk in the shop, in the passageway that allows access to the Exhibition Space, the Exhibition Space itself and the BoKE. During the first phase, a sensor was placed in the stairwell to the first floor level, six were located on the south side of the Long Room (three at floor level and three at gallery level) and a final one at the stairwell that returns to the shop.

Three sensors were placed in the attic to attempt to discern the heat loss from the Long Room into the attic as well as to ascertain the effect of the environment in the attic, which is comparable to those externally, on the Long Room. Due to the layout of the attic, placement of the loggers in the space was limited so sensors were placed in the centre of the three compartments and 0.5m to the south side of the gangway that runs along the spine of the Long Room.

The remaining three sensors were placed in unoccupied rooms that were used to store collection items. The colonnades are located in the west end of the building and have a suspended floor that splits the room in two in the vertical plane. This area also has some internal insulation fitted to provide a stable indoor environment with the purpose of protecting the parchment and manuscript items located within. As well as defining the baseline conditions in the room, monitoring of this area also provided an interesting insight as to the potential effect of one retrofit option on the building as a whole. The other unoccupied room is located on the top level of the building and shares a wall with both the Long Room and the attic. Furthermore, this room is located immediately beneath the roof area in the East Pavilion. Data collected in this room could be compared with that in the colonnades to investigate the effect of infiltration from the external environment as no retrofit options had been implemented to this area.

As aforementioned, the objective of Phase 2 of monitoring in the Old Library was to further investigate the effect of high occupancy levels on the IEQ in the building. Accordingly, the number of data-loggers located along the route that visitors take through the building was increased, particularly in the Exhibition Space and the Long Room. Each window in the Long Room has been retrofitted with a low-emissivity film as well as a light-coloured blind. By placing a number of sensors on the north side of the Long Room, the effectiveness of these measures could also be assessed in terms of reducing the effects of solar gains, a factor which, given the large number of south facing windows in the area, could potentially have a detrimental effect on the IEQ when considering the importance of a stable environment for preservation.

As with the data from the Museum Building, when collected from the Old Library, data was subdivided into daily, weekly and monthly charts of the thermo-hygrometric parameters and then analysed.

Under typical circumstances, when one is carrying out an assessment of the environmental conditions in a building, the ventilation rate may be measured using a blower door test, which involves sealing all gaps in the building and then pressurising the building to 50kPa. This is particularly pertinent when one is carrying out a BER of a building as the outcome of this test, if favourable, can improve the building's BER rating. When considering the Old Library in TCD, however, the large volume of the building, coupled with the leakages that are occurring through the building envelope, make it unlikely that adequate pressurisation of the building would have been achieved for the test to be carried out. Measurment of the infiltration rate in the Old Library using tracer gas dilution were suggested, however due to difficulties in gaining access to the building out of hours this was not pursued. In other building's, however, such a test could be very valuable to the analysis of the building.

It was possible to obtain accurate visitor Old Library numbers from recordings in the shop as the number of people entering the building through the turnstiles is recorded. This data is recorded in one-hour intervals and was collected on a monthly basis and transferred to a spreadsheet. This was a valuable resource in assessing the influence of people on the IEQ in detail.

3.6. Computer Modelling of the Case study Building

Ideally, once a full analysis of the Old Library is completed, a number of retrofit options for the improvement of the IEQ would be recommended and implemented and the thermo-

hygrometric behaviour should be monitored and compared with the pre-upgrade values. For this analysis to be complete such that the effect of retrofitting might be predicted and evaluated in advance, accordingly, it was determined that a model of the Old Library and its indoor environment would provide an in-depth analysis of the potential influence of a range of retrofit options on the IEQ. This in turn would allow for more informed decision-making in the event that an upgrade of the building was to be carried out.

After reviewing a number of various software packages, <VirtualEnvironment> developed by Integrated Environmental Solutions (IES-VE) was chosen. IESVE comprises a suite of integrated environmental analysis tools capable of modelling environmental conditions in a building, particularly temperature and relative humidity variations. It has been successfully used to model a historic building in a study by Historic_Scotland and IES (2009).

IES-VE allows for a wide range of customisation, particularly in terms of load input and the definition of the building fabric. Different zones with alternate loading scenarios can be integrated into a model to allow a more accurate and realistic analysis of a particular building. Furthermore, IESVE is compatible with AutoCAD software, which allows more accurate construction of the model geometry. A full description of the software and the theoretical models it uses for analysis can be found in Chapter 7 and Appendix D.

The modelling of the Old Library was carried out in a number of stages. Existing AutoCAD floor plans of the building were obtained from the Building's Office in Trinity College and converted into dxf files. These were then loaded into IES-VE. The geometry of the building was then enhanced in the software and adjacent buildings were also inserted into the model to account for the shading provided by these. Once the geometry was completed, the building envelope properties were inputted. To achieve this it was first necessary to identify the various constituents of the building fabric. This process involved consultation with the architectural services officer of TCD, Mr. Michael Murray, a member of the academic staff in the Department of Civil Engineering in TCD, Dr. Sara Pavia, and a review of a number of reports commissioned by Bioletti and her staff. This allowed for a reasonably accurate model, insofar as it was possible since no tests on the building fabric were permitted. When this process was completed, material properties were obtained from CIBSE Guide A3 (Anderson, 2006) and used to construct the building fabric in the model. The final stage of building the model involved inputting the loads that the building experiences. This involved the load due to solar gains, people, lighting, heating (and air conditioning where applicable) and infiltration. In terms of the load due to people, the actual visitor numbers recorded throughout the monitoring period were used. Furthermore, for calculating infiltration rates and the effect of these on the internal environment, the software requires external data.

Although external weather data was available from the IESVE website, to obtain a more accurate representation of the building, actual data observed during the two monitoring phases was substituted into the software and used for analysis. To obtain the heating loads in the building, it was necessary to meet with a member of the Building's Office staff, in this case Mr. Paul Bolger, with whom a tour of the building was conducted in which the various heating elements, their power output and the schedule of operation were defined. The number of lights in each area of the building was also noted at this stage. All the various loads that define the environmental conditions of the building were then inputted into the software and simulations were conducted.

To increase the accuracy of the model, it was compared against actual data observed in the Old Library during the Christmas period. This allowed for refinement of the model before simulations of the consequences of potential retrofit options could be carried out, while also verifying the quality of the model in terms of accuracy. One matter that became apparent during modelling was that, despite assurances, IESVE could not model the effect of hygroscopic surfaces. As a consequence, an open-source software package was used to demonstrate the influence of books and their associated adsorption and desorption of moisture on the environment in the Long Room.

3.7. Concluding Remarks

The methodology described in this chapter will be conducted in three stages, namely definition and validation of the thermo-hygrometric signatures associated with environmental stimuli, initially through the use of small-scale experiments and subsequently in a full-scale historic building, the conduction of a POE to examine the environmental conditions in the Old Library in TCD and using the findings of the signature tests to determine the factors influencing the environmental conditions in the building and, finally, the modelling of the Old Library and a number of retrofit option to assess the suitability and effectiveness of various retrofit strategies in addressing the issues highlighted by the POE.

A common feature throughout this research project is the definition, validation and use of the signature tests as a tool to determine the factors influencing the environmental conditions in a historic building, particularly the Museum Building and the Old Library. The definition and validation of these signatures will now be discussed in Chapters 4 and 5.

4. Signature Tests

The following chapter describes the different small-scale signature tests carried out during this project. The function, projected goals, description as well as the results obtained and conclusions drawn from them will be discussed for each test. Before each experiment, all loggers used for the test were compared to ensure they were within 0.5°C of each other, the sensitivity of the devices as outlined in Section 3.2.

This chapter will briefly discuss the signatures associated with a number of environmental stimuli, namely, the effect of heat loading, the effect of moisture loading, altering the infiltration rate in the room by opening an external window and finally the effect of occupancy (both "dry" and "wet" occupants). A full description and analysis of the data collected in each experiment is supplied in the digital appendix that accompanies this thesis. In each experiment, the stimulus that is being tested will be altered while all other boundary conditions will be held constant. The purpose of these tests is to identify the environmental response to each change load or stimulus and use this information to better inform a thermo-hygrometric survey of the two historic case study buildings (Chapters 5 and 6) and the factors that are determining the environmental conditions in these buildings.

4.1. Description of the Test Room

Before discussing each experiment individually, it is first necessary to describe the test room that is used to conduct each test. After considering a number of rooms on the TCD campus, a basement room in a historic Georgian mid-terraced building was chosen. The room is unoccupied and is approximately 5m long and 3m wide with an air volume of 49.7m^3. Floor plans of the general layout of the room are presented in Fig. 4-1. The room is bordered to the north and south sides by two rooms, the north of which is contained within the same building and can be accessed and the south, which is part of an adjacent building and not accessable. Of these two adjacent rooms, the north room is unheated, while it is believed that the south room is normally heated as, when viewed from street level, it appears to be typically occupied. To the west side of the room is a corridor that links an adjacent heated stairwell to a number of rooms in the basement. The external wall of the room contains two windows, one large (1290mm wide) and one small (62mm wide), which are single glazed and fitted with supplementary secondary glazing that sits over the entire window and is not incorporated into the existing window frame.

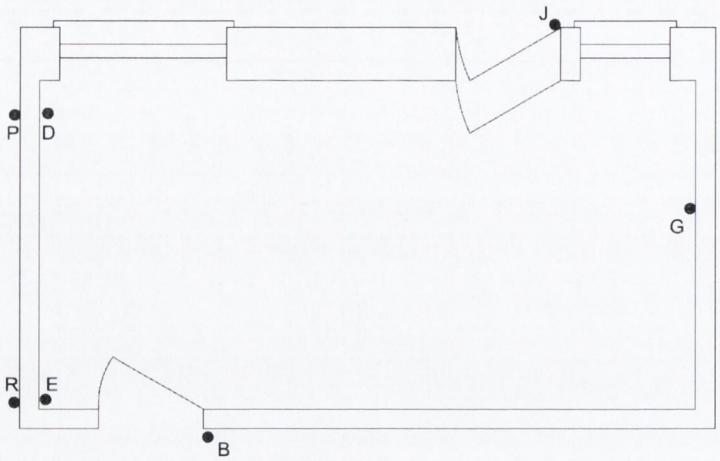


Fig. 4-1: Outline of the test room and locations of the data loggers in the room.

Further to the windows, a pair of single external timber doors allow access to a small courtyard outside the building that is approximately 5m below street level. As a result the room is not subjected to solar gains.

The walls of the building, both internally and externally, have been constructed using masonry. The external wall is approximately 0.5m thick while the internal walls are constructed using 120mm masonry blocks. Mechanical heating is generally provided to the room by a single double panelled radiator that is located beneath the large window, however, in order to achieve natural environmental conditions in the room, this heat source was deactivated 2 weeks prior to the commencement of the experiments.

Fig. 4-1 also displays the location of the loggers used for each experiment, with the exception of the open window test which used different devices due to a drift in calibration of the sensors associated with depleting batteries (see Section 4.5). Fig. 4-2 displays a photograph of the test room used for each experiment.



Fig. 4-2: Image of the test room used during the small-scale signature tests

4.2. Room Base Signature

In order to determine the baseline environmental conditions in the test room, three data loggers were placed at standing waist (shoulder when seated) height (see Fig. 4-1). Furthermore, external conditions were recorded as well as the environment in an adjacent room and in the adjoining corridor. T and RH values were recorded at five-minute intervals over a two-hour period and were then used to calculate the H_{abs} values observed at each logger.

T data recorded in the room and adjacent areas are displayed in Fig. 4-3. The overall trend observed in the chart is one of stable T conditions with minimal diurnal fluctuations. Heat loss from the room to the external environment is occurring at a relatively slow rate (an average of 1°C/day). There may also be some heat gains in the room as a result of heat ingress from the adjacent corridor (despite the door being permanently shut), which records a higher T value for the duration of monitoring. External T during this time (6-8°C) is noticeably lower than T conditions in the room (13-16°C) and so a temperature gradient between the room itself and the external environment is observed, which results in the reduction in T observed in the room during this process.

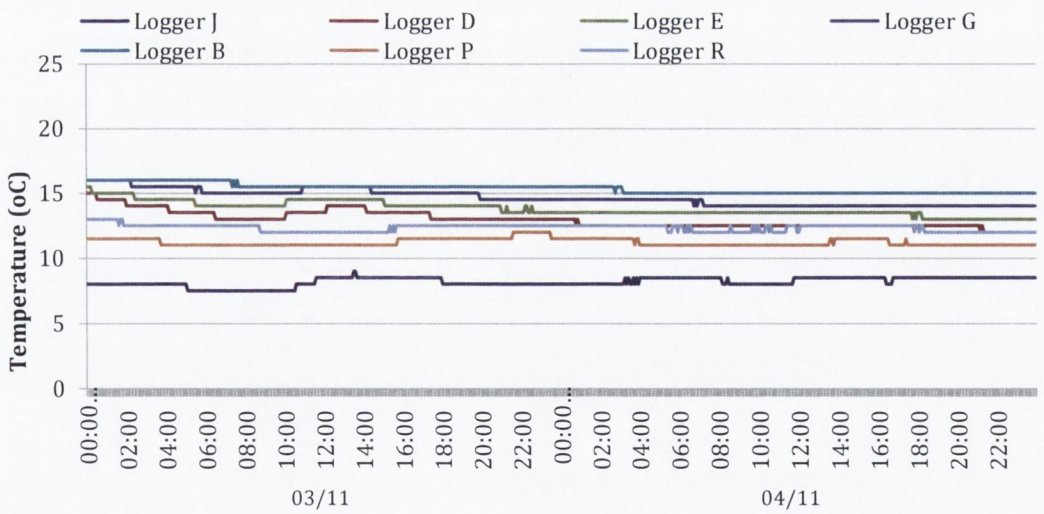


Fig. 4-3: Temperature data for the test room during the baseline monitoring period.

T variations between the different loggers in the room are observed and may be attributed to their location in the room (Loggers P and R). From Fig. 4-3 it may be observed that T conditions in the adjacent room to the test room are lower than those observed in the room. Conversely, the corridor in which Logger B is located is indirectly heated. Loggers D and E are located on the same wall with Logger D placed beside the window and Logger E in close

proximity to the door to the corridor. Given the higher T values observed in the corridor, heat is transferred from the corridor into the test room by convection. As the hot air passes Logger E initially, the T at this location increases slightly. The air cools as it moves further into the room resulting in the lower T at Logger D. Alternatively, heat losses through the window adjacent to Logger D could be responsible for its marginally lower readings.

As aforementioned, the room adjacent to the wall on which Loggers D and E are located is unheated. Conversely, the adjacent room to the opposite wall, on which Logger G is placed, is heated (although this room was inaccessible and could not be monitored) and accordingly, T values recorded at Logger G are marginally higher than those observed at the other two loggers in the room. Based on Fig. 4-3 it may be concluded that very slight variations in the T distribution throughout the test room are observed. These fluctuations are due to the heating regime in adjacent rooms, the corridor and losses through the windows and external door.

The corresponding RH data recorded during this time period is presented in Fig. 4-4. As expected, the magnitudes of the RH trends are the inverse of those observed in the T values, as the highest RH is observed in the adjacent room and lowest in the adjoining corridor where T is highest. Similarly, the highest RH in the test room is observed at Logger D followed by Loggers E and G.

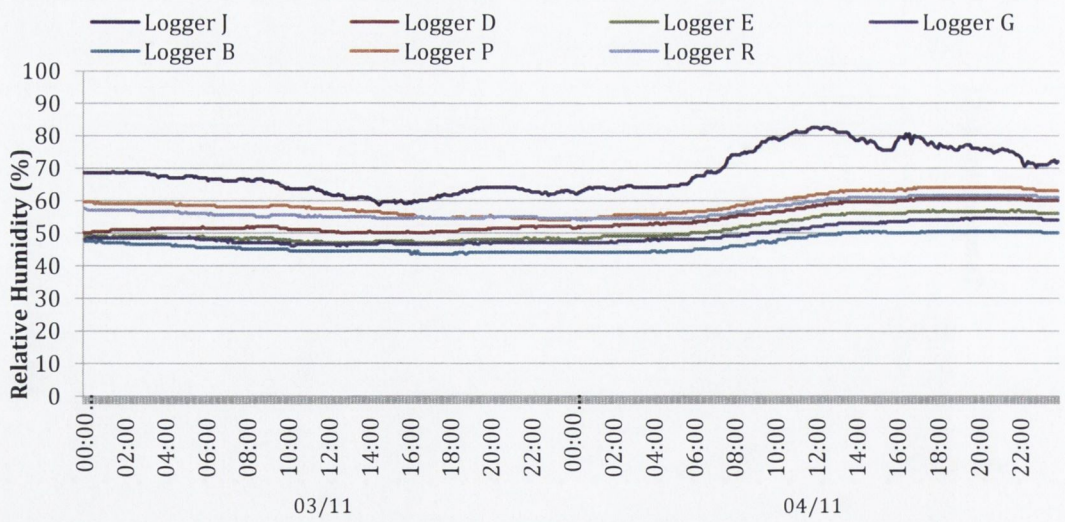


Fig. 4-4: Relative humidity recorded in the test room during the baseline monitoring period.

Varations at each logger are small and, as T fluctuations during the test are small, this indicates that minimal moisture changes are observed in the room during this time. It appears from the chart that internal RH readings are somewhat influenced by fluctuations in

the external RH as the overall trends are comparable, albeit that the internal fluctuations are significantly smaller than those outside. Given that the T values at each logger are different, H_{abs} is a more useful parameter to observe moisture movement in the test room.

The H_{abs} data calculated for the test room during the baseline test is presented in Fig. 4-5. Considering the external moisture trend observed on the chart it is clear to see that the moisture leakage rate from the room to the outside occurs relatively slowly, but occurs nonetheless. On 03/11, external H_{abs} is lower than that observed internally and the moisture conditions in the room are decreasing, albeit at a very slow rate. From approximately 04:00 on 04/11, external H_{abs} begins to increase and is noticeably higher than that internally at approximately midday. The change in moisture gradient observed at this time has an effect on the H_{abs} conditions in the building as moisture diffuses into the room and drives up internal H_{abs}. Accordingly, it may be concluded that H_{abs} conditions in the room are influenced by those externally, however, during this particular study the moisture gradient and the variations observed in the room are small and changes are slow to occur under these natural conditions.

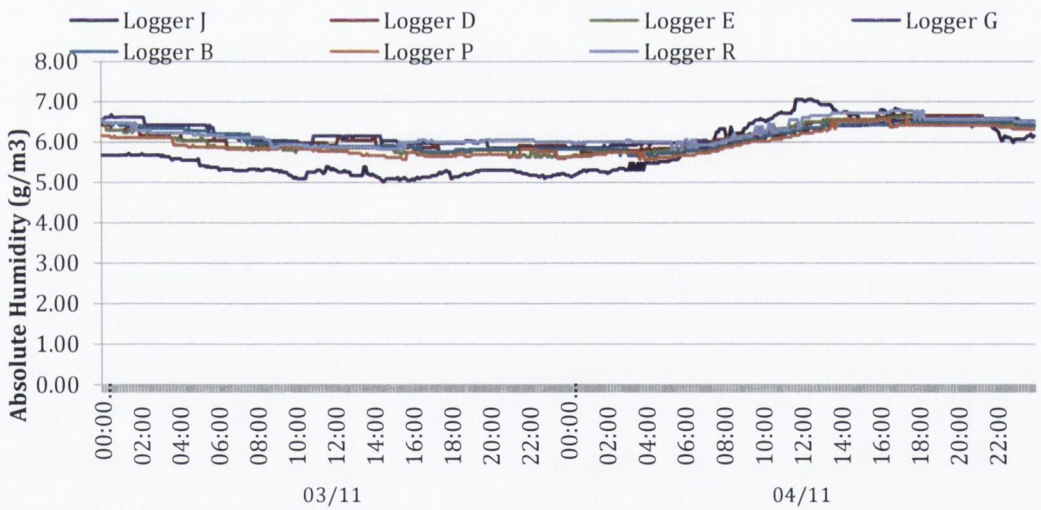


Fig. 4-5: Absolute Humidity data calculated for the test room during the baseline monitoring period.

Hence it can be concluded that, in terms of the natural baseline conditions in the test room, reasonably stable conditions have been achieved. Heat losses from the room are occurring slowly (at a rate of approximately 1°C/day) while RH conditions, while reasonably stable, are exhibiting some variations which are comparable in trend to those observed in the H_{abs} chart. These H_{abs} variations correlate well with the external conditions and so it can be seen that moisture infiltration into the space is the factor determining the RH and H_{abs} trends since T variations are reasonably small.

4.3. Heat Loading Tests

4.3.1. Description of Test

The test took place in two distinct phases in the test room (Section 4.2), initially with the door closed and subsequently with the door being held open. The aim of the former test was to determine the rate at which the room would reach equilibrium once the heat source was removed. Heating was provided to the room using an electric, oil filled radiator that was connected to power via an extension lead that was plugged in from outside the room and which was placed in the centre of the room, equidistant from the three loggers. This enabled the heat source to be activated and deactivated from outside the room without the need to enter the space. For both tests, heat was supplied to the space for a period of 2 hours with T and RH values being recorded at 1-minute intervals. As a means of determining the baseline conditions in the room, recording commenced three hours before the heat source was switched on and continued for a further six hours following removal of the heat so as to monitor the time required for conditions to return to the baseline values. Although every effort was made to create a stable environment in the test room, a number of miscellaneous external influences, such as external infiltration, led to an inability to obtain constant initial thermal values and subsequently the difficulties in achieving a large T change over a short period of time and, as a result, unsatisfactory results for this particular experiment were obtained and were, hence, disregarded.

Consequently it was necessary to redesign the test in order to achieve constant baseline conditions prior to the commencement of the test, as this would facilitate more accurate examination of the actual T vs. RH relationship. The most effective manner in which this could be achieved was to significantly reduce the scale of the test space, with better control over the external influences so that the direct relationship between T and RH could be assessed. Accordingly, the test was carried out in a fan-assisted domestic oven. The oven was deemed suitable owing to the insulating properties of the oven walls as well as the seals surrounding the oven door that would act to prevent moisture transfer between the microclimate in the oven and the external environment. A single data logger was placed in the test space that monitored T and RH conditions at one-minute intervals before, during and after the test. The oven, which was set to a constant T of 87°C, was turned on at 21:25 and was turned off 67 minutes later at 22:32. The data logger was removed from the test space the following morning so as to enable examination of the environmental response once the heat source had been removed. T and RH values were also used to calculate H_{abs} using the methodology defined in Section 2.5.1.3.

4.3.2. Results

T, RH and H_{abs} data recorded during the heat loading test are illustrated in Fig. 4-6. Prior to the introduction of the heat source, highly stable environmental conditions are observed in the test space, indicating that the air inside the oven is well isolated from external influences. Initial T and RH values of 18.5°C and 69% are noted until the introduction of the heat load. Thereafter, the air in the space experiences a rapid increase in T, with a maximum value of 87°C being reached at 21:40, 15 minutes after the heating has been turned on. This maximum T is then maintained until 22:33, one minute after the heat source has been deactivated. The rate of decay of the heat load observed during the experiment is significantly slower than the time taken to achieve the maximum T, owing primarily to the insulating properties of the walls of the oven and the negligible infiltration rate.

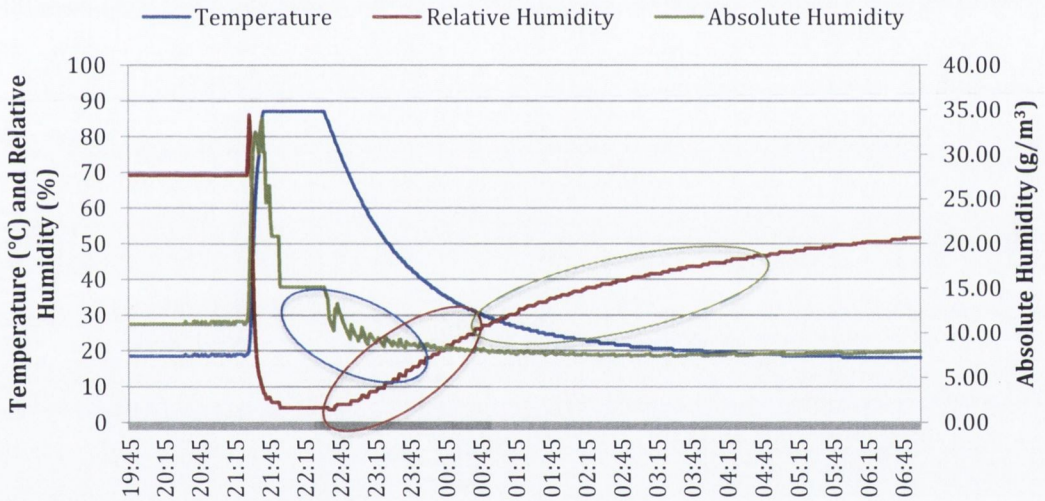


Fig. 4-6: Average T, RH and H_{abs} results for the small-scale heat loading tests.

The initial rate of decrease in T is the highest observed with a 37°C drop from 87°C to 50°C occurring over the first 54 minutes following the oven being turned off (a rate of 41.1°C/hour). This initial decrease is due to leakage of heat from the inside of the oven to the external environment through the double door, particularly the glass element of the door. Although the rate of decrease of T has dropped by 23:26, over the next 54 minutes it continues to decrease quite quickly reducing an additional 21.5°C to 29.5°C, a rate of 13.9°C/hour. At this point, the smaller T gradient between the microclimate inside the oven and the external conditions lead to the asymptotic effect observed in Fig. 4-6 after 01:00. The T decrease continues until equilibrium between internal and external conditions is apparently achieved at approximately 05:00 when T returns to its initial value of 18.5°C, 392 minutes after the heat source was deactivated.

As with T, the initial RH and H_{abs} are observed to be constant at 69% and 10.92g/m^3 respectively. Once the oven is switched on and T begins to increase, the expected initial decrease in RH surprisingly does not occur as the RH value increases to 86% RH at 21:28 before very rapidly decreasing to a constant value of 4% at 21:55, 15 minutes after T had stabilised. To explain why this occurred, it is necessary to examine the H_{abs} trend, which is also observed to increase rapidly when the heat source is activated. As the T increases, the volume of water vapour in the air also increases due to the initial evaporation of available moisture from the surfaces in the oven. Accordingly, the RH responds to the increase in moisture in the air by also increasing rapidly, by 16% RH in this case, before the change in T becomes the dominating factor in the RH trend and drives the values down. As mentioned previously, a 15-minute lag exists between equilibrium T and RH values being achieved in the test space and this again relates to the H_{abs} trend, which reaches an equilibrium value of 15.12g/m^3 at 21:54. Maximum H_{abs} is noted at 21:39 with a value of 34.00g/m^3, one minute before the corresponding equilibrium and maximum T. In the case of H_{abs}, however, the maximum value is maintained for one minute before decreasing rapidly to its equilibrium value as moisture is extracted by the action of the fan in the oven. This would also explain why the equilibrium RH value of 4% does not occur until 15 minutes after constant T values have been achieved. Between approximately 21:45 and 22:30, conditions in the oven for T, RH and H_{abs} are constant.

When the oven is switched off (both heating and the fan) at 22:32, a sudden decrease in H_{abs} occurs (15.12g/m^3 to 10.21g/m^3) during the first 7 minutes. This decrease in H_{abs} is a result of the drop in T, which leads to moisture in the air being re-adsorbed into the surfaces in the oven. A period of fluctuation occurs in H_{abs} as moisture evaporates and condenses following deactivation of the heat source, leading to the trend observed in the H_{abs} line (circled in blue in Fig. 4-6), between 22:39 and 02:00, where it stabilises at a value of approximately 7.51g/m^3, although small fluctuations continue to occur. Compared to the initial value, the final H_{abs} of 7.51g/m^3 illustrates a net decrease of 3.41g/m^3 as moisture was removed from the oven during the heating period by the action of the fan. It appears that this H_{abs} variation does not significantly influence the RH trend over the same time period as the expected relationship between T and RH is observed, albeit after a brief lag.

The initial decrease of 4.91g/m^3 in H_{abs} following the deactivation of the heat source, results in a 0.5% drop in RH (4% to 3.5%) for the very short period before the change in T causes the RH to rise, beginning at 22:41, 9 minutes after the end of the heating period. Once the RH begins to increase once more, it does so at an approximately exponential rate (circled in red in Fig. 4-6), reaching 27.5% RH at 00:55 as it gradually slows down (circled in green in Fig.

4-6). RH continues to increase until the end of the monitoring period at 07:00, when a value of 51.5% RH is recorded, a reduction of 17.5% RH compared to the initial value. As mentioned previously, this lower value is a result of the decreased concentration of moisture present in the air as a result of the action of the fan, because the final T is identical to the initial T at this point.

In conclusion, the signature behaviour that defines a heat load in a space is, assuming no change in moisture conditions in the air (that is, H_{abs}), when the T increases there is a corresponding decrease in RH. On the other hand, if there is moisture created or lost in the space it is possible that the RH will either increase or decrease in accordance with the H_{abs} change due to the change in moisture in the room. Therefore, it doesn't necessarily follow that if the RH changes in a room that there is a change in T present as it may be due to either a change in H_{abs} or a change in T, or a combination of both.

4.4. Moisture Loading Test

4.4.1. Description of Test

A similar experiment to that outlined in Section 4.3.1 was devised to examine the influence of moisture loads on the indoor environment of a space. The test room, as described in Section 4.1, was used for this experiment. Although this room was not used for the heat-loading test described previously, given that the natural baseline conditions, as well as the signature associated with a heat load are understood, the signature associated with a moisture load could be established in the room, despite leakage or infiltration occurring in the room. The moisture load was provided to the room using a beaker of boiling water placed in the centre of the room, equidistant from the data loggers, at floor level. So as to ensure that a sufficient volume of water could be evaporated into the air without interruption due to door opening, the beaker was placed on a hot plate that was connected to power via an extension lead that could be activated from outside the room. The water used in the test was boiled immediately prior to its placement in the room so that steam was immediately available at the start of the moisture load period. This was selected as the most efficient method of supplying the moisture load at a constant rate over a prolonged period of time. The test began at 14:20 at which point the boiling water was placed on the hot plate, which was disconnected an hour later at 15:20. When placed in the room initially, the beaker contained 800g of water, a value that had decreased to 550g at the end of the test, hence indicating that a moisture load of 250g or 5.03g/m^3 had been induced in the space as a

result of the boiling water. The data loggers were collected the following morning whereupon the T and RH values were used to calculate H_{abs}.

4.4.2. Results

The thermo-hygrometric environmental conditions recorded in the test room during the moisture loading experiment are illustrated in Fig. 4-7. Although three sensors were placed in the room, similar behaviour was simultaneously exhibited in all three and so only data collected from Logger G is discussed.

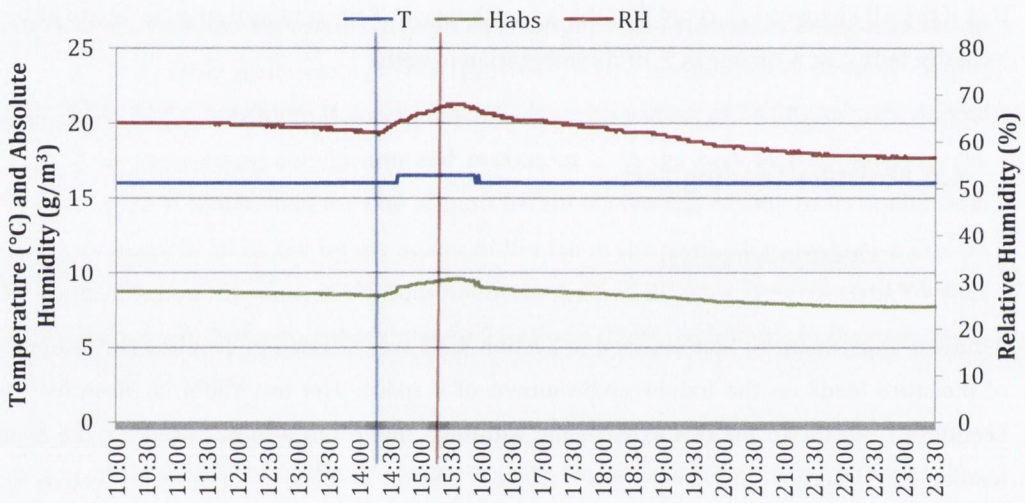


Fig. 4-7: T, RH and Habs variations observed at Logger G during the moisture loading test. The blue and red lines represent the start and finish times of the moisture loading period, that is, when the hot plate is turned on

Prior to the introduction of the moisture load, relatively stable environmental conditions are observed in the test room as T is recorded at a constant value of 16°C. The overall RH and H_{abs} trends are decreasing slightly over the course of the period before the load is induced in the space and, considering the constant T value in the room, these variations may be attributed to exfiltration from the room.

At 14:20, the hot plate in the room is activated and a constant moisture load is induced in the space. Over the course of this period, a small increase in T (0.5°C) is observed due to the small heat load arising from the presence of the hot plate. Thereafter, stable T conditions in the room are maintained.

The first increase in RH is observed in the room at approximately 14:24, after which the RH increases at a steady rate to a maximum value of 68%, a 6% increase on the initial value. This maximum value occurs at 15:30, 10 minutes after the hot plate has been deactivated. This lag period is longer than would have been observed had the water been removed from the room completely as the water would have continued to provide a moisture load to the room after the hot plate had been turned off.

When the application of the moisture load to the room ceases, a relatively quick decrease in RH is observed in the room, with a 3%RH reduction recorded over a 40 minute period. RH reaches a state of equilibrium at approximately 16:25 and a value of 65%, 3% RH higher than that observed initially. Shortly afterwards, the background trend of decreasing moisture conditions due to exfiltration from the room becomes the driving factor behind the RH in the room. This is reflected by the decreasing RH trend observed in the room after approximately 17:00 despite the stable T conditions.

Unsurprisingly, considering the stable T conditions in the test room, H_{abs} variations over the course of the experiment are comparable to the RH trends. A H_{abs} value of 8.45g/m^3 is observed immediately prior to the introduction of the moisture load, rising to a value of 8.99g/m^3 by 14:37. At 15:29, maximum H_{abs} of 9.55g/m^3 is observed in the room, equating to an overall increase of 1.10g/m^3 over the course of the experiment.

Given that the total moisture load induced in the room due to the boiling water was 5.03g/m^3 (due to 250g of evaporated water) resulted in an increase in H_{abs} of 1.10g/m^3 (corresponding to 54.69g of water), it is clear that a significant amount of the moisture load is lost to the external environment through exfiltration from the room and absorption by hygroscopic materials. This is effective in buffering the impact of moisture loads in a space, assuming that external conditions are such that exfiltration is possible.

Hence it may be concluded that the introduction of a moisture load into a room under constant T conditions results in an increase in both humidity parameters, which will exhibit similar trends. If T increases during the moisture-loading period, however, the expected relationship between T and RH will not necessarily be observed, as it is possible that the extra moisture in the air will compensate for the increase in T and both RH and T may be observed to increase simultaneously. Once the load is removed, the moisture parameters in the room revert to their original trend relatively quickly as the moisture is dissipated from the space through exfiltration (assuming that it is possible), ventilation and absorption by hygroscopic materials.

4.5. Open Window Test

4.5.1. Description of Test

This experiment was also carried out in the test room described in Section 4.1. The purpose of the open window test was to determine the signature associated with a high infiltration rate in a building, which may result from a window or external door being left open, as is often the case in the Old Library. A total of 6 loggers were used during the test, four placed inside the room, one sensor was placed in an adjacent hallway and one additional sensor monitoring the external conditions. For this experiment, a different array of loggers were used due to drift in calibration between the loggers that were typically used for the small-scale tests, which was identified during a calibration test. Fig. 4-8 indicates the locations of all sensors used during the test as well as displaying the layout of and openings within the room. Logger J, which monitors external conditions, is located beside the window that was opened during the test. Environmental conditions recorded at Logger E will be discussed as the trends at this location are representative of those in the room.

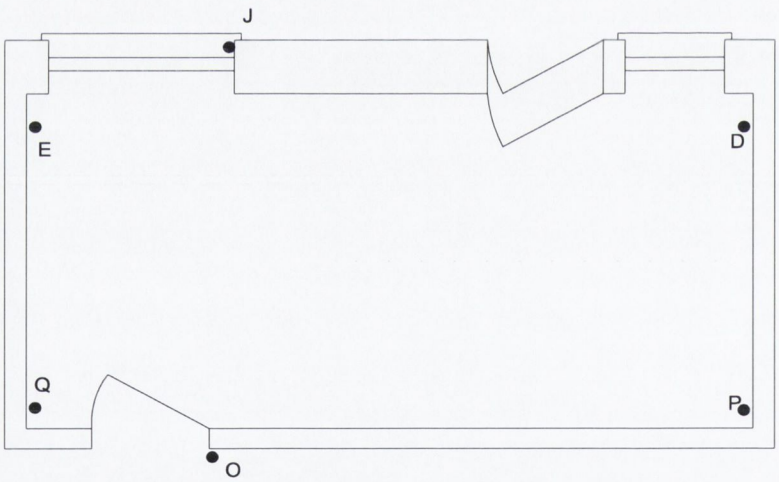


Fig. 4-8: Sketch of test room including locations of sensors in the space. Not to Scale.

Temperature (T) and relative humidity (RH) data were collected at 1-minute intervals, over the duration of the test, which lasted 3 hours in total. The test commenced at 17:00 and the window was opened at 18:02 and closed again at 18:45. The recording process was ended at 20:00 and the data graphed and examined.

4.5.2. Results

4.5.2.1. Temperature Effects

Prior to the window being opened, thermal conditions in the room are stable at a value of 15.5°C, as illustrated in Fig. 4-9. Similarly, external conditions (Logger J) are stable, albeit lower by 8°C in magnitude than those internally, resulting in a thermal gradient between the two spaces when the window is opened and the experiment begins.

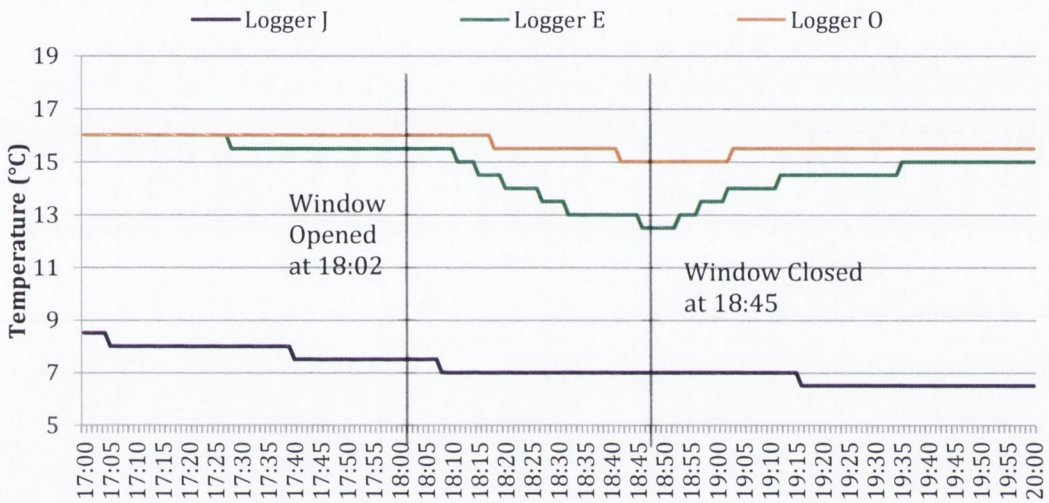


Fig. 4-9: T conditions recorded at each data logger over the duration of the Open Window Test.

When the window in the test space is opened to form a gap of 100mm, the infiltration rate in the room increases accordingly. Heat begins to move from the room to the external environment, resulting in the reduction in T observed over the duration of the experiment. In total, a 3°C reduction (15.5°C to 12.5°C) in T is occurs over the 43 minute period when the window is opened. The majority of this decrease in T occurs over the initial 30 minutes of the window being opened before the effect of thermal mass and heat infiltration from adjacent rooms results in the rate of heat loss from the room. This infiltration of heat into the test room from adjacent spaces is reflected in the reduction in T observed in the corridor outside the room (Logger O).

Once the window has been closed again at 18:45, no further T decreases are noted as the significant T gradient between the internal and external conditions no longer exist. Logger E, having reached the lowest T during the test (12.5°C) is the first to recover and increase with its first increase in T observed at 18:51, six minutes after the window closed. Although T values are continuously changing slightly, Loggers D and P begin to show recovery at 18:54 while Logger Q increases initially at 18:55. During the 75 minutes over which recording

continued after the window was closed, a steady increase in T is noted at all sensors. At the end of recording, the T observed at each logger is 0.5°C lower than that recorded at the start of the test although the initial T may have been reached shortly after recording had ceased.

Logger O, which is located in the hallway and is isolated from the room by a closed door, records a very stable temperature at 16°C. At 18:18, 16 minutes after the window is opened, a decrease in temperature of 0.5°C (16°C -15.5°C) is observed in the hallway before decreasing a further 0.5°C to 15°C during the period while the window is opened. Once the window has been closed, T remains at 15°C until 19:02 at which point an increase of 0.5°C is observed at Location O. Hence it may be concluded that the open window influences not only the indoor environment of the room in which it is located, but, to a lesser extent, also rooms and passageways in close proximity to the room as heat is lost from these ancillary areas into the room due to the loss of heat out of the window. In all of these observations, it should be noted that movements in T are continuous but are only recorded for every 0.5°C and, because overall T changes are small, too much inference should not be attributed to the exact timings of the small T changes.

Fig. 4-10 displays the H_{abs} values calculated using the T and RH values recorded at Logger E over the course of the test. From the chart it can be seen that H_{abs} undergoes a similar variation to that observed for T over the course of the experiment. Before the window is opened, stable H_{abs} conditions are observed in the room with a value of 6.21g/m^3. External conditions (Logger J) are observed to be lower in magnitude resulting in a moisture gradient between the two spaces.

When the window is opened at 18:02, moisture transfers from the room to the external environment through the mechanisms of air flow and diffusion, thus reducing the volume of moisture in the room. This decrease in moisture is reflected through the fall in H_{abs} in the room to a minimum value of 5.50g/m^3 at 18:32, 30 minutes after the window has been opened. At this point the reduction in H_{abs} in the room steadies as the reduction in the moisture gradient coupled with the infiltration of moisture into the room from the adjacent spaces decreases the rate of moisture loss from the room. The effect of the increase in infiltration rate is also observed in the adjacent corridor (Logger O) where a decrease in H_{abs} is also observed over the duration of the experiment.

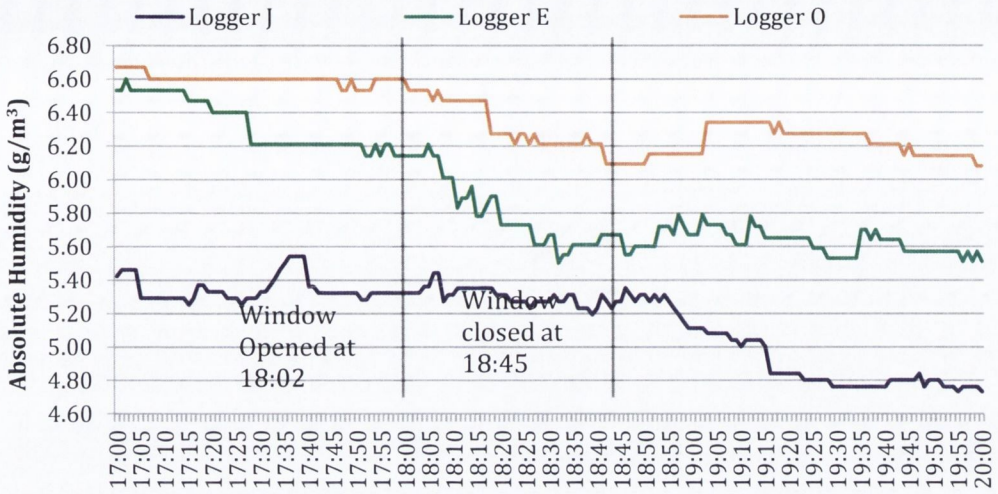


Fig. 4-10: Absolute Humidity values calculated at each monitoring location during the open window test.

When the window is closed again at 18:45, some variations in H_{abs} are observed, however, the H_{abs} does not begin to approach the values observed before the window was opened. This is a result of the removal of moisture from the air in the room coupled with the lack of an additional moisture load to increase H_{abs} following the reduction of the infiltration rate again.

Data collected at the start of the recording period indicate that a constant RH is not present across all loggers in the room (Fig. 4-11). From the chart it can be seen that, as would be expected considering the T and H_{abs} trends, RH conditions prior to the window being opened are relatively stable at a value of 47%. Once the window is opened and the infiltration rate is increased, RH remains relatively stable for a period of time and does not appear to change in a noteworthy manner until approximately 18:20.

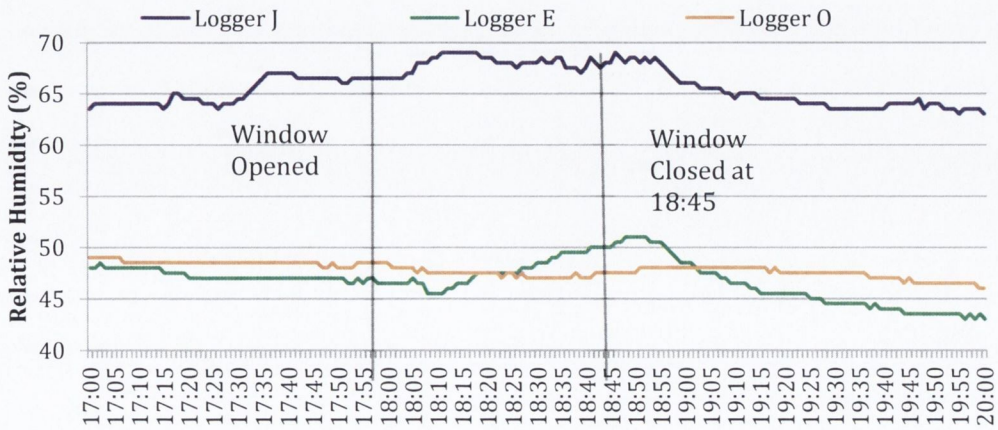


Fig. 4-11: RH values observed at each data logger in the test room during the open window test.

Between the window being opened and the increase in the infiltration rate inducing a change in RH, T and H_{abs} conditions are changing, with both decreasing as described previously. The effect of each influence offsets the other and leads to the relatively stable RH conditions at this time. Thereafter, RH conditions in the room are observed to increase, indicating that the T variations in the room arising from the increased in the infiltration rate are the dominating factor behind the change in RH. The effect of the decrease in H_{abs} decreases the effect of the T change at this time. RH continues to increase until approximately 18:50 and a maximum value of 51% before decreasing again as the T increases. After this point, RH begins to decrease once more, stabilising at a value of 45.5%, slightly lower than its original value and due primarily to the reduction in moisture in the room.

Based on the observations made during the open window experiment it may be concluded that the signature associated with an open window or external door is a rapid change in T and H_{abs} as internal conditions approach those observed externally occurring throughout the room when the window is opened. The RH behaviour is influenced by both the T and H_{abs} variations depending on which is the most dominating factor. In this experiment, for example, initial RH change (decreasing RH) due to the open window was driven by the H_{abs} variation before the decreasing T caused the RH to increase thereafter. When the window (or door) is closed once again, both T and humidity conditions stabilise before changing in accordance with loading conditions in the room. Thus, to fully understand the thermo-hygrometric behaviour, T, RH and H_{abs} may all need to be considered. It is worth noting that, although this experiment was conducted for conditions that promote exfiltration from the room, the same principles would apply had infiltration into the room from the external environment been the dominating conditions. There are, however a wide range of ancillary effects that may contribute to the trends observed during a period when an external window or door are opened. These include, but are not limited to the season, external weather conditions, wind direction and velocity, the area of the window or door and the indoor conditions.

4.6. Occupancy Tests

4.6.1. Description of Test

The occupancy signature test for sedentary occupants, whose clothes were "dry", was designed to assess the influence of people on internal environmental parameters, specifically temperature, relative humidity and absolute humidity. The test involved inviting

a number of participants to sit at rest in a test room and monitoring the change in environmental conditions over the duration of their occupancy. As this specific test required that participants be at rest and dry, mechanical heat and air conditioning appliances were turned off to ensure that any changes in environmental conditions, particularly RH and H_{abs} would be as a result of the metabolic activities, i.e. perspiration and respiration, of the people themselves, compared to the baseline in which no people were present under similar starting conditions or compared to a forced moisture load, as described in Section 4.5.

This particular test used the same test room as the previous experiments. During this experiment, 5 data loggers were used, three of which, Loggers 'D', 'E', and 'G', were placed in the room, Logger 'J' was placed outside to monitor external conditions, and Logger 'B' was placed in the adjacent hallway. The test took place between 05:00 and 19:00 and recorded the change in environmental parameters under exposure to initially one person who sat in the vicinity of Logger G (Fig. 4-1) and subsequently by five people in total who were seated at random places throughout the room. The first person entered the space at 08:40, followed by the remaining four at 09:10 and remained in the room until 10:45. Once participants exited the room at 10:45, the door linking the room with the hallway remained opened for a two hour period and the change in environmental parameters in the hallway were monitored as well as the changes in the room itself. The test was then repeated (although all participants entered at the same time) and the participants were asked to spend a 15-minute interval externally in the rain to mimic a typical waiting period that a visitor to the Old Library might expect to spend queuing during busy spells. This would allow for analysis of the effect "wet" occupants would have on the internal thermo-hygrometric conditions in a room.

4.6.2. **Results**

For the purposes of this summary of data collected during the experiment, only data recorded at Logger G will be discussed. T results for this test are illustrated in Fig. 4-12. At the beginning of the recording period, T conditions of 18°C are noted in the adjacent hallway (Logger B), 17°C at Loggers G and 11.5°C externally (Logger J) indicating thermal gradient between the room and the external environment. This gradient, however, does not appear to influence the thermal conditions in the room as stable T conditions are observed prior to occupancy.

When the test space becomes occupied by one person at 08:40, the effect on the thermal environment in the room is negligible as no change in T is observed over the course of this

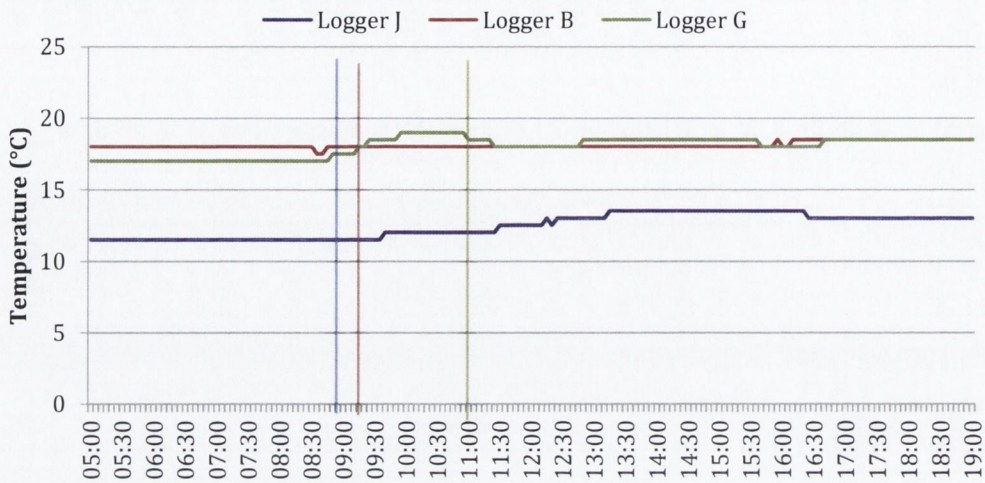


Fig. 4-12: Temperature variations observed during the occupancy test. The blue, red and green lines represent the start of occupancy phases 1 and 2 and the termination of the occupancy period.

occupancy period. At 09:10, when the additional 4 people enter the room, it appears that their presence in the room begins to cause an increase in T in the room. Over the first 30 minutes of this second occupancy period, T in the room increases by 1°C as a result of the heat loads associated with the metabolic processes of the occupants in the room. One further increase in T, albeit small in magnitude, is observed in the room over the remainder of the occupancy period. Considering the relatively small volume of the room, the low heat losses from the room and the presence of 5 people, the effect of occupants on the thermal conditions appears to be small. After the room is vacated, the door to the adjacent hallway is left open and comparable T values are observed between the room and the adjacent corridor.

The H_{abs} trends observed externally (Logger J), in the room (Logger G) and in the adjacent corridor (Logger B) are displayed in Fig. 4-13. The three important times during this experiment, namely when the first occupant enters the room at 08:40, when the four additional occupants enter the room at 09:10 and finally when the room is vacated at 10:45 and the door left open, are indicated by the blue, red and green regions in the chart.

Prior to the commencement of occupancy in the room, stable H_{abs} conditions are observed in the test room at a value of 8.47g/m^3. When the occupancy period commences with a single occupant at 08:40, the effect on the hygrometric conditions in the room is almost instant. The presence of the single occupant, through perspiration and respiration, causes an increase in H_{abs} to 8.80g/m^3 over a 15 minute period before stabilising. These stable conditions are observed until the additional occupants enter the room at 09:10, after which a large increase in H_{abs} is observed, increasing by 1.27g/m^3 over a 15 minute interval.

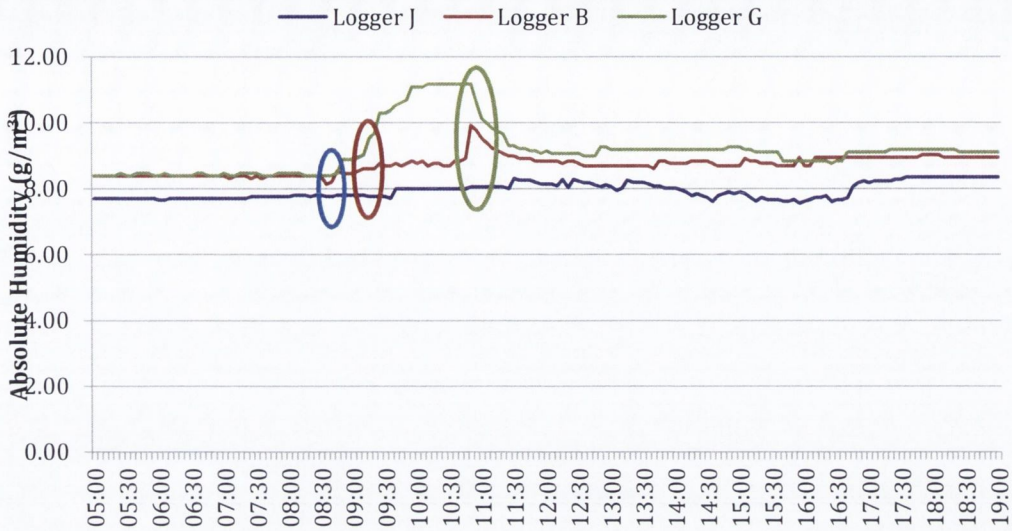


Fig. 4-13: Absolute humidity calculated during the occupancy test

Thereafter, H_{abs} continues to increase, albeit at a lower rate before reaching a maximum value of 11.17g/m^3, equating to an overall increase of 2.70g/m^3. This maximum value is maintained until the end of the occupancy period when the door is opened and the moisture is quickly dissipated into the adjacent corridor. From this brief analysis of the H_{abs} conditions observed over the course of the experiment it is clear that the presence of people has a significant effect on the moisture conditions in a room.

RH conditions in the test room during the occupancy test are displayed in Fig. 4-14. As before, the blue region refers to the first occupant entering the room, the red region represents the time when the additional 4 people entered and the green region illustrates the vacation of the room. As can be seen from the chart, the RH variations are comparable to those observed in H_{abs}. Stable conditions are observed prior to the commencement of the experiment at a value of 58%

At 08:40, the first occupant enters the room and induces a small moisture load in the room. Over this period there is no change in T (as described previously) and an increase in RH of 2% is observed (58% to 60%). The room is fully occupied at 09:10 and the presence of these additional people results in a large increase in the moisture load in the room, as well as a small increase in T. The effect of these two stimuli on the RH in the room is reflected in an increase in RH, initially to a value of 65.5%, at which point the rate is reduced. Driven by the H_{abs} change, RH continues to increase to a maximum value of 68.5% over the course of the experiment before stabilising once more. The total change in RH over the course of this experiment as a result of the presence of people was 10.5%, a fluctuation that exceeds the

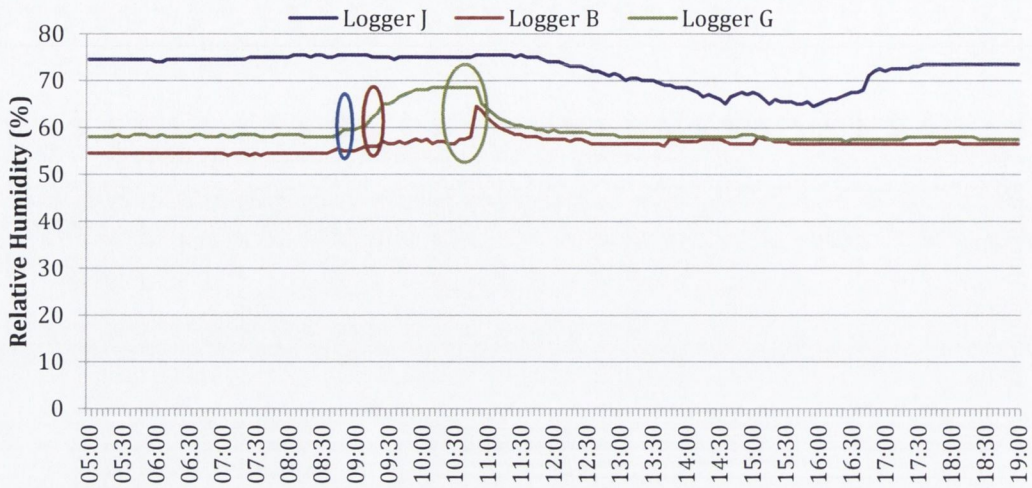


Fig. 4-14: Relative humidity observed during the occupancy test.

maximum allowable variation specified by BSI (2012) and discussed in Section 2.6. Accordingly it can be seen that the presence of people in a room has the capability to cause unacceptable environmental variations in a room. When the experiment ends and the room is vacated, RH conditions decrease rapidly as moisture exfiltrates the room into the adjacent corridor.

From this experiment it may be concluded that, the environmental signature associated with the presence of dry occupants in a room is large perturbations in the humidity parameters about an existing general trend whereby the fluctuations in the general trend are exacerbated by the additional moisture load induced in the space by the metabolic processes of the people that were not previously present. The effect of people on the T conditions in the space is relatively small.

Having examined the effect of dry occupants on the environmental conditions in the test room, it was then essential to determine whether people with wet clothes and belongings induced a different environmental response in the room. In this case, all 5 occupants entered the room simultaneously. Given that the presence of people had a small influence on the thermal environment relative to the hygrometric environment, the T variations over the duration of this experiment were small and as expected. Again, variations in Logger G are discussed as follows.

H_{abs} data calculated for the test room during the "wet" occupancy test is displayed in Fig. 4-15. Once more, stable H_{abs} conditions are observed in the room (8.30g/m^3) before the occupancy period commences. At 09:00, the five occupants enter the room having spent a 15 minute period in the heavy rain. Their presence in the room has an instant influence on the

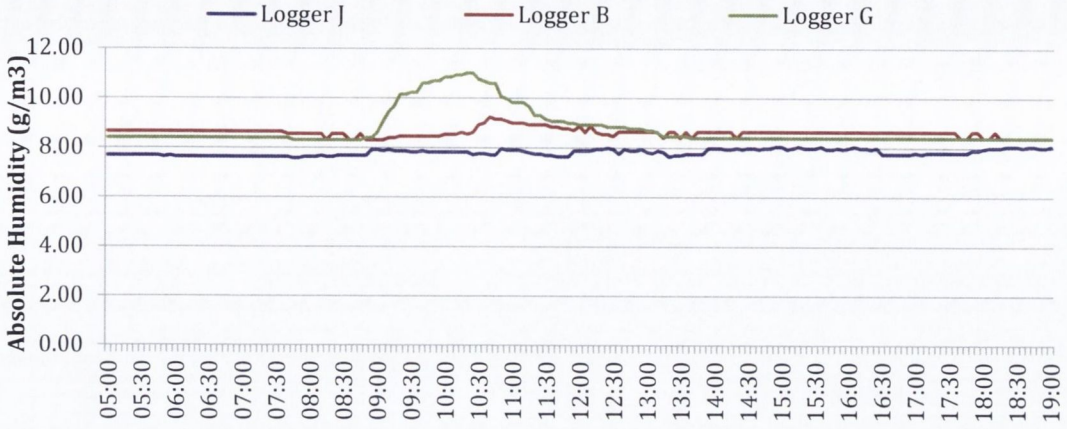


Fig. 4-15: Absolute humidity data calculated in the test room, externally and in the adjacent hallway for the "wet" occupants test.

H_{abs} conditions in the room. H_{abs} in the room is observed to increase rapidly from its initial value to 10.14g/m^3 over the first 20 minutes of occupancy before stabilising briefly. Thereafter, a slower rate of increase is observed before a maximum H_{abs} of 11.31g/m^3 is observed in the room, an increase of 3.01g/m^3. When compared to the corresponding increase in H_{abs} observed during the dry occupancy test, the effect of the wet occupants results in a H_{abs} variation that is 0.31g/m^3 higher than that observed on the dry day, that is, about 10% greater. Considering that the people used for the two occupancy experiment were identical, as were their activity level during the test (i.e. sedentary), this difference in H_{abs} increase between the two tests is attributable to the additional moisture on the clothes and belongings of the occupants.

RH data collected during the test is displayed in Fig. 4-16. The important point to note in this chart is the large variation in RH observed in the test room over the course of the occupancy period. The effect of the 5 "wet" occupants results in an increase in RH in the room of 10%, a value that well exceeds the upper limit specified in BSI (2012) for environmental variations in museums. Accordingly, the potential damaging effects of occupants on the environmental conditions in smaller museums, libraries and archives is confirmed. Furthermore, in cases where people are forced to queue outside in the rain prior to entering a building can result in greater fluctuations in the hygrometric environment in the building and, as a result, potentially greater damage to collection items.

Accordingly, from the occupancy tests of both dry and wet occupants it can be concluded that people have a very small influence on the thermal conditions in the room. The presence of people, however, has the potential to cause large scale variations about a background

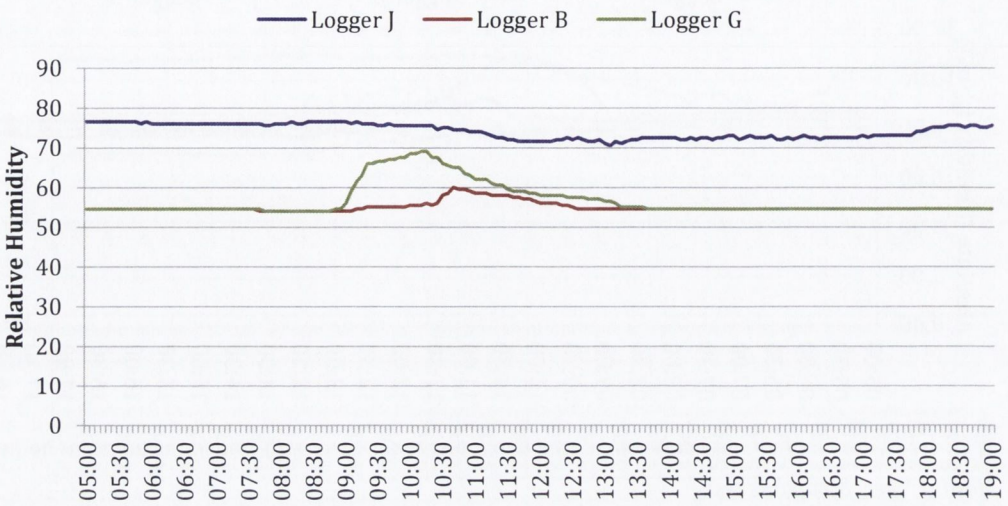


Fig. 4-16: RH variations observed in the test room, externally and in an adjacent hallway during the "wet" occupant test.

trend in the hygrometric conditions. When the occupancy period ends, the internal conditions revert to the background environment in the room, unlike when a window or door is left open.

4.7. Conclusions and Knowledge Gained from the Small Scale Signature Tests

The purpose of the small-scale experiments, outlined in this chapter, was to ascertain the environmental signatures associated with a range of stimuli. This knowledge will then be applied to a larger scale as discussed in Chapters 5 and 6. Fig. 4-17 displays a summary of the findings as follows:

- *Heat Loading Test*: While the inverse relationship between T and RH was generally observed, the increase in H_{abs} at the beginning of the heating period indicated that the effect of evaporation of moisture from hygroscopic surfaces and materials may cause unexpected variations in RH during a heating period.

- *Moisture Loading Test*: The outcome of this experiment was as expected with a close correlation between both RH and H_{abs} being observed.

- *Open Window Test*: As mentioned previously, the external environmental conditions during this experiment promoted exfiltration from the room. Had infiltration been the factor involved in this experiment it is expected that the principles would be the same (i.e. heat and moisture transfer according to the thermal and hygric gradients respectively).

Stimulus	T Change	RH Change	H_{abs} Change
Heat	↑	↓	?
Moisture	→	↑	↑
Infiltration	?	?	?
People	↑	↑	↑

Fig. 4-17: Effect of the environental stimuli on the thermo-hygrometric environment as determined by the small scale signature tests.

- *Occupancy Tests*: Both the "dry" and "wet" occupancy tests indicated that the presence of people does not significantly influence the thermal environment in a building. The metabolic processes of occupants (respiration and perspiration) have, however, a measurable effect on the humidity parameters in a building and may result in unacceptable RH variations in buildings used to house cultural items.

Accordingly, the key signatures associated with each environmental stimulus may be defined, as follows:

- Heat Loading Test: Assuming no change in moisture conditions in the air (that is, H_{abs}), when the T increases there is a corresponding decrease in RH. On the other hand, if there is moisture created or lost in the space it is possible that the RH will either increase or decrease in accordance with the H_{abs} change due to the change in moisture in the room. Therefore, it doesn't necessarily follow that if the RH changes

in a room that there is a change in T present as it may be due to either a change in H_{abs} or a change in T, or a combination of both.

- Moisture Loading Test: The introduction of a moisture load into a room under constant T conditions results in an increase in both humidity parameters, which will exhibit similar trends. If T increases during the moisture-loading period, however, the expected relationship between T and RH will not necessarily be observed, as it is possible that the extra moisture in the air will compensate for the increase in T and both RH and T will be observed to increase simultaneously.

- Open Window Test: The signature associated with an open window or external door (representing a high infiltration/exfiltration rate) is a rapid change in T and H_{abs} as internal conditions approach those observed externally occurring throughout the room when the window is opened. The RH behaviour is influenced by both the T and H_{abs} variations depending on which is the more dominating factor. In this experiment, for example, the initial RH change (decreasing RH) due to the open window was driven by the H_{abs} variation before the decreasing T caused the RH to increase thereafter. When the window (or door) is closed once again, both T and humidity conditions stabilise before changing in accordance with loading conditions in the room.

- Occupancy Test: From this experiment it may be concluded that the environmental signature associated with the presence of occupants in a room is large perturbations in the humidity parameters about an existing general trend whereby the fluctuations in the general trend are exacerbated by the additional moisture load induced in the space by the metabolic processes of the people that were not previously present. The effect of people on the T conditions in the space is less pronounced. When occupants are "wet", the increase in H_{abs} is more pronounced owing to the additional moisture load on the clothing and belongings of the occupants.

Having defined the signatures associated with each stimulus, it is now necessary to validate them in a large historic building.

5. The Museum Building

5.1. A Brief Description of the Museum Building

Overlooking New Square to the north and College Park to the south (Fig. 5-1), the Museum Building in Trinity College Dublin was designed by Thomas Deane and Benjamin Woodward, who gained inspiration for the design from the Byzantine architecture of Venice (GSoNSTCD, 2009). Constructed between 1853 and 1857, the exterior walls are composed primarily of Wicklow granite and Portland stone and are highly ornate, with intricate carvings of animals and flowers surrounding each opening in the external façade. The Cork-born brothers John and James O'Shea carried out all carvings in the building. Fig. 5-2 presents a view of the Museum Building from the south east corner of the building. Floor layouts and plans of the interior of the building are displayed in Appendix A.

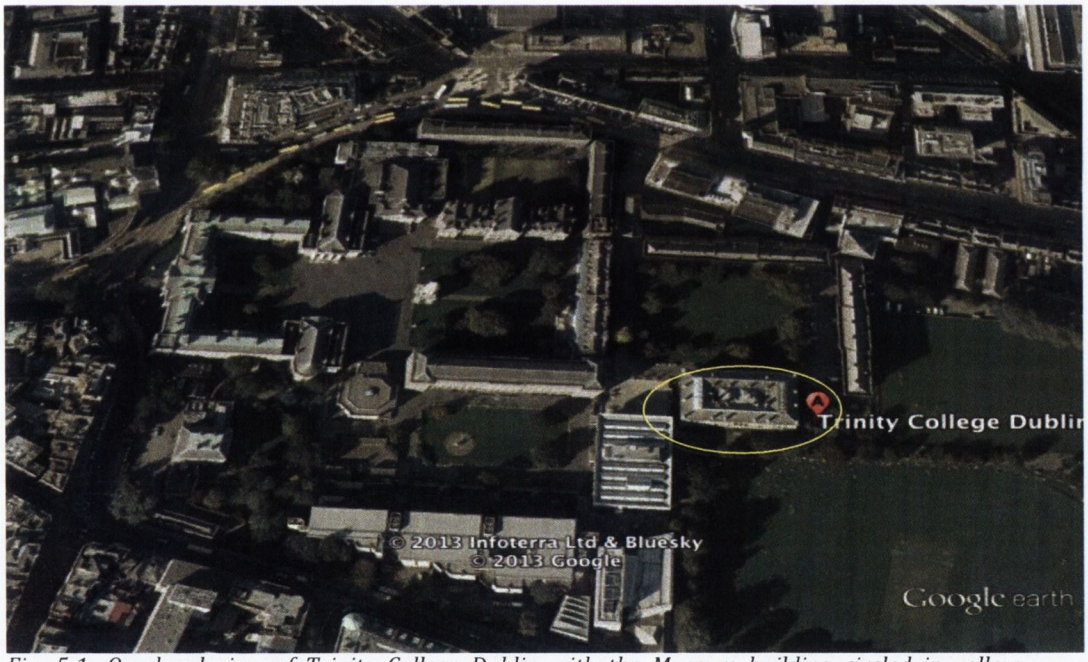


Fig. 5-1: Overhead view of Trinity College Dublin with the Museum building circled in yellow (Google_Earth, 2008)

Having completed the small-scale tests, it was necessary to investigate whether the key signatures identified during the experiments could be observed at a larger scale. Accordingly, two monitoring phases were carried out in the Museum Building in TCD, the first between February and May and the second over the Christmas period . The locations for investigation in this building focused on lecture theatres and a variety of offices within the building.



Fig. 5-2: View of the Museum Building from the south-east (ISServices).

The data collected from the lecture theatres in the building will be discussed in three distinct phases relating to three different conditions, namely unoccupied and unheated, unoccupied and heated and heated and occupied. By grouping the data in this manner, the baseline environmental conditions, the effect of mechanical heating and the effect of people on the building's internal environment will be assessed. For completeness, data recorded in the four different offices as well as the Civil Engineering Library will also be discussed, however the primary focus of this discussion will centre on the lecture theatres as occupancy conditions are somewhat comparable to those in the Old Library, which is discussed in detail in Chapter 6.

The number of sensors in each room as well as their approximate location within the room are provided in Appendix A. As aforementioned, loggers were placed at a height of 1.2m above ground level during the data collection periods.

5.2. Room Types and Occupancy Patterns

The Museum Building is one of the most multifunctional buildings on the Trinity College campus. The primary function of the building is to house the School of Engineering, Civil Engineering, Geography and Geology departments' administrative centre. Moreover, a large

number of lecture theatres as well as libraries and laboratories are contained within the building, which provides facilities for teaching.

For the purpose of monitoring the environmental conditions in the Museum building, a number of rooms with different purposes was selected to investigate the effect of varying numbers of occupants, orientation and geometry of the rooms and different mechanical heat input on the environmental conditions. During the first phase of thermo-hygrometric data collection, four offices, four lecture theatres, a library, the atrium area and a laboratory were chosen and the T and RH in these rooms were monitored over a period of approximately three months. A second phase of monitoring focused on the environmental conditions in lecture theatres and so additional sensors were placed into the theatres M4, M17, Geography Lecture Theatre (GLT) and the Drawing Office (DO). The location of each of these rooms, which are spread throughout the building, facilitated the comparison of different external and geometrical effects on the T and RH conditions inside the building. The location and occupancy patterns of the rooms that were monitored in the Museum Building are summarised in Table 5-1 and the reader is referred to Appendix A for the location of each room within the building.

M4 is located in the basement and accordingly there are no windows or general access to the external ambient conditions in this area although an emergency door provides access to the external environment. The GLT is located on the north side of the building and so is not subjected to solar effects. Conversely M17 is located to the south of the building and has tall south facing windows which facilitate large solar gains in the space Finally, the DO is situated on the top floor of the building and has a number of skylights in its ceiling. Access to the roof may also be gained from the DO, which may leave the space susceptible to moisture and heat ingress and egress.

Of the offices chosen for monitoring, two are north facing and two face south. Office 01 is north facing and is located on the first floor of the building. It is used as a work and study space for a number of postgraduate students. Maximum occupancy levels in this room are 8 people and periods of occupancy are sporadic and varied. Office 02 refers to a single occupancy room located on the south side of the first floor mezzanine. The occupant of this room generally observes business hours, and, although typically only occupied by one person, this number can climb to two or three throughout the day. Office 03 is also south facing and is single occupant. This particular space houses the administrative office for the Department of Geology and, during office hours, the door is generally left open. Furthermore, occupancy levels, although generally single occupant, vary throughout the day. Similarly, Office 04 houses the Department of Civil Engineering administrative office, and, as

with Office 03, the door generally remains open during working hours. This office, however, is north facing and typical occupancy of the area is two, although this number can fluctuate between one and several people on a daily basis.

The Civil Engineering Library, which is located at a mezzanine level directly above the Civil Engineering administration office and an adjacent office, is studied during this phase of monitoring. Occupancy of the room is low and short relative to the offices and lecture theatres, although a number of meetings may take place in the room on a weekly basis. It is north facing and has the same envelope properties as the Civil Engineering office beneath. Furthermore, the room is not heated directly by mechanical means and heat is supplied by infiltration from below.

Given that it is an administrative and teaching centre, occupancy periods tend to observe regular office hours of 09:00-18:00 in the case of the lecture theatres and 09:00-17:00 for the offices from Monday to Friday. Due to additional courses that are run in the building, classes also occur in many of the theatres until 22:00 on Friday evenings and from 09:30 until 12:30 on Saturday mornings. Two additional rooms in the building that may be used outside the specified hours are the DO and the postgraduate office. Students in the Engineering department occasionally use the DO as a meeting room outside of teaching hours while the postgraduate office tends to be occupied later into the evening.

The physical properties (such as the area of glazing and thermal mass) of each room monitored during the data collection regime in the Museum are displayed in Table 5-2. It should be noted that M4 benefits from a large volume of additional thermal mass resulting from the ground adjacent to its external wall. This factor is not included in the measurements in Table 5-2. All measurements displayed in Table 5-2 have been extracted directly from floor plans and elevations of the Museum Building that were supplied by Mr. the Buildings' Office of TCD. It is worth noting that, in the case of the measurements supplied for the Civil Engineering Library, the area of thermal mass relates to the stone walls only and does not include the contribution of the many books to the mass of the room. It is important to note that during both monitoring phases conducted in the building no mechanical ventilation was extant and the only plant was the central convection heating system provided in each room from radiators. Subsequent works to the building were carried out and a mechanical ventilation system was installed in M17. Furthermore, during the monitoring periods, a permeable timber floor and varnished timber benches were present in the GLT. This timber furniture and floor in the GLT was replaced with plastic furniture and impermeable floor surfaces after the readings contained herein were recorded.

Table 5-1: Description of the offices and lecture theatres monitored in the Museum Building.

Room Reference	Orientation and Location within the Building	Room Use and Occupancy Pattern
Offices		
Office 01	North facing room located in the east part of the building on the 1st floor.	Postgraduate research office with variable occupancy levels ranging from 0-8. No specified hours of occupancy.
Office 02	South facing room in the west part of the building on the 1st floor mezzanine.	Generally single occupancy although occasionally increasing to 2/3. Generally occupied on weekdays from 9-5.
Office 03	South facing office located in the east end of the building on the 1st floor.	Single occupancy with frequent additional temporary visitors. Usually occupied from 9-5 weekdays.
Office 04	North facing room located in the west end of the building on the 1st floor.	Generally 2 occupants with frequent additional temporary visitors. Occupied from 9-5 weekdays.
Civ Eng Library	North facing and located on the 1st floor mezzanine in the east end of the building.	Varying occupancy times and numbers but generally opened weekdays from 15:00-17:30. Also used for department meetings.
Lecture Theatres		
DO	Located in the east end of the building on the 2nd (top) floor of the building.	Large lecture theatre with potential for large occupancy levels. Sporadic occupancy levels that differ day to day.
M17	South facing room in the east end of the building on the 1st floor.	Large lecture theatre capable of holding up to 100 occupants. Generally most used of the lecture theatres and occupied 9-5 but holds night classes Fridays (19:00-22:00) and Saturdays (9:30-12:30).
M4	Located in the basement in the south east of the building.	Lecture theatre used at varying time periods throughout the week.
GLT	North facing room in the east end of the building on the 1st floor.	As M4.

Table 5-2: Physical properties of the monitored rooms.

Room	Floor Area (m^2)	Volume (m^3)	Area of Thermal Mass (m^2)	Area of Mass / Volume (m^{-1})	Area of Glazing (m^2)	Area of Glazing/ Volume (m^{-1})
M17	106.5	532.5	214.4	0.40	22.12	0.04
GLT	51.0	301.2	121.4	0.40	15.32	0.05
M4	105.2	526.0	205.0	0.39	0	0
DO	261.4	1307.0	277.5	0.21	75.6 (in roof)	0.27
Office 01	33.2	166.0	87.2	0.53	11.06	0.07
Office 02	13.9	38.9	20.2	0.52	2.73	0.07
Office 03	16.0	80.0	55.5	0.72	5.53	0.07
Office 04	26.2	62.9	23.8	0.38	2.81	0.04
Civ Eng Library	46.0	128.8	41.6	0.32	2.73	0.02

5.3. The Internal Environmental Condition in Lecture Theatres

5.3.1. Unoccupied and Unheated

5.3.1.1. Temperature Trends

Temperature data collected in the four lecture theatres in the Museum Building during the Christmas vacation is presented in Fig. 5-3. During this monitoring period, the college campus is closed and mechanical heat sources to the college buildings are deactivated. Based on Fig. 5-3, the four lecture theatres may be subdivided into high fluctuating T (M17 and the DO) and low fluctuating T (the GLT and M4). Examining Fig. 5-3 generally allows an explanation as to the trends observed in the lecture theatres. It is expected that some stratification would occur in the building, meaning that rooms on higher floors would observe higher T values. This, however, is not the case as the GLT (1st Floor and north-facing) consistently records the highest T followed by M17 (also 1st Floor). M17's lower T, when compared to the GLT, suggests that heat losses from M17 are noticeably higher than those in the GLT. The DO, despite being located on the top floor of the building, observes the lowest internal T amongst lecture theatres. This is not a surprising result as it indicates that significant thermal losses are occurring in this lecture theatre primarily through the glazing in the roof. M4, which is located in the basement, records a T range that is lower than those

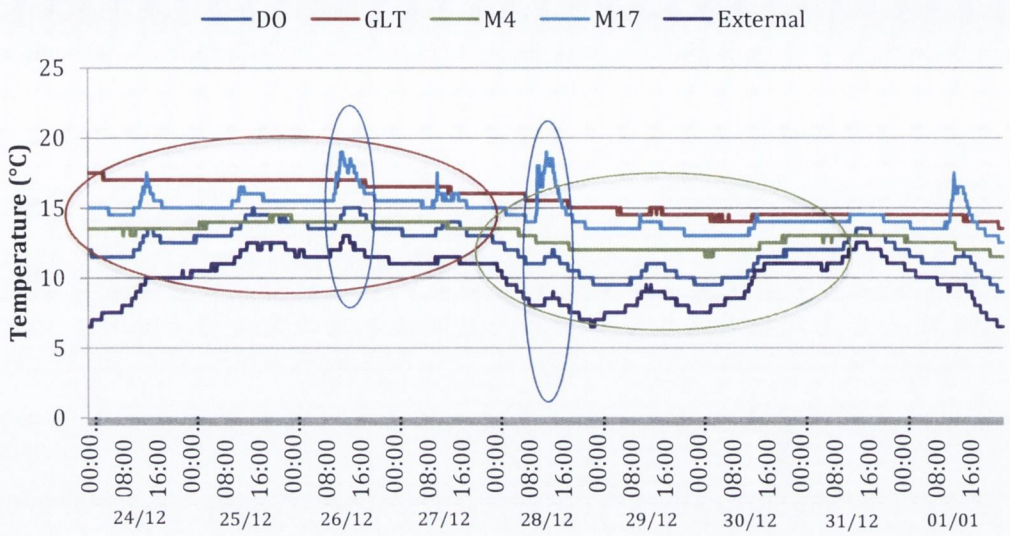


Fig. 5-3: Temperature data recorded in four lecture theatres in the Museum building during the Christmas vacation.

in rooms located on the 1st floor as expected, indicating that all rooms are behaving as might be expected in terms of the general thermal environment.

Given their location in the building, T variations in M17 (south facing) and the DO (top floor and containing several skylights) are heavily influenced by solar effects. As can be observed in Fig. 5-3, particularly on 26/12 and 28/12 (circled in blue), solar gains in M17 result in large T variations over the course of the day, despite the relatively low external T and the absence of additional heat sources in the room. As the south-facing wall in the room is primarily glazed, the potential for heat gains due to solar effects is highest in this room when compared to the rest of the building. Diurnal T variations of 3.5°C (15.5°C to 19°C) and 5°C (14°C to 19°C), in the absence of mechanical heating, are observed in M17 on 26/12 and 28/12 respectively, which, in the presence of additional heat sources during occupation may lead to thermal discomfort due to over-heating. Solar gains are also observed in the DO although to a much smaller extent owing to the low angle of the winter sun, which reduces the effect of solar gains penetrating the room through the skylights. Nevertheless, the effect of solar gains on the space is discernible, particularly on 26/12, where T increases by 1.5°C (13.5°C to 15°C).

Over the course of the monitoring period, the T trend observed in the DO is comparable to that externally, indicating that large thermal losses are occurring from this particular lecture theatre. These losses are most likely to be recorded through the unsealed skylights, which comprise a large percentage of the ceiling space as well as through the unsealed access points to the roof that are located in the DO.

In contrast to these lecture theatres, M4 (located in the basement of the building) and the GLT (north-facing) are not located so as to benefit from solar gains and, accordingly, observe the low fluctuating T trend displayed in Fig. 5-3. Thermal losses from these lecture theatres are relatively small, resulting in the slow rate of T decrease observed during this monitoring period.

Despite being located in the same building, the differing orientation and boundary conditions (i.e. relative thermal mass and glazed area) in the four lecture theatres result in individual T variations in each room over the duration of the Christmas vacation. Considering this period in two distinct time intervals, namely the period with a small thermal gradient between the inside and outside of the building (24/12-27/12, red region) and the time with a large thermal gradient (28/12-30/12, green region) provide an insight into the background thermal processes at work in the building when no other heat loads are present.

Over the first time interval (red region) in M17, no net change in T is observed, although solar effects result in diurnal variations in T. Accordingly, the heat gains, coupled with the heat storage capacity of the stone walls result in the T being maintained at an average of 15.5°C during this period. Conversely, the GLT, which has the same relative area of thermal mass as in M17 (Table 5-2), does not maintain the same background T over this time interval and a drop of 0.5°C is observed in the room. The reason for this decrease is due to the position of the GLT on the north side of the building. The lack of solar gains to this room mean that no thermal loads are present in the room at this time and, accordingly, a reduction in T is observed as heat is lost from the room and not replaced, albeit at a slow rate.

Thermal trends in M4 appear to be similar to those in the GLT, although, as in M17, no net change in T is observed during this time period. As it is located in the basement, the large volume of soil that is in contact with the external walls of the theatre means that the room benefits from a large amount of thermal mass and this results in the stable conditions observed in the room during this time interval.

Conversely, the DO records a net increase in T during this stage of the Christmas vacation, despite the largest losses being observed in this room. As the thermal gradient between the room and the external environment is relatively small at this time, heat losses from the DO are small. This, coupled with the heat gains due to solar effects as well as infiltration from the lower floors result in the increase in T observed during this period.

During the second time interval of the Christmas vacation, the physical properties of the rooms (outlined in Table 5-2) are more relevant in determining the thermal behaviour of the lecture theatres. The larger volume of thermal mass in M4 results in the relatively small T observed in the room. M17 and the GLT have the same relative area of thermal mass as well as comparable relative glazed areas and, as a result, rates of T decrease in these rooms are identical. The large glazed area and relatively small area of thermal mass in the DO results in large heat losses from the space and the corresponding large drop in T compared to the other lecture theatres.

Accordingly it can be concluded that the relative area of thermal mass and glazing are significant factors in determining the background T values during periods when the thermal gradient between the inside and outside is large. When this gradient is small however, solar gains and heat movement within the building determine the thermal behaviour of the rooms.

5.3.1.2. Humidity Trends

In addition to T monitoring, data for RH was also collected during this recording period and is displayed in Fig. 5-4. From this chart, it is observed that three of the lecture theatres, DO, M17 and, surprisingly, M4, exhibit highly variable RH conditions, indicating high moisture movement rates from these particular rooms. Conversely, the GLT has little variation in its RH, indicating a very stable environment with very low moisture leakage rate between the theatre and external conditions.

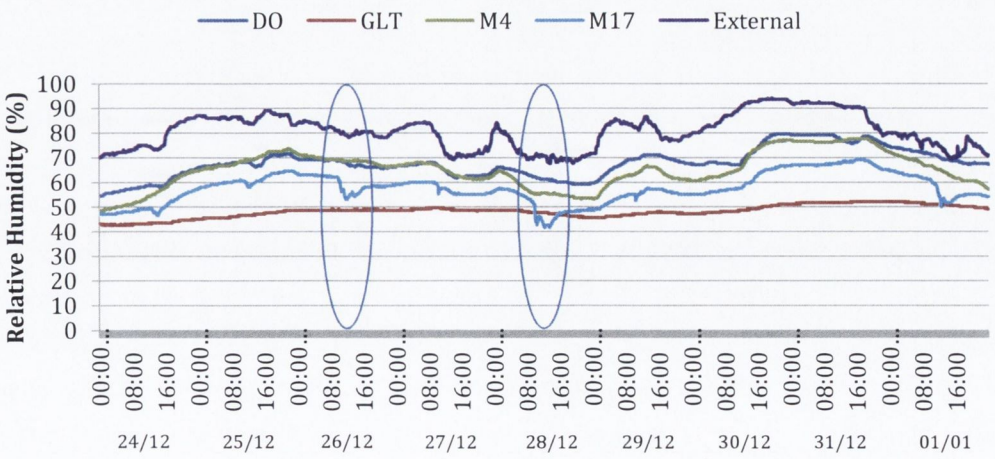


Fig. 5-4: Relative Humidity data collected in four lecture theatres in the Museum Building during the Christmas vacation.

There is also evidence to suggest that the large solar gains in M17 are influencing the RH conditions in the space. On 26/12 and 28/12 (circled in blue), for example, relatively sudden and large decreases in RH are observed that are not observed in other lecture theatres in the building. These decreases correspond to times of T increases due to solar gains as discussed previously, although it is likely that some changes in absolute humidity also occur at this time as discussed later. On 26/12, a drop of 9% RH (62% to 53%) is observed over an approximately 2 hour period while a decrease of 11% RH (53.5% to 42.5%) is observed over a 2.5 hour period on 28/12. Surprisingly, the effect of solar gains on RH is not particularly noticeable in the DO, once more suggesting a large leakage rate between the room and the external environment.

Unlike T, internal RH does not become asymptotic to external RH. This is a result of the T differences between the internal and external thermal environments. Internal T, in this case, is observed to be lower than that outside, resulting in the external RH having a higher value. Although a useful indicator of moisture trends, its strong dependency on T variations means the RH readings are not particularly useful for observing actual moisture gradients. Accordingly, H_{abs} data is calculated using T and RH values and will be examined in order to determine the actual moisture movement in the lecture theatres.

H_{abs} data calculated for the Christmas vacation is presented in Fig. 5-5. Given the T and RH profiles recorded in the GLT, its H_{abs} trend is relatively stable when compared to the environment in the other lecture theatres. Moisture gains in the GLT are modest and occur only when the gradient between the room and the external environment is high, as observed on 25/12 and 30/12 in Fig. 5-5. It would appear that this room is well sealed against air and moisture movements to the outside.

During 24/12 and 25/12 (circled in blue), the moisture gradient between the GLT and the external environment increases from $0g/m^3$ to $1.32g/m^3$. At this point, H_{abs} in the lecture theatre begins to increase as a larger quantity of moisture diffuses into the room. External H_{abs} continues to rise and with it the moisture conditions in GLT, albeit at a very slow rate. H_{abs} in the lecture theatre stabilises at approximately 21:00 on 25/12. This constitutes an increase in H_{abs} of $0.73g/m^3$ ($6.28g/m^3$ to $7.01g/m^3$) over a 33-hour period (approximately 12:00 on 24/12 to 21:00 on 25/12), a rate of increase of $0.02g/m^3$/hour. This very low rate of moisture increase in the room illustrates the low moisture movement rate. It is also possible that furniture and surfaces in the room may exhibit hygroscopic properties that can regulate H_{abs} in the room to some degree. This is especially likely in this room as, at the time of monitoring, a relatively large area of the floor was comprised of unvarnished and

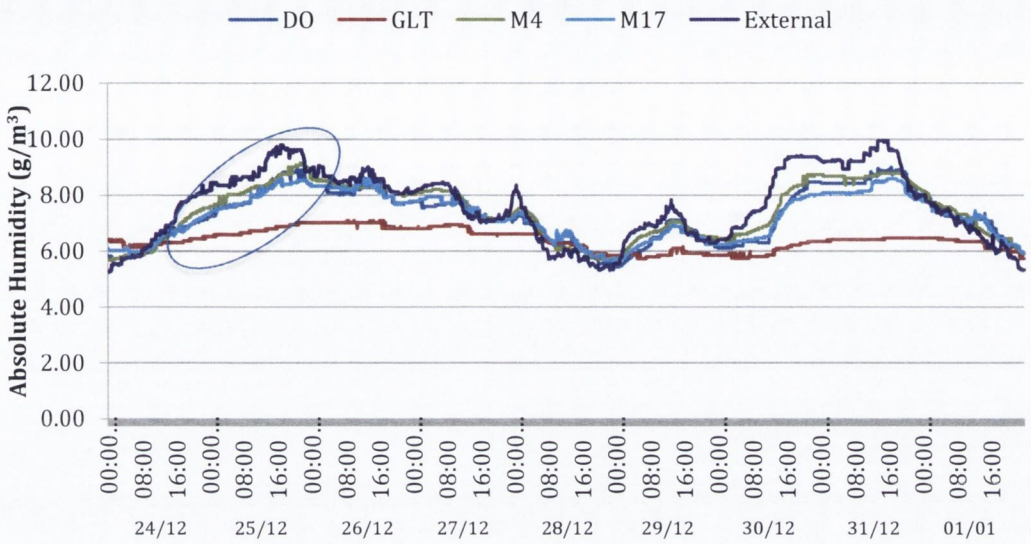


Fig. 5-5: Absolute Humidity data calculated for four lecture theatres in the Museum Building during the Christmas vacation.

unsealed timber, although this has recently been covered by an impermeable plastic covering.

It is also worth noting that, although H_{abs} in the GLT stabilises at 21:00 on 25/12, the moisture gradient remains high (approximately 2.61g/m^3). It would be expected at this time that internal H_{abs} would continue to rise, however this is not the case. This stabilisation in the lecture theatre may be due to the environment in the room reaching equilibrium and the rate of moisture gain through infiltration is balanced by the rate of moisture loss from the room into adjacent internal spaces as well as moisture adsorption by hygroscopic materials and surface in the room. Similar behaviour is observed on 30/12 in the GLT.

As suggested by the RH trends, moisture variations are high in DO, M17 and M4 and appear to closely follow the external trends, confirming high moisture leakage rates within these particular areas of the building as moisture diffuses according to the moisture gradient.

Taking M17 as an example, the close correlation between internal and external moisture conditions becomes obvious as observed in Fig. 5-6. At approximately 11:00 on 30/12 (circled in blue on the chart), external H_{abs} begins to increase from 7.56g/m^3 before stabilising at 8.92g/m^3 at approximately 13:30, equating to 1.36g/m^3 at a rate of 0.54g/m^3/hour. This increases the moisture gradient between M17 and the external environment and results in moisture infiltration into the lecture theatre. At approximately 12:00, one hour after external H_{abs} increases, the effect of the larger moisture gradient

begins to influence the internal environment as the H_{abs} in M17 is observed to rise. Over the course of approximately 5 hours, H_{abs} in M17 increases in magnitude by 1.25g/m^3 (6.52g/m^3 to 7.77g/m^3), a rate of increase of 0.25g/m^3/hour. Shortly after this, external conditions stabilise at approximately 9.36g/m^3 and equilibrium is reached internally at a value of 7.96g/m^3. The difference between the two values may be attributed to the moisture buffering properties of materials, surfaces and furniture contained within the room that adsorb excess moisture in the air in a similar way to the effect of thermal mass as well as losses to elsewhere in the building through, for example, doors and other openings in the building envelope.

Conditions in both M17 and externally remain stable until 31/12 (circled in red in Fig. 5-6) when, once again, an increase in external H_{abs} (9.21g/m^3 to 9.94g/m^3) results in an increase in the internal moisture conditions as values increase from 8.08g/m^3 to 8.58g/m^3 over the course of the afternoon. At approximately 17:30 on the same day, external conditions change as the H_{abs} trend, begins to decrease suddenly. Small falls in internal H_{abs} are also noted at this time, as inside and outside moisture conditions are almost identical. At approximately 09:30 on 01/01 (circled in green), external H_{abs} decreases and is smaller in magnitude than that internally, causing moisture to egress from M17 to the external environment as the moisture gradient is reversed.

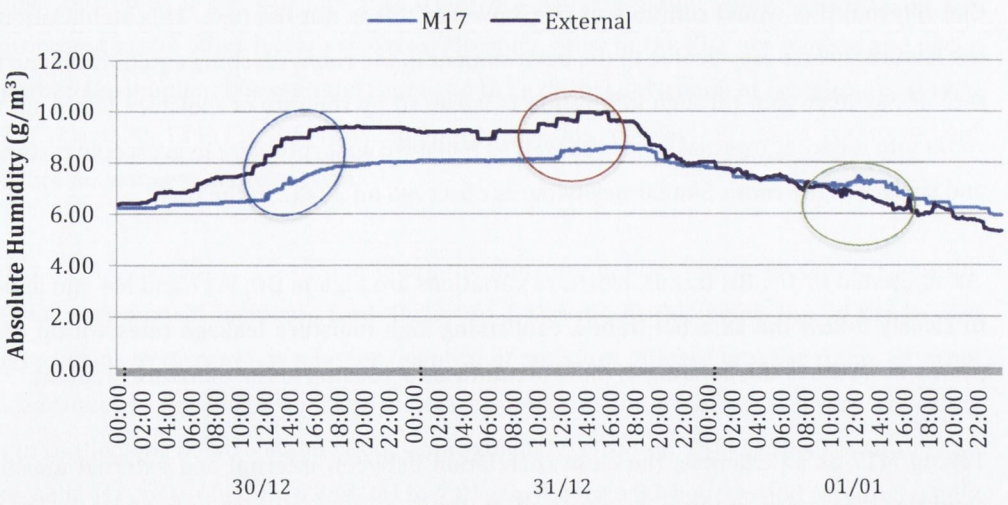


Fig. 5-6: Absolute Humidity data in M17 and externally calculated for the time period 30/12 to 01/01.

Similar behaviour is observed in the DO and M4 during this time period. Although high leakage rates are expected in the DO, given the stability exhibited by the thermal conditions recorded in M4 during this data collection period, the highly variable moisture environment

observed in this lecture theatre is initially surprising. Upon further examination of the room it was found that the highly varying H_{abs} trend is due to a large unsealed emergency door through which a large volume of moisture can pass into the room. As a result, large variations in H_{abs} are observed in M4, as external moisture is free to diffuse into the theatre leading to a relationship that is comparable to that observed during the open window signature test where the internal conditions approached those externally. Fig. 5-5 illustrates this as the H_{abs} in M4 follows the external environmental H_{abs} closely. This behaviour is not exhibited in the thermal conditions in the room as discussed previously, however, when considering the small scale tests discussed in Chapter 4, and in particular the open window test described in Section 4.5, moisture parameters are more reactive to gradients and are so observed to be more reactive than the thermal conditions.

The study of the lectures during this monitoring period (i.e. unoccupied and unheated) have provided an additional signature that had not been studied during the small-scale experiments, namely the effect of solar gains on the building. This signature was particularly noticeable in M17 on 28/12 and is defined by a sudden, relatively large increase in T in a room, the timing of which corresponds to the hours of sunshine intensity. When the intensity of the solar gains decreases, the T is observed to decrease rapidly as the heat associated with solar infiltration is removed. In terms of the humidity parameters, the large T increase, unsurprisingly, results in a decrease in the RH values in the room and, where hygroscopic materials are present in the room, the increase in T can result in additional evaporation from such surfaces leading to an increase in H_{abs} in the room, however, this increase is not sufficient to result in an increase in RH in this case. The fact that this is the signature due to solar effects is confirmed by the observation that the signature is not observed in north facing rooms that are not subject to gains from solar effects and, moreover, the phenomenon is only observed during daylight hours on sunny days.

5.3.2. Unoccupied and Heated

5.3.2.1. Temperature Trends

On 02/01, the college campus reopened following the Christmas vacation resulting in mechanical heating being supplied to the Museum building once more. Lectures did not resume for a number of weeks after this time allowing the influence of mechanical heating alone on the environmental conditions in the lecture rooms to be assessed.

Fig. 5-7 presents T data collected in the four theatres during the week immediately following the Christmas vacation. Once more, the four theatres can be considered in two distinct groups, those that benefit from solar gains (DO and M17) and those that do not (M4 and GLT). By comparing Fig. 5-7 to Fig. 5-3, the effect of mechanical heating becomes obvious as diurnal heating and cooling trends are observed in each theatre, as would be expected.

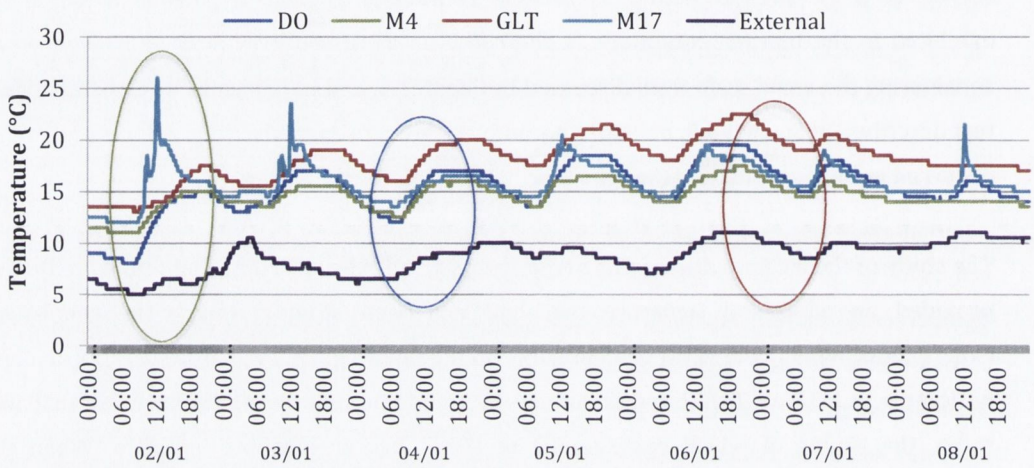


Fig. 5-7: Temperature data recorded in the four lecture theatres in the week immediately following the Christmas vacation where heating was applied without occupancy.

The DO is the largest of the theatres considered at more than double the floor area when compared to M17 (Table 5-3). In terms of heat outputs from the radiators in each lecture theatre, DO has significantly more powerful heat sources when compared to the other rooms. In terms of heat output per unit area in each room, DO's mechanical heat sources emit approximately 27W/m^2 more heat than M17 and over double that supplied to M4, while the radiators in M17 provides approximately 1.5 times more heat energy to the theatre than those in M4.

In order to assess the effect of mechanical heating alone on the thermal environment in the four lecture theatres, T data from 04/01 (circled in blue in Fig. 5-7) will be examined as no heat increases due to solar gains existed on this date, according to the meteorological office weather data and also by comparing the T trend observed in M17 on 02/01 (circled in green in Fig. 5-7) with that on 04/01. Accordingly any T increases during this time will be due to the effect of the radiators as well as the typical diurnal variations due to external daytime increases in T.

Table 5-3: Lecture Theatre Sizes as well as the estimated total heat output in each room due to the radiators.

Lecture Theatre	Floor Area (m^2)	Total Output (W)	Output per unit area (W/m^2)
DO	261.4	18120	75.1
M17	106.5	5112	48.0
GLT	61.0	2136	35.0
M4	105.2	3500	33.3

Table 5-4 displays the net T change, as well as the rate of change of T, using data obtained from Fig. 5-7. This provides an interesting insight into the thermal interactions occurring in the lecture theatres. The largest T change of 5.5°C (12°C to 17°C) is observed in the DO, despite the large losses from the room as discussed previously. Given the large output of the radiators in this theatre ($75.1W/m^2$), large changes in T occur relatively quickly in this space before the thermal losses from the room offset the thermal gains from the heat sources and equilibrium is reached. This occurs at approximately 13:40, after which no rise in T is observed as a stable value of 17°C is noted.

Table 5-4: Rate of T increase observed in the lecture theatres on 04/01 in the absense of solar effects.

Lecture Theatre	T change (°C)	Time Taken (hours)	Rate of T change (°C/hour)
M4	3.5	5.3	0.67
M17	2.5	7.6	0.33
GLT	4.0	8.5	0.47
DO	5.0	5.5	0.91

Despite having a lower heat output per square metre of $33.3W/m^2$, M4 observes the second highest rate of T change amongst the lecture theatres, as its T increases by 3.5°C (12.5°C to 16°C) at a rate of 0.67°C/hour. This relatively high rate of T change is due to the smaller thermal losses occurring from M4 due to its position in the basement of the building and its associated additional thermal mass due to the external ground. Accordingly, a smaller heat input to the room results in larger changes in T and takes place at a relatively rapid rate. A similar trend is observed in the GLT, which has a heat output per square metre of $35.0W/m^2$, and a large increase in T of 4.0°C is observed as losses from the room are low.

In comparison, M17, which obtains 1.5 times more mechanical heat than M4, observes the lowest rate of T gain, as a change in T of just 2.5°C is recorded over a period of 7.6 hours. Like the DO, thermal losses in M17 are high as heat passes easily through the single glazed external windows as well as into an unheated mezzanine type area at the rear of the room that is directly beneath the roof area, resulting in the low rate of T change observed in this particular lecture theatre.

In addition to studying the rate of T gain due to heating, it is also interesting to examine the effect of deactivating the heat source on the thermal environment. The T change and associated rate of T decrease due to the radiators being turned off on 06/01 (circled in red in Fig. 5-7) are presented in Table 5-5. In general, the rate of T reduction is lower than the corresponding rate of T increase due to the lag effect induced by the thermal mass of the room. The only lecture theatre to which this does not apply is M17, where the rate of increase (0.33°C /hour) is practically identical to its rate of decrease (0.35°C /hour). This implies that, in the absence of solar gains, M17 heats and discharges its heat at a steady rate as losses occur at a very similar rate to the rate of heat gain provided by the radiators. Despite the large thermal mass in the room, it appears that heat gains due to the effect of the radiators are equal to the heat losses observed when the mechanical heat is deactivated. As expected, the highest rate of T decrease occurs in the DO, owing to the high thermal losses occurring in this theatre through the poorly insulated roof, unsealed skylights and access points to the roof.

Table 5-5: Rate of T drop observed in the lecture theatres on 06/01 and 07/01.

Lecture Theatre	T change (°C)	Time Taken (hours)	Rate of T change (°C/hour)
DO	3.5	6.67	0.53
M17	3.0	8.50	0.35
GLT	2.5	8.67	0.29
M4	3.0	9.92	0.30

For M4 and GLT, despite having different rates of T gain (0.67°C/hour in M4 compared to 0.47°C/hour in GLT), the thermal losses from these lecture theatres appear to be very similar. The low losses, in the case of M4, are due to its location in the basement where it benefits from a large volume of supplementary thermal mass. The GLT, despite being glazed on one wall, may benefit from the thermal mass of the large exposed stone walls located in the lecture theatre as well as its smaller glazed area that results in relatively smaller thermal losses in comparison to M17. Considering also, the shape of the GLT relative to the M17 (see

Appendix A), it can be seen that the GLT has a relatively small external wall in comparison to M17, which has a relatively large external wall. These internal walls are typically warm and, as a result, T values in the GLT are typically the highest amongst theatres in the building. Furthermore, considering the RH conditions outlined in Section 5.3.2, the GLT appears to be a well-sealed and draught-proofed space resulting in lower thermal losses.

Referring back to the T trend for M17 in Fig. 5-7, particularly on 02/01 (circled in green), the effect of solar gains, in tandem with mechanical heating, on the thermal environment becomes obvious. As stated previously, solar gains, in conjunction with alternative heat sources could potentially lead to large variations in T and thus lead to levels of thermal discomfort. Between approximately 11:30 and 12:30 on 02/01, T in M17 increases very rapidly from 16.5°C to 26°C, a rise of 9.5°C. Despite only maintaining the T for a short period and given that external T values are low (approximately 5.5°C) and that the room is unoccupied, the effect of solar gains on the thermal environment in M17 is significant. Should external T happen to be higher and the sun's intensity sustained at a high level for a longer interval, such as in the summer, overheating in M17 would lead to prolonged periods where thermal conditions would remain outside of comfort conditions. As a result, it is recommended that supplemental mechanical cooling, or alternative means of reducing heat gains due to solar influences, be implemented into M17 as a means of maintaining comfort conditions in the lecture theatre. This measure has since been implemented in the room, subsequent to the monitoring phases discussed in this chapter, as a means of regulating the thermal environment.

5.3.2.2. Humidity Trends

RH variations recorded in the four lecture theatres during the heating only period are presented in Fig. 5-8. As was the case during the Christmas vacation, RH conditions in the DO, M17 and M4 are highly variable and appear to generally follow the external RH trends, albeit at a lower magnitude, as is particularly obvious on 03/01 (circled in blue). Stable RH conditions are observed initially, both internally and externally, before a large increase of 19%RH (73.5% to 92.5%) is observed outside the building. A corresponding increase in internal RH is observed in three of the lecture theatres (DO, M17 and M4). Considering the RH trends observed in the GLT, it appears that there is relatively little moisture movement into or out of this room during the monitoring period, which confirms earlier observations.

The effect of solar gains on RH conditions in M17 may once again be observed in Fig. 5-8. On 02/01, as discussed previously, a sudden 9.5°C increase in T is observed in M17

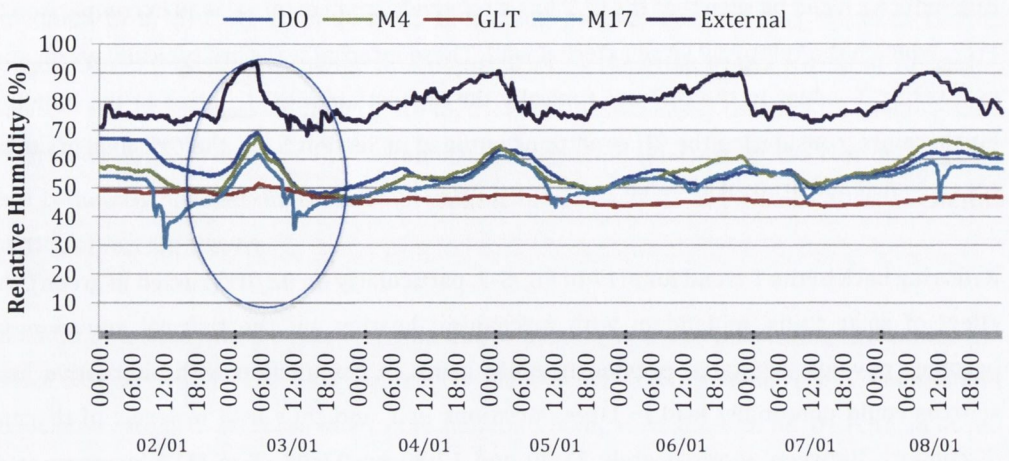


Fig. 5-8: Relative Humidity data recorded in the lecture theatres in the Museum Building in the week immediately after the Christmas vacation.

corresponding to the time of maximum solar intensity. This in turn has an influence on the RH conditions in the room as the value decreases by 14%RH (43.5% to 29.5%) during this T change. As a result, the indoor humidity conditions no longer fall within comfort conditions as specified by ASHRAE (2004) and Humphreys and Nicol (2006), who specified a lower limit of 40% for RH conditions.

In order to determine the actual moisture movement in the lecture theatres during this time, H_{abs} values are calculated and analysed. H_{abs} conditions during the heating only period are displayed in Fig. 5-9. The general trends for H_{abs} in the DO, M17 and M4 are comparable to those recorded during the Christmas period. The high leakage rates in the rooms result in the variations observed in Fig. 5-9 whereby internal H_{abs} appears to follow, and in some cases overlap, the trends observed externally.

This behaviour was indicated in the RH variations observed in Fig. 5-8. Accordingly, it appears that mechanical heating, as well as solar gains, have little effect on H_{abs} conditions in these three lecture theatres as the trends are comparable to those observed when no heating was present in the rooms. There appears to be some increase in H_{abs} corresponding to periods of high solar gains (green region in M17 in Fig. 5-9) where the external conditions remain stable. Given that there are no other moisture loads in the room at this time, this change in H_{abs} must be due to the increased evaporation from hygroscopic surfaces in the space associated with the relatively large increase in T associated with the solar influences.

Despite observing stable RH conditions, the effect of mechanical heating on H_{abs} in the GLT is significantly different. Comparing the trends recorded in the GLT in Fig. 5-9 to that in

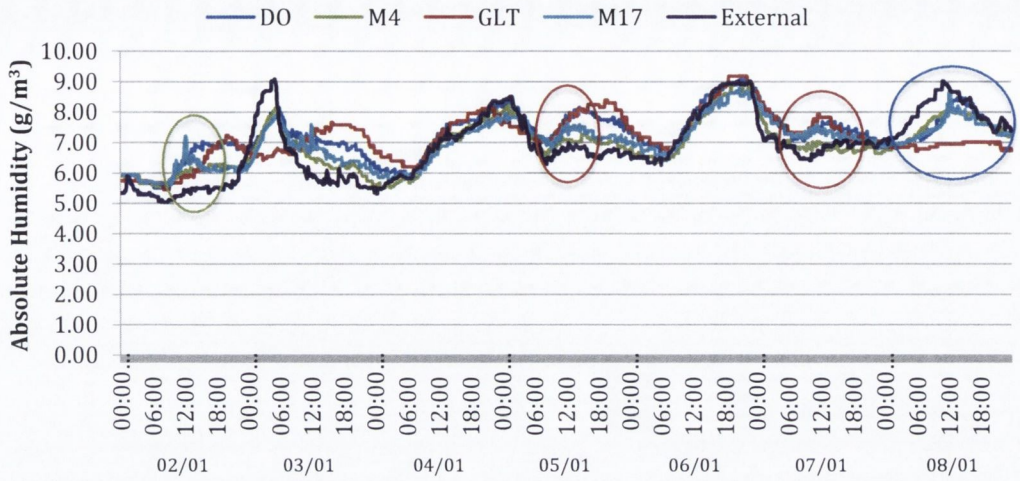


Fig. 5-9: Absolute Humidity data recorded in the lecture theatres in the Museum Building in the week immediately after the Christmas vacation.

Fig. 5-5 illustrates the large variations present during the heating period and, once again, shows how RH trends can be misleading.

Despite appearing to follow the external conditions, the GLT is much less influenced by outside H_{abs} and fluctuations in this room are probably due to evaporation from surfaces, particularly from the unfinished timber floor, as a result of T changes. This is supported by the trend observed in the GLT on 08/01 (circled in blue) at which time (the weekend) no mechanical heat is supplied to the building. As illustrated in Fig. 5-7, a constant T value of 17.5°C is observed in GLT and stable H_{abs} (approximately 6.93g/m^3) is recorded, despite the large difference between external H_{abs} and that in GLT, which at its maximum is 2.08g/m^3 (9.01g/m^3 externally compared to 6.93g/m^3 in GLT). This variation contrasts with those observed in the other lecture theatres that once again behave according to the moisture gradient and H_{abs} increases in magnitude as moisture infiltrates into the rooms when external H_{abs} is high.

H_{abs} data for the GLT and externally from 04/01 to 06/01 is displayed in Fig. 5-10 and can be used to determine the causes of the moisture variations observed in this particular lecture theatre. Considering the trend observed, both internally and externally, on 06/01 (circled in blue on Fig. 5-10), it could would appear that external H_{abs} has a major influence on H_{abs} conditions in the GLT, as internal H_{abs} fluctuations appear to follow those calculated for outside the building. However, when the variations on 04/01 and particularly on 05/01 (circled in green) are examined, it is not correct to conclude that GLT is noticeably influenced by external moisture conditions.

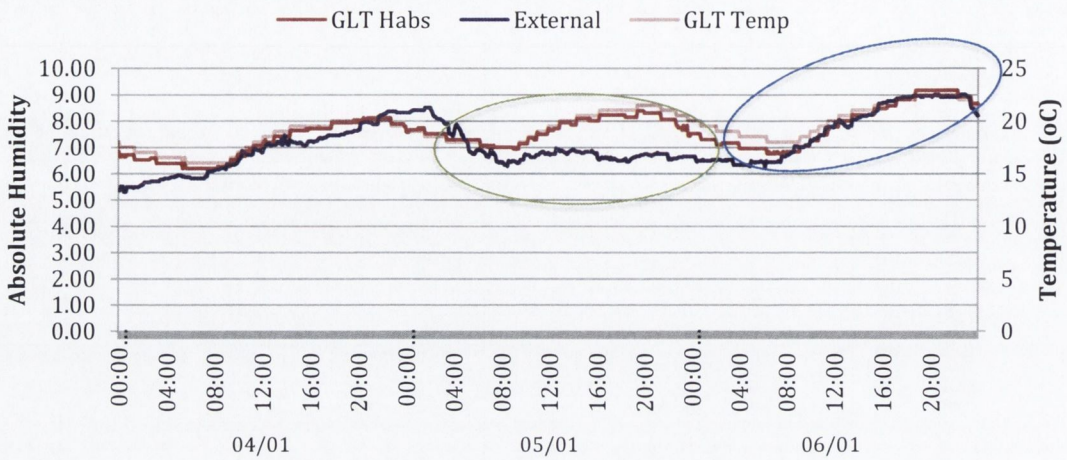


Fig. 5-10: Absolute humidity data calculated for the GLT between 04/01 and 06/01. Temperature in the GLT is also placed on the chart.

On 05/01, external H_{abs} conditions are initially relatively high, recording a value of 8.41g/m^3 at approximately 01:00. Over the course of the night this value decreases rapidly before stabilising at a value of 6.45g/m^3 at approximately 08:00. External H_{abs} fluctuates slightly about this value over the course of the day. Stable H_{abs} conditions of 7.00g/m^3 are observed in the GLT prior to the mechanical heat in the building being switched on at 07:30. Shortly after this, T in the GLT begins to increase. At the same time, H_{abs} in the room also begins to increase, despite external H_{abs} maintaining a lower value of approximately 6.45g/m^3. The increase in moisture conditions in the GLT is mostly due, therefore, to additional moisture being released into the atmosphere through evaporation from hydroscopic materials and particularly timber surfaces as a result of the increase in T in the room, as shown in Fig. 5-10. H_{abs} continues to increase with the increasing T and reaches a maximum value of 8.38g/m^3 at approximately 19:30, corresponding to the time of maximum T. Once the heat source to the room is switched off, T begins to decrease and the excess moisture in the air is re-adsorbed by the hydroscopic materials and surfaces. As a result H_{abs} values in the GLT are observed to decrease despite the steady conditions externally.

It is also worth noting that, over the course of the day, the RH in the GLT does not undergo the fluctuations observed in both T and H_{abs}. This indicates that the effect of T on RH in the room is offset by the increase in H_{abs} resulting in broadly stable RH conditions in the lecture theatre.

From the observations made in the GLT, it may be concluded that the effect of T on H_{abs} is a further factor driving the H_{abs} trends observed in the lecture theatres in the Museum building. Given that large moisture leakage rates occur in the DO, M17 and M4, it is generally

difficult to identify where T changes result in changes in H_{abs}, however, a number of times where this is the case are identified by the red circles on Fig. 5-9, thus illustrating that such trends do exist, even when they are not the principal driving force behind internal H_{abs} trends.

Based on the discussions of the H_{abs} trends it may be concluded that, generally, when the building is unoccupied the internal moisture variations are determined by the external variations, as infiltration of moisture into the building is sufficient to control internal H_{abs}. This is the case in the DO, M17 and M4, however, a moisture trend that appears to be more comparable to the T variations is observed in the GLT. At the time of monitoring, the GLT, which is well sealed from the external environment, had an untreated wooden floor that acted as a large hygroscopic surface from which moisture was absorbed and evaporated depending on the T of the room. Accordingly, when the room was heated, H_{abs} in the space was observed to increase with increasing T. The other three lecture theatres, however, did not have exposed timber or other large areas of hygroscopic materials resulting in the correlation between these rooms and the external environment.

Referring back to the signature defined for heating during the small-scale experiments, it can be seen that, while the presence of a heat load, unsurprisingly, results in an increase in T, the large rate of infiltration in a historic building means that the typical inverse relationship between T and RH is not necessarily observed. When there is a sudden, relatively large increase in T, such as when solar effects are altering the thermal conditions, the RH is observed to decrease, however, in general, the RH trend in a building fluctuates and is predominantly driven by the H_{abs} trends, which in this case are primarily determined by the external environment.

This monitoring period (unoccupied and heated) has also provided an additional signature that had not been observed previously, namely the effect of hygroscopic surfaces on the environmental conditions in a room. Based on the description of the T and H_{abs} variations observed in the GLT during this period (when compared to the unoccupied and unheated period), the signature associated with the presence of hygroscopic materials is a H_{abs} trend that is extremely similar in nature to the corresponding T variations (as shown in Fig. 5-10) as moisture is evaporated into the air from the hygroscopic materials. RH variations increase with increasing T, indicating that additional moisture is present in the system, although the magnitudes of the variations, when compared to T and H_{abs} fluctuations, are small as the increase in T prevents the RH from increasing significantly. Although this signature is similar to that for the moisture loading test, its distinguishing feature is the close correlation between T and H_{abs}.

5.3.3. Occupied and Heated

5.3.3.1. Humidity Trends

Although T variations are generally discussed first, given that this analysis of data is based on the effect of occupancy, considering the conclusions from the small-scale test described in Section 4.6, RH and H_{abs} data will be examined before T in this section. Over the course of this monitoring period, lectures were held in the Museum Building and mechanical heat was also supplied. As mentioned in Section 3.4, attempts were made to obtain accurate occupant numbers for a period during the monitoring period to investigate the relationship between occupant numbers and the internal environment in the theatres. Due to a lack of participation, however, a comprehensive set of occupant data was not collected. Despite this, however, some data was obtained and will be applied to the relevant environmental conditions to ascertain the influence of people on the environment and thus verify the conclusions from the small-scale occupancy tests discussed in Section 4.6 when applied to a large historic building. RH variations obtained in the four lecture theatres between 07/03 and 13/03 are displayed in Fig. 5-11.

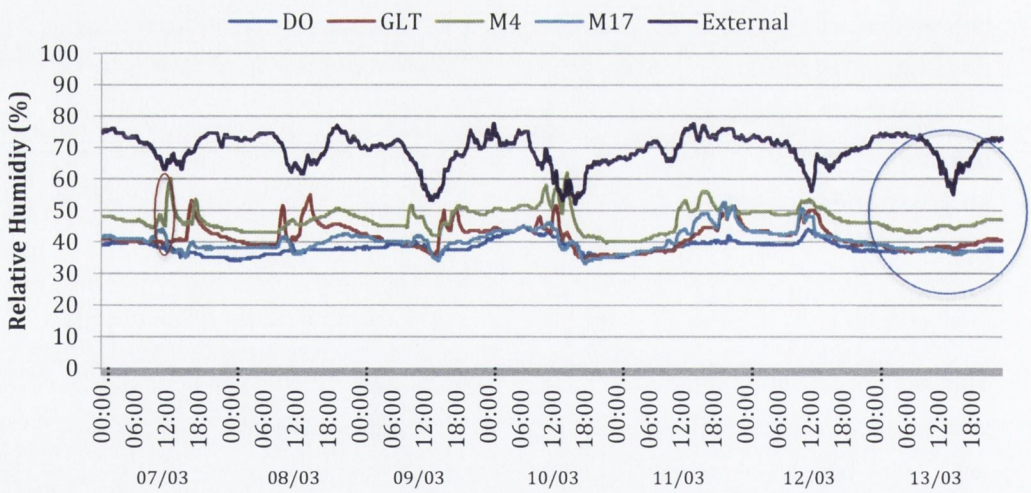


Fig. 5-11: Relative Humidity data recorded in the lecture theatres in the Museum Building when the building was both heated and occupied.

Referring back to the occupancy signature tests discussed in Section 4.6, it is expected that the presence of people in a room will result in relatively large fluctuations in RH and H_{abs} due to the moisture loads associated with people. These fluctuations occur about a general trend and conditions will, typically, revert to the general trend shortly after occupancy is terminated. Although RH is dependent on T fluctuations, since the influence of people on the thermal conditions is relatively small compared to their corresponding effect on the

hygrometric environment, RH can be discussed in isolation to illustrate the influence of people on a room's environment.

Considering the RH trend observed on 13/03, which is a Sunday (when occupancy in the lecture theatres is nil and no mechanical heating is supplied to the building) yields the baseline humidity conditions present in the Museum building at this time. Despite fluctuating external RH, circled in blue on Fig. 5-11, internal RH values across all lecture theatres are relatively stable. M4 records a higher magnitude for RH; however, this is most likely due to a lower T value being observed in the room.

By contrast, RH values throughout the rest of the monitoring period are highly variable, with large increases in RH occurring, generally, over a short period of time before decreasing again at a rapid rate. Given that these jumps in RH do not occur simultaneously in each lecture theatre, and that they are maintained for a period of approximately one hour, it may be concluded that these variations are due to occupancy of lecture theatres, which will be discussed presently. Taking M4 on 07/03 for example (circled in red in Fig. 5-11), an 11.5%RH increase (48.5% to 60%) in RH is observed over the period of approximately 55 minutes, which suggests that a large number of occupants attended a lecture in the room. At 12:00, RH begins to decrease as the room empties before RH returns to its initial value of 48% approximately 1 hour after the lecture ended. Similar variations are observed throughout all the lecture theatres at some point during the monitoring period and correspond to lectures held in the building. The spike in RH observed indicates an increased moisture load in the rooms due to the metabolic processes of the occupants in the lecture theatres. As well as the presence of people, the T in the room will have an influence on the RH trends, a factor that is discussed in the subsequent discussion on the thermal environment during this period.

Fig. 5-12 displays the H_{abs} variations observed in the lecture theatres during this monitoring period. Once more, when 13/03 is considered, the baseline H_{abs} conditions are observed to be stable. In general, external H_{abs} values appear to be the primary driving force behind the overall H_{abs} trends in the lecture theatres, as presented in Fig. 5-12 and is particularly observable on 13/03 when the internal and external moisture conditions follow similar trends and magnitudes. This is consistent with the observations made in previous discussion of the H_{abs} variations in the building. However, during times when a lecture theatre becomes occupied, the moisture load due to people causes H_{abs} in that lecture theatre to deviate significantly from the overall trend as H_{abs} increases rapidly. Once people leave the room, H_{abs} decreases once more as observed in the RH trends. These sudden increases and decreases are not observed during either of the previous charts (e.g. for the unoccupied and

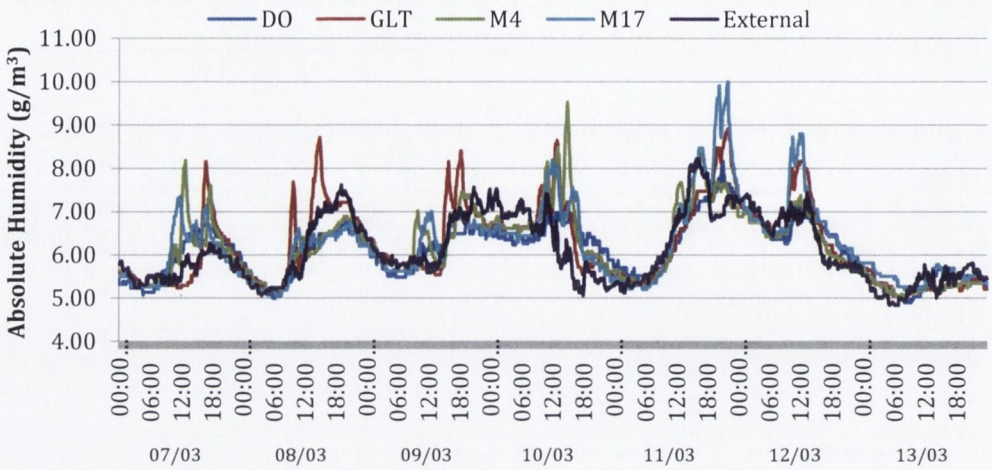


Fig. 5-12: Absolute humidity calculated for the lecture theatres in the Museum Building when the building was both heated and occupied.

unheated and unoccupied and heated charts discussed previously) and, given that the only difference between the three cases is the presence of people, it may be concluded that the large variations observed in the lecture theatres is a result of the presence of people in these rooms, an observation that would be expected given the trends observed in the small-scale occupancy experiment.

Fig. 5-13 illustrates the effect of people on the internal environment of lecture theatres and is the basis for subsequent argument on the matter of people and the environment in the lecture theatres. The H_{abs} data displayed on the chart was obtained on 21/03 and lecturers recorded the associated occupant numbers during their particular lectures. The theatre timetable was also crosschecked with the time of each lecture to ensure that a full set of occupancy data for the day was obtained. From Fig. 5-13 it can be seen that two distinct occupancy periods exist, namely between 09:00 and 12:00 and then from 15:00 to 17:00.

For the purposes of analysis, it is assumed that lectures end at approximately ten minutes to the hour and, during the ten-minute period between the end of a lecture and the beginning of the subsequent lecture, that the door to the room is opened and a number of occupants is present in the room during the changeover time. The moisture conditions in the Atrium and externally are also displayed on the chart as a means of explaining the trends observed in the room on 21/03.

Over the course of the night on 21/03, moisture conditions in M17 are relatively stable, as are those in the Atrium and externally with a slight upward trend. A moisture gradient between the room and the outside environment is present, however the slow infiltration

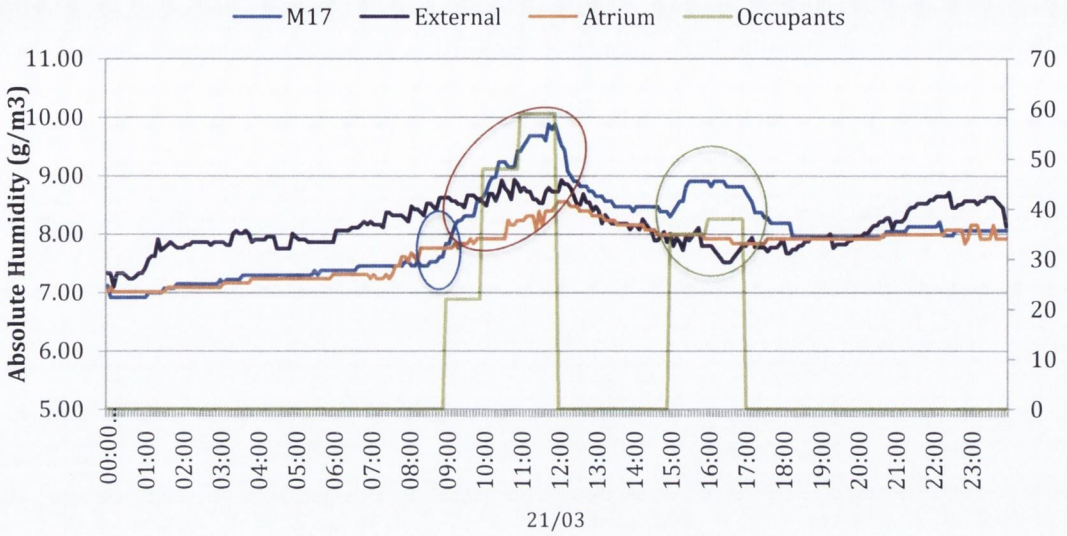


Fig. 5-13: Absolute humidity conditions in M17 with associated occupancy times and the number of people present in the room at the particular time as recorded on 21/03.

rate results in the H_{abs} increasing by a relatively small amount (0.39g/m^3, from 6.92g/m^3 to 7.31g/m^3), a rate of approximately 0.07g/m^3/hour. At approximately 08:40 however, these stable conditions begin to change as the building is opened. This is particular noticeable in the Atrium at approximately 07:30 (circled in blue), when cleaning staff open the front door and a sudden increase in H_{abs} is observed due to moisture infiltration through the door.

The area circled in red on Fig. 5-13 represents the first occupancy period in M17 and spans a time period from approximately 08:30 to 12:00. Although lectures were not scheduled to begin until 09:00, typically the occupancy period starts from 10 minutes before the lecture. Accordingly, H_{abs} in the room is observed to increase from approximately 08:45 as students begin to filter into M17. When the lecture starts at 09:00, 22 people are noted as being present in the room. An increase in H_{abs} occurs, as a moisture load is induced in the room by the sedentary students, rising from 7.53g/m^3 to 8.23g/m^3 at approximately 09:20, a rate of increase of 1.4g/m^3/hour. At this point, the moisture emitted by the occupants equals the rate of moisture loss from the room and equilibrium is reached as little further increase in H_{abs} is observed until approximately 09:55, midway through the lecture changeover.

At 09:50, a H_{abs} of 8.56g/m^3 is observed in the room. Between this time and approximately 10:00, occupancy in the room more than doubles, increasing from 22 to 48. From 10:00 onwards, the previous period of relatively stable H_{abs} is interrupted as the larger number of occupants induce a larger moisture load in the theatre. H_{abs} increases from 8.56g/m^3 to 9.23g/m^3 over a period of approximately 30 minutes, a rate of 1.34g/m^3/hour, slightly lower

than the rate observed between 09:00 and 10:00. Due to the larger moisture load in the space during this time, the moisture gradient between the internal and external environment is reversed and so moisture is lost from M17, not only to the Atrium but also to the external environment. This larger rate of heat loss, relative to that observe during lecture 1, is a principal reason why the increase in H_{abs} as well as the rate of change of moisture gain in the room are lower at this time, despite the larger moisture load due to occupancy.

For the final lecture in this occupancy period, the number of students increases by 11, from 48 to 59. The relatively small increase in occupancy is reflected in the H_{abs} trend as a relatively modest increase in H_{abs} is observed between 10:55 and 11:20, where an increase of $0.53g/m^3$ is observed, the smallest increase observed during this particular occupancy period. This equated to a rate of $1.27g/m^3$/hour. The reason for this reduced rate may be twofold. Firstly, when compared with the increase in occupancy before the first and between the first and second lectures, an additional 11 people in the room will have a smaller effect on the moisture conditions as the occupancy before this lecture was relatively large. Secondly, the moisture gradient between M17 and both the Atrium and the external environment is relatively large at this time, resulting in an increased rate of moisture loss from the room and thus reducing the impact of the people on the hygrometric properties of the environment.

When the final morning lecture ends at approximately 11:50, the door is opened and moisture can, again, move freely into the large volume of air in the Atrium according to the moisture gradient between the two spaces. This results in the rapid decrease in H_{abs} in M17, from $9.78g/m^3$ to $8.90g/m^3$ over a period of approximately 25minutes, a rate of $1.96g/m^3$/hour. H_{abs} continues to decrease, albeit at a decreasing rate, before stabilising at approximately 13:30 with a value of $8.47g/m^3$. It is postulated that the stabilisation observed at this point is due to the door of M17 being closed, thus reducing the rate of moisture movement between the room and the adjacent Atrium. This theory may also explain the reduction in H_{abs} that occurs at approximately 14:40 as the moisture gradient between M17 and the Atrium would promote moisture loss from M17 at this time period. At 14:40, just before the second occupancy period (circled in green in Fig. 5-13) and after a one-hour period of stability, a drop in H_{abs} of $0.17g/m^3$ is observed in M17, which may be consistent with the door being opened before the second occupancy period, where the findings of the open window test outlined in Section 4.5 also displayed similar behaviour.

As observed during the first period of occupancy on 21/03, H_{abs} in the room increases in accordance with the presence of people in the room. At 15:00, the first lecture begins and a

0.6g/m^3 increase in H_{abs} is observed (8.30g/m^3 to 8.90g/m^3) in the room at a rate of 1.20g/m^3. This value is maintained over the course of the occupancy period and a similar trend to that observed after the first occupancy period is recorded when the room is vacated. Table 5-6 tabulates the various occupancy numbers and associated change in H_{abs} observed throughout 21/03.

From Table 5-6, it can be seen that the largest rate of increase over the course of the day occurs during the first lecture, as no moisture load had been present in the room previously and no residual moisture from previous occupation. Thereafter, moisture losses from the room increase due to the reversal of the moisture gradient as well as its increase in magnitude, which reduces the rate of moisture increase despite the additional load due to the higher number of occupants. When the door to the room is opened and the room vacated, the decrease in H_{abs} occurs relatively quickly as moisture can move freely into the large volume of air in the Atrium according to the moisture gradient.

Table 5-6: H_{abs} changes and occupancy numbers observed in M17 on 21/03.

Time Period	Occupant Number	Change in H_{abs} (g/m^3)	Rate of Change (g/m^3/hour)
08:50	0	0	0
08:50-09:20	22	+0.70	+1.40
09:55-10:25	48	+0.67	+1.34
10:55-11:15	59	+0.53	+1.27
11:55-12:25	0	-0.98	-1.96
15:00-15:30	35	+0.6	+1.2
17:00-17:40	0	-0.62	-0.93

From these observations it may be concluded that the effect of occupants on the hygrometric environment in a room depends, not only on the number of occupants, but also the moisture loss from the room due to the moisture gradient or otherwise but also on the residual moisture in the room from previous occupation or other moisture loads. The moisture gradient is also important as it determines the rate of moisture loss from the room and can thus decrease the impact of the occupants. This was particularly the case when considering that a small number of occupants caused the largest increase and rate of increase in H_{abs} over the course of the day as no residual moisture was present in the room. Although the moisture gradient between the room and the external environment at this time was such as to promote infiltration into the room, the slow leakage rate into the space from the external

environment as mentioned previously means that it did not contribute to this increase in H_{abs}.

The principal observations arising from the preceding discussion are that the magnitude of changes in H_{abs} due to the moisture load associated with the presence of people produces significantly larger variations in the humidity parameters compared to the background external moisture conditions. Furthermore, the rates of increase in H_{abs} as well as the magnitude of the peaks in a space appear to be in proportion to the number of people present in the room. The effect of the room being vacated, even for a brief period (such as a coffee break for example) is clearly discernible in the RH and H_{abs} trends. Finally, the rate of moisture loss through a door into an adjacent space or to the external environment occurs at a quasi-exponential rate.

5.3.3.2. Temperature Trends

T variations in the four lecture theatres in the Museum building are displayed in Fig. 5-14. This particular monitoring took place over a period of one week in March, which means that the diurnal T trends observed at this time are typical variations observed in the lecture theatres throughout the heating period.

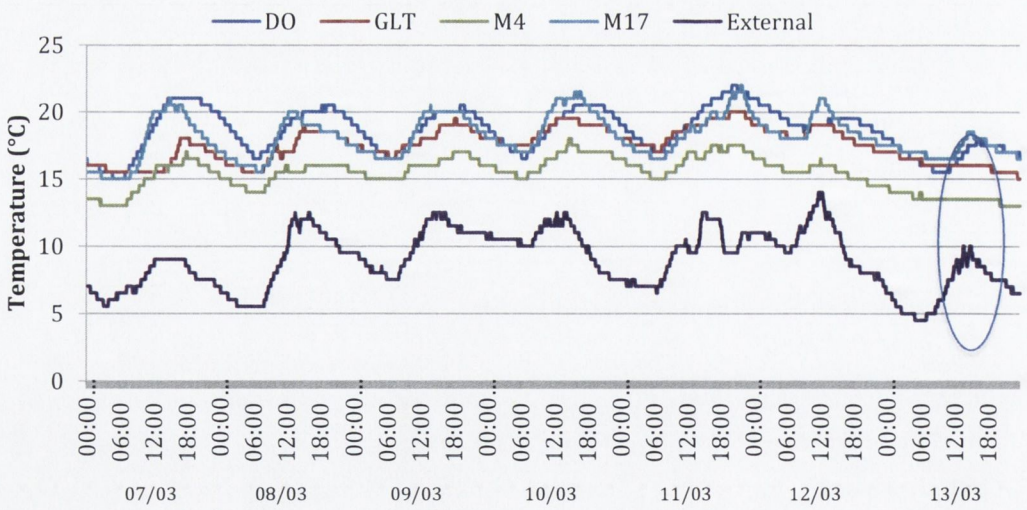


Fig. 5-14: Temperature data recorded in the lecture theatres in the Museum Building when the building was both heated and occupied.

Mechanical heating is provided to the building between 07:30 and 20:00 from Monday to Thursday. As a result of the lectures on Friday evening, heating is provided to the building

until 21:30, while mechanical heat is also supplied to the building on Saturday morning between 08:00 and 11:30. External T variations are comparable to that observed during the heating only period, as shown in Fig. 5-7.

T values in the GLT were generally the highest in magnitude amongst the monitored lecture theatres during the heating-only period (Fig. 5-7). This is no longer the case, as may be observed in Fig. 5-14. T values in the DO and M17 are noticeably higher at this point as compared to those illustrated in Fig. 5-7 and this is due to the fact that, at this point in the year, the building has heated up again after the Christmas break.

Although night-time T values are similar in the DO, M17 and the GLT, the relatively large heat output per unit area provided to the DO and M17 when compared to that supplied to the GLT, coupled with the fact that the building has undergone its "heating up period" after the Christmas vacation, results in higher T values occurring in these rooms during the day. M4, however, remains comparable in T to that observed during the heating only stage as the T of the ground adjacent to the external walls of the room remains relatively cold, thus regulating the T in the room.

On 07/03, for example, the mechanical heating supplied to the building results in large T increases in DO and M17 of 5.5°C (15.5°C to 21°C) compared to the more modest 2.5°C (15.5°C to 18°C) increase observed in GLT. It is also worth mentioning that the maximum T of 21°C is maintained for a longer period in the DO which is unsurprising considering the existence of its large heat load due to radiators. M4 consistently experiences the lowest T change due to its smaller heat output per unit area and colder external walls due to the ground that borders these elements.

The effect of solar gains is generally not observed in the building throughout this monitoring period (due to overcast external conditions) with the exception of 12/03 and 13/03, which is a Sunday and, as such, no mechanical heat source is supplied to the building. T gains are observed between approximately 11:00 and 15:00, corresponding to the period of maximum solar intensity, in the DO and M17. M4 and GLT maintain stable constant T values on this particular day, as they are not subjected to solar influences (see blue region in Fig. 5-14).

Taking Fig. 5-14 in isolation is not sufficient in determining the effect of occupancy on T and, accordingly, the T variations observed in the GLT on 08/03 are displayed in Fig. 5-15. As discussed previously, the GLT differs from M17 in its size and orientation. Furthermore it faces north and heat loss from the room occurs at a slower rate than that in M17. Occupancy in the room is indicated by the RH data, which is superimposed on the plot and two distinct

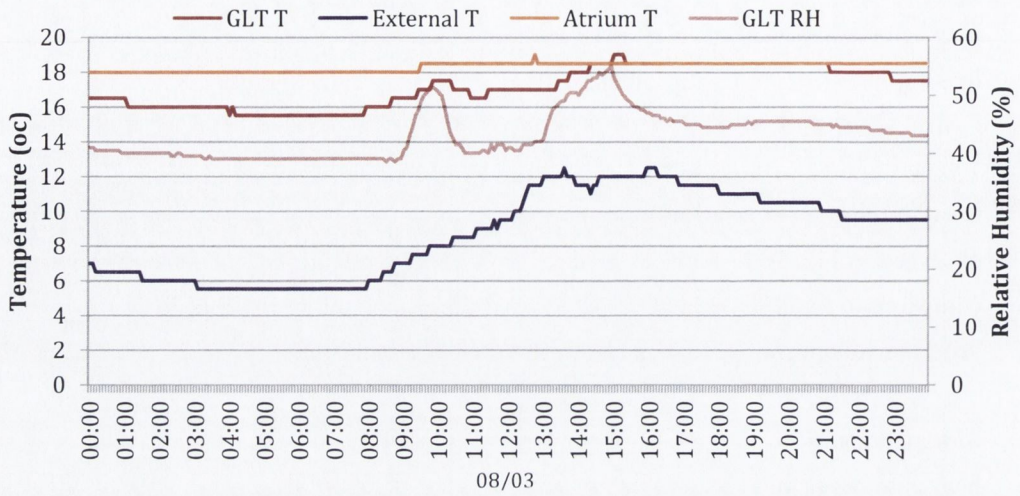


Fig. 5-15: T data recorded in the GLT, externally and in the Atrium on 08/03. RH is also included to indicate occupancy.

occupancy periods may be discerned, namely between 09:00 and 09:55 and between 13:00 and 14:55. Again it should be noticed that the exact number of occupants during these times was not obtained, and the supposed presence of people in the room at these times is based on the previous discussion on the effect of occupants on the hygrometric properties in the room. Additionally, the heating schedule in the GLT is identical to that in M17.

Given that 08/03 is a weekday, mechanical heating is supplied to the building between 07:30 and 20:00 and this is reflected in the T trends, as T in the GLT begins to increase slowly, from a value of 15.5°C at approximately 07:45 to 16.5°C at approximately 08:40. From approximately 08:50, RH in the room increases, indicating the presence of people and a corresponding T value of 16.5°C is observed at this time and maintained until 09:30.. This lag period between the commencement of an occupancy period and a change in T value is consistent with the findings of the small-scale occupancy experiments that were discussed in Section 4.6.

Between 09:30 and the end of the first occupancy period (at approximately 09:50), T in the room increases by 1°C to 17.5°C, which appears to be an accelerated rate compared to that observed prior to the occupation of the room. At this point (i.e. 09:50), the room is vacated and the T value of 17.5°C is maintained for a short period of approximately 30 minutes before decreasing slightly. This reduction in T, despite the higher magnitude of T values in the Atrium would suggest that the door into the GLT was closed after this lecture and heat losses occurred through the windows of the building as the thermal gradient between the room and the Atrium would have resulted in heat flow into the space,. Between 10:30 and

13:30, constant T conditions are observed in the GLT despite the continued presence of mechanical heating in the room throughout this interval.

Although the second occupancy period commenced at 13:00, a lag period of approximately 30 minutes is again observed before T increases from 17.5°C to 19°C over the course of the occupancy period. Given that the heat output of the mechanical heat source has not changed, and a constant T value of 17°C is observed in the room until 13:30, it appears that the heat load due to the people is responsible for the increase in T observed during this occupancy period. When the room is vacated (and the door left open) at approximately 14:50, T remains stable for a brief interval before decreasing to 18.5°C, identical to that observed in the Atrium. From the trends observed in the GLT, it appears that the presence of people in relatively large numbers, have a discernible, albeit small, influence on the thermal conditions in a small lecture theatre and act to supplement existing heat loads, resulting in an increase in T over the course of an occupancy period. Considering the lag period observed between the commencement of the occupancy intervals and the measured increase in T, however, it appears that a residency time of approximately 30 minutes is required in the case of the GLT, although this may vary depending on the boundary conditions of the particular room being considered.

Generally, however, the effect of occupants on a space is too small to be easily observed when mechanical heating is supplied to the building. It can thus be concluded that mechanical heat, in this case, is the primary factor in determining the thermal conditions in a larger lecture theatre, although solar gains in a south facing room, when present, also has an effect on the thermal environment. Compared to these two effects, the presence of people is the least relevant of these three influences in determining the thermal conditions in a large room. This, however, does not accurately represent the effect of people in all rooms, as illustrated in Fig. 5-15, where a more noticeable correlation between people and the internal T are observed. As a result, when considering the effect of occupancy on a room, factors related to the building fabric are also important. In a well sealed, smaller room, such as the GLT, the effect of people on the T in the room are more pronounced and noticeable than in M17, which is larger and less well sealed. Furthermore the heating in the particular rooms must also be considered.

Referring back to Section 4.7, the signature associated with the presence of people in a room is that the moisture load associated with people is sufficient to result in relatively large fluctuations in the hygrometric environment about a general trend. Based on the preceeding discussion, this was found to hold true in a large scale historic building as fluctuations in RH and H_{abs} due to people was sufficient to predict whether the room was occupied or not. In

terms of the thermal environment, however, the effect of people on T values in a room is not as obvious. Although the heat load induced in a space due to people can result in an increase in T, as observed in the GLT, other factors, such asroom size, mechanical heating, solar gains, infiltration and heat losses from the room, can be sufficient to reduce the impact of people on the thermal environment significantly and thus make it difficult to correlate T changes to occupancy times.

The monitoring of the lecture theatres was a useful exercise in assessing the effect of a large number of occupants with a specified residency time on the thermo-hygrometric properties in a room. In order to further examine the effectiveness of signatures in aiding analysis of environmental condition in a buiding, the study must be also applied to smaller rooms with low levels of occupancy. Accordingly, four offices in the Museum Building were also monitored.

5.4. The Internal Environmental Conditions in Offices

As mentioned previously, although the primary focus of this study is centred on the environmental conditions in lecture theatres owing to the size and relatively high occupancy levels and residency time in the room, it is also useful to examine the fluctuations in the thermal and moisture conditions in smaller rooms. Accordingly, four offices in the Museum, ranging in occupancy from one to eight have also been monitored. This data will be discussed to assess whether the environmental trends due to high occupancy in large spaces may also be identified in smaller rooms with typically low occupancy.

5.4.1. Temperature Trends

T data recorded in the four offices, externally and in the Atrium are presented in Fig. 5-16. Mechanical heat was supplied to the offices between 26/04 and 29/04. Due to a bank holiday, the building was generally unoccupied and unheated on 24/05, with the exception of Office 01, in which occupancy and an alternative heat source were noted. Similarly, the building was unheated and unoccupied on 01/05, although again both heating and occupancy were noted in Office 01, due to the presence of postgraduate students and their use of an electric heater.

The thermal environment in the atrium during this recording period is very stable as no heat source and large thermal mass are present in this area. The glazed dome area is also

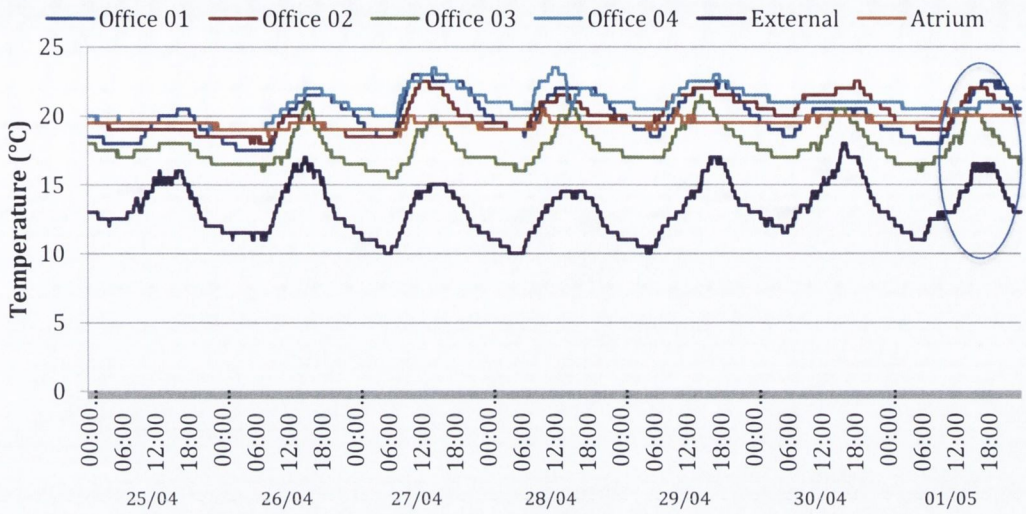


Fig. 5-16: Temperature data recorded in four offices in the Museum Building. External T as well as T values in the Atrium are also included on the chart.

relatively small and the main external door, although frequently opened is small in size relative to the total volume of the area, resulting in minimal heat losses when compared to other spaces in the building. Thus T changes in the Atrium are small in magnitude and increases in T most likely due to heat infiltration from adjacent heated spaces, while T reductions are likely due to heat loss out through the glazed roof dome as well as through the front door as no draught lobby exists. The stability of the thermal environment in this area is due to its large air volume and small heat loads due to infiltration, coupled with its large quantity of exposed thermal mass and low heat losses.

Examining the general T trends illustrated in Fig. 5-16 provides an insight into the thermal behaviour in the offices in the building. Despite facing south, and thus benefitting from solar gains, the lowest diurnal T values are observed in Office 03, indicating that losses from the room are high due to the relatively large, single glazed window on its external wall. It is also observed that the diurnal T variations in Office 03 occur over a short period of time and the maximum daily T is short lived. One explanation is that a large amount of heat is lost from the room through the external windows, which were damaged at the time of monitoring. This damage comprised a cracked frame and small holes in a number of the glass panes. The effect of the damaged window is that heat losses from the room are increased, thus negating the effect of the large volume of thermal mass in the room (see Table 5-2) that should provide some regulation to the thermal environment and prevent the relatively quick heat up and cool down times observed in Office 03.

Similarly to Office 03, high heat losses are observed from Office 01, which is also located in the east end of the building, but faces north. Despite consistently recording one of the highest daytime T values, when the heating is deactivated, T decreases relatively quickly, falling to a value that is the second lowest amongst the four monitored offices. This indicates a high rate of heat loss. As is the case in Office 03, the external single-glazed surface area in Office 01 is relatively large, leading to high thermal losses when mechanical heat is removed from the space, despite the large thermal mass in the area as illustrated in Table 5-2.

Conversely, Office 04 undergoes the lowest T fluctuations amongst the four monitored offices, despite having the lowest relative area of thermal mass. Office 04, however, has a smaller relative glazed area in comparison to the other offices (see Table 5-2) and, as a result of this feature, heat losses from Office 04 are smaller, resulting in the higher T values in this room when compared to Office 03. Furthermore, high T values in Office 04 are sustained throughout the day and the reduction in T after working hours occurs at a relatively slow rate. From the floor plans (Appendix A) it can also be seen that Office 04 is separated from another heated room by a lightweight partition through which heat can move relatively unopposed when compared to the mass of the large stonewalls in the other offices. Despite having a lower relative thermal mass when compared to the other offices, it is observed that Office 04 is the only one that maintains a T value that is higher than that observed in the Atrium, further indicating the relatively lower thermal losses occurring from this room.

Office 02 is the smallest of the four offices monitored during this study. Diurnal trends in this room appear to behave in a similar manner to those in Office 01, although maximum T values are maintained for a shorter period, indicating high losses from this office. The relatively small glazed area results in a higher night-time equilibrium value when compared to Office 01 as heat losses during periods when mechanical heating is off are lower. It is possible that mechanical heat in Office 01 is supplemented by an electric heat source that occupants of the room use and would result in a larger range between maximum and minimum diurnal T, as an oil-filled electric radiator was observed in the room during collection of the sensors.

Evidence for the effect of solar gains on the thermal environment in the south facing offices is evident on 01/05, which is circled in blue on Fig. 5-16. Despite no heat sources being activated in Offices 02 and 03 (01/05 was a Sunday and these offices were unheated and unoccupied accordingly), T gains are observed in these rooms between approximately 11:00 and 15:00, corresponding to the times of maximum solar intensity, as confirmed by weather

data. T in Office 02, which has a small external window, increases by 3°C (19°C to 22°C) during this time, while Office 03 rises from 17°C to 21.5°C, a change of 4.5°C. Conversely, in the north facing Office 04, no major change in the thermal conditions is observed during this time as T fluctuates between 20°C and 20.5°C. The other north facing office (Office 01) observes a sizeable increase, however, as it changes from 19°C to 22.5°C. This change in T is a result of the presence of people in the room on this day and, more relevantly, due, in all likelihood, to the electric heater being used by the occupants whilst in the room. By comparing the two south facing offices to Office 04, the impact of solar gains on the thermal environment becomes clear and, as discussed previously, the risk of overheating and thermal discomfort in these offices may be increasingly relevant during prolonged periods of high solar intensity while heating is also on.

Based on the T trends observed in the four offices during this time period, it appears that low occupancy has a negligible effect on the thermal conditions in the room and, when compared to mechanical heating, infiltration and heat losses, is an insignificant factor in determining T conditions in a room in a historic building. This was shown to be the case in Offices 03 and 04 on 27/04 when heat flow into and out of the Atrium were more significant in determining T variations than the actual occupants.

5.4.2. Humidity Trends

RH data values recorded in the four offices are displayed in Fig. 5-17. Based on the T data discussed previously, the distribution and trends for the RH is somewhat as expected. As it experiences the lowest T, with large variations throughout the monitoring period, Office 03's RH is the highest in magnitude and has the largest range between maximum (58.5%) and minimum (37%). Conversely, Office 04 has the most stable RH trend with fluctuations ranging between 36.5% and 47%. It should be noted, however, that night-time RH values are relatively stable and the variations typically occur during office opening hours, corresponding with times of occupancy and mechanical heating. The RH fluctuations observed in Offices 01 and 02 are quite similar, varying in magnitude according to the differences in their T values.

The T conditions in the Atrium were recorded as being relatively constant during this period, with small increases in T (0.5°C) occurring at a very slow rate (Fig. 5-16). The RH in this area does not follow this stable trend as fluctuations in RH are observed throughout the monitoring period. This indicates fluctuating H_{abs} conditions in this space that may be a

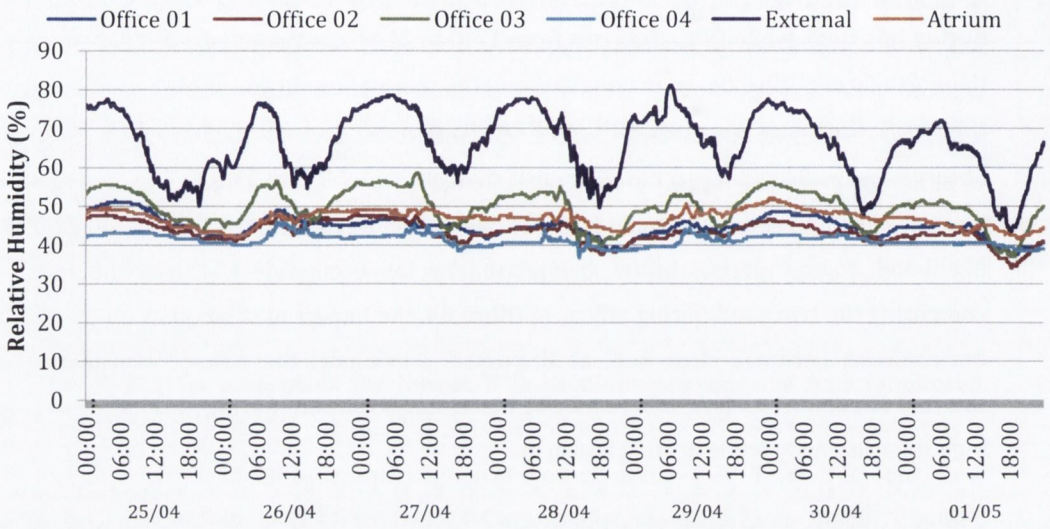


Fig. 5-17: Relative humidity data recorded in four offices in the Museum Building. External RH as well as RH in the Atrium are also included on the chart.

result of a combination of moisture loading due to people or infiltration of moisture into the space from the external environment.

In general, RH trends in the offices tend to increase during opening hours of the offices. These increases are small in magnitude when compared to those observed in the lecture theatres, however, given that T values at these times are observed to increase, these RH changes indicate occupancy, as a decrease in RH would be expected with the increasing T. As a means of determining the causes of these RH changes, H_{abs} values are calculated and displayed in Fig. 5-18.

From Fig. 5-18, it may be observed that the external environment has a significant influence on H_{abs} conditions in the four offices. This is particularly the case in Offices 02 and 03, where internal and external moisture conditions appear to be generally similar. Over the course of the monitoring period, there is no evidence of occupancy as it appears that the moisture load associated with a single person in a room is not sufficient to noticeably alter H_{abs} in a room with unsealed windows and doors. Accordingly it can be concluded that the moisture gradient between inside and outside is the determining factor for the H_{abs} trend in these two offices.

Evidence for the effect of people on the moisture conditions in a room can be found in Office 01 and, to a lesser extent, Office 04. During periods of zero occupancy, H_{abs} variations in the offices generally follow the external conditions, as per the area of Fig. 5-18 that is circled in

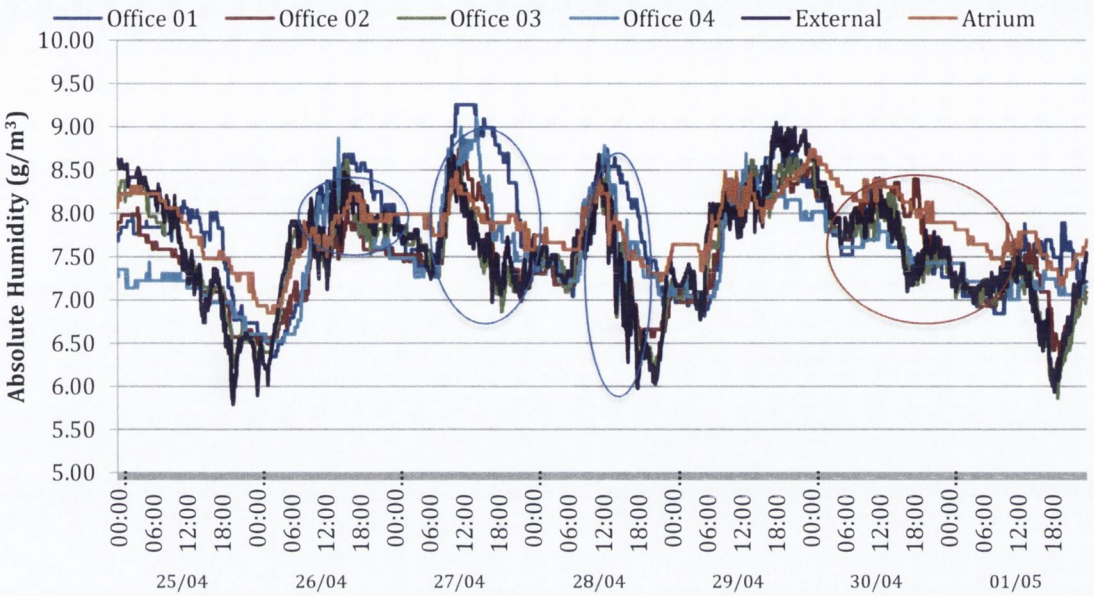


Fig. 5-18: Absolute humidity data calculated for the four offices in the Museum as well as externally and in the Atrium.

red. However, considering the areas in Fig. 5-18 that are highlighted in blue, it can be seen that H_{abs} variations no longer follow the external trend as the moisture load due to people is sufficient to increase H_{abs} to a value higher than that observed externally. This indicates that additional moisture sources are present in the room, which in this case are resulting from occupancy of the respective offices.

In order to examine the effect of people in more detail, H_{abs} calculated from the data collected on 27/04 is presented in Fig. 5-19. Before people enter the offices, relatively stable moisture conditions are observed throughout the building and are consistent with external conditions. At approximately 07:30, external H_{abs} begins to increase, inducing a moisture gradient that results in moisture ingress to the offices. As a result, H_{abs} in the four offices also increases. From approximately 09:00, moisture conditions in Office 04 begin to deviate from those externally as people enter the room, causing a measurable increase in H_{abs}. Similarly, Office 01 experiences a large increase in H_{abs} at approximately 09:30, reaching an equilibrium value that is approximately 1.00g/m^3 higher than the corresponding external value.

As the period of occupancy in Office 01 occurs over a prolonged length of time, the H_{abs} trend in this room differs to those in the other offices. In general, H_{abs} conditions in Office 01 are stable, however, there are three distinct decreases in the H_{abs} trend that correspond with a person leaving the room. These occur at approximately 14:15 (9.25g/m^3 to 8.89g/m^3) 19:40

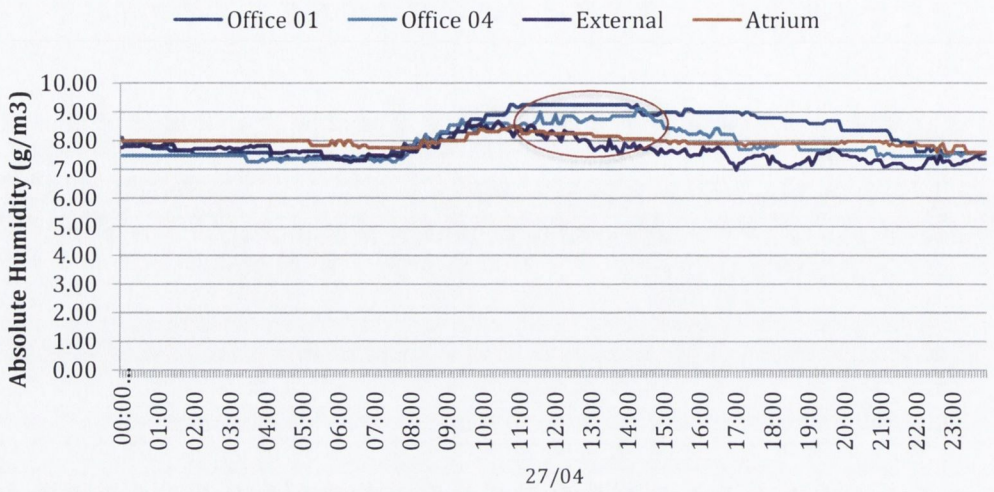


Fig. 5-19: Absolute humidity calculated for 27/04 in the four offices in the Museum.

(8.69g/m^3 to 8.35g/m^3) and at 21:00 (8.35g/m^3 to 7.92g/m^3). Once the room is vacated, leakage from the room is large resulting in H_{abs} quickly approaching the external conditions. Hence it may be concluded that, during periods of occupancy, the moisture loads associated with metabolic processes is the factor that determines the moisture conditions in the offices. Thereafter, H_{abs} variations in the rooms are driven by infiltration or exfiltration to or from the external environment as H_{abs} fluctuates in accordance with the external conditions.

Relating the variations in the humidity parameters observed in the four offices, it appears that low occupancy levels are identifiable as fluctuations about a general trend, which agrees with the findings of the small scale signature tests. When compared to rooms that typically have a large number of occupants, the influence of small occupancy on a room is less, unsurprisingly, and the small nature of the RH and Habs fluctuations associated with low occupancy can make it difficult to discern the presence of people in a room as other factors, such as infiltration and exfiltration from the external environments and T changes (in terms of RH variations) may be a more dominating influence on the hygrometric environment than the moisture load associated with people.

5.5. The Internal Environmental Conditions in the Civil Engineering Library

In addition to monitoring the lecture theatres and offices in the Museum building, environmental data in the Civil Engineering Library was also collected. This room is situated directly above Office 04, in the west end of the building, is north facing and has a relatively small single-glazed window on its external wall and high thermal mass due to its stone walls. No direct heating is supplied to the room, and heat infiltrates into the room from the heated

offices below. Occupancy patterns in the room are generally sporadic and occur between 15:30 and 17:30 on weekday afternoons, however, a number of meetings also take place in the library where occupancy can approach 20 people. The Civil Engineering is densely stocked with library material and contains approximately 100m of shelving, which is occupied by books and magazines. Some staff occasionally use the room for coffee breaks at 11:00, as coffee making facilities are present in the room. Given the primary case study in this project, the purpose of monitoring the room is to try to identify particular trends that may be characteristic to a library in historic buildings.

5.5.1. Temperature Trends

T data recorded in the Civil Engineering Library and externally are presented in Fig. 5-20. From Fig. 5-20, the highly stable thermal conditions become evident. Although other rooms exhibit somewhat stable environments, T variations observed in the library are smaller than in any other room monitored during the heating period, partly due to the absence of direct heating.

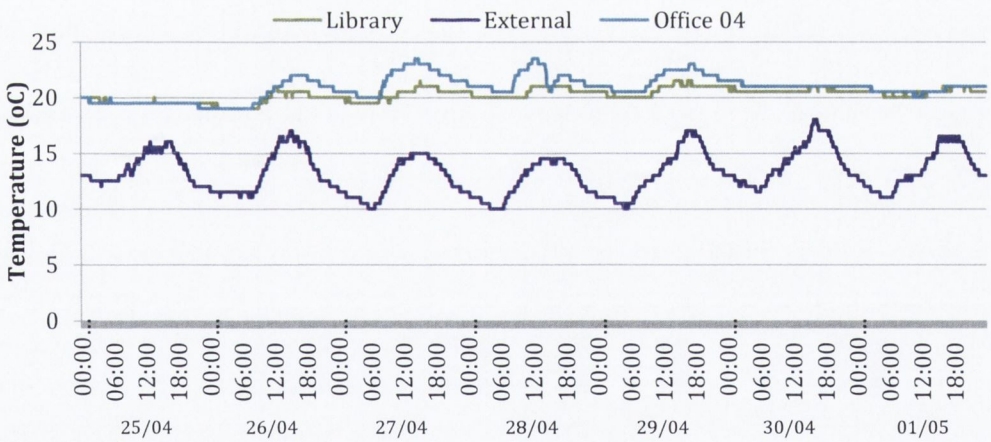


Fig. 5-20: Temperature data recorded in the Civil Engineering Library n the Museum Building. External T is also displayed on the chart.

Thermal losses from the library occur at a very slow rate, indicated by the measured rate of decrease observed in the room on 25/04. As this was a bank holiday, no occupancy was noted during this time and, as mechanical heating to the building had been deactivated since noon on 23/04 no heat loads due to infiltration from the office below are noted. Accordingly, T in the room remains at a relatively constant value throughout the unheated time period (23/04 until 26/04). Given the very slow rate of T decrease observed during this time interval, it can be noted that thermal losses from the room appear to occur very slowly,

owing to the relatively small single-glazed area as well as the thermal mass of the room and its contents, which would function to regulate the thermal conditions and this phenomenon is discussed later in this section.

Throughout the monitoring period, the effect of heat loads, either due to the external environment, mechanical heat sources or people, is observable on the diurnal trends. The baseline T value in the Civil Engineering Library in April is approximately 20°C and is the value typically observed during the night-time period when heating is not supplied to the room from the office below. The effect of the heat is sufficient to increase daytime T values by approximately 1°C, although slightly larger variations are observed, particularly on 26/04.

As mentioned previously, the very stable thermal environment observed in the Civil Engineering Library is due in part to the low losses that occur from the room. The library has an additional feature that is not present in the other rooms in the building that contributes to the constant T conditions recorded during this monitoring period. The presence of a large volume of books that are shelved together in a compact manner provides additional thermal mass in the room. This additional mass acts in tandem with the heavy stone walls to regulate the thermal conditions in the room. As a result, small fluctuations in T are observed throughout the heating period and T losses at night are low. The large volume of books that are located in the Library may contribute to the overall thermal mass of the area. Referring back to Table 5-2 it can be seen that the relative area of thermal mass in each room, due to the walls alone, is larger in Office 04 ($0.38m^2/m^3$) when compared to the Library ($0.32m^2/m^3$). Nevertheless, the T trend displayed in Fig. 5-20 for the library exhibits less variation than the corresponding trend in Office 04. As the heat source in Office 04 also provides heat to the Library, the differing trends between the rooms must be due to some other effect. In this case, the thermal mass provided by the books regulates the thermal conditions in the Library and results in the stable T trend observed in Fig. 5-20. Hence it may be concluded that, when books in large quantities are packed tightly together in a room, such as a library or archive, they act as additional thermal mass and regulate the thermal environment, to some degree, as a result.

5.5.2. Humidity Trends

RH data for the Civil Engineering Library is presented in Fig. 5-21. As expected based on the T variations discussed previously, RH conditions in the room are generally very stable. Some variations exist at times when changes in T are noted, however, as RH increases correspond

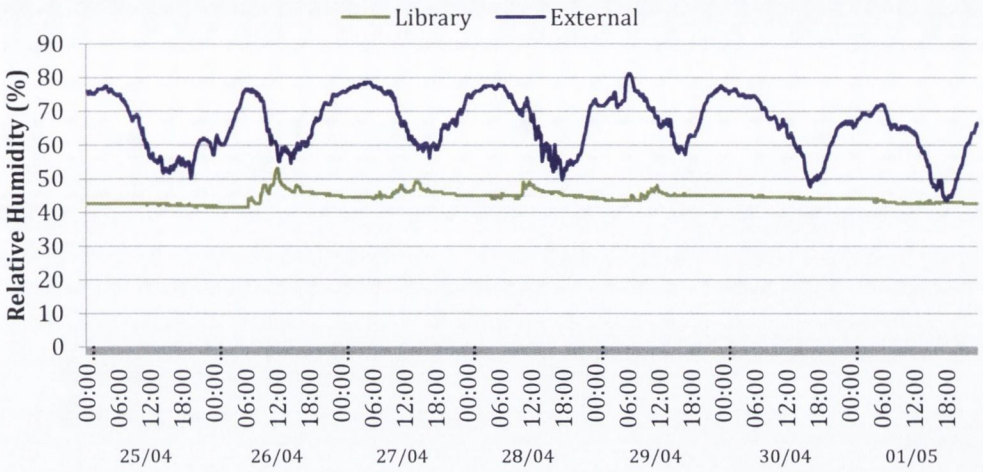


Fig. 5-21: Relative humidity data recorded in the Library in the Museum Building.

to times of increasing T, it is likely that moisture loads due to the respiration and perspiration of people are causing the RH changes.

The largest RH fluctuation in the library occurs on 26/04 and is a result of the large occupancy levels observed in the room for a brief period. The overall RH trend would suggest that there is very little interaction between moisture conditions in the Civil Engineering Library and the external environment, indicating that moisture leakage from the room is minimal and, when it does occur, does so at an extremely slow rate.

As a means of determining whether this is the case, H_{abs} data for the monitoring period is displayed in Fig. 5-22. As expected based on the T and RH trends, there appears to be little correlation between internal and external conditions. On 25/04, relatively constant H_{abs} conditions are observed in the library despite the presence of a large moisture gradient between inside ($7.35g/m^3$) and outside ($8.57g/m^3$). Furthermore on 01/05, a large moisture gradient is observed that would have resulted in moisture egress from the room, had there been leakage.

At its maximum, a difference of $1.95g/m^3$ is observed between the room and outside yet no reduction in H_{abs} is observed in the library. This behaviour illustrates an extremely slow rate of moisture diffusion between the internal and external environments and suggests that the windows are well sealed Moreover, the large volume of books may also act to regulate the moisture conditions. As paper is a hydroscopic material, the books adsorb and release moisture into the air as required, resulting in the stable environmental conditions observed in the room (see Section 2.5.1.4).



Fig. 5-22: Absolute humidity data calculated for the Library in the Museum Building.

To further examine the factors influencing the moisture conditions in the Civil Engineering Library, H_{abs} data for 26/04 is presented in Fig. 5-23. As mentioned previously, a period of relatively large occupancy was noted in this room between 11:30 and 12:15. During the night of 26/04, H_{abs} conditions in the library are constant at a value of 6.77g/m^3, while the moisture gradient between the room and the external environment varies from negative (inducing moisture egress from the room) to positive (inducing moisture infiltration to the room). At 09:00 (circled in blue) a large change in H_{abs} is recorded (6.93g/m^3 to 8.03g/m^3) as a result of two members of staff entering the room and boiling a kettle for coffee in the room.

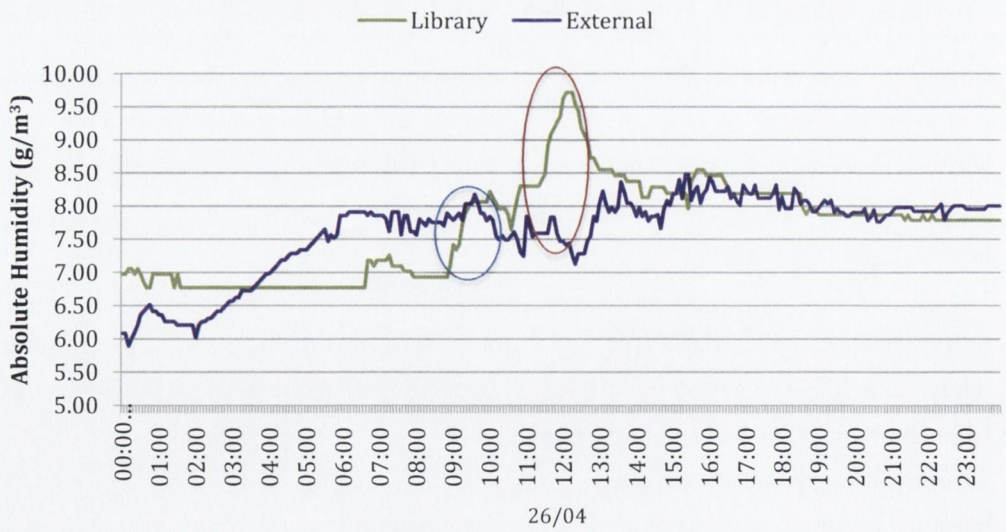


Fig. 5-23: Absolute humidity data calculated for the Library in the Museum Building on 26/04.

At 11:30 (circled in red) the room becomes occupied for a meeting and a large change in H_{abs} is observed as an increase of 1.41g/m^3 (8.30g/m^3 to 9.71g/m^3) occurs over a 20-minute

period, a rate of 4.23g/m^3/hour. H_{abs} remains at 9.71g/m^3 until 12:15 when the meeting ends and as soon as the room is vacated the door to the room is again locked.

Despite the slow moisture egress rate from the room, the rapid decrease in H_{abs} indicates that the moisture load due to people is quickly dissipated at a rate of 1.61g/m^3/hour. This relatively quick rate of decrease from the room may be due to adsorption of moisture by the exposed hygroscopic paper, both books and magazines, in the Library.

H_{abs} stabilises at a value of 8.55g/m^3, 0.25g/m^3 higher than observed originally. The difference between the two values is due to the residual moisture in the room after the meeting that is not adsorbed into the books or that cannot diffuse from the room at a sufficient rate due to the low moisture losses externally observed in the room.

From this study, it may be concluded that the presence of a large volume of books in a room not only regulates the thermal environment to some degree but also the moisture conditions. Accordingly, buildings such as libraries and archives should exhibit more stable indoor environments than typical, assuming that excessive heat and moisture loads are not present in the building and that the indoor environment is not closely related to that externally. Furthermore, it may be concluded that a large volume of books and open magazines can be effective in quickly dissipating moisture loads in a small confined room when leakage rates from the room are slow, as seen immediately following the meeting in the Library on 26/04.

The purpose of monitoring the Civil Engineering Library during the study of the Museum Building was to ascertain whether a relatively large quantity of books in a room would have an effect on the thermo-hygrometric properties in a room. Upon analysis and discussion of the data collected in the library it appears that the signature associated with the books is a highly stable environment in terms of both T and humidity parameters. A large volume of books provides additional thermal mass to the building and greatly reduces fluctuations in T due to heating, people or infiltration. Similarly, relatively constant RH and H_{abs} conditions are observed in a room as the hygroscopic nature of library collection items regulate, to some extent, the water vapour in the air. Although the presence of moisture loads, such as occupants or the boiling of a kettle, cause relatively large increases in RH and H_{abs}, these loads are quickly dissipated upon their removal from the room as the books and magazines appear to adsorb the excess moisture in the air leading to stable hygrometric conditions. Accordingly, the signature associated with books is a stable environment in which additional moisture in the air is quickly dissipated and the T values in the room undergo fluctuations at a relatively slow rate. Had the collection been removed from the library, it is suspected that

the environmental conditions would have had larger variations than those observed during this study.

5.6. Discussion and Conclusions

5.6.1. Validation of the Signature Experiments

Monitoring of the thermo-hygrometric properties in the Museum Building was conducted for two principal purposes. Firstly, it was a means of validating (or otherwise) the conclusions and signatures derived from the small-scale experiments for the four stimuli examined, namely heat loading, moisture loading, varying the infiltration rate and occupancy. Since these experiments were carried out in a controlled environment where only one stimulus was induced at a time, it was necessary to determine how such signatures would apply to a dynamic environment where more than one stimulus may be observed simultaneously. Secondly, analysis of the thermo-hygrometric environment in the Museum Building was used to assess the influence of additional stimuli that may not have been present in the small-scale tests. Accordingly, three additional signatures were developed based on the data obtained from the Museum Building, namely the effect of solar gains, the effect of hygroscopic surfaces and the effect of a large volume of books in a room. The following discussion will outline the key observations and conclusion derived from this case study.

In terms of validating the heat-loading test, T variations in the building were generally found, unsurprisingly, to correlate closely with the mechanical heating. In terms of the relationship between T and RH, the inverse relationship that would be expected, and that was observed during the signature test, did not necessarily hold true. Comparing the boundary conditions in the small-scale experiment to those in this building it can be seen that, in terms of the small-scale test, little or no infiltration or additional moisture loads were observed. In the Museum Building, however, additional moisture loads due to infiltration from the external environment and people were sufficient to alter the expected T-RH relationship, as H_{abs} values tended to be closely related to those externally, which had an influence on the RH trends. Accordingly, it may be concluded that, in terms of the humidity factors, due to additional factors such as infiltration for example, the signature behaviour associated with heating may not necessarily hold true.

The second signature test examined the effect of moisture loading in a space and found a close correlation between the presence of a moisture load and an increase in RH and H_{abs}.

This signature was observed to hold true in the Civil Engineering Library when a kettle was boiled during a coffee break. The consequence of this moisture load was reflected in a discernable increase in RH and H_{abs} about a general trend, thus validating the signature.

The signature associated with an open window or door was also confirmed in the Museum Building. Although external windows and doors were not present in the monitored rooms, the effect of opening a door to the Atrium was frequently observed in the data, particularly in M17 and Offices 03 and 04 during the heating up stage. It is expected that, had an external window in an office or theatre been opened, the thermo-hygrometric environment in the room would have quickly approached those externally.

The signature trend associated with the presence of occupants in a room was conducted for both large occupant numbers (the lecture theatres) and small occupant numbers (the offices). Considering firstly the lecture theatres, it may be concluded that the signature associated with occupants on the hygrometric environment, namely relatively large perturbations about a general trend, was validated as the presence of people in the rooms during lectures resulted in large variations in RH and H_{abs} during the occupancy period. These increases returned to the normal background levels at a relatively high rate once the respective room was vacated post lecture as the moisture load is dissipated by moisture movement and exfiltration. In terms of the effect of people on the thermal environment in the lecture theatres, the signature test found that people have little or no influence on the thermal environment in a room, however, this test was conducted with a relatively small number of occupants. In terms of the signature in a historic building, the effect of a large number of occupants in a room is dictated primarily by the boundary conditions in the room. Considering M17 and the GLT illustrates the point. In M17, heat losses from the room occur relatively quickly and additional heat sources, such as solar gains and mechanical heating, have a large effect on the thermal conditions. As a result, the impact of people is of little consequence to the thermal environment when compared to the other heat loads. In the GLT, however, losses from the room occur quite slowly, the room does not benefit from solar gains and the mechanical heat load supplied to the room is low compared to that in M17. As a result, people appear to have a discernable effect on the T values in the room. Accordingly it can be concluded that, when occupancy levels are high, the effect of people on the thermal environment will be dictated by the boundary conditions of the room and the magnitude of other heat sources. In some cases this can lead to high levels of user discomfort.

In the offices, the signature associated with people was observed as expected, however, the low occupancy had a significantly smaller influence on the humidity conditions as moisture loads were low and, in terms of Office 03 and 04, access to the environment in the Atrium

was uninhibited resulting in moisture movement to the space from these offices. The effect of people on the thermal environment was again negligible and hence it may be concluded that the signature associated with people that was developed using the small scale signature test is valid, although in areas with low occupancy the signature may be more difficult to discern, but can be observed nonetheless.

Having validated the existing signatures it is now necessary to define those associated with solar gains, hygroscopic materials and the presence of books. The signature associated with solar gains was determined by examining environmental variations in M17 and, to a lesser extent, the DO. M17 was most suitable owing to its orientation (south facing) and relatively large glazed area. The signatures associated with solar gains are characterized by a sudden, relatively large perturbation in T about a general trend that is quickly dissipated when direct sunshine is no longer entering the room. Furthermore, a similar but opposite fluctuation in RH that is a result of the large increase in T is observed during the period of solar gain.

Hygroscopic surfaces by their nature absorb excess moisture in the air during times of high humidity and subsequently release it into the atmosphere during periods of low humidity. Furthermore, an increase in T can lead to evaporation of moisture from such materials and surfaces. In terms of this stimulus, the GLT is a useful example in defining the signature, as it is the only lecture theatre that contained a large, untreated timber floor. During an unheated and unoccupied interval, RH and H_{abs} conditions in the room were very stable in comparison to the other lecture theatres. There appeared to be no influence from the external environment and a very slow leakage rate. When the heating was activated after the Christmas vacation, large variations in H_{abs}, corresponding almost exactly to the changes in T were observed indicating that as the T increases, more moisture is released into the air from the hygroscopic materials. Accordingly, the signature associated with hygroscopic surfaces is relatively stable RH and H_{abs} conditions generally. When heating is then applied to the room, H_{abs} correlates very closely to the T variations as moisture is released into the air from the surfaces when T increases and then adsorbed when T decreases again.

The final signature observed in the Museum Building is the influence of a large volume of books in a room. From examining the thermo-hygrometric conditions in the Civil Engineering Library and comparing them to Office 04, which is located immediately beneath the library, it was seen that the books act so as to stabilize the environment in the library by acting as thermal mass and a hygroscopic material. Accordingly, a general background environment of relatively stable T and humidity parameter values would be expected in a

library, which would undergo the fluctuations associated with the other stimuli when they are observed in the room or building.

Hence it may be concluded that the development of signatures with the aim of analyzing the environmental conditions in a building is a useful exercise. Given that the conclusions of the small-scale experiments have been validated in a full-scale historic building, in which the environment is relatively dynamic and multi-faceted in comparison to the small-scale tests, the signatures are validated and extended and may be used to assess the environmental conditions in the primary case study, namely the Old Library in TCD.

6. Old Library

Having conducted the preliminary small scale experiments to define the environmental signatures associated with a range of environmental stimuli (initially heat and moisture loads, large infiltration rate due to an open window and the presence of "dry" and "wet" occupants) and the subsequent validation and definition of signatures associated with additional stimuli (namely solar gains, the presence of hygroscopic surfaces/materials and the presence of books), analysis of the environmental conditions in the primary case-study, that is the Old Library in TCD, can now be carried out. As described in Section 3.5, two monitoring phases were implemented in the building, the first of which was between September and January and included the Christmas vacation and the second in July corresponding to the period of maximum occupancy in the building. The location of each logger during each data collection phase is described in Table 3-5 and Appendix B.

6.1. A Brief History of the Old Library

Situated on the south side of Library Square at the east end of the University (Fig. 6-1), the Old Library in Trinity College Dublin was designed by the engineer, architect and politician Thomas Burgh (Casey, 2005). Construction on the building began in 1712 and continued over the following thirty-one years, with the first books being shelved in 1733. The building envelope consists of a masonry façade with a rubble infill and a significant amount of glazing. The windows are relatively tall elements and located in close proximity to each other, a feature that was intended to maximize the natural light entering the building while allowing the occupied spaces room to benefit from large solar gains, particularly in winter. This feature was especially important, as there were no fireplaces incorporated into the design of the Old Library so as to reduce the potential risk of damage to the collection due to fire.

The masonry façade consisted of two different materials and this remains the case today. The lower level, known as the arcades, is of blue-grey calp, a stone with similar properties to limestone. When built, the upper masonry levels comprised of pale sandstone that was sourced from the Darley quarries at Scrabo in Co. Down. This stone, however, failed within decades of completion and was subsequently replaced with the granite that remains today, as displayed in Fig. 6-2.

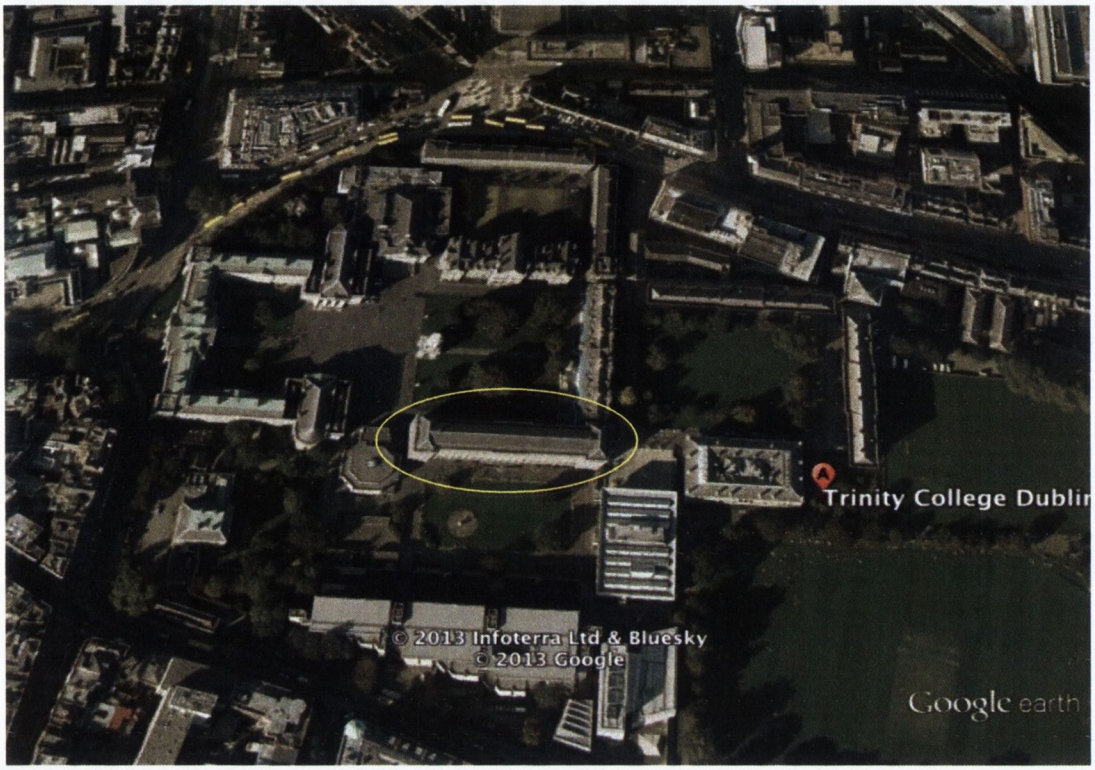


Fig. 6-1: Overhead view of the main campus of Trinity College Dublin with the Old Library circled in yellow (Google_Earth, 2008).



Fig. 6-2: Exterior view of south-side of Old Library

The most famous feature of the Old Library is the Long Room which houses approximately 200,000 of the Library's oldest books (TCD, 2011), over two thirds of the collection housed

in the building. Described by Casey (2005) as *"one of the grandest interiors in Ireland"*, the Long Room measures over 61 metres in length and is 12.2 metres wide, and, along with the Book of Kells, which is also situated in the Old Library, attract more than 500,000 visitors to Trinity College annually. The Long Room (see Fig. 6-3) comprises two storeys and twenty-one bays of storage space. The iconic vaulted-barrel ceiling that can be seen today varies from Burgh's original design for the space. When completed in 1732, the Long Room contained storage space on the lower level only. The gallery was entirely empty and patrons were allowed to walk along this area. The need for additional storage manifested itself following the introduction of the Copyright Act of 1801, which gave the Library in Trinity College the right to claim one free copy of every book published in Britain and Ireland, a right that it still holds today (TCD, 2011).

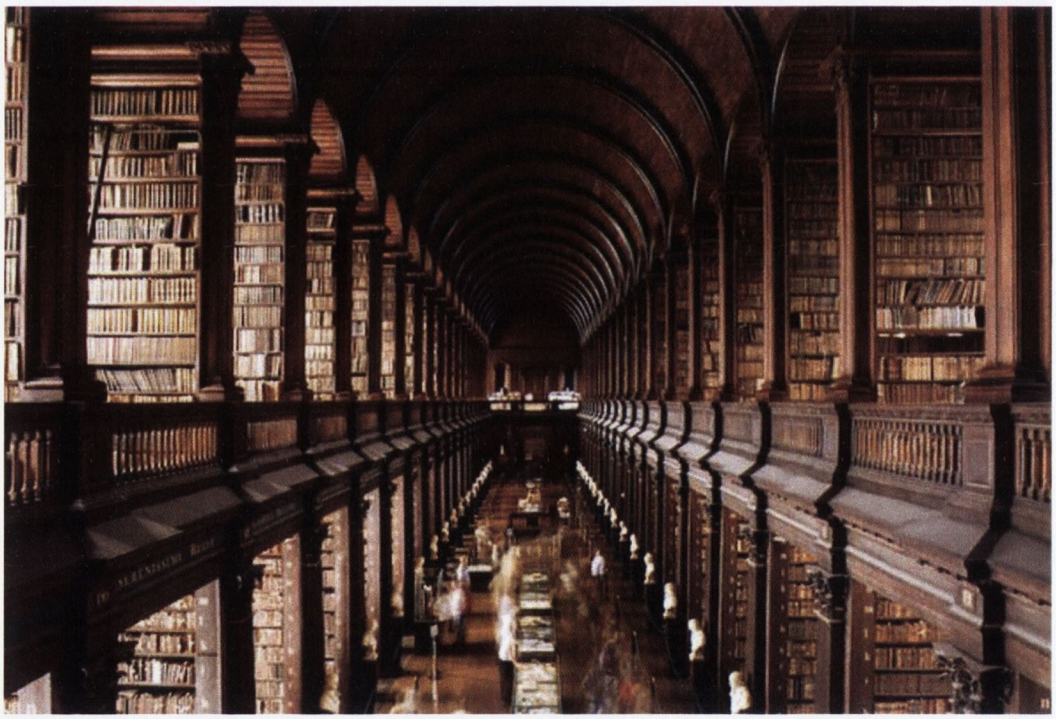


Fig. 6-3: View from gallery level of the Long Room (TCD, 2011)

By 1850 the Long Room floor had begun to sag, which in turn began to negatively influence the vertical alignment of the walls in the building. In 1859 the building had reached capacity and the Dublin based architects Deane and Woodward were tasked with altering the Long Room to increase capacity while reducing the structural damage to the floor and external walls that was being caused by the mass of the collection. Their solution involved changing the Long Room to its current configuration. They added shelving to the gallery level while replacing the flat ceiling over the central aisle of the Long Room with a grand barrel vault, a

feature which may also be observed above the alcoves resulting from the additional shelving at the gallery level.

Marble busts line the Long Room, the first fourteen of which were commissioned in 1743 from the sculptor Peter Schemakers. The busts are of great writers and philosophers of the western world and also of men connected with Trinity College Dublin, both famous and not so famous. The finest bust in the collection is that of the writer Jonathan Swift by Louis Roubiliac (TCD, 2011). The space also houses a number of other treasures including one of the few remaining copies of the 1916 Proclamation of the Irish Republic that Padraig Pearse read outside the General Post Office on April 24th 1916. A harp, the oldest of its kind in Ireland and dating from the 15th Century and which is the model on which the emblem of Ireland is based is also displayed.

6.2. Environmental Conditions in the Old Library during Zero and Low Occupancy Periods.

6.2.1. The Long Room

Having defined and validated the signatures associated with a range of environmental stimuli, either through the conducting of small-scale signature experiments or through observation of trends in the Museum Building, it is now possible to apply this knowledge to the primary case-study, namely, the Old Library in TCD. The objective of monitoring the Old Library is to determine the major factors influencing the environmental conditions in the building. This information will then be used to recommend alterations to the building with a view to improving environmental conditions in the building and extend the life span of the collection items contained within.

In order to assess the influence of solar gains, the metabolic processes of people and mechanical heating on the indoor environment in the Old Library, it is first necessary to evaluate the environmental conditions during a period of zero occupancy. As a means of fully identifying the influence of the various parameters mentioned above, data collected during two different time periods will be examined, namely the closed period itself, which corresponds to the Christmas vacation (24/12-03/01) and the reopening phase (04/01-07/01). Where relevant, data obtained prior to the building closing (20/12-23/12) will also be presented and discussed. During the closed period of monitoring, occupancy levels were zero and mechanical heating to the building was not in operation. For a description of the

location of each data logger in the building the reader is referred to Section 3.5 and Appendix B.

6.2.1.1. Temperature Baseline

Fig. 6-4 illustrates the T variations recorded at Logger H (central Long Room, ground floor) in the Long Room between 20/12 and 23/12, during which time low occupancy levels are observed and daily mechanical heating is in operation in the building between 07:30 and approximately 16:30. External weather conditions over the course of this period were cloudy on each day with the exception of 22/12, which was partially cloudy. Snow showers were also noted daily during this monitoring period. T values observed externally range from -5°C to 2.5°C. Despite the mechanical heating and presence of people, T values in the Long Room are low.

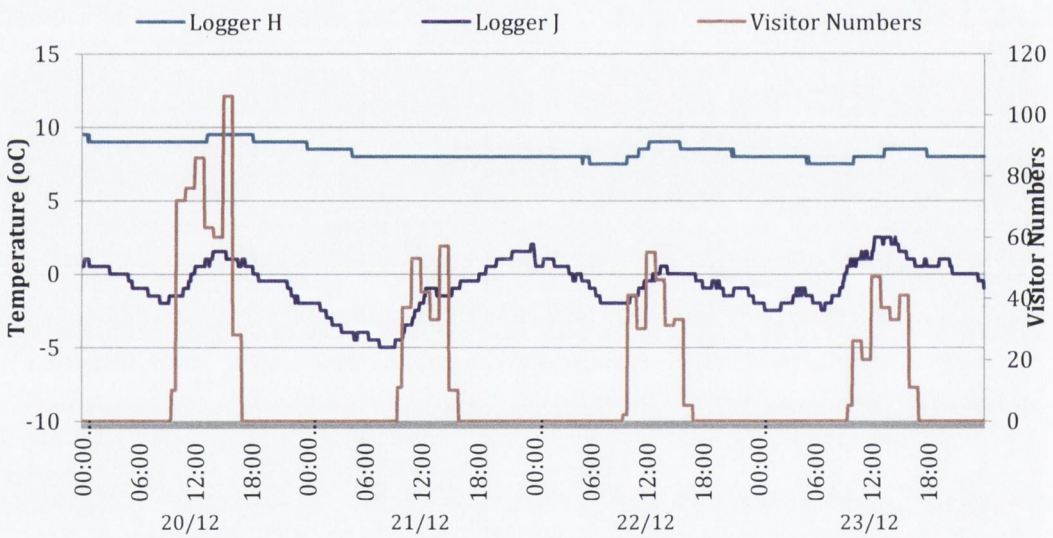


Fig. 6-4: Temperature data collected in the Long Room between 20/12 and 23/12. This time is immediately prior to the Christmas vacation.

T values recorded at Logger H during this time provide a good overall representation of T fluctuations observed in the Long Room during this pre-Christmas monitoring period. At the start of recording, a T of 9°C is noted at Logger H and this value remains constant until approximately 13:00 on 20/12 when a small increase is observed. Considering that the mechanical heat source in the building had been operating since 07:30, the delay in a T increase in the room may be surprising, as is the low value of the average ambient T.

Given that a large temperature gradient exists, ranging in magnitude from 8°C to 11°C, between the Long Room and the external conditions, thermal losses from the building are high and the heat loads due to mechanical sources are insufficient to increase T at this time. The internal thermal mass in the area, due to the books as well as the building envelope, regulates T in the room, preventing a decrease in T and maintaining equilibrium, despite the large T gradient. It is also worth noting that a total of ten storage heaters provide mechanical heat to the room. Of these heaters, six are located centrally in the space and are encased by large timber benches and two additional heaters are located at each end of the room. Given the magnitude of the room and the extent of its losses, these heaters are inadequate to overcome the thermal losses due to the large temperature gradient, observed at the time, resulting in no gain in T. A similar trend in the internal T is observed on 21/12 as a result of the temperature gradient where constant T conditions are observed throughout the day as the combined effect of thermal mass and mechanical heating offsets the thermal losses from the building resulting in equilibrium in the room.

As mentioned previously, external conditions on 22/12 were noted as partly cloudy, the only day during the given time period when such conditions were observed for an extended period. As a result, the diurnal T variations differ to those observed throughout the remainder of the monitoring time and resemble conditions that would be typically expected (i.e. a diurnal deviation in T from constant values). As with the other days monitored during this interval, mechanical heating in the building is in operation from 07:30. Internal T begins to increase, albeit slowly, from 10:00, which is approximately 3.5 hours earlier than observed on other cloudy days during this testing. Large T variations between inside and outside, ranging from 5.5°C to 10.5°C, are also recorded on 22/12, however, T conditions recorded at Logger H are observed to increase from 7.5°C to 9°C. Although this increase is small in magnitude, when compared to the diurnal variations observed during the two previous days and considering that visitor numbers are lower on 22/12 relative to the other days, it illustrates that heat loads due to solar effects in the Long Room have some influence on thermal conditions in the room, albeit small. T conditions in the Long Room decrease slightly shortly after the heat source to the building is deactivated at approximately 16:30. The reduced internal heat loads coupled with thermal losses to the exterior result in the T drop observed during this time. The thermal mass then regulates the T at a value of 8.5°C as equilibrium is reached in the space. It should also be noted that a larger T change due to solar influences would be expected in the Long Room, owing to the large glazed area, particularly on the south of the room. The reason that solar gains result in only small T changes is due to the light coloured blinds and the low emissivity film that has been retrofitted to the windows on the south side of the building. As a result of these interventions, heat gains in the space due to solar effects are limited as light is reflected back

through the windows by the blinds while the low emissivity layer reflects infrared light back out through the window, thus reducing potential solar gains.

Fig. 6-5 illustrates the T data collected between 24/12 and 01/01, which represents the majority of the time period when the Old Library was closed for the Christmas vacation. At this time the electric storage heaters that supply heat to the Long Room were also switched off and thus the only heat loads to the space were from solar gains and infiltration, if applicable.

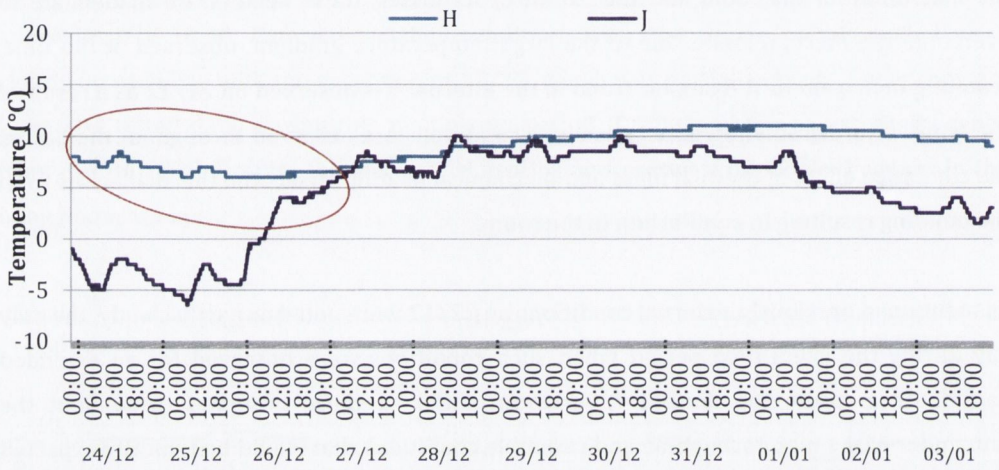


Fig. 6-5: Temperature data collected at Logger H in the Long Room and externally (Logger J) during period of unoccupancy of the Old Library

Given the nature of the T gradient, generally there is no load in the building arising from heat infiltration as the external conditions remain below those in the building for the majority of the monitoring period. The first two days displayed in Fig. 6-5 (24/12 and 25/12) observed extremely low external conditions, as indicated by Logger J, and a minimum T value of –6.5°C was recorded at approximately 09:00 on 25/12. This induced a large T difference (approximately 13°C) between the Long Room and the external environment and thus there was potential for relatively high heat losses from the building.

Accordingly, T in the Long Room decreases by approximately 2°C over these 2 days, which is a slow rate considering the large T gradient. This slow rate of decrease is a result of the large thermal inertia in the building, not only by the thick dense walls but also by the vast quantity of books that are present in the space, a trend that is consistent with the signature defined for a room in which a large volume of books are located. Given that the external conditions on these two days were sunny, maximum T values (8°C on 24/12 and 7°C on 25/12) in the room were recorded between 12:00 and 15:00 and as such correspond to times of maximum sun intensity, indicating the small influence of solar gains on the internal conditions.

Considering the large percentage of glazed area on the south face of the building, the effect of the solar energy on the indoor T of the Long Room is modest, equating to a diurnal increase in T of 1.5°C on 24/12 and 1°C on 25/12. However, as aforementioned, the presence of a low emissivity film, coupled with beige coloured blinds on each window and the large volume of air in the space, effectively reduces the impact of solar influences on the T conditions in the Long Room. Moreover, the potentially large heat losses occurring from the building due to the low external T values is a further cause of the relatively minimal impact of solar gains on the space at this particular time interval.

Significant increases in external T conditions are observed on the 26/12 and the increased T is maintained until 01/01. Prior to the increase in T observed from 26/12, T values in the Long Room had begun to stabilise from late on 25/12. T increases occur from approximately 06:30 on 26/12, albeit slowly as a constant value of 6°C is recorded until 26/12. As discussed previously, the rate of change of T in the space is slow as a result of the large thermal mass of the space. As the external T increases by 4.5°C between late 25/12 and early 26/12, the large T gradient that had been previously observed between the external and internal environments is significantly reduced, particularly as the external T continues to increase on the 26/12. A maximum external T of 4.5°C, equating to a 9°C net increase in external T over the course of the day, is observed on the 26/12, and the external T continues to rise over the following days. Given the large reduction in the temperature gradient recorded at this time, internal heat losses are significantly decreased, resulting in a modest increase in the internal T between 26/12 and 31/12 at which point equilibrium is reached at a value of 11.5°C. During this time period, conventional internal heat loads are not present, the internal thermal mass slowly releases its stored heat energy. Before 26/12, a large thermal gradient between inside and outside exists and, accordingly, thermal losses from the building are relatively high. Once external T conditions increase, the losses from the building are reduced. As the thermal mass continues to release its stored heat energy and as the losses are smaller, the internal T begins to rise. As the heat is slowly released, however, the increase in T occurs at an extremely gradual rate, increasing by 5°C over the course of 5 days. Once again, this relatively slow rate of change in T conditions corresponds to the influences of thermal mass and, furthermore, to the signature associated with a large volume of books in a space, as illustrated in the study of the Museum Building in Section 5.5.

Fig. 6-6 depicts the T conditions recorded at Logger H in the Long Room between 01/01 and 07/01. Given that the Old Library reopened to staff and the general public on 04/01, this particular chart facilitates comparison of conditions when the building is closed and subsequently occupied.

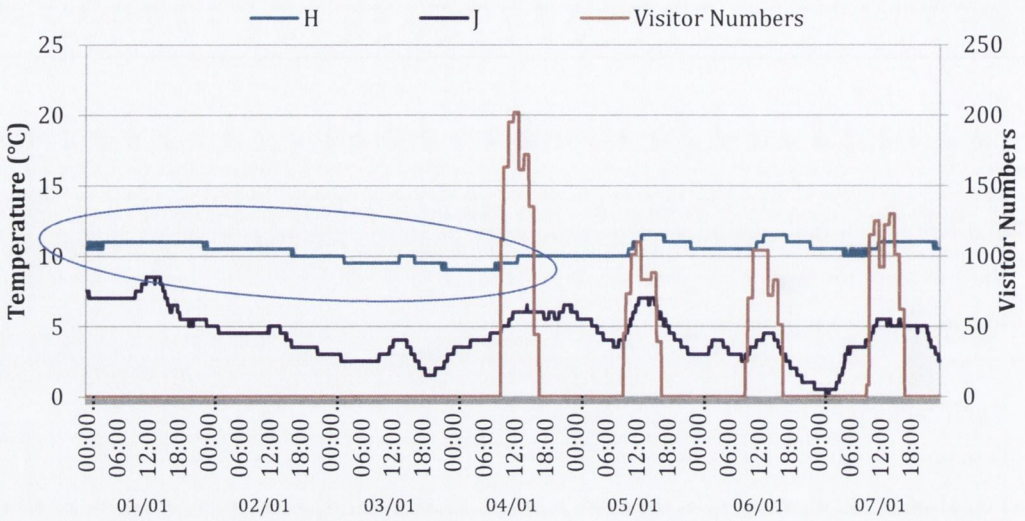


Fig. 6-6: Temperature data collected in the Long Room between 01/01 and 07/01. The building became occupied again on 04/01.

The Old Library reopened to staff and the public following the Christmas vacation on 04/01 and, accordingly, two new heat loads were applied to the building, namely mechanical heating and heat loads associated with occupancy. Referring back to the small-scale signature experiments, it would be expected that, in terms of defining diurnal T trends in the Long Room, the presence of mechanical heating would be considerably more effective than occupants in inducing a measurable change in T in the space. Furthermore from the analysis of the environment in the Civil Engineering Library (Section 5.5), it would be expected that the heat sources would have a relatively small impact on the T in the area as a result of the thermal mass. Not only does this feature of the building slow the rate of heat loss when the building is unoccupied and unheated, it also regulates the rate of heat gain in the space leading to the slow T increase equating to the 1°C increase over the course of the day to a maximum T value of 10°C.

Another reason for the slow rate of increase in the room may be attributable to the large air volume in the space coupled with the low capacity mechanical heat source. Six relatively small electric storage heaters (approximately 2kWh each) are located centrally in the Long Room and are built into wooden benches, which absorb the heat emitted from the storage heaters in the short term. An additional four storage heaters are used in the Long Room, however the heat output of these is modest in comparison to the volume of air contained in the Long Room. Furthermore, the attic space is very poorly insulated; hence heat that is not absorbed by the benches, books or walls will generally escape through the ceiling (where environmental conditions in the attic are comparable to those externally) as well as the relatively large external area that comprises leaky, single glazed windows. Given the low T

values observed in the Long Room throughout this particular monitoring period it may be concluded that the mechanical heat sources in the space are insufficient to maintain occupant comfort conditions during the winter period. However, in terms of providing correct thermal conditions for the collection contained within the area, the low magnitude of T variations for the preservation of the collection as diurnal variations are typically lower than the recommended 5°C as described in Section 2.6.

When normal heating and occupancy schedules return to the Old Library building on 04/01, it may be assumed that a large amount of the heat energy stored in the thermal mass, both due to the books and also the dense external walls, has been released into the Long Room and so the stored energy remaining in the thermal mass is relatively low. When the heating is reactivated on 04/01, low initial gains in T in the Long Room are observed as the heat energy is absorbed by the thermal mass to replenish the stored energy that was lost during the Christmas vacation. Accordingly, a reheating phase is observed where diurnal variations in T between 04/01 and 07/01 are low in magnitude. It is observed, however, that the daily T values are increasing modestly day on day as the building begins to heat up once more. Night-time T values are also increasing night on night as the thermal mass continues to regulate T fluctuations in the Long Room.

The final parameter that requires consideration is the influence of occupancy on T. For the given recording period occupancy levels are highest on 04/01 (1183) and again on 07/01 (755) with the two remaining days having visitor numbers of 622 and 613 respectively. Despite this, the internal T conditions are highest on the days of lower occupancy, which happen to correspond to the days of highest solar intensity. Considering this observation, it appears that solar intensity has more influence on internal T conditions than the occupancy levels. This observation is consistent with the findings of the small-scale occupancy test as discussed in Section 4.6 where the presence of people was observed to have little effect on the thermal conditions of the indoor environment when compared to mechanical heat sources or, as described in Section 5.3, the effect of solar gains.

The T variations observed in the Long Room over the Christmas vacation, as well as the period immediately before and after this interval, illustrate the value of defining the environmental signatures when analysing the thermal conditions in a building. Throughout the monitoring period, fluctuations in T occur slowly and are low in magnitude despite a relatively large T gradient that would generally be expected to result in high heat losses from the building, especially as there is a relatively large glazed area on the external walls and the attic is poorly insulated. Considering the signature associated with a large volume of books in a space, this effect is expected for the Long Room. Furthermore, the mechanical

heat sources in the room are the dominating factor in determining T variations in the space when heated; however, given the volume of air in the space and the extensive thermal mass, increases in T associated with the mechanical heat source are modest. As observed previously, the presence of people does not induce a significant heat load to the building. Accordingly it may be concluded that, during this data collection interval, the general behaviour that would be expected from the signature tests and subsequent analysis of the Museum Building is observed in the Long Room.

6.2.1.2. Humidity Baseline

RH conditions in the Long Room, recorded at Logger H over the duration of the Christmas vacation, are displayed in Fig. 6-7. In the case of this chart, relatively small RH fluctuations are observed (consistent with the T trends discussed previously).

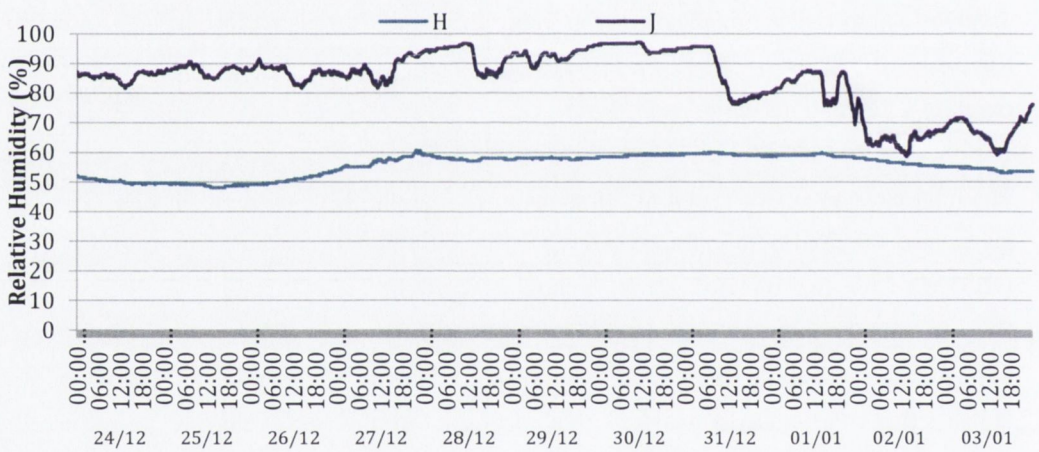


Fig. 6-7: Relative Humidity data collected at Logger H in the Long Room during period of unoccupancy of the Old Library

As illustrated in Fig. 6-8, there is a large variation in the external H_{abs} over the course of this particular monitoring period where a minimum value of 2.55g/m^3 is calculated on 25/12 and a maximum of 8.93g/m^3 on 30/12. Since there are no additional moisture loads induced in the space, the changes in H_{abs} observed in the Long Room are a result of infiltration and exfiltration occurring through the building fabric itself through cracks, gaps and diffusion within. On 24/12 and again on 25/12 (circled in blue), external H_{abs} conditions are lower than those in the Long Room resulting in moisture in the Long Room exiting the space according to the moisture gradient induced between the two areas. This is expected when the moisture gradient and given that no additional loads are present in the space during this time period.

At approximately midnight on the 26/12, external hygrometric conditions change and a rapid increase in H_{abs} of 1g/m^3 is observed over a short period of 2.5 hour, which effectively reverses the moisture gradient and forces humidity infiltration into the space. The effect of this reversal is detected in the Long Room shortly after the direction of moisture transfer was reversed. External H_{abs} continues to rise over the next 5 days, although the rate of increase fell on the 28/12. Diurnal fluctuations also occur over this time, however, the differences between the indoor and outdoor conditions remain relatively large, ranging from 2.00 g/m^3 to 3.00 g/m^3. During this interval, moisture leaks into the building from the external environment and, hence, the internal H_{abs} is observed to increase from 3.41g/m^3 to 5.66g/m^3 due to the increased moisture load that can be attributed directly to the infiltration. This trend in internal H_{abs} suggests a strong relationship between the internal and external humidity conditions. Unlike the external conditions, however, the change in internal H_{abs} appears to occur at a relatively slow and uniform, rate, which is most likely regulated by books and furniture in the space, which absorb some moisture as it enters the Long Room, as would be expected from the hygroscopic materials signature from the study of the Civil Engineering Library.

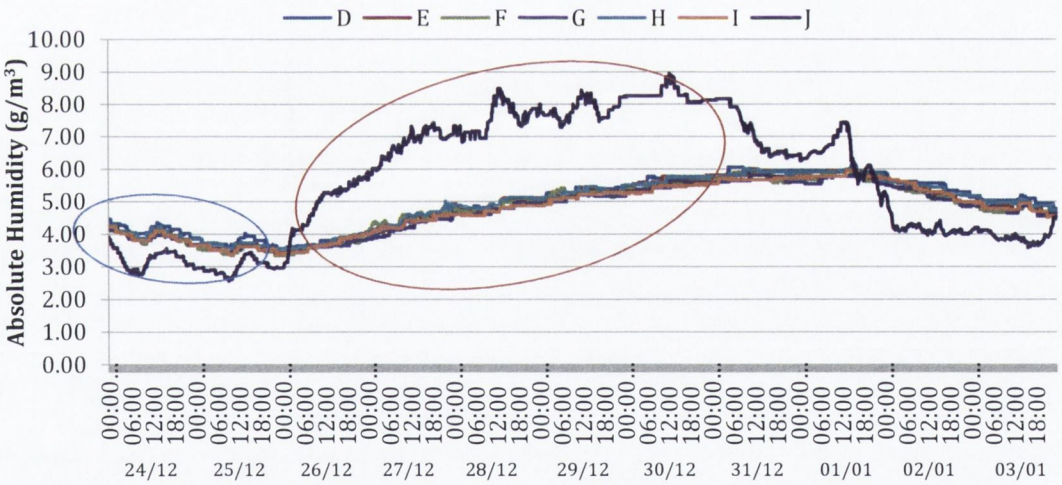


Fig. 6-8: Absolute humidity data calculated for the Long Room during period of unoccupancy of the Old Library

As well as this, a slow leakage rate in and out of the Long Room through the walls, windows and ceiling is another factor that may be contributing to the slow rate of change of H_{abs} in the Long Room. Should one (or more) of the windows in the area be opened, the rate of change of H_{abs} is likely to increase considerably as illustrated in the open window test described in Section 4.5. One further factor that may be responsible for the slow rate of increase in H_{abs} observed in the Long Room may be the volume of air in the space itself which may reduce the rate at which H_{abs} approaches equilibrium with the external environment when

compared to a smaller room. On 31/12, external H_{abs} conditions drop rapidly by 1.66g/m^3 (8.15g/m^3 to 6.49g/m^3) in a few hours, thus reducing the moisture gradient with the Long Room, where a (negative) difference of approximately 0.70g/m^3 is now observed. Accordingly, this results in a reduced rate of increase in internal H_{abs} as equilibrium between inside and out is approached.

Despite increasing again briefly at the start of the day on 01/01, no further noteworthy increases in H_{abs} occurs in the Long Room during this particular period. At approximately 13:30 on this day (01/01), however, a rapid decrease in external H_{abs} once again occurs and by 21:00, external moisture conditions have fallen well below those in the Long Room, hence reversing the direction of the moisture gradient again (Fig. 6-9). As a result, moisture is lost from the Long Room to the external environment at a faster rate than the corresponding rate of increase. Hence it can be concluded that during times of unoccupancy and assuming that no other major moisture source is present in the Old Library, H_{abs} conditions in the Long Room change primarily in accordance with the direction of moisture gradient between the internal and external environments, at a rate that is dependent on the magnitude of the gradient itself, the leakage rate and moisture absorption and evaporation internally from hygroscopic surfaces.

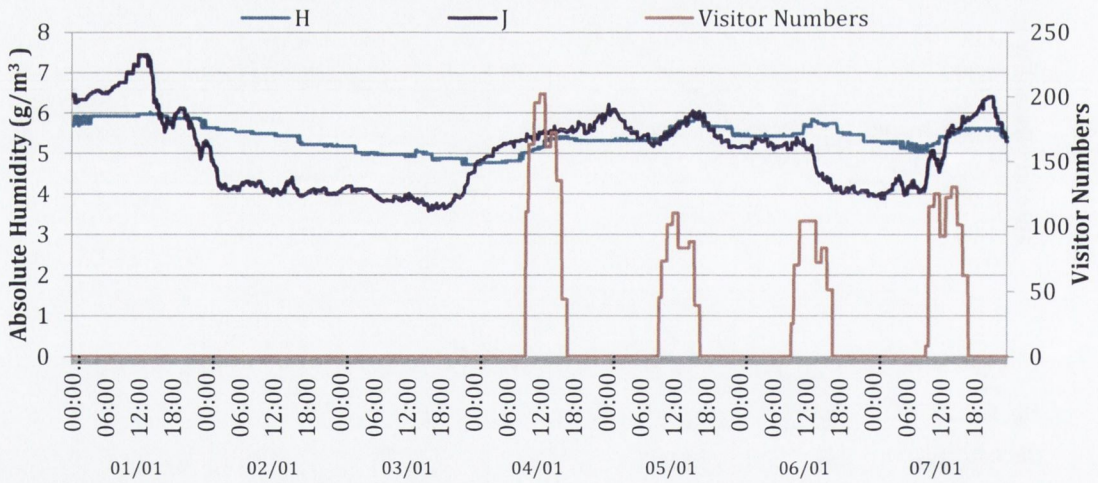


Fig. 6-9: Absolute Humidity conditions calculated for the Long Room between 01/01 and 07/01 including visitor numbers.

Although it would be expected that the H_{abs} conditions in the Long Room would closely follow those externally, the stable trend and slow rate of change in the space may not have been expected. Referring back to the analysis of the thermo-hygrometric environment in the Civil Engineering Museum (Section 5.5), however, the stability of the H_{abs} environment in the Long Room during this time interval is unsurprising. The hygroscopic properties of the

books that are stored in the Long Room are effective in regulating the moisture conditions in the room, thus resulting in the stable environmental conditions observed in the building at this time, despite the relatively large moisture gradient between the Long Room and the external environment (particularly during the time period circled in red on Fig. 6-8).

Once the building reopens following the Christmas vacation, the variations in H_{abs} described previously change as occupancy leads to additional moisture loads being induced in the building. From the occupancy signature, it would be expected that the presence of people in the Long Room would result in relatively large perturbations in the H_{abs} conditions in the building, however these would be fluctuations about a general trend. H_{abs} data from 06/01 give a good insight into the influence of people on the internal humidity parameters. Here, the external H_{abs} conditions are generally marginally lower than those in the Long Room and hence exfiltration of moisture from the Long Room to the external environment results in a corresponding reduction in internal H_{abs}. The presence of people in the space, however, prevents this expected behaviour from occurring as their metabolic processes induce a moisture load in the space resulting in deviations from the background trend.

Considering Logger E, which is located at gallery level in the central compartment of the Long Room, the influence of people on the humidity parameters can be assessed more clearly. Fig. 6-10 illustrates H_{abs} data calculated at Logger E between 04/01 and 06/01 and is divided into four different phases, which are indicated by the blue, red, green and purple regions on the chart. By comparing the H_{abs} variations illustrated at each phase, the effect of infiltration of moisture, evaporation and absorption by hygroscopic surfaces and moisture loads due to the presence of people may be identified.

Phase 1, as illustrated on Fig. 6-10, refers to the time period from 07:00 to 17:00 on 04/01. A small moisture gradient of $0.51g/m^3$ exists between the inside and outside initially. Mechanical heat is in operation in the Long Room from 07:30 and a small increase in T is noted at 08:50, corresponding with an increase in H_{abs} that is larger than would be expected due to infiltration of moisture at this particular time. Given also that the building is empty at this time, occupancy can be discounted as a reason for the sudden change in rate.

From 09:30 onwards, H_{abs} conditions at Logger E continue to increase steadily, however, given that there is a moisture gradient and people presence in the room, it is difficult to identify whether the increase in H_{abs} is due to either one or both effects and whether one is more significant than the other.

Phase 2, illustrated by the red region gives an interesting insight into the effect of external conditions on the internal environment over a short time period. Between approximately 20:00 on 04/01 and 04:30 on 05/01, there is a sudden, relatively large, fluctuation in external H_{abs}, where the value increases from 5.52g/m^3 to 6.08g/m^3 over a time period of approximately 5 hours before returning to a value of 5.49g/m^3 at approximately 04:30. When external H_{abs} is at a maximum value, a moisture gradient of 0.79g/m^3 exists between the Long Room and the external conditions. During this time, however, humidity conditions remain constant with minor perturbations noted when the maximum external H_{abs} are observed. As a low leakage rate exists from within the Long Room to the external environment, the moisture gradient was not large enough in magnitude or in place for sufficient time to influence H_{abs} in the Long Room during this phase of measurement. Furthermore, the presence of a large volume of hygroscopic materials in the space is effective in regulating the H_{abs} conditions in the space, as discussed previously.

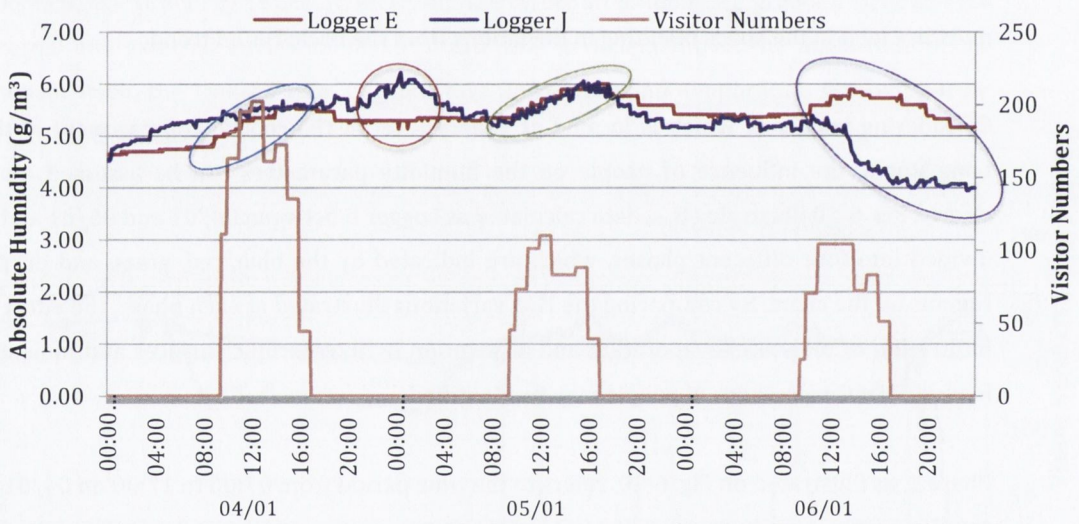


Fig. 6-10: Absolute Humidity calculated for Logger E in the Long Room between 04/01 and 06/01 including visitor numbers. Phases 1 to 4 are illustrated by the blue, red, green and purple regions respectively.

The importance of people on the moisture conditions in the Long Room is illustrated during Phase 3 of this measurement stage. Although external H_{abs} conditions are also observed to increase during this phase, as outlined previously, the moisture gradient is not large enough to have a significant influence on the internal conditions. H_{abs} at Logger E, however, is observed to increase measurably throughout the day, despite visitor numbers remaining relatively small. In total, an increase in H_{abs} of 0.65g/m^3, rising from 5.34g/m^3 at 09:30 to 5.99g/m^3 at approximately 16:45, which corresponds to a rate of approximately 0.10g/m^3/hour. When the Old Library closes at 17:00, humidity conditions in the Old

Library begin to fall once more as the moisture load due to people is removed from the space, returning to a value of 5.36g/m^3 at approximately 05:00, a rate of 0.05g/m^3/hour, a value that is half that of the rate of increase due to people owing to the relatively small moisture gradient between inside and outside but also due to the slow leakage rate from the building. Upon examining Phase 3 and comparing it to Phase 2, it may be concluded that, when the moisture gradient between inside and outside is relatively small and short lived, H_{abs} in the Long Room remains constant. However, when people are present, the moisture load is sufficient to noticeably increase the H_{abs} value in the area, however, as was observed in the small-scale experiments and subsequent analysis of the Museum Building, such behaviour is the signature associated strongly with occupancy. This is further illustrated and confirmed on 06/01 (Fig. 6-10, Phase 4) where the presence of large numbers of people in the Old Library can have a more significant influence on the humidity parameters in the building than the external moisture conditions. However, once the building has emptied, moisture moves slowly according to the moisture gradient that exists naturally between the internal and external environments, an observation that is consistent with the findings of the occupancy signature test.

Of the signatures defined previously, in terms of the hygrometric environment in the Long Room over the course of the data collection stage discussed to date, the relatively stable environmental conditions in the space mean that only the signatures associated with a large hygroscopic area (in this case the large volume of books) as well as the influence of occupants are identified in and relevant to the Long Room during this time interval. A matter of concern for the preservation of the space, however, is the frequency with which the RH conditions in the space exceed the limits specified by the Smithsonian Institute and BSI respectively (37% and 53% RH limits or variations not exceeding ±10% RH). For the continued preservation of the collection contained within the Long Room, increased control of the thermo-hygrometric environment in the room is required.

6.2.1.3. Characterisation of the Current Environmental Conditions in the Long Room

As mentioned in Section 2.6, Michalski (2003, 2007) developed the concept of environmental classification in museums and libraries, which were labelled as AA, A, B, C and D and published by ASHRAE (2011) This concept was developed into a visualisation tool for climate assessment by Martens et al. (2006) who defined the Climate Evaluation Chart (CEC). Accordingly, a CEC was developed based on the environmental conditions recorded in the Long Room during this project using an open-source online tool that was developed by Smulders and Martens (2014) and are displayed in Fig. 6-11.

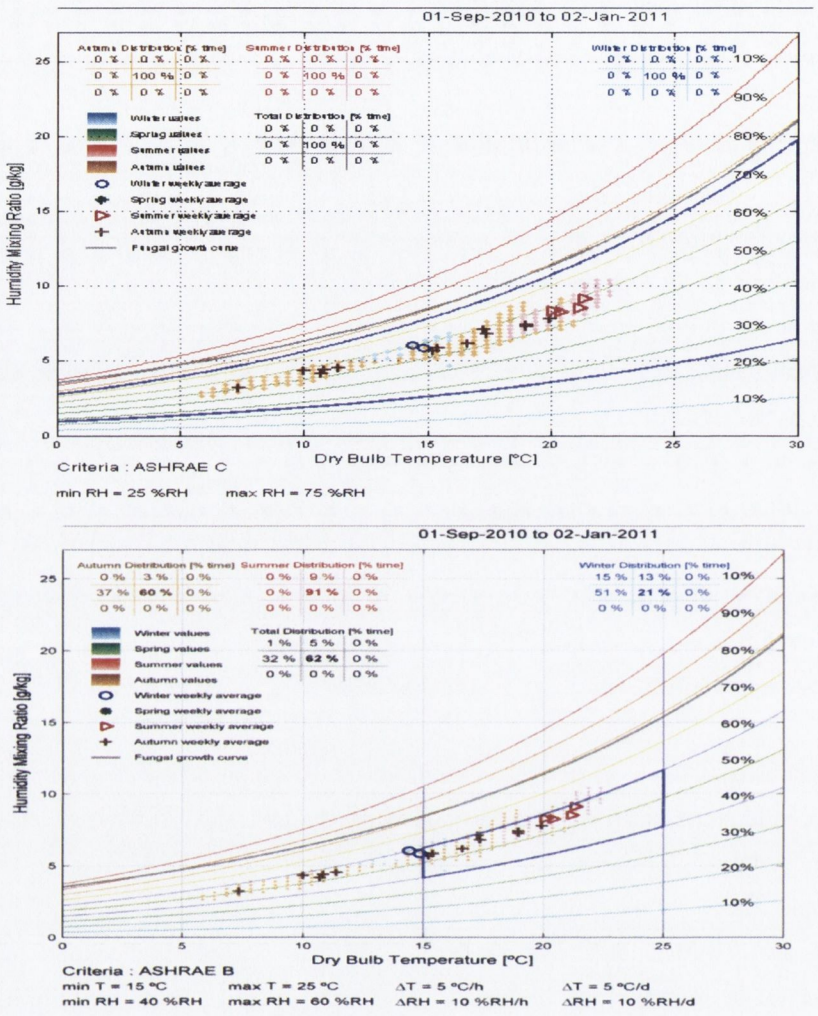


Fig. 6-11: Climate Evaluation Charts developed for the Long Room and displaying the limits for Environmental Classification C (top) and B as specified by ASHRAE (2011).

From Fig. 6-11 it can be seen that, currently, the environmental conditions in the Long Room fall into category C, which specifies RH values between 25% and 75% with a T maintained below 25°C. All environmental readings obtained within Long Room during the monitoring period fall within this range. As mentioned in Chapter 2, the current environmental conditions in the building are resulting in unacceptable damage to the collection and, hence it is clear that a category C environment is unsuitable for the Long Room. Given the nature of the building, it is unreasonable to expect environmental conditions to be improved greatly, as the installation of plant in a building such as the Old Library will have an unacceptable effect on the character of the building. As a result, it may only be possible to improve the environmental classification to a B, which implies environmental variations of ±10% RH and ±5°C.

From Fig. 6-11, it can be seen that the major reason that current conditions fall short of a B classification is due to the unacceptably low thermal conditions that are observed 37% of the time as well as the excessive RH observed in 9% of the readings. Furthermore, seasonal variations in both T and RH are large, which is not compatible with preservation of the collection. In order to improve the environmental conditions in the Long Room and thus improve the permanence of the collection, measures to address the large seasonal variations in both T and RH are required.

6.2.2. Occupied Public Ground Floor Rooms

Occupied ground floor rooms in the Old Library refer to those that are open to the general public. In total three such areas are considered, namely the visitor shop (Loggers L and M), the passageway between the shop and exhibition space (Logger O) and the exhibition space located in the western compartment of the building (Logger S) (refer to Appendix B for context). Of these areas, the shop is the only one that is subjected to the effects of solar gains. Loggers L and M are also located in different areas of the shop, Logger L being situated beside the open staircase that links the shop to the Long Room and may be influenced by air flow up the stairs while Logger M was placed behind the ticket desk in the interior of the room. Logger O is placed in a short narrow passageway that functions as the barriered entrance to the exhibition space and, accordingly, all visitors in the building pass through this corridor. Finally, Logger S is located in the Book of Kells' exhibition room. As aforementioned, Logger J measures the external environmental conditions over the duration of the monitoring period.

6.2.2.1. Temperature Baseline

Fig. 6-12 displays the T variations that occur at the ground floor sensor locations during the Christmas vacation. The heating system in the building was turned off one day prior to the commencement of the data collection period. Hence on 24/12 and 25/12, T is observed to fall across all loggers at approximately the same rate and is driven by the removal of the mechanical heating as well as the low external T values and equates to a total reduction of between 3.5°C and 4°C.

The difference in T values observed in the different occupied areas is apparent from Fig. 6-12. Logger O consistently records the highest value of T throughout the test period followed by Loggers M and L. Logger S observes the lowest T over the entire duration of the

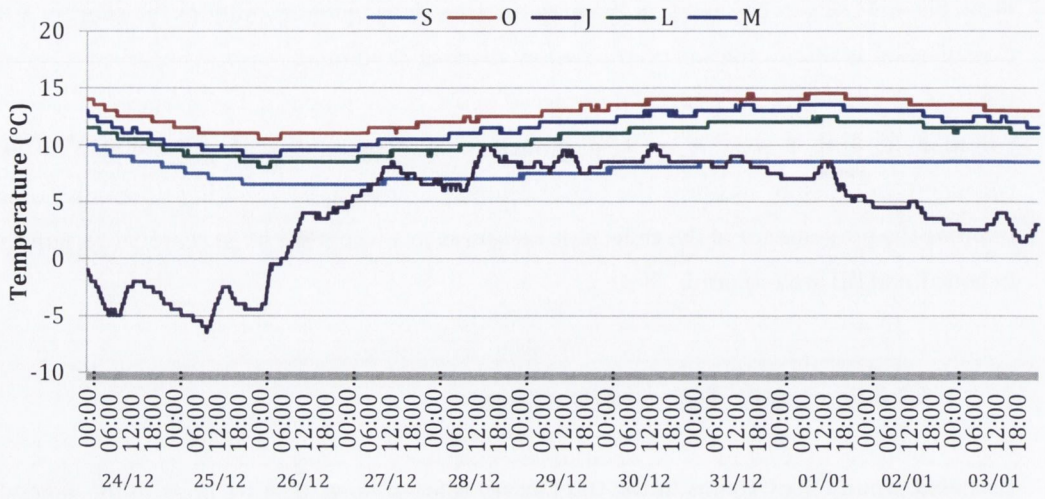


Fig. 6-12: Temperature conditions in occupied ground floor spaces in the Old Library during the Christmas vacation.

recording period. Furthermore the T trends for Loggers O, M and L are all very similar, which is expected given their locations in close proximity to each other. Logger O is located in a small internal passageway and, as such, the temperature gradient between the internal and external environment do not directly influence the thermal environment at this location. This corridor is more likely to benefit from heat flow from adjacent spaces and subsequently to the external environment resulting in the higher T observed at Logger O in Fig. 6-12.

Despite being located in the same room, a slight T difference exists between Loggers L and M. This is a result of their locations in the room. Logger L was located beside the stairs linking the ground floor to the Long Room and, hence, may be subjected to heat and airflow between the two levels in the building, which would act to reduce the T at this location as heat rises from the shop and into the Long Room. Logger M on the other hand is sheltered from such effects and, thus, the T observed at this data logger is higher. It may also be noted that the general T trend at these three locations is similar to those observed in the Long Room over the same time period as presented in Section 6.2.1.1, however, it should be mentioned that the difference in T between Loggers L and M during this time generally fall within the sensitivity of the device.

Logger S on the other hand does not observe the diurnal trend recorded at the other sensors, other than on 24/12 and 25/12. Because of the sensitive and delicate contents in the Book of Kells' room, it has been modified so as to prevent any sunlight and pollutants entering the space from the external environment, a measure that was achieved by comprehensively blocking up the windows in this particular zone. Furthermore, a modest HVAC system is also located in this area of the building that is intended to further regulate the environment in

the BOKE, although it was deactivated for the duration of the Christmas vacation. Hence the variations in the external weather conditions do not appear to have a significant influence on this space as indicated in the trends for Logger S in Fig. 6-12. The rate of increase at this location from 26/12 is much slower than that observed in the other areas and the external T is seen to reach a higher value than Logger S at various periods between 27/12 and 31/12 without any apparent effect on its T. The very slow rate of increase of T at Logger S indicates that this area is well insulated from the external environment.

As a means of observing the different thermal behaviour at each monitoring location, data obtained on 06/01 will be discussed. As mentioned previously, a mechanical heat source in the building is turned on at 07:30 on the morning of 06/01 and is left on until approximately 16:30. External T conditions throughout the day remain relatively low, reaching a maximum value of 4.5°C at approximately noon before subsequently falling to a value of 1°C at approximately 20:30.

The highest initial internal T values are observed at Logger O (15.5°C). This is followed by Logger M (14.5°C) and Logger L (13°C) despite their location in the same room. The lower T value observed at Logger L is due primarily to its location, in close proximity to the central staircase. Heat is free to flow up this central staircase and into the Long Room, which (as shown in Fig. 6-13) typically observes a lower T than the shop. As a result a T gradient exists between the shop and the Long Room and heat is lost from the shop through the central staircase and into the Long Room resulting in the disparity in T values in different areas of the shop.

Logger S has an initial T value of 12°C while conditions in the Long Room are 11°C at the beginning of measuring. Due to the low external T conditions, the temperature gradient between the internal and external environment is high, however the slow leakage rate observed in the Long Room and discussed earlier is also observed at the ground floor level of the building, as practically no reduction in T is observed over the course of the night, during which time there is no heating in the building. Given that the corridor in which Logger O is placed is open to the shop area, a temperature gradient is also observed between these two areas, as T at Loggers M and L are initially lower than those at Logger O.

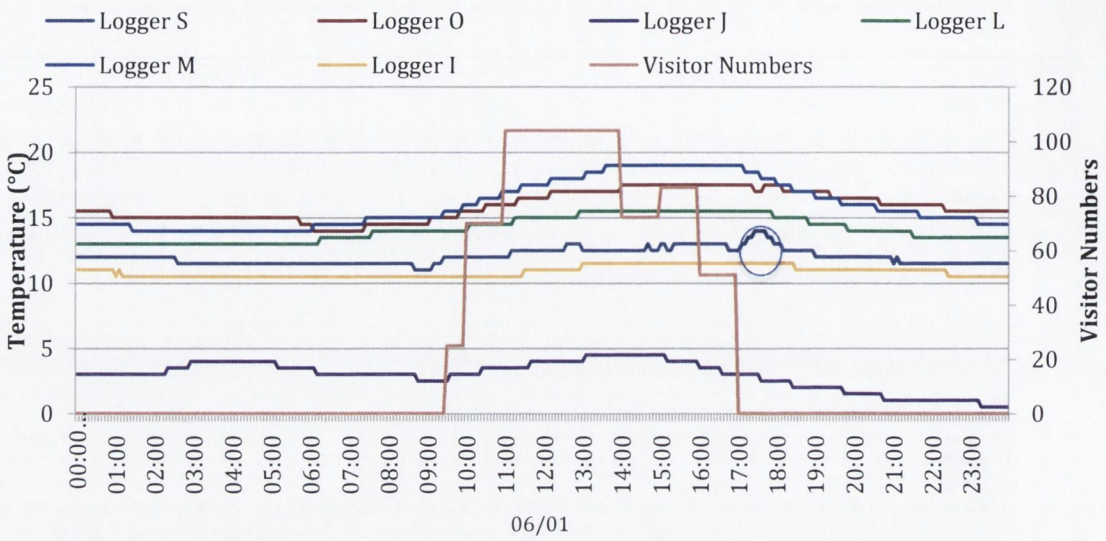


Fig. 6-13: T data recorded on the ground floor on 06/01 as well as T in the Long Room (Logger I).

When the mechanical heat source to the building is turned on at 07:30, T at Logger M is recorded at 15°C. A steady rise in T at Logger M is observed between approximately 09:30 and 13:30 when a maximum value of 19°C is recorded, an increase of 4°C (or an average rate of change of 1°C/hour). The initial rate of change in T in the shop results in an increase in T from 15°C to 17°C between approximately 09:30 and 11:00. At 11:00 T begins to plateau as an increases to 18°C is observed between approximately 11:00 and 12:15. At this point, however, external cloud conditions clear somewhat, facilitating solar gains in the shop. Accordingly T increases to 19°C between approximately 12:30 and 13:30, a value that remains for the duration of the open period of the building. At this point, solar influences no longer apply as cloud cover is observed once again and the rate of heat gain is the same as the rate of losses resulting in the constant T observed for the rest of the day. The rate is not observed to change when people are present indicating that the mechanical heat load, in tandem with solar influences, are the most important in determining diurnal T variations at Logger M, a finding that is consistent with the signatures arising from occupancy testing in the Museum Building.

Logger O is observed to increase in T at approximately 09:50, indicating a brief lag between locations O and M, as the heat in the shop is turned on. The rate of increase of T is slower than that observed at Logger M as a total change in T of 2.5°C (15°C to 17.5°C) is observed between 09:50 and 14:00, a rate of just over 0.5°C per hour, half that observed at Logger M. Although heat flows from the shop through the passageway, given that the exhibition space is also colder still when compared to the corridor, the heat continues to pass from the corridor into the exhibition space resulting in the slower rate of increase observed at Logger O relative to Logger M.

Logger L, despite being located in the same area as Loggers O and M, exhibits a thermal response that is smaller in magnitude than the other Loggers in the space. From Fig. 6-13, it is observed that Logger L records lower maximum T values as well as smaller diurnal T fluctuations. Taking 06/01 as an example illustrates the different thermal responses observed at Logger L compared to the other zones. T at Logger L begins to increase at 10:00, rising from 14°C to 14.5°C. T continues to increase at a steady rate until reaching a maximum value of 15.5°C at approximately 13:00, a 2.5°C increase over the course of the day. This equates to a 3.5°C, compared to Logger M, and 2°C, compared to Logger O, difference in maximum diurnal T gain, despite being located in the same room as Logger M. In order to determine the reason for this different thermal behaviour in comparison to Logger M, it is also necessary to consider T in the Long Room. The reason for the smaller response noted at Logger L is a result of the location of the data logger, which is close to the stairs linking the shop to the Long Room. As can be seen from Fig. 6-13, the thermal gradient between the shop and the Long Room is maintained throughout the day, as a T difference of 4°C is observed between the two areas. As a result heat is lost from this space as it rises up the stairs into the Long Room thus reducing the impact of the mechanical heating on T and also accounting for the quicker rate of stabilization of T observed at this location. Consequently, this heat loss may be contributing to the low T values observed in the Shop over the duration of the monitoring period.

Once the Old Library is closed for the day and the mechanical heating is turned off (from 17:00), Logger M is observed to decrease in T at a higher rate compared to Loggers O and L. The initial rate of decrease over the first 2 hours following the building closing is 1.25°C/hour as T falls from 19°C at 17:00 to 16.5°C at 19:00. The rate then slows down as the thermal gradient between location M and the rest of the shop as well as the thermal losses are reduced. The rate then falls to 0.5°C/hour as T falls to 14.5°C at approximately 23:00. The initial rate of T drop recorded at Logger M is the highest observed within the Old Library during this test. Due to its location in close proximity to a heat source, the deactivation of mechanical heating will have a more pronounced effect on Logger M in comparison to the other loggers on the ground floor. When the building closed and the heating was switched off, an immediate drop in T in the areas surrounding the heater would be observed. This change was detected immediately at Logger M and resulted in the large rate of T reduction observed. By comparison, the T decrease at Logger O occurred at a relatively constant rate over the course of the evening, dropping from 17.5°C to 15.5°C between approximately 18:00 and 22:30, a rate of 0.25°C. A similar trend to that observed at Logger O is noted at Logger L.

In conclusion, thermal conditions in the occupied spaces on the ground floor are characterised by relatively stable conditions with low fluctuations when the building is unoccupied and the trends are comparable to those observed in the Long Room. When the building is opened again following the Christmas vacation, the T trends in the space are characterised by the heat-loading signature as fluctuations in T correspond to the operational period of the mechanical heating. The effects of solar gains and people on the thermal environment appear to be minimal which is to be expected considering that the majority of ground floor window are partially or entirely covered. It may be expected that the presence of people in relatively large numbers would contribute to the diurnal T variations on the ground floor, however, heat flow through the central staircase to the Long Room coupled with the presence of HVAC in BOKE result in no apparent correlation between T and occupancy numbers in this area, surprisingly. Furthermore, leakage of heat from the ground floor level into the Long Room is occurring and may contribute to environmental perturbations in the Long Room.

6.2.2.2. Humidity Parameter Baseline

The RH trends observed during the Christmas vacation differ marginally in magnitude across all occupied areas on the ground floor. Given that RH and T are subject to an inverse relationship, and considering the T variations discussed in Section 6.2.2.1, one important cause of the different magnitude in RH observed during the data collection period is a result of the T variations between areas as outlined previously. Logger S experiences the highest RH values followed by Logger L, M and O, in that order. This is the reverse of the T magnitudes illustrated in Fig. 6-12, indicating that the primary reason for the differing RH magnitudes observed at each individual sensor is due to the T magnitudes observed on the ground floor as indicated in Table 6-1. Although H_{abs} varies for each of the loggers in Table 6-1, RH is observed to increase with decreasing T, which in this case is the dominating factor in the RH trends.

Table 6-1: T and RH values recorded at the loggers in public occupied ground floor rooms in the Old Library at 13:00 on 24/12.

Logger	T (°C)	RH (%)	H_{abs} (g/m^3)
S	8.5	42.5	3.63
L	10.5	39.5	3.83
M	11.5	36.5	3.77
O	12.5	34	3.74

Although RH values in this area of the library all differ slightly in magnitude, the core trends in the data are very similar and comparable to those observed in the Long Room and as discussed in Section 6.2.1.2. Loggers O, M and L all record very similar fluctuations over the course of the monitoring period as displayed in Fig. 6-14.

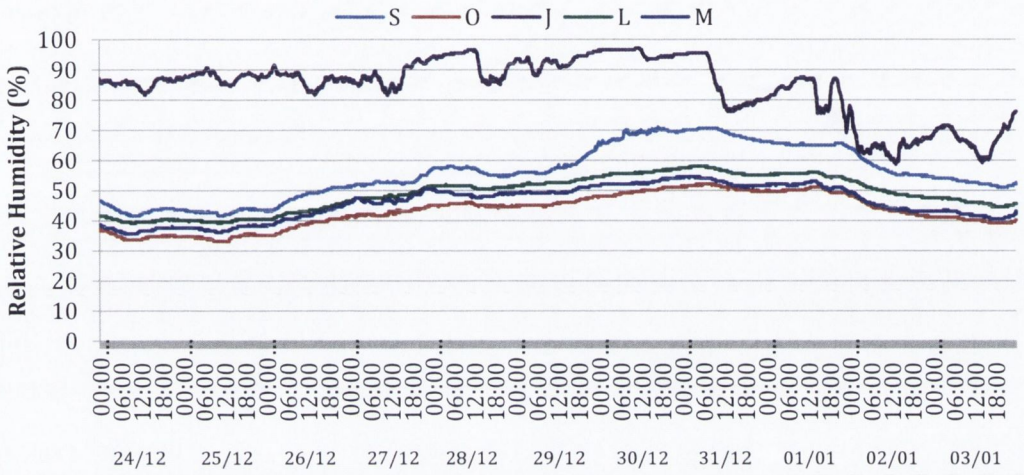


Fig. 6-14: Relative Humidity conditions in occupied ground floor spaces in the Old Library during the Christmas vacation.

The trend at Logger S is slightly different from that of the other three but again this is due solely to the changes in H_{abs} during the Christmas vacation which are slightly different at Logger S when compared to the other three data collection zones and slightly more variations are observed in the RH during this time period owing to the security doors that isolate BOKE from the rest of the building during this time interval. Given that the T conditions are relatively stable and that the HVAC system is not in operation during this time period, the RH trend observed at Logger S is related (and comparable to) the H_{abs} trend observed. As fluctuations in RH exceed those specified by the Smithsonian Institute (i.e. a maximum limit of 53% RH), this area would generally not provide acceptable environmental conditions for the storage of collection items when HVAC is deactivated, although it should be noted that the Book of Kells is placed in an environmentally controlled display cabinet.

The effect of mechanical heating and occupancy levels is more noticeable on the ground floor of the Old Library compared with the Long Room owing to the smaller volume of air at ground floor level (Fig. 6-15), which would mean moisture loads would have a greater impact on environmental conditions on the ground floor when compared to those observed in the large volume of the Long Room.

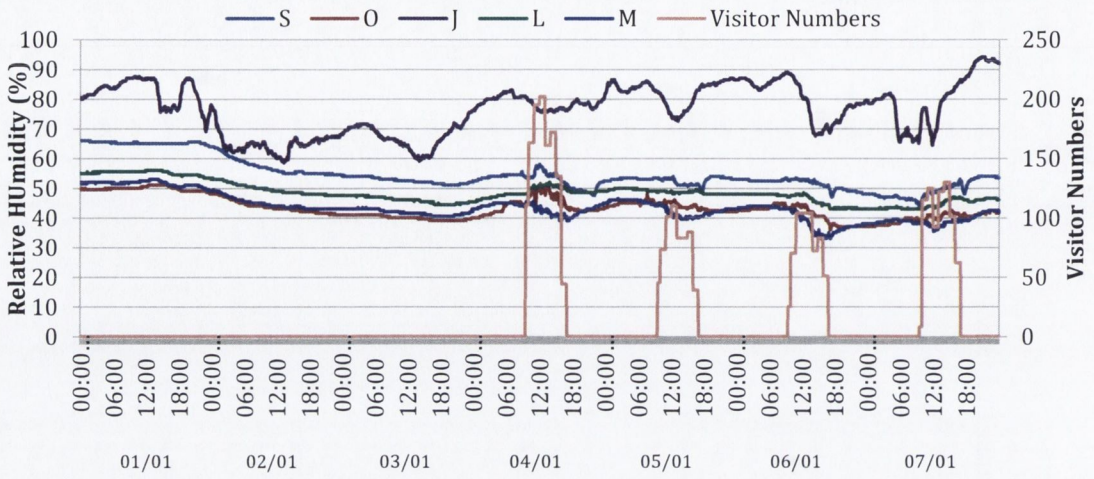


Fig. 6-15:Relative Humidity in occupied rooms on the ground floor of the Old Library between 01/01 and 07/01. Visitor Numbers are displayed where applicable.

When heating is turned on, T values at Logger M reach a higher value than those at Logger O and the effect is observed in RH also. On 04/01, the mechanical heating to the building results in Logger M climbing above O in terms of T, which has a corresponding effect in lowering the RH at Logger M. In this case, changes in T have a noticeable effect on RH. The presence of people leads to the fluctuations in RH observed during occupancy hours. As the RH trends in this area of the Old Library are similar in nature to those observed in the Long Room it is more useful, at this point, to discuss the H_{abs}.

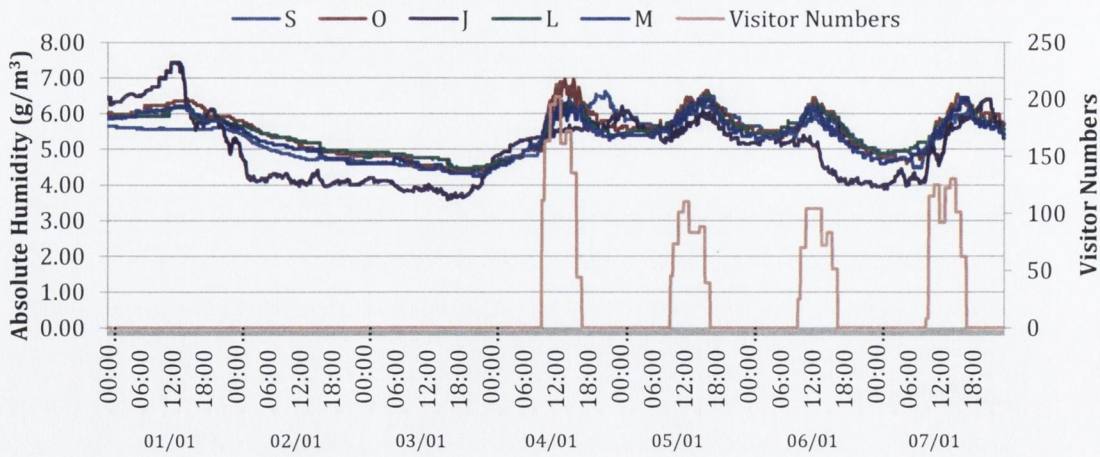


Fig. 6-16: Absolute Humidity in occupied rooms on the ground floor of the Old Library between 01/01 and 07/01. Visitor Numbers are displayed where applicable.

Taking Logger O as an example, on 06/01, the varying influence of both people and the external environment can be demonstrated. H_{abs} at Logger O is initially recorded at a value

of 5.52g/m^3, a value that it approximately maintained from 02:00. At 09:30, the first occupants enter the building and, at 09:40, H_{abs} at Logger O begins to increase. A relatively constant rate of increase is observed between approximately 09:45 and approximately 11:00 as H_{abs} climbs from its initial value to 6.07g/m^3 over this particular time period. This equates to a rate of increase of H_{abs} of 0.42 g/m^3/hour. Visitor numbers are also observed to increase over this time period and, as external H_{abs} values are lower than those recorded at Sensor O, the moisture load resulting from occupancy is the reason for the upward trend outlined in green on Fig. 6-17.

The maximum visitor numbers for the day are observed between 11:00 and 14:00 where 104 people per hour enter the building during this three hour period. It is worth mentioning at this point that visitor number data for the Old Library is collected on an hourly basis and, as such, does not account for the exact time, during a particular hour, that people enter. This observation accounts for the differing rates of change of H_{abs} observed at Logger O during the maximum occupancy time, as would be expected from the analysis of the environmental conditions in lecture theatres in the Museum Building during occupancy.

Between approximately 11:00 and 11:30, the rate of increase of H_{abs} reduces and a brief plateau is observed in the trend. During this time, H_{abs} increases from 6.07g/m^3 to 6.25g/m^3, a rate of 0.36g/m^3 per hour, indicating that the number of people passing through the corridor has reduced, or, as described in Section 4.6, a constant stream of people are passing through the corridor and equilibrium is being approached. Given that H_{abs} decreases to 6.11g/m^3 at approximately 11:45, which indicates a reduced moisture load in the area, it is more likely that reduced visitor numbers is responsible for the reduced rate at this time.

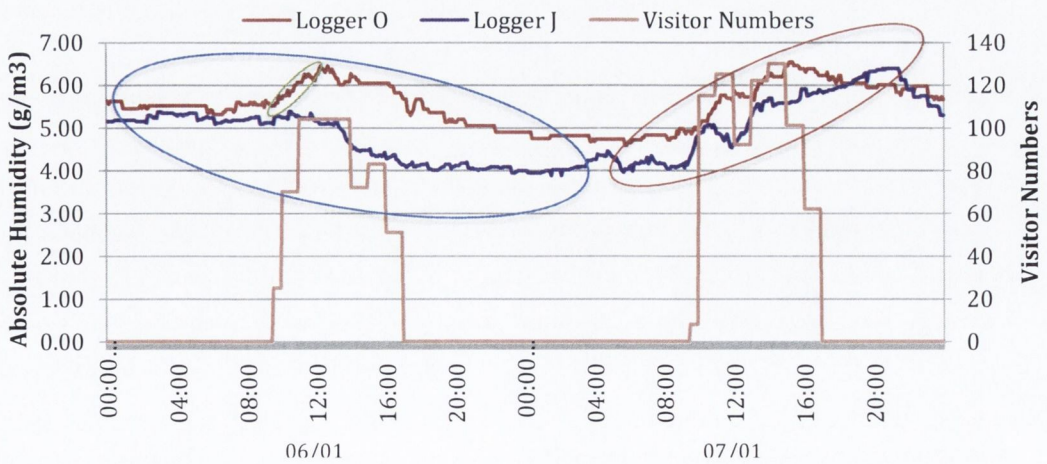


Fig. 6-17: Absolute humidity conditions recorded at Logger O as well as visitor numbers on 06/01 and 07/01.

At approximately 12:00, H_{abs} increases once more to its maximum value for the day of 6.44g/m^3. Given that this increase occurred over a 15-minute period, a rate of 1.32g/m^3/hour is observed. H_{abs} then fluctuates between 6.37g/m^3 and the maximum value of 6.44g/m^3 for approximately an hour as small groups of people pass through the corridor. The large rate of increase observed at Logger O (1.32g/m^3/hour) is most likely due to a sudden influx of a large number of people, such as a tour group. In the case of a tour bus, up to 50 people could enter the building simultaneously, resulting in the sudden increase observed in H_{abs}. Given the low residency time of people in the passageway, a relatively modest increase in H_{abs} is observed, however, the rate is quite high indicating that, even if only in a room for a short time, the presence of people has a significant effect on moisture conditions in the room.

At 16:15 visitor numbers have declined significantly and H_{abs} begins to decline, initially at a slow rate. At 17:00 the building is closed and this rate of decline of H_{abs} increases as the moisture loads due to the metabolic processes of people are removed. External H_{abs} had also dropped substantially during the day and this resulted in a large moisture gradient between the indoor and outdoor conditions. As a result, exfiltration of moisture from the Old Library occurs and H_{abs} decreases in accordance with the moisture gradient between internal and external moisture conditions. H_{abs}, calculated at Logger O, stabilises at a value of 4.75g/m^3 at approximately 00:30, a value that is 0.77g/m^3 lower than the corresponding value the previous night because of the lower external H_{abs} and the associated larger moisture gradient observed that would result in greater moisture losses from the building, again illustrating the signature associated with occupancy.

One further note, which confirms the effect of the presence of people on internal moisture conditions can be observed in Fig. 6-17 by comparing the H_{abs} trend with the occupancy figures on 07/01. Between 10:00 and 10:55 (115 visitors) and 11:00 and 11:55 (125 visitors) visitor numbers increase significantly compared to those observed between 09:30 and 09:55 (8 visitors) resulting in a noticeable increase in the rate of change of H_{abs}. Between 12:00 and 12:55, visitor numbers fall to 92 and as a result, H_{abs} at Logger O is also observed to drop from 5.86g/m^3 to 5.65g/m^3 during this period. Visitor numbers are recorded at 122 between 13:00 and 13:55 and at 130 between 14:00 and 14:55 and H_{abs} increases once more, reaching a maximum value of 6.53g/m^3 at approximately 15:00 accordingly. After 15:00, visitor numbers begin to drop and, as a result, H_{abs} decreases once more as the moisture load due to people is reduced. This observation is consistent with conclusions that were drawn following analysis of the environmental data in lecture theatres in the Museum Building during occupancy periods and further confirms the occupancy signature. To determine whether this influence is due directly to the presence of

people or the varying external conditions, further analysis of the internal variations on 07/01 will be conducted.

The correlation coefficients that have been calculated using the *"correl"* function in MS Excel for the internal and external H_{abs} data and visitor numbers on 07/01 and are now displayed in Table 6-2. It is clear from the magnitude of the coefficients that the external environment has a significantly more influence on conditions in the building compared to the effect of the people. Although the people do appear to have correlation with the H_{abs} conditions in the Old Library, signified by a correlation coefficient of 0.45, the corresponding coefficient between H_{abs} conditions inside and outside of the building indicates a close correlation between the two. These correlation coefficients support the conclusions of the small-scale occupancy tests where occupancy merely caused a variation about a background trend in H_{abs} that was typically driven by infiltration/exfiltration from the external environment.

Table 6-2: Correlation coefficients between Habs in the Building, exernally and Visitor Numbers

	External Habs	Visitor Numbers
Internal Habs:	0.90	0.45

In conclusion, the hygrometric environment on the ground floor is comparable to that observed in the Long Room throughout the Christmas vacation. Leakage rates from the building to the external environment are slow and the presence of hygroscopic materials throughout the building result in relatively small RH and H_{abs} variations over the time interval when the building is closed. Conditions in the building at this time are characterised by the signature associated with the presence of hygroscopic materials as defined by the study of the Civil Engineering Library in the Museum Building, however, variations that do occur at this time, albeit small, are a result of the relatively large moisture gradient between the internal and external environments. When the building reopens to the public following the Christmas vacation, the moisture conditions at ground floor level are in accordance with the signature associated with the presence of people, namely, that occupancy of the building results in relatively large perturbations about the general background trend. Accordingly, it may be concluded that although people have some influence on the hygrometric properties in the Old Library, this influence is relatively small in comparison to the effect of the external environment, which appears to be closely correlated to the internal environment, despite the low leakage rate and regulation of the moisture environment associated with the presence of hygroscopic materials.

6.3. Seasonal Variations in the Internal Environment in the Old Library

Previous discussions on data obtained from the Old Library have focused solely on data collected during the winter period and have ignored summer data. Furthermore, the distinction between the internal environments observed when external weather conditions have been "dry" (that is. not raining) or "wet" (that is raining) has not been made. For the purposes of this section, data recorded on four different days will be presented and compared. These days represent "dry" summer (26-07) and winter (19-11) as well as rainy ("wet") summer (21-07) and winter (22-11) days. "Dry" and "wet" days for each season will be compared initially followed by a comparison between the seasons. As T values during both seasons are relatively stable with little fluctuations, the following discussion will focus primarily on the humidity parameters. The reader is referred to Appendix C for the T data corresponding to the humidity parameters presented in this section. As the area known as the passageway was monitored during both seasons and as all visitors must pass through this space when entering the exhibition space, it will be used to compare the humidity response for the various external conditions. It should be noted that this corridor is not enclosed at either end and, as a result, is influenced by conditions in both the Shop and Exhibition Space. Furthermore, this area is not subject to direct mechanical heating or air conditioning and so the response of the corridor to moisture loads will be most discernible here.

Considering the signatures determined for "dry" and "wet" occupants, it is expected that, when the building is occupied, the additional load induced in the Old Library due to moisture on the body, clothing and belongings of the occupants on "wet" days will lead to a larger diurnal fluctuation in the hygrometric environment when compared to those on the corresponding "dry" days. When the building is vacated, it is expected that conditions will revert to the typical background conditions as the moisture load is removed.

6.3.1. Dry Day vs. Wet Day in Summer

As a means of comparing the H_{abs} trends observed in the Old Library on a wet and dry day during the summer season when visitor numbers are relatively high, H_{abs} values calculated throughout the area of the building occupied by tourists on 26/07 (dry) and 21/07 (wet) will be discussed. Variations observed on each day will be observed individually initially before a comparison between the moisture environments in the Passageway on each day will be conducted.

Firstly, H_{abs} observed on 26/07 will be examined and is displayed in Fig. 6-18. Between the commencement of monitoring and the opening of the building at 09:30, relatively constant H_{abs} values are observed throughout the Old Library, despite the large moisture gradient between the internal and external environments. Between approximately 00:30 and 03:00 (circled in blue), H_{abs} conditions outside the building are noticeably higher than those in the building leading to moisture infiltration from the external environment. This infiltration is reflected in the internal conditions, where an increase in H_{abs} is observed, albeit at a very slow rate. Furthermore, the magnitude of the H_{abs} change is not uniform throughout the building, as a relatively small increase of $0.10g/m^3$ (central compartment) and $0.28g/m^3$ (east compartment) recorded in the Long Room while the Passageway, Shop and BoKE observing increases of $0.75g/m^3$, $0.56g/m^3$ and $0.55g/m^3$ respectively. The large volume of air in the Long Room, compared to the other zones, contributes to the low rate of change of H_{abs} observed in the area during this period. Thereafter, no noteworthy changes in H_{abs} occur until the building opens at 09:30.

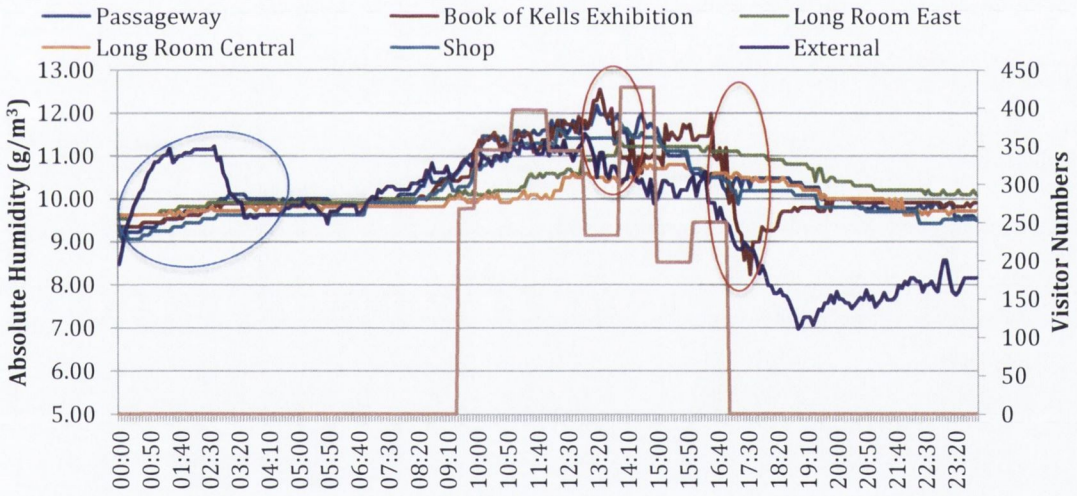


Fig. 6-18: Absolute humidity variations throughout the Old Library building on 26-07 (dry day). Also displayed are external absolute humidity and visitor numbers.

At 09:30, visitors begin to enter the building, causing the H_{abs} profile to change from its relatively stable state and begin to increase throughout the occupied ground floor spaces as a result of moisture loads due to occupants that are induced in the building. The largest rate of increase is initially observed in BoKE as the residency time of visitors in this area of the building is relatively high and, at this time, visitors can pass through the Passageway relatively quickly as queues are small. The initial increase in BoKE occurs at approximately 09:50, 20 minutes after the building opened. This time lag is consistent with the time period that it takes the typical visitor to reach the room. The rate of change of H_{abs} at this time is

3.44g/m^3/hour as the concentration of moisture in the air increases from 10.50g/m^3 to 11.36g/m^3 over a 15 minute interval. H_{abs} in the Passageway is observed to increase immediately following the opening of the building, changing from 10.66g/m^3 to 11.46g/m^3 at a rate of 1.2g/m^3/hour. The smaller rate of increase at this point is due to the short residency time of occupants in this area compared to BoKE.

In contrast, the effect of occupants on the Long Room is minimal and only minor perturbations are observed during this time as moisture loads are dispersed by the extensive volume of air in the space. Furthermore, any H_{abs} increases in the Long Room may be due to moisture infiltration from the external environment according to the moisture gradient. From approximately noon onwards, the moisture load due to people appears to influence H_{abs} in the Long Room as an increase in H_{abs} is observed, with internal moisture conditions exceeding those externally. From approximately 13:30 onwards, H_{abs} in the Long Room remained relatively stable as equilibrium is reached between moisture loads and losses. Once the building is vacated, the moisture gradient becomes the dominating factor, once more, in terms of H_{abs} in the Long Room, which is consistent with the general trend associated with the occupancy signatures.

Following the initial H_{abs} increase recorded in the Passageway and BoKE spaces, moisture conditions over the course of the day fluctuate in accordance with the moisture load induced by people and their passage through the building. Once the number of occupants decreases, so too does the H_{abs} as the smaller moisture load resulting from fewer occupants can be dissipated at a relatively quick rate. Two relatively large decreases in H_{abs} are observed in BoKE (circled in red in Fig. 6-18) and are not consistent with natural moisture movement or a reduced moisture load. The BoKE space contains two HVAC units whose purpose is to regulate and control environmental conditions in the room. At approximately 13:30, H_{abs} in the BoKE reach a diurnal maximum value of 12.55g/m^3 and, over the course of an hour, decreases to 10.50g/m^3, a rate of 2.05g/m^3/hour. This rate of change occurs too quickly to be attributed to diffusion or a reduced moisture load and is due to the effect of the HVAC system in the space. Although not displayed on the chart, the corresponding change in RH at this time is 7.5%RH (66.5% to 59%), which is a relatively large decrease over a 1-hour period and would potentially be damaging to any collection items placed in this environment (that is, such RH cycles occurring continuously) for a prolonged period of time.

Similarly, at approximately 16:30, the effect of the HVAC units is evident as visitor numbers decline as closing time approaches. An initial decrease in H_{abs} of 1.08g/m^3 is observed and is followed by a brief stabilisation in H_{abs} as the final visitors enter the area before the security shutters are closed. As the HVAC system is operating, a relatively large decrease in H_{abs}

occurs at a very quick rate of 4.43g/m^3/hour (11.18g/m^3 to 8.23g/m^3). Thereafter, the HVAC system maintains RH and T conditions and H_{abs} in this area begins to increase once more. Despite the moisture gradient between BoKE and the external environment that induces moisture movement out of the building, a moisture gradient between rooms also exists. Given that movement of water vapour between internal and external environments is inhibited by the building envelope, moisture transfers into BoKE from adjacent internal rooms resulting in the increase in H_{abs} observed after the HVAC units have been turned off. H_{abs} in BoKE then converges with that observed in adjacent areas of the Old Library where the moisture gradient between the building and the external environment cause a slowly decreasing H_{abs} trend.

H_{abs} data for 21/07 is presented in Fig. 6-19. Between 00:00 and 09:30, moisture conditions in the Old Library are reasonably stable as are those externally. When the building opens to the public at 09:30, H_{abs} in the Passageway increases almost immediately as a large number of visitors pass through the space at this time, changing from 9.88g/m^3 to 11.24g/m^3 over approximately 50 minutes, a rate of 1.63g/m^3/hour. Rain is observed externally resulting in an additional moisture load due to the wet clothes and belongings of people is induced in the space, and resulting in the large observed rate of change of H_{abs}. Thereafter, visitors enter the building at a steadier rate and the moisture gradient between the internal and external environments dissipate the moisture load in the Passageway. Accordingly, H_{abs} stabilises and, despite some fluctuations throughout the day, remains reasonably constant for the remainder of the opening period.

As discussed previously, a lag period between the opening of the building and a H_{abs} change in BoKE exists and, in the case of the dry day, this time is approximately 20 minutes. On 21/07 however, H_{abs} in BoKE begins to change 10 minutes after visitors enter the building. Although this change could be due to the additional moisture load resulting from the wet clothes and belongings, it should be noted that 161 additional visitors enter the building initially on 21/07 (429) compared to 26/07 (268). H_{abs} in BoKE increases by 1.37g/m^3 (9.46g/m^3 to 10.83g/m^3) during this period at a rate of 3.29g/m^3/hour, slightly lower than that observed on 26/07. Thereafter, the moisture conditions are comparable to that on 26/07 as the effect of both people and the HVAC system dictate the internal environment.

The Long Room observes a larger increase in H_{abs} on 21/07 compared to 26/07 with a change of 0.9g/m^3 recorded on 21/07, 0.41g/m^3 higher than the corresponding value on 26/07, a 45.5% increase on the rainy day.. Given that approximately the same number of visitors enter the building on each day, it can be assumed that the higher change in H_{abs} on 21/07 is a result of the larger moisture load in the space, as discussed presently.

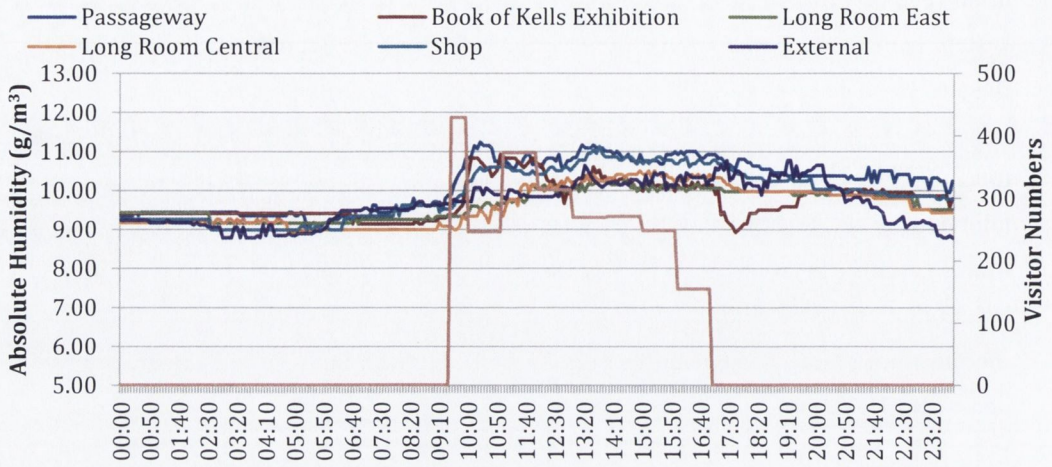


Fig. 6-19: Absolute humidity data for the Old Library on 21-07 (rainy day). External absolute humidity and visitor numbers are also displayed on the chart.

As a means of comparing the indoor environment on a wet and dry day in the summer period, diurnal trends in the Passageway, as well as externally, are plotted on the chart in Fig. 6-20. Also included on the chart are the visitor numbers for each day. The Passageway has been chosen for comparison as it is the first point of contact for visitors to the building and the residency time for people in this space is short and generally will not vary between occupants. As the general trends have been identified previously, the following discussion will focus on the differences between the internal and external H_{abs} values during the opening period of the building.

From the chart in Fig. 6-20 it can be observed that external H_{abs} trend, prior to the building opening on 26-07, is larger in magnitude to the corresponding values on 21-07 and, accordingly, internal H_{abs} conditions are higher on 26-07 than 21-07. When people begin to enter the building, H_{abs} on both days increases; with a change of 0.80g/m^3 being recorded on 26-07 ("dry" day) compared 1.36g/m^3 occurring on 21-07 ("wet" day), a 0.56g/m^3 difference. As mentioned earlier, a larger number of people enter the building initially on 21-07 compared to 26-07.

As shown in Table 6-3, a higher moisture load per person is induced in the Passageway on 21-07 compared to 26-07 and this is reflected in the magnitude of the H_{abs} increase observed during the first hour of opening. This additional load is due to the extra moisture that visitors bring into the Old Library on their person on wet days and, by and large, accounts for the larger increase observed in H_{abs} on the wet day. Furthermore, the difference in magnitude between the internal and external environments on 21-07 is noticeably higher than the corresponding relationship on 26-07. The difference between internal and external

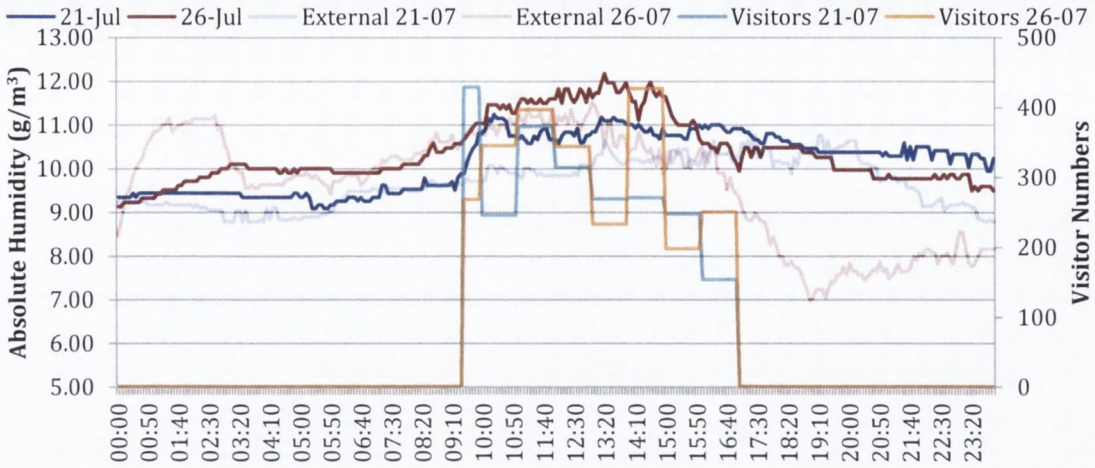


Fig. 6-20: Absolute Humidity observed in the Passageway on both 21-07 (rainy) and 26-07 (dry). External conditions and visitor numbers on both days are also displayed.

conditions is approximately 1.00g/m³ during the opening period on the wet day compared with approximately 0.40g/m³ on the dry day. Again this may be attributed to the additional moisture inadvertently being carried into the building by the visitors.

Table 6-3: Absolute humidity per person calculated in the Passageway on 21/07 and 26/07.

Date	Visitors	ΔH_{abs} (g/m^3)	External H_{abs} – Internal H_{abs}	ΔH_{abs}/visitor (g/m^3/visitor)
21/07	429	1.36	1.00	3.17×10^{-3}
26/07	268	0.80	0.40	2.99×10^{-3}

Table 6-4 illustrates the correlation factor between internal and external H_{abs} as well as internal H_{abs} and visitor numbers on both days. On the dry day (26-07), a high correlation factor (0.87) is recorded between visitor numbers and internal H_{abs} indicating that the internal environment is heavily influenced by the presence of occupants. External H_{abs} conditions, while correlating weakly (0.46) with the internal H_{abs}, are not the dominating factor behind variations in the Passageway. Conversely, on the wet day (21-07), the higher correlation factor is observed between the external H_{abs} and internal H_{abs} indicating that the presence of occupants is no longer the driving force behind the moisture trends. The reason for this, however, may be due to the varying extent of the additional moisture load from person to person, which may be a function of the clothing they are wearing. Accordingly, a more varying moisture load between individual people is observed, resulting in a lower correlation between people and the internal environmental conditions.

Table 6-4: Correlation factors between internal Habs and External Habs and Visitor Numbers on 21-07 and 26-07.

	External H_{abs} (g/m^3)	Visitor Numbers
21-07: Internal H_{abs}	0.77	0.64
26-07: Internal H_{abs}	0.46	0.87

RH conditions, observed in the Passageway in the Old Library, are presented in Fig. 6-21 as a means of determining whether the presence of people in the building, during the summer period, will result in conditions that exceed those specified by either the Smithsonian Institute or BSI for museum environments. As outlined previously, RH fluctuations are a significant factor in reducing the life expectancy of collection items. Accordingly, as stated previously, RH limits of 37% RH and 53% RH have been specified by the Smithsonian Institute while BSI recommend fluctuations that are less than ±10% RH.

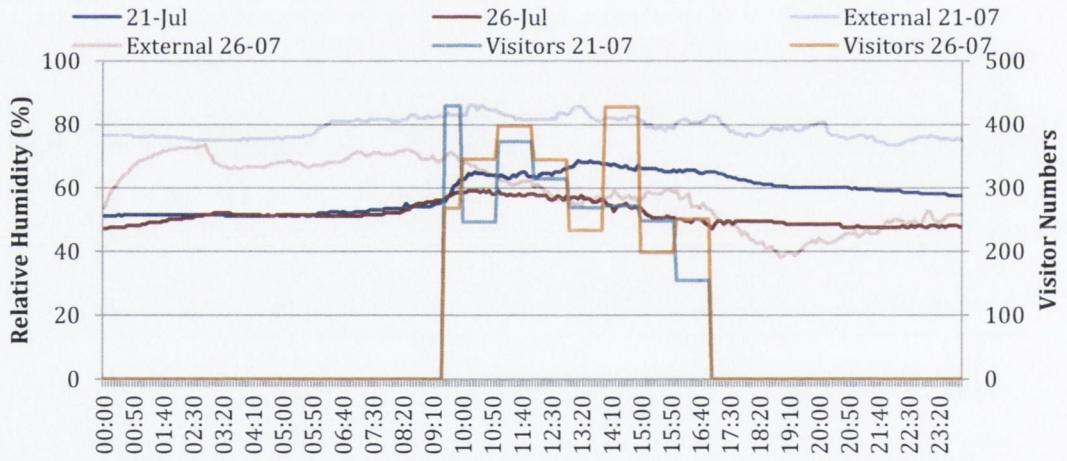


Fig. 6-21: RH conditions in the passageway for the dry (26/07) and wet (21/07) days during the summer period. External RH and visitor numbers are also included on the chart.

From Fig. 6-21 it can be seen that, on the "dry" day, a total change of 12% RH is observed between the maximum (59% at approximately 10:00) and minimum (47% at approximately midnight) values recorded on the day. This change in RH is primarily due to the presence of people in the room and marginally exceeds the limits specified by both the Smithsonian Institute and the BSI. On the "wet" day the change in RH is higher as a result of the additional moisture load due to the wet belongings of visitors and results in an RH range of 17.5% RH between the maximum (68.5% at approximately 14:00) and minimum (51% at approximately midnight) which is significantly higher than the environmental limits specified for the building. Accordingly, it can be seen that the presence of people has the

potential to cause significant fluctuations in RH in the building and cause environmental conditions that are not sympathetic to the preservation of the collection in the building. Due to the volume of air in the Long Room, however, it is unlikely that people would induce a moisture load that is large enough to result in unacceptable variations in the space.

Based on these observations it may be concluded that the moisture load induced in the building on wet days is discernibly higher per person than on dry days, thus causing larger variations in the internal H_{abs} conditions. This is a result of the moisture carried into the building on clothing and other belongings of the visitors. Furthermore on dry days, a strong correlation between internal H_{abs} and visitor numbers exists, while external H_{abs} is a less relevant factor in the internal moisture variations. Considering the two occupancy tests discussed in Section 4.6, the differences between the observations in the Old Library on the "dry" and "wet" day are to be expected. In this case, the moisture load due to people on the "wet" day is 6% higher per person than the corresponding value on the "dry" day resulting in the larger rate of increase in H_{abs} observed on 21/07. Accordingly, it may be concluded that the signature associated with occupancy during the two different weather conditions (that is raining and not raining) is confirmed as being observed in the Old Library during both the winter and summer seasons. Furthermore, the presence of people, on both "wet" and "dry" days can potentially result in RH fluctuations that are unacceptable from a conservation viewpoint and accordingly, options to reduce the impact of people on the environmental conditions, such as environmentally pre-conditioning visitors during an obligatory period in a Visitor Centre or, less desirably, limiting visitor numbers, for example. Both should be explored with the aim of prolonging the lifespan of the priceless collection.

6.3.2. Winter Conditions compared to Summer Conditions

In order to compare the seasonal differences observed in the Old Library, H_{abs} data calculated for the Passageway in the Old Library will be divided into the dry days and wet days and presented on charts. The correlation coefficients between internal and external H_{abs} as well as internal H_{abs} and visitor numbers will be tabulated and discussed.

H_{abs} data calculated for the dry day in each season is presented in Fig. 6-22. From the chart, the large seasonal difference in baseline H_{abs}, both in the building and externally may be observed, with a magnitude in summer of 10.00g/m^3 and a corresponding winter value of 7.20g/m^3, a difference of 2.80g/m^3. This large disparity in the environmental conditions in the building is due to the concentration of moisture in the external air, which is generally noticeably higher in the summer compared to the winter. One other difference between the

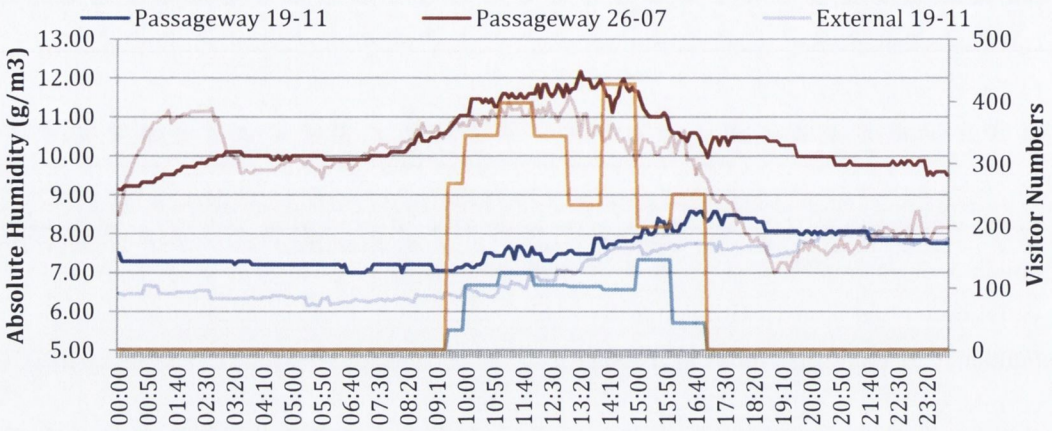


Fig. 6-22: Absolute humidity data for the dry days in winter and summer. External absolute humidity and visitor numbers for both days are also displayed.

summer and winter conditions is the number of visitors during each season. In July, the highest visitor numbers entering the building during a one-hour period is 427 compared with 145 in winter. Furthermore, a total of 2462 visitors enter the building on 26-07 compared to just 762 on 19-11. Despite these differences, comparable diurnal H_{abs} trends are observed in both the summer and winter seasons. When the building is closed, stable hygrometric conditions are observed in the building as moisture leakage into the building, coupled with the large volume of hygroscopic materials located throughout the building regulate the humidity variations.

Table 6-5 provides a more interesting insight into the predominant factors behind the different internal environments observed in the Old Library in winter and summer. As mentioned previously, visitor numbers in winter are significantly lower than those in summer and, as a result, the moisture load due to people in the building in winter is lower than in summer. Accordingly, the correlation factor between internal H_{abs} and visitor numbers is low, with a value of 0.10. Although this would suggest that no correlation exists between Habs and visitor numbers, the signature associated with occupancy is observed in Fig. 6-22 where occupancy results in variations about a background trend. Conversely, high visitor numbers are observed during the summer resulting in a significantly larger moisture load in the building due to the occupants, and this is reflected in a large correlation factor of 0.87. In contrast, the correlation factors between external and internal H_{abs} indicate seasonal differences in the prevalent influence of internal moisture conditions between seasons. A high value of 0.88 is observed in winter compared to just 0.46 in summer. Considering the correlation factors as a whole, it becomes evident that the driving force behind internal H_{abs} varies seasonally as external H_{abs} defines internal conditions in winter, while moisture due to visitors is the primary determinant during the summer period.

Table 6-5: Correlation factors between internal H_{abs} and external H_{abs} and internal H_{abs} and visitor numbers in both winter and summer.

	External H_{abs} (g/m^3)	Visitor Numbers
19-11	0.88	0.10
26-07	0.46	0.87

In both seasons, the effects of occupancy on the hygrometric parameters in the building is characterised by the occupancy signatures, where relatively large fluctuations about a general trend are observed during periods of occupancy before conditions revert to the background trend when the building is vacated.

Fig. 6-23 displays the internal and external H_{abs} trends calculated on 22-11 and 21-07 in the Passageway. Also presented on the chart are the visitor numbers for each day. Once more, the magnitude of H_{abs}, both internally and externally, are higher in July than November owing to the seasonal variations. Furthermore, visitor numbers are significantly higher in summer compared to winter (2304 in summer and 762 in winter), which would result in an appreciable difference in the diurnal moisture load due to occupants. Despite these differences there are similarities between the trends observed in both winter and summer.

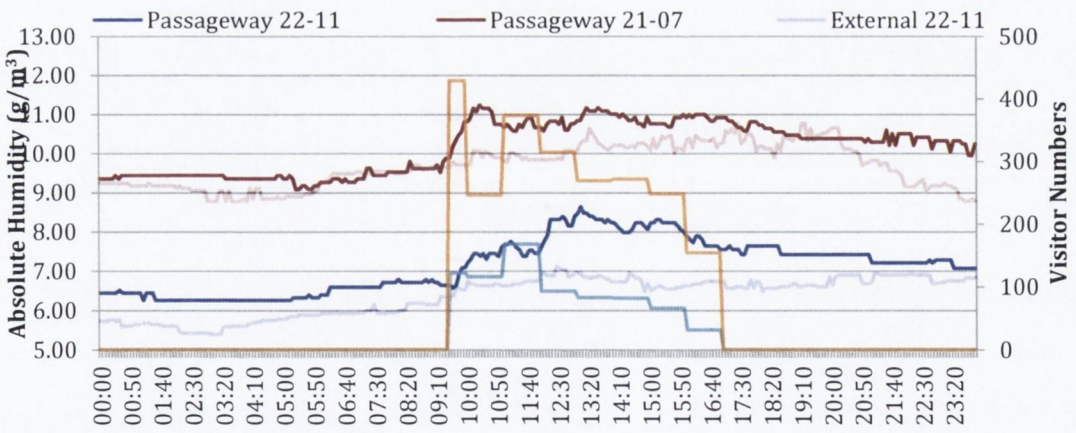


Fig. 6-23: Absolute Humidity data for the two wet days, 22-11 and 21-07. External absolute humidity and visitor numbers for both days are also displayed on the chart.

Firstly, a large initial increase is observed in H_{abs} on both days as the moisture load is suddenly imposed on the space. After this initial change, moisture conditions plateau, however further increases are observed in winter as discussed previously. The difference in magnitude between internal and external H_{abs} is large when compared to that on dry days in

both winter and summer, indicating that the moisture carried into the building on the wet clothes of the occupants is important in increasing internal H_{abs}.

the internal conditions with factors of 0.85 and 0.77 calculated in winter and summer. Visitor numbers, however, also show a strong correlation with the internal moisture conditions, as values of 0.56 and 0.64 are noted in winter and summer.

Table 6-6 presents the correlation factors between the relevant parameters for both winter and summer and are comparable. In both seasons, external H_{abs} is correlated more closely to the internal conditions with factors of 0.85 and 0.77 calculated in winter and summer. Visitor numbers, however, also show a strong correlation with the internal moisture conditions, as values of 0.56 and 0.64 are noted in winter and summer.

Table 6-6: Correlation factors between internal and external H_{abs} and internal H_{abs} and visitor numbers for a wet day in winter and summer.

	External H_{abs} (g/m^3)	Visitor Numbers
22-11	0.85	0.56
21-07	0.77	0.64

The higher factor in summer is most likely the result of the larger number of visitors and the larger associated moisture load. Furthermore, the additional moisture held on the clothing and belongings of the occupants on the wet day may not be consistent from individual to individual, hence reducing the correlation factor between visitors and internal H_{abs}. The effect of the external conditions on both days is commensurate, which is in contrast to the observations made on the dry days. Internal H_{abs} on wet days is closely influenced by both external conditions and visitor numbers, with the dominating effect appearing to be the external H_{abs} owing to its slightly higher correlation factor on both days.

In both the winter and summer seasons, the hygrometric environment in the Old Library are characterised by stable conditions when the building is unoccupied, corresponding to the signature associated with the presence of hygroscopic surfaces and indicating a slow leakage rate, and with the occupancy signature when the room is opened to the public indicating that the signatures defined by experiment and validated in the Museum Building are accurate and applicable to multiple buildings.

6.4. Conclusions and Recommendations

6.4.1. Conclusions

Owing to its two disparate functions, primarily a book repository for ancient books but also a major tourist attraction, the Old Library at TCD presents as a building with conflicting environmental requirements. Previous literature (Section 2.6) has specified that, for the purposes of preservation of precious collection items, stable environmental conditions with low temperatures and relatively stable hygrometric properties are preferable as it is the variations in environmental conditions that may be most detrimental to the collection. This study on the Old Library TCD was conducted to determine whether the environmental conditions in the building were providing suitable thermo-hygrometric properties for the purposes of prolonging the permanence of the collection using the limits specified by the Smithsonian Institute and the BSI. The cause of variations in the environment could then be determined using the environmental signatures developed previously.

Considering that aspects of the building envelope, such as the relatively large area of leaky single glazed windows and the poorly insulated attic, environmental conditions observed in the Long Room during the Christmas vacation are surprisingly stable, despite the existence of a large T gradient between the internal and external environments that should have resulted in a relatively large rate of heat loss from the building. Taking this in the context of the environmental signatures defined previously, this behaviour is similar to the environmental variations observed in the Civil Engineering Library in the Museum Building and indicates that the presence of the large volume of books contained within the Long Room, coupled with the dense external walls, acts as thermal mass and effectively regulates the thermal conditions in the space, when the building is unoccupied and unheated. Moreover, the blinds that are located at each window in the Long Room are effective in significantly reducing the impact of solar gains in the space, as, given the relatively large, south-facing glazed area in the building, heat gains due to solar effects was expected to be large. Furthermore, given that similar environmental conditions are also observed in other areas of the building during this time period, it appears that the Long Room may be regulating thermal conditions in the building as a whole. Given that the shop is directly linked to the shop, and subsequently to the Exhibition Space, by the central staircase, the presence of the large thermal mass due to the books is experienced, not only in the Long Room, but also in ancillary areas in the building.

Similarly, in terms of the hygrometric parameters in the building over the duration of the Christmas vacation, the signatures relating to the presence of hygrometric materials as well

as those observed in the Civil Engineering Library define the variations in RH and H_{abs} conditions in the building during this monitoring interval. As mentioned previously, variations in humidity are perceived as the environmental parameter that is the most detrimental to collection items and, over the course of the Christmas vacation, RH conditions in the Long Room generally fulfil the environmental requirements outlined by BSI, namely, RH variations that are smaller in magnitude than ±10% RH. The upper limit for RH defined by the Smithsonian Institute of 53%, however, are generally exceeded in the Long Room, indicating that conditions in the building may be unsuitable for the storage of collection items. Given that it is the variations that are most damaging to collection items, however, conditions observed in the Long Room throughout the Christmas vacation, do not exceed the value of 60% (above which mould growth may become an issue), and hygrometric conditions in the Long Room may be considered suitable for the storage of collection items. The stability of the hygrometric conditions in the space further illustrates the importance of the presence of hygroscopic materials in regulating moisture in the environment.

Upon reopening after the Christmas vacation, mechanical heating is present in the building again, as are additional heat and moisture loads due to occupancy. The relatively small heat source located in the Long Room coupled with the vast volume of air in the space mean that the loads induced in the space are quickly dissipated as heat flows throughout the room and is absorbed by the mass in the room or lost to the external environment through the windows and ceiling. Accordingly, T variations due to the heat loads are modest and do not result in excessive diurnal T variations. Furthermore, T conditions in the space fall significantly below those required for thermal comfort. Given that colder conditions provide more suitable conditions for preservation, however, it may be concluded that the T magnitudes observed in the Long Room in the winter season are perceived as conducive for preservation.

Owing to the smaller volume of rooms on the ground floor of the building when compared to the Long Room, the mechanical heat sources are observed to have a relatively large impact on the thermal conditions in the space when the building reopens. As was observed in the Museum Building, the presence of mechanical heating in the building is the dominating factor behind the diurnal T variations in the Old Library as people are observed to have a minimal influence, despite the large numbers. Furthermore, heating at ground floor level is providing an additional heat load to the Long Room as heat moves from the ground floor, up the central staircase and into the Long Room.

Following the Christmas vacation and the re-occupancy of the building, the hygrometric signature associated with the presence of people is observed in the Old Library as

perturbations in RH and H_{abs}, about the general background trend that is defined by the signature associated with hygroscopic surfaces, are observed in the building. Despite the large air volume in the Long Room, the presence of people has a discernible impact on both the RH and H_{abs} conditions in the space, however, at this time (winter) the visitor numbers are not sufficient to result in variations above the ±10% RH specified by BSI. In the ground floor rooms, the presence of people is more obvious owing to the smaller volume of rooms and the signature associated with occupants is clearly identifiable in the space. Accordingly, it may be concluded that the presence of people in the Old Library in winter, despite being relatively small in numbers, is having a measurable impact on the environmental conditions in the building.

Considering the environmental conditions observed in the Colonnades over the duration of the monitoring period it may be concluded that retrofit options on the external walls of the building may be effective in regulating the environmental conditions in the building. Stable T, RH and H_{abs} conditions were observed in this space during the monitoring period; however, extending this alteration to the building as a whole will be unsuitable as it will negatively impact on the character of the building and may lead to ancillary issues such as interstitial condensation. Accordingly, it may be concluded that, for the building as a whole, a holistic approach to building upgrade options must be taken so not to damage the heritage and cultural qualities of the building and collections.

The presence of people in the building during the summer, particularly on "wet" days is resulting in relatively large diurnal RH variations that may be detrimental to the collection. Currently there is no cap on the number of visitors entering the building per day and on "wet" days, the large number of visitors have a larger impact on the hygrometric environment in the building, as is consistent with the occupancy signature for "wet" occupants. Diurnal RH fluctuations on a wet and dry day were 17.5% RH and 12% RH respectively, which exceed the limit specified by BSI. Accordingly, it may be concluded that the presence of people in the building during the summer is sufficient to result in unsuitable environmental conditions for the collection. Furthermore, the seasonal variations between parameters is excessive and more regulation on the environment is required for the preservation of the collection.

The use of signatures as a means of determining the dominating influences on the environmental conditions in the Old Library has been validated as signatures observed during the experiments and hence refined in the Museum Building have also been noted in the Old Library under different boundary conditions.

Based on the study of the Old Library it may be concluded that the presence of people, particularly in summer, are resulting in large fluctuations in the hygrometric environment in the Old Library, leading to environmental conditions that are not suitable for the conservation of the collection. The environmental conditions in the Long Room were classified as Category C, and, in the case of the collection in the Old Library, are not suitable for the preservation of the cultural objects in the building. Furthermore, the presence of mechanical heating is the dominating factor behind the thermal conditions in the Old Library and is leading to relatively large T fluctuations at ground level. The background environmental conditions in the building continue to be defined by the external environment, however, and, accordingly, in order to improve the environmental conditions in the building so as to provide a more suitable environment for the collection, measures to upgrade the building fabric should be considered initially. Thereafter, strategies to mitigate the environmental loads due to the presence of people as well as the mechanical heating should be investigated.

6.4.2. Recommendations based on Monitoring in the Old Library

Before recommending any potential interventions to the Old Library, it is first necessary to identify and prioritise the primary issues that are influencing the environment. Based on the findings of the data analysis and conclusions described previously, a number of environmental problems have been identified in the Old Library. These issues relate to both thermal comfort and environmental quality for enhancing the life-time of the collection and are listed as follows:

- Building fabric
- Heating plant and regime; and
- The presence of people.

Before considering any alterations or retrofit options it is first necessary to consider the primary function of the building and the issues to be addressed by such alterations. In relatively recent years, the Old Library has been developed into a major tourist attraction, which has over 500,000 visitors per year. Although this has increased awareness of and revenue for the preservation of the collection, it is not the primary function of the building and, as a result, should not be allowed to compromise the condition of the collection. The building is, first and foremost, a working research library and archive for rare books, manuscripts and other valuable printed works. The priority of any interventions to the building should be stabilisation of environmental conditions for the purposes of preservation of the collection. Occupant comfort should be secondary to this issue.

Variations in the humidity parameters in the building have been occurring for two primary reasons, namely the presence of people and the moisture loads associated with them and infiltration from the external environment. The reduction of infiltration rates could be achieved by the implementation of draughtproofing as well as the repair of damaged windows. Although this measure may be effective in reducing environmental variations due to infiltration, which are relatively small as heat and moisture movement between the building and the external environment appears to occur at a relatively slow rate, it is important that such alterations are carried out in a manner that is compatible with the building fabric and does not lead to oversealing, which in turn could lead to significant damage to the building fabric.

As mentioned previously, the Old Library is a major tourist attraction and revenue source for the University. As such, dealing with the issue of the influence of visitors on the hygrometric environment in the building is a sensitive one. Although the staff who deal with the preservation of the collection would like to see the building revert to its original purpose, this is not a practical solution as the cultural heritage of the building and its contents should be experienced and enjoyed by the general public and not a small circle of scholars, preservation staff and students. As a result, alternative options must be explored.

One potential solution is a compromise between the interests of the college authorities and the preservation staff. Currently there is no limit on the number of people who may enter the building on an hourly or daily basis. During peak times, over 700 people per hour have been observed to enter the building, resulting in unacceptably large variations in RH and H_{abs}. By introducing a cap on the number of visitors admitted per hour, such large loads can be avoided, and the actual fluctuation would thus be more predictable. This could be achieved with minimal capital expenditure and could be implemented simply by a system of pre-reservation of tickets for admission to the building. Although this approach may reduce annual revenues, it may be effective in stabilising the environment and prolonging the life time of the collection, with the need for very little additional infrastructure. As a result, this would be the most sustainable and cost-effective approach to reducing the impact of visitors on the environment in the Old Library, while maintaining the two primary functions of the building.

Another measure that may be incorporated into the building to deal with the influence of people, particularly on wet days, would involve the implementation of plant in either the Exhibition Space or a Visitor Centre with the purpose of pre-conditioning visitors before they enter the more sensitive areas of the building. This could be achieved by installing dehumidifiers to maintain RH conditions at approximately 40-45%, the lower end of the

scale of acceptable values. This would function to remove excess moisture from the people as they visit the lesser known exhibits in the building, however, it would increase the energy consumption of the building and may require unacceptable alterations to the fabric to the building fabric for its integration into the area.

An alternative solution may involve the provision of cloakroom facilities where visitors could remove and store their personal belongings, particularly when wet, for the duration of their visit. This strategy, however, may be difficult to enforce and, unless implemented in tandem with measures to regulate the number of people entering the building, may cause unacceptable congestion of people. Based on these considerations, management of the throughput of people in the building is the most practical solution to reducing the environmental impact of people.

Altering the thermal environment will also have a corresponding effect on the moisture conditions in the building. Given that hygrometric properties are the most important factor in determining the deterioration of collection items, thermal upgrades should also assist in the stabilisation of moisture conditions. Considering the retrofit scheme carried out in the Wren Library, Cambridge (outlined in Section 2.1.4), where a simple *"low-tech"* intervention was carried out and stabilised the environmental conditions in the building, a similar scheme could be implemented in the Old Library as the two buildings share some distinct similarities. Currently, mechanical heating is supplied to the building at pre-specified times using convection heaters (radiators, hot air blowers) and storage heaters. No consideration is placed on the effect of the heating on the humidity conditions. By upgrading the heating systems to function on a humidity controlled conservation system while also introducing dehumidifiers, particularly in collection storage areas and the Long Room, the thermo-hygrometric properties of the environment would be more suitable in terms of preservation. Such a scheme could be implemented across the building and supplementary radiant heat sources be provided in reading rooms and work spaces.

The final element that could undergo some alterations is the building envelope itself. Retrofitting internal insulation has been observed to be an effective measure in regulating the environmental conditions, however, extending such work to the building as a whole would be unacceptable in terms of conservation of the building itself. Similarly, external insulation would adversely affect the character of the building and may be discounted as a potential intervention for the Old Library.

From the literature (Section 2.1.3), 25% of heat loss from a building occurs through the roof. Considering the large ceiling in the Long Room, installing a modern, breathable and

compatible insulation system, would be an effective measure in reducing heat loss from the building, while potentially improving other IAQ issues not observed during this project (particulate deposition for example). This in turn could improve comfort conditions and reduce seasonal variations in temperature in the building, a factor that would extend the life of the collection and improve the sustainability of the building in general. It is recommended that the installation of loft insulation is the first intervention to the building fabric.

One final aspect of the building envelope that may be altered without significant loss of character of the building are the windows. Secondary glazing has been found to be an effective method of reducing infiltration and heat loss (Section 2.1.4), however in terms of the Old Library, it may costly to implement owing to the large number of windows in the building. Alternatively, the renovation and use of the existing internal shutters could be a viable option in reducing heat loss through the windows. Closing shutters decreases the U-value of historic windows (see Table 2-1) and, in conjunction with the blinds that are currently in place, could be practically as effective in reducing heat loss as the installation of secondary glazing, with no associated loss in building fabric. Although effective in reducing heat losses from windows, the implementation of shutters may not be a viable option in the Old Library owing to the on-going labour cost associated with the daily opening and closing of these fixtures, which may be unacceptable.

Considering that environmental conditions in the building undergo large seasonal variations, implementation of a single alteration in isolation may not be effective in regulating the thermo-hygrometric variations in the building and, as a result, may not deliver a timely return on investment. Accordingly, a holistic overall approach to the building may be required that would involve compatible retrofit options for the building envelope (insulation of the envelope, upgrading of the windows, etc.) as well as an alteration to the existing mechanical heating, perhaps with the installation of a non-intrusive HVAC system, will potentially lead to the greatest improvement in environmental conditions in the building. A number of potential retrofit options, as well as alteration of plant in the Old Library building will now be modelled using the IES <VE> software as a means of developing an alteration strategy for improving the environmental conditions in the Old Library in terms of preservation of the collection.

6.4.3. General Conclusions for Historic Buildings

Based on the analysis of the data collected from both the Museum Building and the Old Library, a number of general conclusions can be drawn that apply to historic buildings in general as follows:

- Assessment of the thermo-hygrometric environment of a historic building using environmental signatures can be an efficient and accurate method of determining the key stimuli that are driving the indoor environmental conditions in a historic building.
- The effect of solar gains on the environmental conditions in historic buildings has the potential to cause unacceptable variations in T with regards both the comfort of the occupants and the preservation of cultural heritage in the building. The use of light coloured blinds and low emissivity coratings on windows, particularly those that are south facing, can eggectively reduce the impact of these gains.
- Areas within historic buildings that are used to store a large number of books typically undergo stable environmental conditions in the short term. The books not only regulate the hygric environment but also the thermal conditions by acting as thermal mass and hygroscopic surfaces. Seasonal variations may remain large, however, unless supplementary measures, such as the installation of HVAC equipment or conservation heating sytems, are implemented to regulate moisture generation and RH fluctuations in the space.
- Passive methods of imporoving the hygric variations in a building can be effective in reducing diurnal RH variations.
- The presence of people in a historic building has the potential to cause unacceptable environmental variations in a building, particularly those where cultural objects are stored. These variations are noticeably higher on wet days than dry days as the additional moisture load on the clothes and belongings of the people induce additional loadings in the buildings. Maintaining adequate ventilation rates is paramount in order to quickly dissipate moisture loads due to people in historic museums and libraries.
- Evaluation of the indoor climate in historic museums and libraries, through the use of climate evaluation charts, is an important step in identifying potential issues in the buildings. Furthermore, careful consideration to both the demands of the building, the collection and the occupants should be taken when specifying the required climate classification for a given building. Although a compromise betweeen the three disparate requirements should be achieved, in all instances the

permanance of the collection should not be compromised through the specification of the environmental conditions.

- Although standards and guidance documents are typically used to specify the environmental conditons in museums, libraries and archives, it is important to first understand the contents and the building itself. For example, the specification of an environmental classification of C in the Old Library was leading to unacceptable damage to the collection. As a result, before choosing a specific guideline, standard or classification for a building containing cultural heritage, it is first necessary to assess the condition of the collection and the environmental conditions in the building to ensure that the current environmental standards are being achieved and are suitable for the collection.

7. Computer Modelling and Simulation

7.1. An Introduction to the Software

<Virtual Environment> by Integrated Environmental Solutions (IES-VE) is a software package comprising a suite of integrated analysis tools capable of modelling thermal conditions in a building as well as value engineering, cost planning, lifecycle analysis and lighting (IES, 2011d, Kumar, 2008, University-of-Cambridge, 2013, USDOE, 2011). The software can be used to investigate building performance either retrospectively or during the design stages of a construction project.

The analysis tools contained within IES-VE are linked by a Common User Interface (CUI) and a single Integrated Data Model (IDM), which results in applications having a consistent *"look and feel"* (IES, 2011d). Furthermore, input for one application can also be used by others within the package. For the purposes of this research project, three specific applications within the software will be used as follows:

- ModelIT: the model-building component of IES-VE, ModelIT allows the user to create the 3D models required by other components in the software package (IES, 2012).
- Apache: the thermal analysis application in IES-VE. Apache facilitates preparation of input data for the thermal analysis and conducts the calculations and simulations (IES, 2011b).
- Vista: used to review the results from a dynamic thermal simulation performed using Apache (IES, 2011c).

Two other features of the IESVE package that are used to model environmental conditions in a building are SunCast and MacroFlo. SunCast is used to investigate external obstruction and self-shading of a building, solar mapping through windows and openings and the effect of changing orientation of the building. SunCast generates shadows and internal solar insolation from any sun position, which is defined by date, time, orientation, site latitude and longitude.

MacroFlo is a program within IESVE for analysing infiltration and natural ventilation in buildings. It uses a zonal airflow model to calculate bulk air movement in and through buildings, which is driven by wind and buoyancy induced pressures.

For a comprehensive description of the physical models that are used by IES-VE in simulating the thermal environment the reader is referred to Appendix D.

7.2. Modelling of the Old Library

7.2.1. Building Characteristics

The Old Library was constructed using traditional materials and techniques, a number of which are still visible in the building today. The external walls comprising of two leaves of stone block, either granite or limestone, are used for the interior and exterior façade while the cavity is filled with rubble. These walls, ranging in depth from 1 to 1.4m, provide the building with a large amount of thermal inertia, thus allowing it to somewhat self-regulate the internal thermal environment.

A large number of tall windows were originally integrated into the design of the building in order to maximize the solar gains from which the building can benefit, thus reducing the requirement for heating by other means. As a means of providing ventilation to the building, all materials used in construction are permeable. This is a very important feature as this ventilation is the means by which excess moisture and harmful chemicals are removed from the building.

Generally, in traditional buildings, there are a number of fireplaces that provide heat and facilitate ventilation of the building by allowing air to exit through the chimneystack, inducing airflow as a result. In the Old Library, however, there are no fireplaces so as to prevent the possibility of fire in the building that could destroy the collection.

The probability of damage to the collection by high moisture and airborne contaminant levels is considerably increased as a result of the reduced ventilation levels caused by the absence of fireplaces. A compromise to these absent features can be observed in the Old Library however.

The central staircase in the building connects the Long Room on the first level to the shop on the ground level. This facilitates airflow from the lower level upwards through the Long Room. There is also an attic that runs the length of the building, which is not comprehensively sealed and is also very poorly insulated. Accordingly, the air can flow up the staircase into the Long Room and escape up through the Long Room ceiling into the attic space and hence out through the roof, thus providing the building with enough ventilation to adequately deal with natural moisture and contaminant loads. Furthermore, heat losses through the ceiling will be high as the insulation provided is substandard and aged.

7.2.2. Building the Geometry

Construction of the Old Library model in IES-VE was carried out in a number of stages, namely definition of the geometry, orientation and location, computation of the solar parameters, formulation of material and element properties and input of the various loading scenarios.

The first stage of building the model involved specifying the geometry. Floor plans of the Old Library, that had been drawn using AutoCAD, were obtained from the Buildings' Office in TCD and converted into *"dxf"* format. This allowed them to be imported directly into the software and used to build the geometry of the building. The internal perimeter was used to construct the building envelope as IES-VE formulates the building elements (i.e. walls, roof, partitions) from the inside of the building out. Using the *"draw extruded shape"* function and specifying the height of the particular level (obtained from on-site measurements and from elevation drawings) allowed the external perimeter of the building to be constructed. Thereafter, the building was partitioned as required and any openings (windows, doors, voids) were incorporated into the model. Fig. 7-1 illustrates the ground floor of the Old Library when constructed in IES-VE while Fig. 7-2 displays the entire building as viewed in the model viewer element of the software.

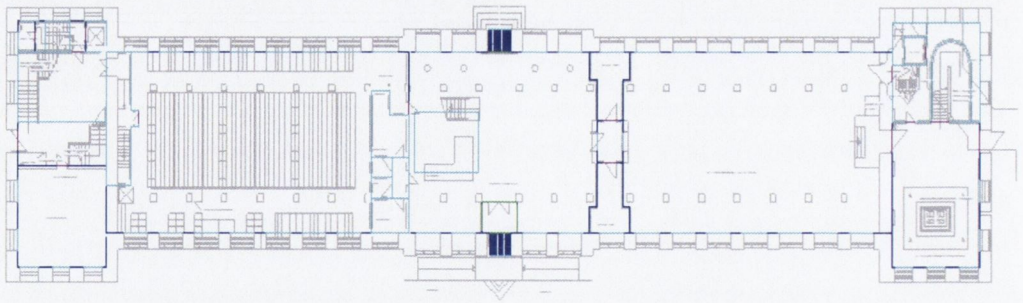


Fig. 7-1: Ground floor of the Old Library modelled in IES-VE.

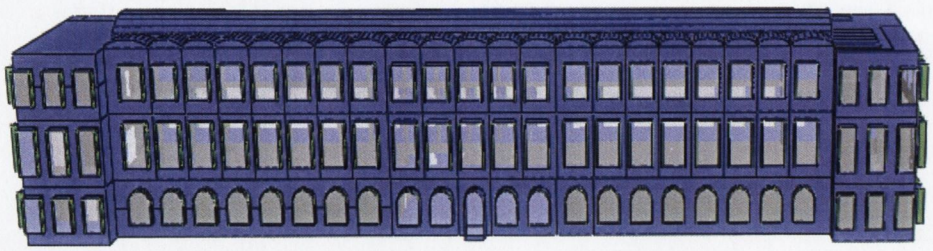


Fig. 7-2: Full axonometric view of the Old Library model constructed using ModelIT in IES-VE

Construction of the external windows was altered during the model-building process, since simply incorporating them into the external walls, while architecturally correct, would not have allowed accurate simulations. As the walls of the Old Library are thick, the windows are not located relatively close to the internal surface of the wall and are, in fact, closer to the external part of the element. As a result, the window reveals provide a large amount of thermal mass as well as some solar shading to the internal environment, meaning that it was necessary to incorporate the reveals into the model as required. Furthermore, a local shading feature was also built into the window construction to account for the shade provided by the external reveal of each window. Fig. 7-3 displays the typical external window construction used in the software.

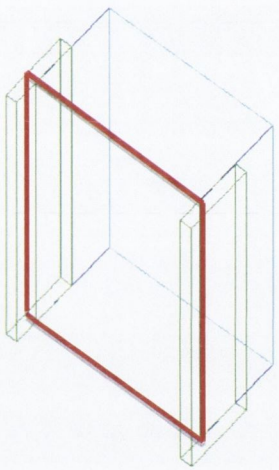


Fig. 7-3:Typical window element construction as modelled in IES-VE.

The green elements are the external reveals that are incorporated into the model as local shade. The window is connected to the internal environment with a void that is represented by the turquoise lines in Fig. 7-3. The window itself is generally presented as a green line in the software, however to avoid confusion it is defined by the red line in Fig. 7-3.

Once the geometry of the building had been defined, it was necessary to specify the location and orientation of the Old Library for the purposes of the solar calculations. Using the APlocate function in the software, the longitudinal and latitudinal coordinates of the Old Library (obtained from Google_Earth (2008)) as well as the relevant weather file were inserted at this time. As mentioned previously, actual weather data recorded on site throughout the various monitoring sessions were used for simulations. Thereafter, the Suncast package within IES-VE was used to calculate the solar properties that would be used during the modelling process. This programme calculated the sun altitude for the 15th day of each month and applied it to the model. Fig. 7-4 displays the results of sun altitude obtained

Month	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	24:00
Jan	-	-	-	-	-	-	-	-	2.26	8.29	12.66	15.03	15.19	13.12	9.02	3.21	-	-	-	-	-	-	-	-
Feb	-	-	-	-	-	-	-	0.88	8.62	15.16	20.05	22.84	23.23	21.18	16.92	10.86	3.45	-	-	-	-	-	-	-
Mar	-	-	-	-	-	-	1.51	10.23	18.30	25.23	30.45	33.38	33.60	31.07	26.17	19.46	11.53	2.89	-	-	-	-	-	-
Apr	-	-	-	-	-	3.81	12.72	21.59	29.97	37.30	42.85	45.79	45.52	42.12	36.23	28.69	20.20	11.30	2.41	-	-	-	-	-
May	-	-	-	-	3.56	11.89	20.70	29.64	38.27	46.03	52.05	55.21	54.65	50.54	43.90	35.81	27.04	18.10	9.39	1.27	-	-	-	-
Jun	-	-	-	-	6.78	14.90	23.60	32.53	41.32	49.41	55.93	59.61	59.27	55.05	48.20	39.96	31.11	22.19	13.57	5.57	-	-	-	-
Jul	-	-	-	-	4.60	12.72	21.42	30.36	39.14	47.23	53.80	57.65	57.70	53.91	47.38	39.32	30.54	21.61	12.90	4.76	-	-	-	-
Aug	-	-	-	-	-	6.76	15.61	24.53	33.10	40.74	46.71	50.04	49.99	46.56	40.53	32.85	24.27	15.34	6.50	-	-	-	-	-
Sep	-	-	-	-	-	-	7.84	16.55	24.58	31.39	36.33	38.74	38.20	34.83	29.15	21.83	13.51	4.67	-	-	-	-	-	-
Oct	-	-	-	-	-	-	-	7.94	15.31	21.28	25.33	27.04	26.18	22.87	17.49	10.53	2.49	-	-	-	-	-	-	-
Nov	-	-	-	-	-	-	-	-	6.75	12.26	15.95	17.49	16.73	13.75	8.82	2.33	-	-	-	-	-	-	-	-
Dec	-	-	-	-	-	-	-	-	1.87	7.46	11.34	13.20	12.87	10.40	5.98	-	-	-	-	-	-	-	-	-

Fig. 7-4: Sun altitudes computed using the Suncast programme in IES-VE.

for the model using the Suncast programme in IES-VE. As well as enabling the modelling of solar gains in the model, obtaining the sunshine properties in the software also allowed a full shading analysis to be completed in the software. Fig. 7-5 displays a snapshot of an animation of the shading of the Old Library due to adjacent buildings.

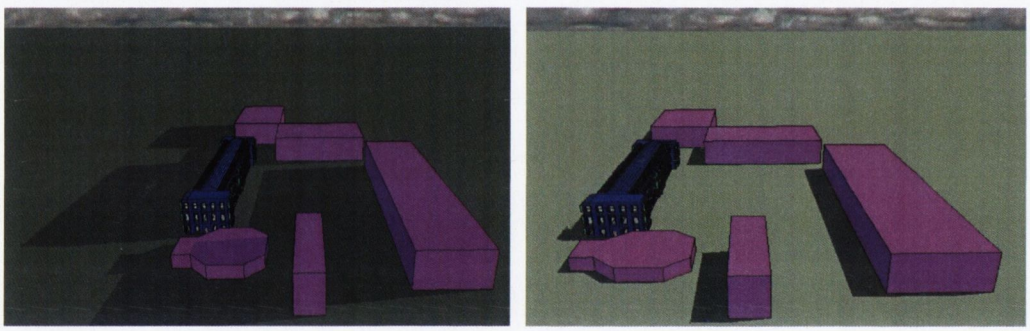


Fig. 7-5: Snapshot of the solar shading of the Old Library due to adjacent buildings (represented in pink) at noon on the 15th of January (left) and July (right).

The next stage in creating the model involved specifying the materials and thermal properties of the elements of the building. This process is completed using the Apache package within the IES-VE software. The programme requires the density, thermal conductivity and specific heat capacity of each material and its thickness within the particular element being constructed. IES-VE has a large database of materials and their relevant thermal properties inbuilt in Apache that were obtained from tables in CIBSE Guide A3 (Anderson, 2006).

Before specifying a material in Apache, the thermal properties proposed by IES-VE were cross checked with those in CIBSE Guide A3 and adjusted in the case of deviation. When materials were not found in the software's database, their properties were found in CIBSE Guide A3 and inserted into the software as required. Vapour resistivity values can also be defined in the software and these were obtained from the CIBSE Guide A3 as no such values

are defined in the IESVE material database. Fig. 7-6 displays the construction builder window, which is used to define the thermal properties of individual building elements in IES-VE. These constructions are then assigned to the building fabric as required. The materials used to model the Old Library are displayed in Appendix E while the composition of each structural element is defined in Appendix F.

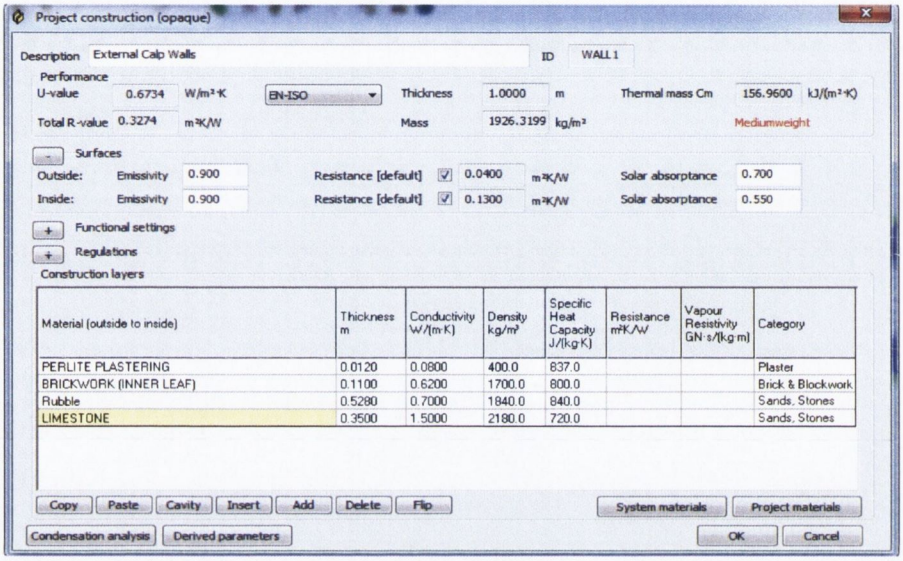


Fig. 7-6: The project construction window used to input structural element properties to IESVE.

7.2.3. Input of Schedules and Loadings

As well as defining and assigning material and structural element properties, Apache was also used to input the profiles and magnitudes of loads due to plant and casual gains (see Appendix D) as well as air exchange (infiltration rates) for the building. Heat gains due to plant use the heat output of the plant itself (in kW) to determine the change in the thermal environment resulting from its operation. Furthermore, the components of heat transfer associated with a particular element of heating plant are defined by the radiant factor, which is the proportion of the heat load that is a radiative heat load.

Casual gains (people, lights, computers, etc.) have both sensible and latent components and may be expressed in terms of either absolute values or on a floor area basis. Each component of the gain is specified as a maximum value modulated by a percentage profile. Taking the profile of heat loads due to people in the building, for example, actual data was inserted into the software as a casual gain. The maximum number of hourly visitors to the building occurred on July 17th when 719 people entered the building between 11:00 and 12:00. Accordingly, when specifying visitor numbers in the software, the maximum value for

people is 719 (i.e. 100%) and the visitor numbers, per hour, were defined in the model as a percentage of 719. Lighting and, where relevant, computers were also defined as casual gains in the Old Library.

In Apache, profiles refer to the schedules of operation of plant and casual gains and specify the percentage of the maximum potential load that is observed over a specific time period. Profiles are constructed in three stages; namely daily, weekly and yearly profiles. Daily profiles were specified using time and value (i.e. percentage of maximum) variables. An example of a daily profile for occupancy is displayed in Fig. 7-7 and the daily profiles used in the software are defined in Appendix G. Once the individual daily profiles are defined, it is necessary to build the weekly profiles. This is achieved by assigning the relevant daily profile to a particular day within the weekly profile (Fig. 7-8). The final stage in creating the profiles is to define the annual profile.

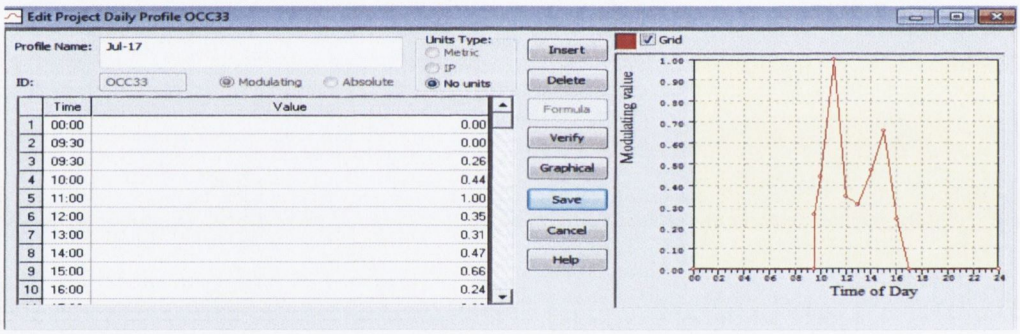


Fig. 7-7: Example of a daily profile for occupancy as used in IES-VE to model the Old Library.

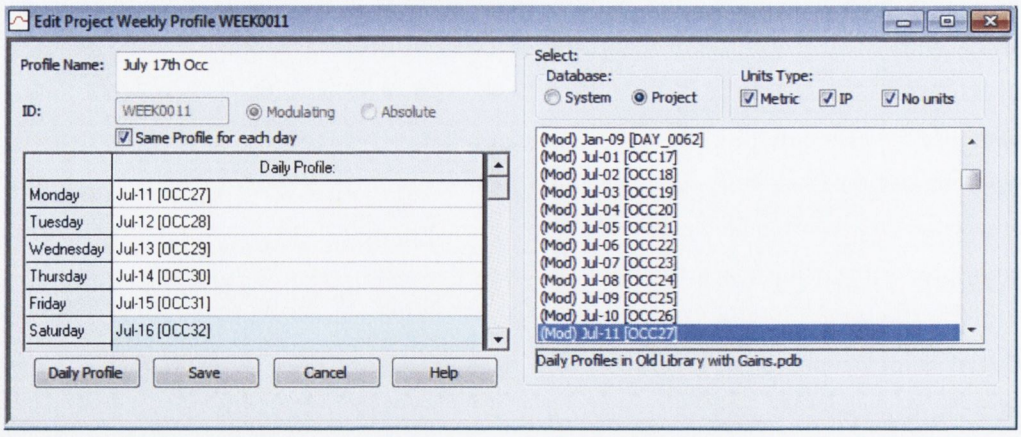


Fig. 7-8: Example of a weekly profile used in IES-VE.

This is achieved by importing the weekly profiles into the yearly profile and specifying its end date. Fig. 7-9 displays the window used to construct the weekly profiles in Apache. For the purposes of modelling the Old Library, five yearly profiles were defined, two of which

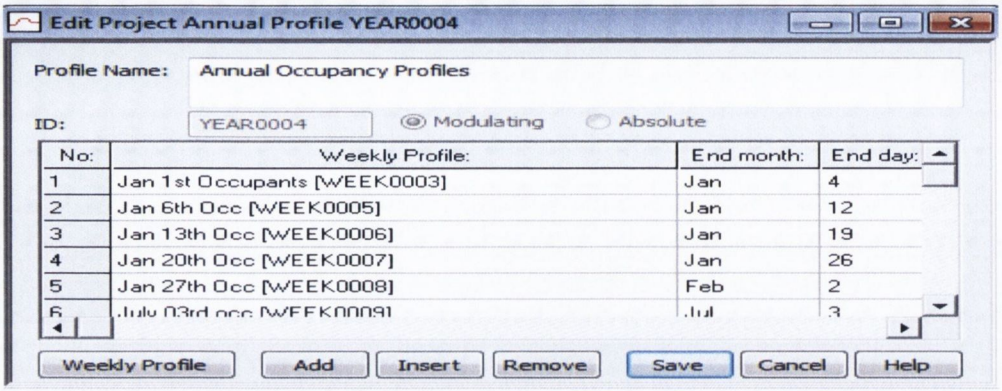


Fig. 7-9: Window to define the yearly profiles in IES-VE.

specified the occupancy levels and times when lighting was used while the remaining three were used to define the operation times of plant in the East Pavilion, West Pavilion and the storage heaters.

At this point, all relevant data for simulations (element properties, solar properties, loads) were inputted into the model. For the purposes of simulation, the ApacheSim (Dynamic Simulation) (Fig. 7-10) option was chosen and the required time period, reporting interval and preconditioning period were specified for the buildings. Once simulations had been completed, the software automatically switched to the Vista programme and the relevant data, in this case the T and RH, were extracted and inserted into Excel for interpretation.

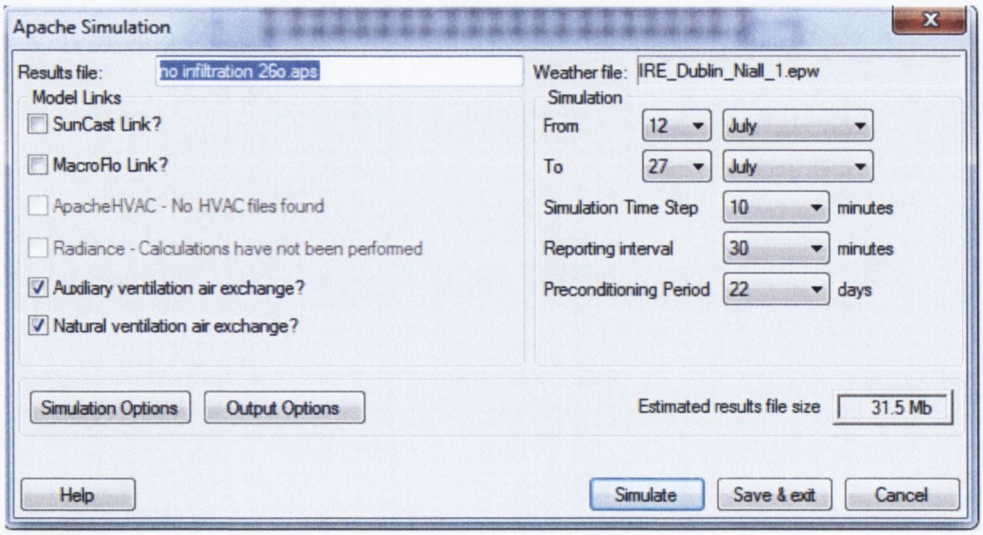


Fig. 7-10: ApacheSim window used to specify the parameters for simulations in IES-VE.

7.3. Calibration of the Model

7.3.1. Results of Initial Simulations

Once the model had been built in IESVE, simulations of the internal environment of the Old Library were conducted with the shop and Long Room being the focus of all tests. Initially, a simulation was carried out to ensure that the model was performing as expected. All loads were specified along with an infiltration rate of 0ach (air changes per hour) and a simulation was carried out for July, when no mechanical heating was present in the building and occupancy rates were at a maximum. Fig. 7-11 illustrates the diurnal T variations observed in the Long Room and Shop as well as the modelled fluctuations.

Considering the fluctuations for the Long Room displayed in the chart in Fig. 7-11, it appears that the software is performing reasonably as expected. Diurnal variations obtained from the model are marginally larger than those observed in the Long Room during the monitoring period.

The time interval displayed in Fig. 7-11 may be subdivided into two distinct periods, namely slight cooling of the building (circled in blue) and a subsequent warming up period (circled in red). The overall trends, modelled and observed, in the building during these time periods appear to be driven by the external temperatures, which undergo similar trends during the two time intervals.

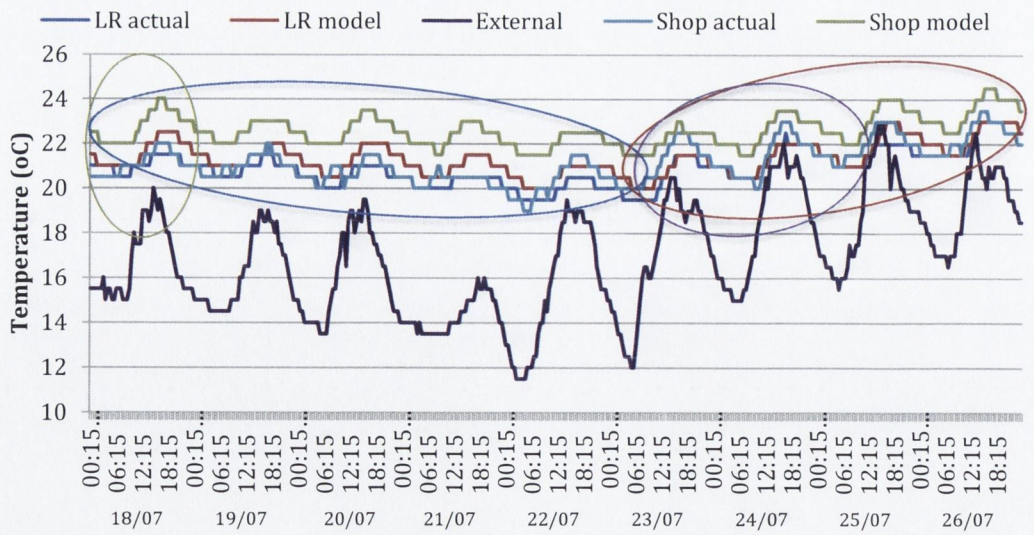


Fig. 7-11: T variations recorded and simulated for the Long Room and Shop in July.

Taking the data observed and modelled on 18/07 (circled in green on Fig. 7-11) it can be seen that initial variations in the model are greater than those observed in the Long Room during the data acquisition phase, although this difference is relatively small. The model indicates a change in T of 1.5°C over the course of the day (21°C increasing to 22.5°C) compared to a change of 1°C (20.5°C increasing to 21.5°C) monitored on site. Over the course of the *"cooling down"* period, external maximum T values decrease by 4°C (20°C to 16°C), which in turn has an effect on T in the Long Room as maximum daily T values also fall by 1.5°C in the case of the model and 1°C for the actual between 18/07 and 22/07.

At this point, external T values begin to increase once more and, as a result, so too do the internal values. Based on Fig. 7-11, it appears that the actual Long Room is more responsive to the external thermal conditions when compared to the simulated space, as the largest diurnal change in T in the recorded data is observed, increasing by 2°C from 19.5°C to 21.5°C as the building reacts to the increase in the outside T values. Over a two day period (23/07 and 24/07), circled in purple, modelled and recorded data appear to undergo identical diurnal variations as both the building and model respond to the increase in external T. Thereafter, the model increases at a quicker rate compared to the actual and the simulated T is higher in magnitude than the actual data once more.

Similarly, the general trends of the thermal conditions in the Old Library Shop modelled using IESVE are comparable to those observed in the shop, although simulated T values are consistently higher than those recorded during the data acquisition phase. As observed in the Long Room, a *"cooling down"* and *"heating up"* period are recorded in the shop in accordance with the external conditions. Once again the actual data appears to react to the external environment at a quicker rate than those in the model. One other observation from the chart is that simulated T values in the shop are higher than those in the Long Room over the entire interval, which suggests that T values in the Long Room may be influenced by those in the Shop as heat is free to pass between the two spaces through the central staircase that connects the two spaces, as modelled in IESVE by the "MacroFlo" option.

Fig. 7-12 displays the RH trends simulated for a period in July compared to the actual data recorded in the Old Library for the corresponding period. From the chart it is clear that a disparity exists between the modelled and actual trends. Large diurnal fluctuations are occurring in the model when the building is open compared to the relatively stable conditions present in the actual building over the course of the time interval shown in Fig. 7-12. Since the diurnal trends observed at this time are reasonably accurate and comparable to the actual conditions at present, the trend in Fig. 7-12 suggests that the model easily

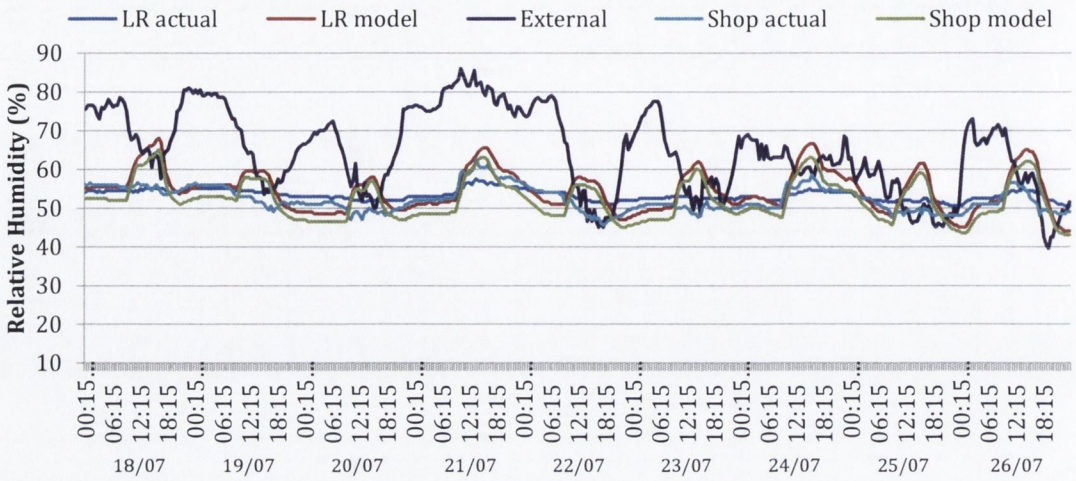


Fig. 7-12: Modelled and actual relative humidity in the Old Library in July.

simulates diffusion but the difficulty lies with the modelling of absorption and desorption by hygroscopic materials. This is be due to the absence of an option to input parameters associated with adsorption and evaporation of hygroscopic surfaces and materials, meaning that they are not modelled in IESVE. Accordingly, IESVE was used for thermal simulations and moisture diffusion and moisture loads only while an alternative software package, HAMBASE, was used for simulating the hygrometric environment in the Long Room.

Based on the trends displayed in Fig. 7-11, it may be concluded that the model is performing reasonably well in terms of the diurnal T variations, although the magnitudes of the simulated and recorded values differ slightly. During opening hours, however, the absence of an infiltration rate coupled with the difficulty in modelling hygroscopic surfaces and materials result in a large variation in the model. Accordingly, a sensitivity analysis of the simulated environmental conditions, particularly as a means of determining the actual infiltration rate and the effect of each load on the model would lead to more accurate simulations of the Old Library and allows a more rigorous calibration of the model when compared to the actual data monitored in the Old Library.

7.3.2. Modelling of the Hygroscopic Environment in the Long Room using HAMBase

7.3.2.1. Introduction to the HAMBase software

Since the IES software does not model the effect of hygroscopic surfaces and materials, it was necessary to use an alternative software package to comprehensively model the hygric conditions in the Long Room. This would allow for the effect of the books on the environmental conditions in the Long Room to be assessed. HAMLab (Heat, Air and Moisture

Laboratory) is an *"all-in-one collection of models and tools suitable for MatLab and/or Simulink and/or COMSOL"* (TUE, 2014). HAMLab was developed by students and researchers under the supervision of Dr. Jos van Schijndel at the Department of the Built Environment at Eindhoven University of Technology. HAMBase (Heat Air and Moisture model for Building And Systems Evaluation) is one of the MatLab tools that was developed by HAMLab (de Wit, 2006, van Schijndel, 2007). HAMBase is a simulation model for the heat and vapour flows in a building, facilitating the modelling of indoor temperature, air humidity and energy use for heating and cooling of a multi-zone building. HAMBase is an open source software package that can be downloaded directly from the HAMBase website (TUE, 2013). The general structure of the HAMBase program is presented in Appendix I.

7.3.2.2. Creating the Model in HAMBase

Currently, a graphical user interface for HAMBase has not been developed. Consequently, in order to generate the model in the HAMBase software package, the source code contained within the "Input" m-file is altered. Using this method, the building data (location, construction properties, geometry, etc.), the plant located within the building and the external weather conditions are defined. For the purposes of this study, the Long Room was created as a single zone and modelled accordingly. Initially, the ground floor was also created as a separate zone but the introduction of air-flow between zones was advised against when the developers of the software were consulted due to the complexity of accurately modelling this effect. Although this would mean that the airflow between the shop and the Long Room would be excluded from the simulations, the primary purpose of this study was to assess the effect of the large quantity of books on the hygric environment in the Long Room and so the airflow between zones is not very relevant in this case. As a result, a single zone model was generated using the existing properties of the Long Room and the code can be found in Appendix J. As with the IESVE model, the actual internal loads (associated with plant, lighting and people) as well as the actual external conditions were used in the HAMBase model.

Material properties are contained in the "matpropf" function of the software. Although this is generally written in Dutch, the majority of the materials required are contained within this function. The thermo-hygrometric properties of all materials used to generate the model of the Long Room were again cross-checked and compared against the literature to ensure that they were accurate. In cases where materials were missing, for example the books, they were added to the matpropf function for use in the construction definition.

When generating the geometry in the software, the model of the Long Room was creating using three external surfaces (north and south walls and roof) and three adiabatic surfaces (east and west walls and the floor of the Long Room). This meant that the Long Room alone could be modelled without the need to create geometries for adjacent zones. The bookshelves were introduced as internal walls in the Long Room and the single glazed windows and sun blinds were also introduced as was the case with the IESVE model.

7.3.2.3. Results of the HAMBase simulations

In order to discern the effect of books on the hygric environment in the Long Room the period of time during which the Old Library was unoccupied was chosen for simulation. As with the IESVE model, a sensitivity analysis was conducted to determine a suitable infiltration rate to use in the model. Following this analysis, an infiltration rate of 0.15ach, which agrees with that determined in the IESVE software, was found to be the most accuate for modelling in the HAMBase software.

To determine the effect of the books, simulations of the Long Room were carried out for infiltration rates of 0ach and 0.15ach respectively. This would allow for the effect of the books to be assessed in both a sealed environment and in the actual environmental conditions in the Old Library during the Christmas vacation. The H_{abs} of each simulation scenario was used for analysis purposes as this is independent of the T and would provide a more representative indication of the effect of the books by illustrating the moisture in the air. This data is presented for each of the four scenarios simulated in Fig. 7-13.

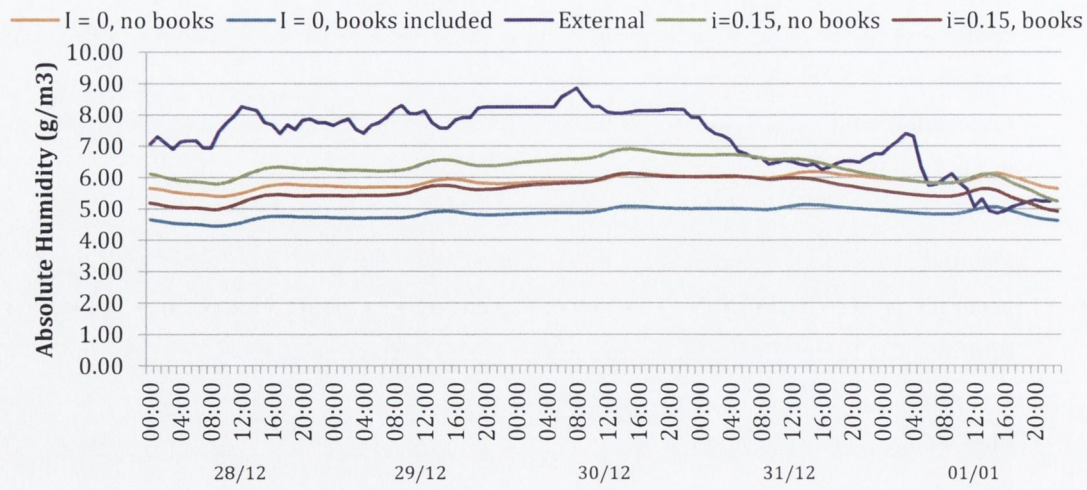


Fig. 7-13: Absolute Humidity data simulated using the HAMBase software.

Based on the trends displayed in Fig. 7-13, it is clear that the books are having a major effect on the moisture environment in the Long Room. The first point to note from the chart is that, in general, the overall H_{abs} trend in the Long Room is stable regardless of whether the books are present or not. This is a somewhat surprising result as it would be expected that the volume of books in the space would be significant in maintinaing a stable moisture environment in the space and that their removal would lead to larger variations in the building. That being said, the large area of timber contained within the Long Room, which was not removed during the modelling, would have a similar effect on the environment as the books and would act so as to regulate the moisture variations in the space, as was seen in the GLT in the Museum Building.

Despite the similar nature of the H_{abs} variations simulated when the books are included and excluded, it is obvious from the chart that there is a discernable increase in H_{abs} in the Long Room when the books are removed. In both cases the moisture buffering effect of the books reduces the RH values in the space by an average of $1.01g/m^3$ when there is no infiltration rate and $0.69g/m^3$ when the infiltration rate of 0.15ach is included in the simulations. This equates to a reduction in water vapour in the Long Room of approximately 7,200g when the Long Room is simulated as a sealed environment and 4,950g when the current infiltration rate is described. As a result the effect of the books in regulating the moisture effect in the Long Room is demonstrated.

In order to assess the individual effect of both the oak panels and the books on the hygric conditions in the Long Room, a number of additional simulations were carried out using the HAMBase software with the infiltration rate set to 0ach. The results of these simulations are displayed in Fig. 7-14. From the chart it is apparent that the oak panels that are used to clad the Long Room are also having a significant impact on the H_{abs} trends in the Long Room.

As was observed when the books were removed from the Long Room, the removal of the oak panels from the space results in a significant increase in the H_{abs} magnitude in the room. According to the simulated data in Fig. 7-14, the extent of the H_{abs} change associated with the removal of the oak panels alone is greater than that observed when the books were omitted from the simulations. While the removal of the books alone resulted in an average increase in H_{abs} over the simulated period of $1.01g/m^3$, when the oak panelling is removed from the Long Room, the average increase in H_{abs} climbs to $1.60g/m^3$. When applied to the volume of the space as a whole, the removal of timber causes the concentration of water vapour in the air to increase by approximately 11,400g. The removal of both the books and the oak leads to a slight increase in the H_{abs} value when compared to the removal of the oak alone, however, the variations observed in the trends increases discernably.

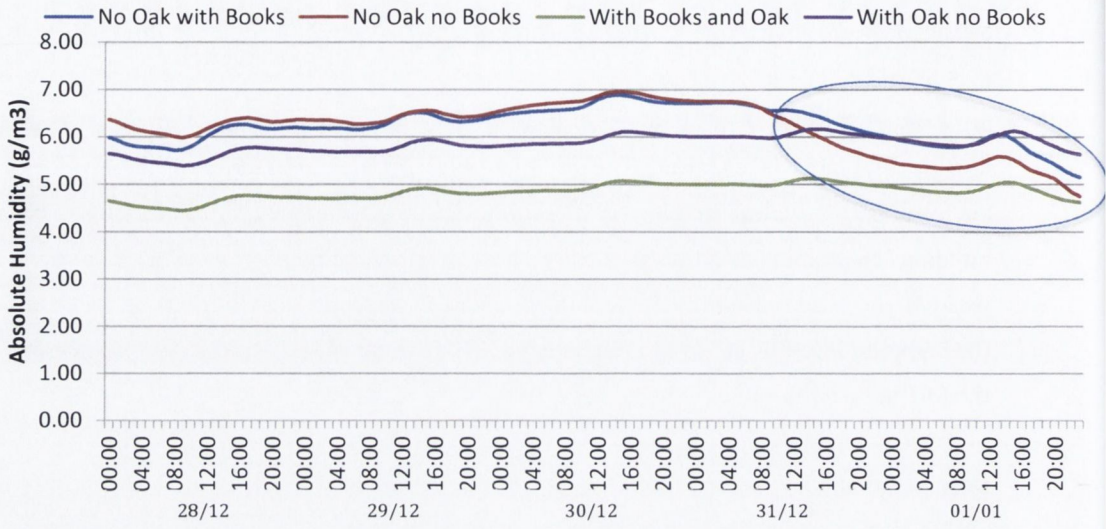


Fig. 7-14: The effect of both books and the oak cladding on the hygrometric environment in the Long Room simulated using HAMBase.

This is particularly noticeable in the blue region in Fig. 7-14, where a relatively large decrease is observed in the red line over a short period of time. The magnitude of this variation is not consistant with those observed in the other modelling scenarios and indicates the effect of the hygroscopic materials on the hygric environment in the Long Room.

Although the HAMBase model has provided a useful insight into the influence of the hygroscopic surfaces and materials in the Long Room, it should be noted that this software is not without its limitations. The omission of the air-flow from the shop to the Long Room may be eliminating a major source of moisture into the space and, in order to gain a full appreciation of the conditions in the Long Room, should be included in future studies. Furthermore, the heavy nature of the buildings external walls, as well as the collection in the space, means that a prolonged period of preconditioning may be required. The duration of this preconditioning period was suggested to be in excess of a year and would require the actual external weather conditions as well as the specification of the internal casual loads. Unfortunately, this level of data was not available and, as a result could not be implemented. It is expected that should these constraints be overcome, the HAMBase model would provide a more accurate representation of the hygrometric conditions in the Long Room. Despite this, the model has effectively illustrated the significant effect of both the books and the oak panels on the hygric environment in the Long Room.

7.3.2.4. Conclusions

The purpose of modelling the Long Room using the HAMBase software was to examine the effect of the 200,000 books contained within the space on the hygric environment of the Long Room. Due to the complexities of modelling air-flow between zones in HAMBase, a single zone model was constructed so that the Long Room alone was considered. As with the IESVE software, an infiltration rate in the region of 0.15ach was determined to be the most accurate for the software. A number of different scenarios were modelled using HAMBase and based on the data generated through these simulations the effect of the hygroscopic materials and surfaces in the space were assessed.

The effect of the presence of books was assessed by simulating the space with and without books for two infiltration rates, 0ach and 0.15ach. It was found that the effect of the presence of books in the sealed environment was relatively large, equating to an average decrease in H_{abs} of 1.01g/m^3. Similarly, the removal of books from the space under the current infiltration rate (0.15ach) resulted in an increase in H_{abs} of 0.69g/m^3 as the ventilation rate is effective in removing some of the moisture from the space. Accordingly it may be concluded that the presence of the books has a major buffering effect on moisture in the space.

The effect of the oak panels were assessed using HAMBase and it was found that the timber has a greater buffering capacity on the Long Room than the books (an average of 1.53g/m^3). As with the removal of the books, the extraction of the oak panels from the Long Room did not increase the magnitude of variation in the space significantly as the books compensated for the removal of the oak by regulating hygric variations in the absence of the timber. Hence it may be concluded that the timber panels that clad the walls and ceiling of the Long Room are the most effective hygroscopic surface regulating the hygric environment in the space, although the books are significant in their effect. When either the books or the oak panels are removed, the remaining hygroscopic material compensates for the removal of the hygroscopic surface. This results in the relatively small H_{abs} variations observed in the simulated data when either the oak panels or the books alone were extracted from the space. The removal of both books and timber will lead to larger variations in the space as moisture is no longer absorbed and evaporated from the surfaces of these hygroscopic materials.

7.3.3. Sensitivity Analysis of the IESVE Model

7.3.3.1. Infiltration Rates

Before conducting simulations to determine the effectiveness of various retrofitting strategies in regulating the environmental conditions in the Old Library, it was first necessary to assess the accuracy of the model in predicting the actual conditions in the building. To achieve this calibration, the infiltration rates and loadings to the building were investigated to determine their effect on the simulated trends. As mentioned previously, actual loads observed in the building during the simulated time intervals were used in the model and after a number of simulations it was determined that these loads needed some slight refinement to obtain a more accurate model. Actual infiltration rates to the building were unknown and, as a result were obtained through trial and error.

In order to obtain reasonable results from the model of the Old Library, it is first necessary to determine the infiltration rate to the buildings, a parameter that is measured in air changes per hour (ach) and is specified for each room in the model. Although the infiltration rate is a dynamic phenomenon that varies throughout the year, for the purposes of the IESVE software it is assumed to be a constant value that does not change with time, however, it may vary in value throughout the building.

Fig. 7-15 illustrates the first series of infiltration modelling carried out on the Long Room in order to identify the most suitable infiltration rate for the space. As can be observed in the chart, as the infiltration rate increases from 0 to 100ach, internal diurnal variations in the Long Room decrease in magnitude before approach those externally. At infiltration rates greater than 10ach, internal conditions are highly influenced by the external environment to the extent that the model is behaving as if the Long Room was entirely open to the outside conditions. This would indicate that a lower infiltration rate is more likely and, upon further examination of the chart in Fig. 7-15, it may be concluded that the actual infiltration rate for the Long Room lies between the values of 0 and 1ach. As a result, it was necessary to extend infiltration rate modelling to rates falling within this range.

Fig. 7-16 displays diurnal T variations for a range of infiltration rates between 0 and 1ach. In this case, the modelled T fluctuations all appear to be comparable to the actual T values and, once again, the T is observed to decrease as the infiltration rate increases. Infiltration rates of 0 and 1ach were discounted as being the actual rates as 0ach is consistently higher than the actual, while 1ach falls noticeably below the trend observed in the Old Library.

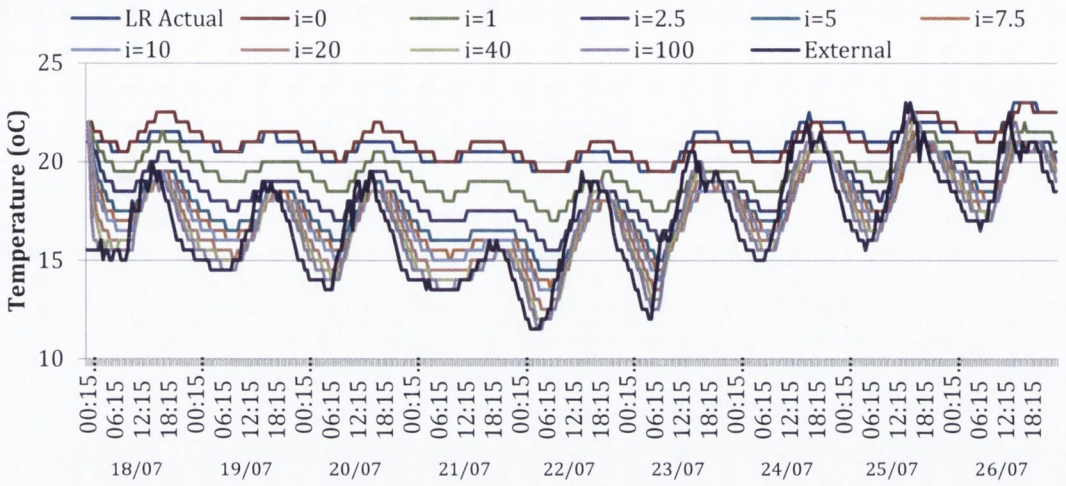


Fig. 7-15: Simulated T variations in the Long Room for high infiltration rates.

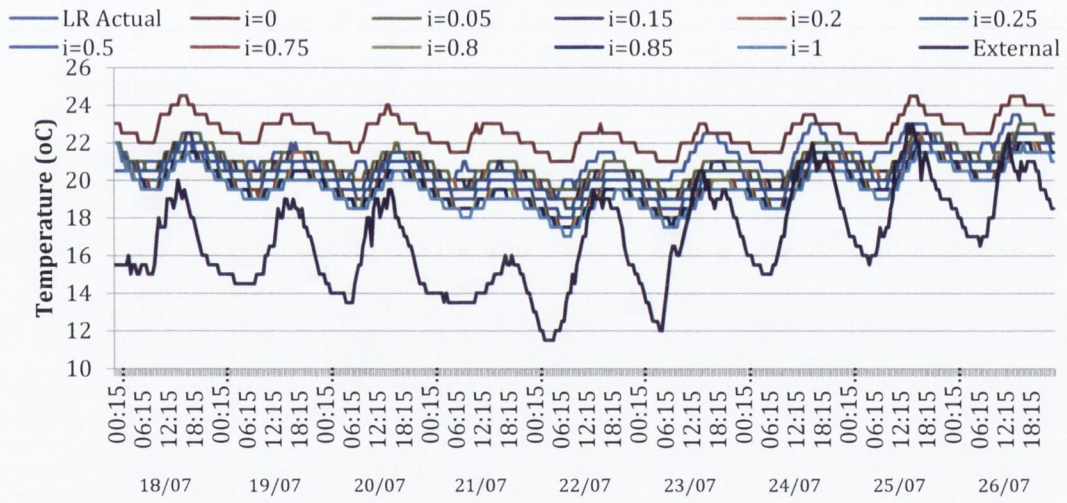


Fig. 7-16: Simulated T variations in the Long Room for low infiltration rates.

Accordingly, upon further examination of the trends, it appears that the infiltration rate for the Long Room lies between 0.05 and 0.25ach.

Focusing on these infiltration rates, as displayed in Fig. 7-17, it appears that, in the case of T variations in the Long Room, an infiltration rate of 0.15ach represents a suitable model of the thermal conditions in the space when compared to actual fluctuations. A similar process was conducted to examine the effect of infiltration rates on the shop beneath the Long Room. Fig. 7-18 and Fig. 7-19 illustrate the T variations associated with the infiltration rates for the shop corresponding to those in the Long Room, as mentioned previously. As before, a higher rate, that is greater than 10ach, leads to the model of the shop behaving in a similar manner

to the external environment. Once again it may be concluded (see Fig. 7-18) that the infiltration rate in the shop lies between 0 and 1ach, although, in this case, it is more likely to be closer to 1ach.

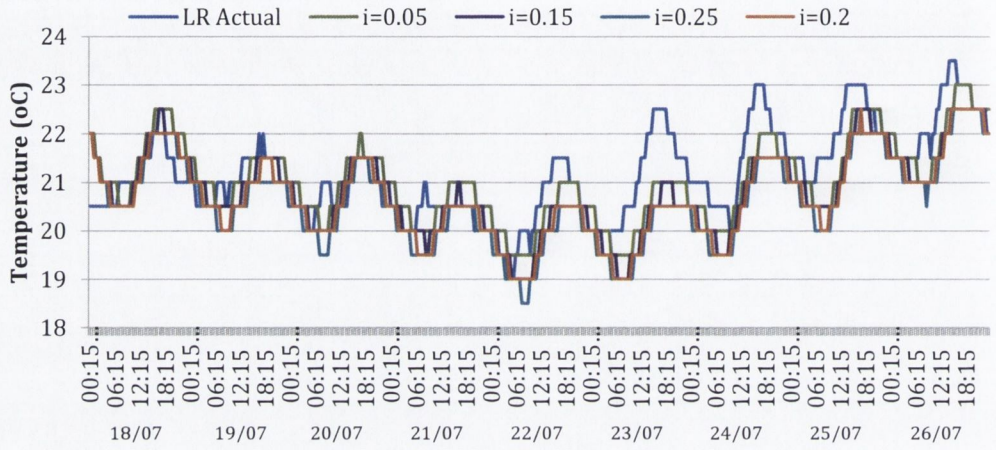


Fig. 7-17: Further examination of the T trends associated with low infiltration rates.

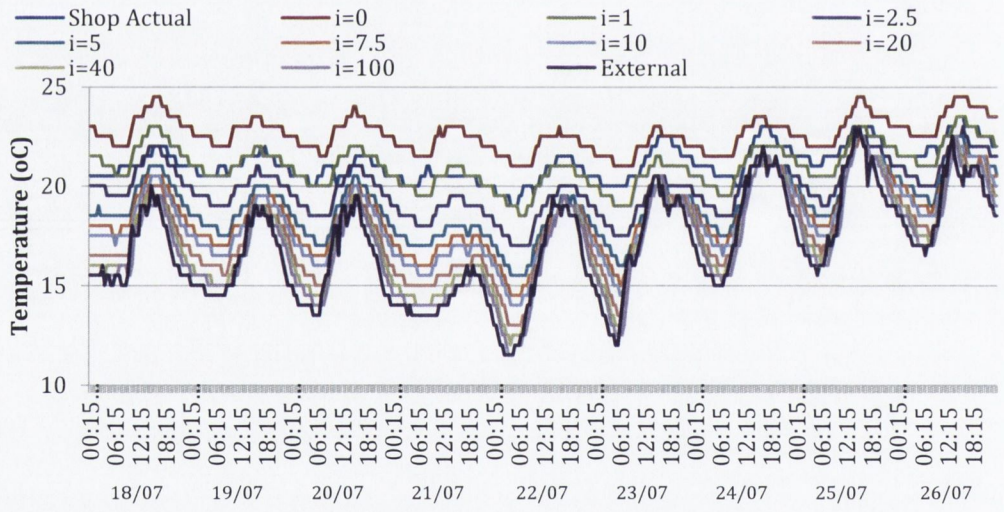


Fig. 7-18: Modelled T variations for high infiltration rates in the shop.

Accordingly, Fig. 7-19 was plotted to determine the actual infiltration rate in the shop. Upon closer examination of the chart it appears that an infiltration rate of 1 provides the closest correlation between the actual thermal conditions in the shop and those that are achieved through simulation. As a result, for the purposes of future simulations, an infiltration rate of 0.15ach will be assumed for the Long Room and 1ach for the shop, as displayed in Fig. 7-20. The higher value in the shop may well be due to its use as an entry and exit to the building for visitors, which means that the external doors typically remain open during business hours with an automatic door for ingress/egress in a draught lobby.

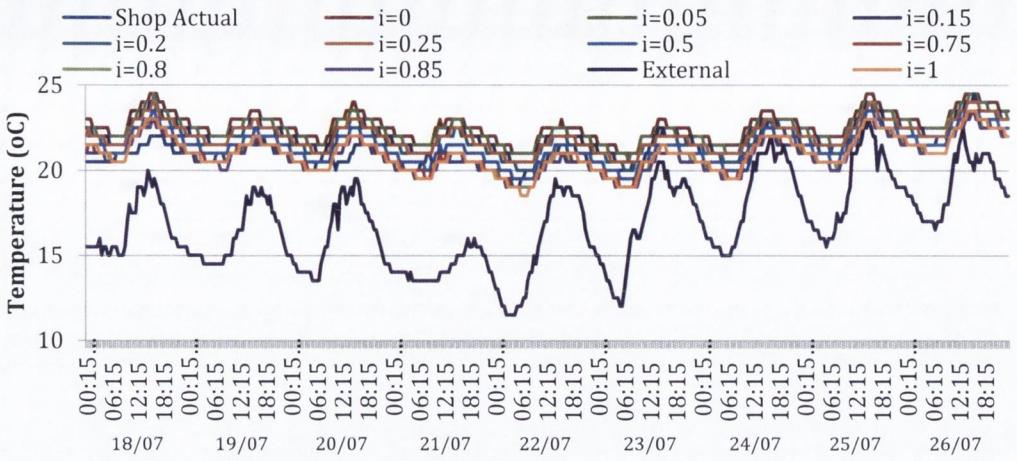


Fig. 7-19: Modelled T variations for low infiltration rates in the shop.

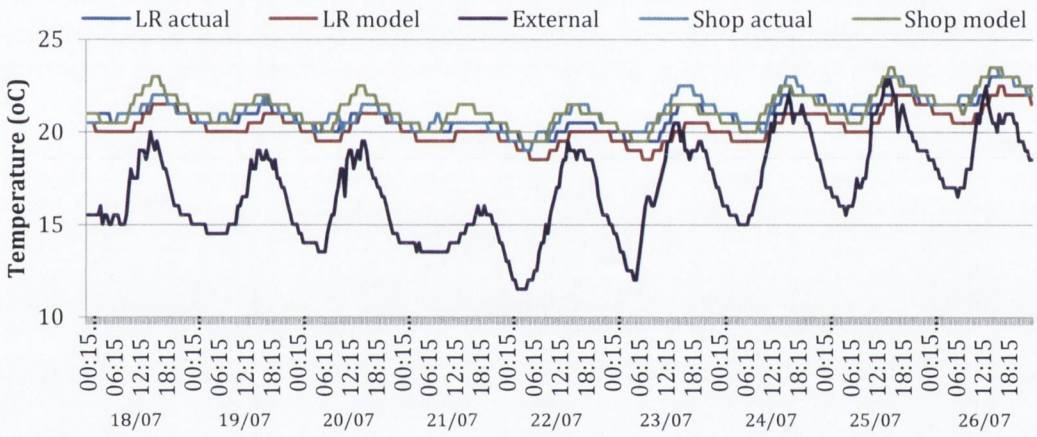


Fig. 7-20: Actual and modelled diurnal T varations in the Long Room (0.15ach) and the Shop (1ach).

It is worth noting that the infiltration rates determined through the sensitivity analysis appear to be relatively small in magnitude compared to current literature. Sinnott and Dyer (2011) conducted a study on the infiltration rates in 28 Irish dwellings using a standard blower door test and found that infiltration rates between the range of 5.39ach and 14.90ach were typical in such buildings. In relation to infiltration rates in large historic buildings, however, the apparently low value observed during the sensitivity analysis in this modelling study may not be as low as perceived. Samek et al (2007) state that in historic chuches, for example, air exchange rate of 0.1 is typical for churches with plaster and stone walls and of 0.5 to 0.75 for churches with wooden vaults. This agrees with the work of Schellen (2002) who measured the infiltration rates in a number of monumental churches. Based on his study, Schellen (2002) determined a range of infiltration rates for the churches, varying from 0.08ach to 1.2ach. In general, infiltration rates between 0.4ach and 1.2ach were considered to be large. Although the Long Room is not a church, it is similar in size and

geometry to a church building and, based on these studies, an infiltration rate of 0.15ach may not be unreasonable for such a space.

7.3.3.2. Winter Simulations

Upon determining the infiltration rates to the building using a sensitivity analysis and the actual data recorded in July it was then necessary to ensure that these were also applicable to the building during the winter season. Accordingly, data obtained from the building during the Christmas vacation was used to assess the accuracy of the model in simulating the building in winter. This period was chosen as it provided data from the building during a period when mechanical heating was deactivated and the building was entirely unoccupied and the subsequent heating up period when the Old Library opened to the public once more. Fig 7-21 displays the actual and simulated T variations in the Long Room and Shop over the Christmas vacation (circled in blue) and subsequent heating up period (circled in red).

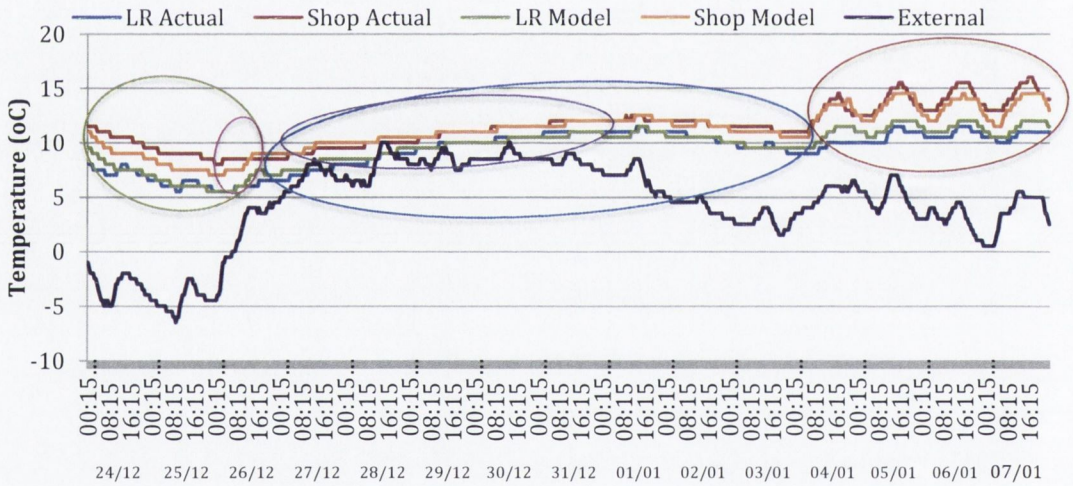


Fig 7-21: Actual and simulated T trends for the Long Room and Shop during the Christmas vacation and subsequent heating up period.

From the chart it can be seen that the model appears to be simulating environmental conditions in the Old Library closely. The diurnal trends observed during the Christmas vacation are comparable to the simulated as the building reacts to the deactivation of mechanical heating as well as the low external temperatures. Over the first two days of the Christmas vacation (circled in green), the external conditions create a large thermal gradient between the Old Library and the outside environment. This results in a relatively quick rate of heat loss and a T decrease in the building occurs accordingly. Considering the Long Room alone, the actual rate of heat loss from the building results in a fall in T of 2.5°C in the space

(8°C falling to 5.5°C), at a rate of 0.07°C/hour. In comparison, IESVE simulates a T decrease of 3°C (9°C to 6°C) occurring at an identical rate of 0.07°C/hour. These identical rates of T decrease indicate that the model is performing as expected, although at this stage in Fig 7-21, the magnitudes of the simulated and actual data differ slightly (by less than 1°C).

From 26/12, external T values begin to increase and this in turn results in the cooling pattern, both observed and simulated in the building, being replaced by a heating up trend as the internal conditions react to the smaller T gradient. The purple circle on Fig 7-21 illustrates this particular trend. Initially the model reacts quicker to the change in external conditions, as seen on 26/12 (pink circle), however, on the 29/12 the actual data observes a slightly higher T value, a trend that is observed over the following number of days. Considering the trends observed in the shop, both simulated and actual, over this time period it can be seen that the differences in behaviour are due to the model stabilising shortly before the actual data resulting in the measured conditions increasing slightly above the simulated. IESVE uses the MacroFlo function to model bulk airflow in the building and accordingly, heat flow from the Shop into the Long Room. As can be seen from the chart in Fig 7-21, actual conditions in the shop also overtake those generated by the model on 29/12. It is important to note that the differences in T values between the model and those measured in the building are typically less than 1°C and the model is responding reasonably accurately to the external conditions.

The final time interval displayed on Fig 7-21 is the subsequent heating up period when the building is reoccupied and mechanical heating is supplied following the Christmas vacation and this is circled in red on the chart. Considering the Long Room in isolation, it may again be concluded that the model agrees with the measured thermal environment and the two trends are similar. At this time, heat loads to the space are provided by mechanical heating, people, lights, solar gains and infiltration from adjacent spaces, in particular the shop, although, given the small number of visitors in the building during this time, people do not contribute significantly to the thermal trends. Sensitivity analyses on these loads are carried out later in this Section. From the chart it appears that the model of the Long Room is simulating conditions in the space correctly as the trends recorded on site correspond closely to those obtained from the simulation. Accordingly, in terms of the simulated trends in the Long Room, it may be concluded that the model is accurately simulating the thermal environment in the space over the course of the Christmas vacation and subsequent heating up time. As with the Long Room, the thermal environment in the shop is performing well (Fig 7-21) and yielding sensible and reasonably accurate T trends. Some small deviation between the actual and simulated T values are observed during the heating up period (circled in red), however, despite the small difference in magnitudes, the overall fluctuations

are comparable. The lower maximum T simulated by the software may be due to excess heat flow between the Shop and the Long Room in the model. It should be noted that, as before, the disparity between the actual and simulated values are small and the model is deemed to be working correctly in terms of the thermal environment in the building.

In terms of the simulated moisture data, however, the absence of the hygroscopic surfaces means that moisture in the modelled building is not adsorbed and evaporated as the environment in the building dictates. Accordingly, the simulated and actual trends (see Fig. 7-22) are behaving differently with the most noticeable divergence between the two trends occurring when the external H_{abs} values climb significantly (circled in red). At this point it becomes clear that the external environment is the determining factor for the simulated H_{abs} trends in the Old Library. The actual data reacts at a slower and steadier rate to the increasing external moisture conditions as the hygroscopic materials in the building control the environment in the building.



Fig. 7-22: Actual and simulated H_{abs} trends for the Long Room and Shop during the Christmas vacation and subsequent heating up period.

There is evidence in Fig. 7-22 to suggest that the model is somewhat simulating the moisture loads associated with the presence of people. The building reopened to the public again following the Christmas vacation on 04/01 and the diurnal H_{abs} trends simulated in the building on this day, as well as the following days (circled in blue on the right side of the chart) are consistent with the presence of people. This is reinforced by the fact that the model simulates diurnal increases in H_{abs} that occur despite the external H_{abs} remaining below the values in the building. The actual effect of people on the simulated H_{abs} values will be further assessed through the use of sensitivity analyses, as discussed later in this Section.

Based on the chart in Fig. 7-22, it appears that, in the case of the winter period, simulated H_{abs} values do not necessarily correspond closely with the actual data obtained from monitoring of the building. It appears that the simulated values are closely correlated with the external environment and this is most likely a result of the difficulty in modelling hygroscopic materials and surfaces in IESVE. There is further evidence to suggest that the model is simulating the effect of people on the building and this will be assessed further through sensitivity analysis.

7.3.3.3. Solar Loads

In terms of modelling solar gains in IESVE, both the SunCast function and the weather file determine the influence of the sun on the internal thermal environment in a simulated building. As mentioned previously, the SunCast function is used to investigate the effect of external obstructions and self-shading of a building, as well as solar mapping through windows and openings. Considering the Old Library, the thick external walls provide local self-shading, which will restrict the amount of solar radiation entering the building at certain times of the day, such as the morning and evening when the sun is not directly south of the building. Direct and diffuse radiation values are specified in the weather file and are the primary parameters involved in modelling the effect of solar gains on the thermal environment in the Old Library. As a result, in order to assess the influence of solar gains on the building, the weather file was changed to eliminate the effect of solar radiation, as well as using the actual solar history profile. Fig 7-23 displays T data simulated in the Long Room and shop for three different loading scenarios, namely all casual loads (people, lighting and solar), no loads and no solar loads Mechanical heating is also included in each simulation.

As can be seen from the chart, the overall trends in all loading cases are comparable during the Christmas vacation, which is circled in blue, however the magnitudes are different. When the heating is turned on again after the Christmas period (circled in red), however, the no loading scenario differs significantly from the other two cases as a relatively stable trend is observed, as expected considering that external variations during this time are reasonably small and there are no heat loads present in the building.

Unsurprisingly, when no loads are applied to the building, the simulated trends are the lowest in magnitude amongst all loading scenarios. Throughout the Christmas period, the difference in T between the no loads and all loads simulations is approximately 4°C,

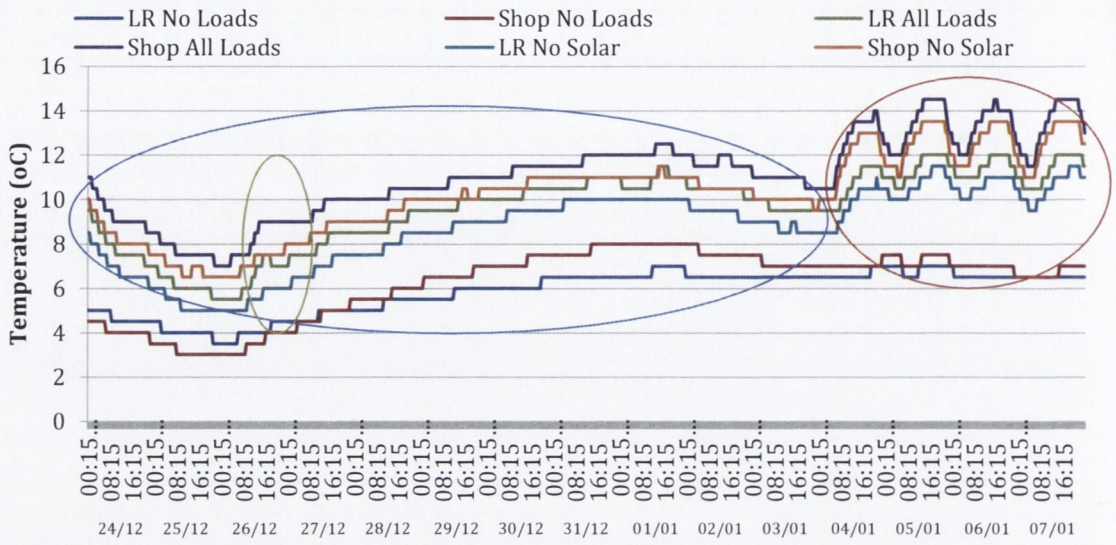


Fig 7-23: Effect of solar gains on the thermal environment in the Old Library

indicating that the presence of people, lighting and the effect of solar gains throughout the year has a discernible, and relatively large effect on the thermal conditions in the building, even when the people and lighting loads are removed as is the case during the Christmas vacation.

Similarly, when the heat load due to solar gains alone is removed from the model, the T values decrease in magnitude accordingly. From the original weather file, maximum solar radiation occurred on 26/12, when the building was empty and thus not subjected to loads associated with people and lighting, and the effect of solar gains on the building can be identified in the thermal data simulated by the software. Considering the portion of the chart in Fig 7-23 that is circled in green and displayed in Fig. 7-24, the contribution of solar gains to the thermal environment in the building can be examined in further detail.



Fig. 7-24: T values in the Old Library shop as well as the solar radiation used for the simulatons on 26/12.

Fig. 7-24 displays the T values simulated in the Old Library Shop on 26/12 for two loading scenarios, namely solar gains and no solar gains. External T values as well as the direct radiation as specified in the weather file are also displayed. Initially, a very small difference (0.5°C) between the solar and non-solar trends is observed and this remains the case until approximately 10:15, when the direct radiation begins to increase.

Over the course of approximately three hours, strong direct radiation exists resulting in an increase in T in the shop in the solar loading scenario. Between approximately 10:15 and 13:45, a 2°C increase in T is observed when loading solar is considered compared to just 0.5°C in the case of no solar loading. Given that, besides the presence of solar gains in one simulation, boundary conditions and casual loadings in both scenarios are identical, the different variations illustrated in Fig. 7-24 may be attributed directly to the effect of solar gains. Given the large glazed area on the south facing wall of the building, this is not a surprising observation but it is notable.

Based on the simulations of the effect of solar gains, it may be concluded that solar radiation produces a discernible T difference in a room, as indicated when these values were removed from the weather file. The influence of direct radiation on internal T variations may be directly identified on a chart and results in larger diurnal T changes compared to when solar gains are removed from the model. In terms of moisture conditions, simulations indicate that solar gains do not have a measurable impact on H_{abs} in the Old Library, however this may be influenced by the difficulties associated with modelling hygroscopic surfaces that are present in the building. From the sensitivity analysis of the effect of solar gains on the building it may be concluded that, in terms of the thermal environment, IESVE is effective in simulating the influence of direct radiation on the internal T conditions in a building.

7.3.3.4. Casual Loads due to Lighting

Lighting is one of the two casual loads provided to the Old Library and is generally provided to the building through the use of fluorescent tubes, although in the shop and exhibition space a number of spotlights are also in place to provide additional light to these rooms for display purposes. After discussions with staff in the Buildings' Office in TCD, it was found that the majority of the bulbs in the Old Library were 35W lights and so, for the purposes of defining the casual light loadings, a value of 35W per bulb was used. The number of bulbs in each room (fluorescent tubes or otherwise) was counted manually during a walkthrough of the building. The heat loads due to lighting in the occupied spaces of the Old Library are displayed in Table 7-1

Table 7-1: Heat Loads due to Lighting

Room	Heat output due to lighting (W)
Shop	4400
Exhibition Space	2870
Long Room	2000
BoKE	560

Fig. 7-25 displays the T variations observed in the Old Library during the Christmas period for four distinct loading scenarios, namely all loads, no casual lighting loads, no solar loads and no loads, although the latter two are included for reference only. Casual light loading in the Old Library is highest in the shop due to the large number of spotlights that are used in display cases. Accordingly, the effect of removing such loads can lead to a discernible reduction in T in the room.

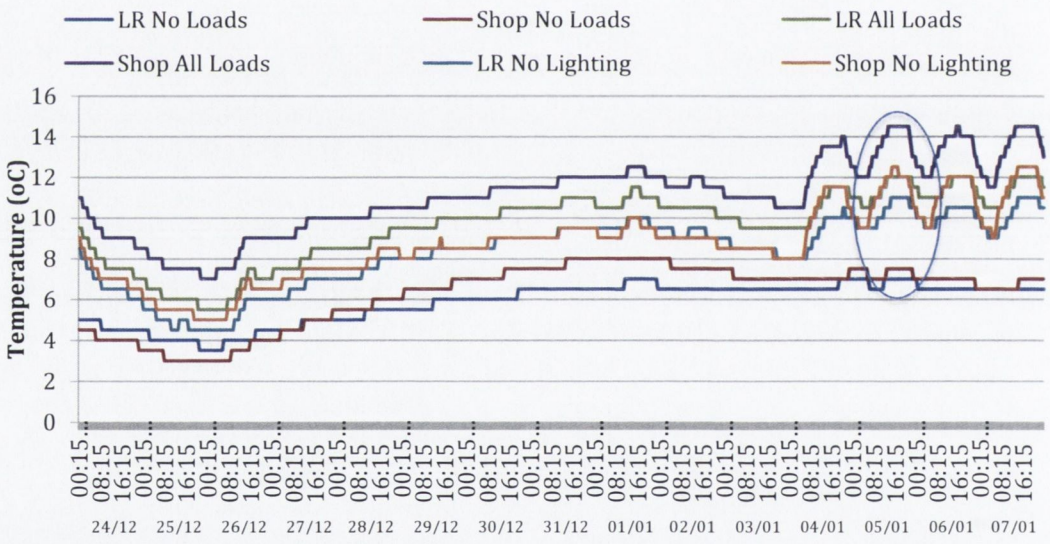


Fig. 7-25: The effect of artificial lighting on the thermal environment in the Shop and Long Room.

From Fig. 7-25 it can be seen that the removal of artificial lighting has a larger effect on thermal conditions in the room than the corresponding elimination of solar effects in the building. Considering the various T values simulated on the afternoon of 05/01 (circled in blue on the chart), the relative effect of each loading scenario is apparent. Mechanical heating has been included in each simulation such that the only difference between the trends is due to the causal loading (lighting, solar, people) scenario of each curve.

When the thermal environment in each of the simulated loading scenarios stabilises on 05/01, a clear disparity between the T values in each model exists. As expected, the simulation of all loads observes the highest recorded T value of 14.5°C. This is followed by the simulation where solar radiation is excluded where a value of 13.5°C is noted. The removal of lighting resulted in a further 1°C decrease in T to 12.5°C and unsurprisingly, when all solar and casual loads are excluded, lowest diurnal T values are observed, in this case at a value of 10.5°C. Based on these observations it may be concluded that, in the Old Library shop, the removal of lighting has a larger effect on the thermal conditions in the room than the removal of solar influences, during the winter season.

Considering the corresponding data for the Long Room, as displayed in Fig. 7-25, it can be observed that the difference in T magnitude between each loading scenario is less than those in the shop. It is most likely that these are due to the significantly lower casual load due to lighting per unit area in the Long Room (23.7W/m^2 in the shop compared to 2.5W/m^2 in the Long Room), although heat flow into the Long Room from the shop would provide additional loadings to the space that are difficult to quantify.

T data on 05/01 (circled in blue on Fig. 7-25) provide an insight into the influences of heat loads associated with artificial lighting and solar gains on the Long Room. When all loads are included in the simulation, T in the Long Room on 05/01 stabilises at a value of 12°C, the highest amongst all simulations as expected. When solar gains are removed, this value reduces to 11.5°C and subsequently 11°C and 10°C when lighting and all casual and solar loads are removed, which is the same as observed in the Shop. In this case, however, the difference in magnitude between the simulation of all loads and no loads reduces from 4°C, as observed in the shop, to 2°C. Furthermore the difference between the removal of solar compared to the removal of lighting has reduced to 05°C from 1°C in the Shop. As mentioned previously, the reduction in the simulated difference may be due to the smaller relative load due to lighting in the Long Room when compared to the Shop, coupled with the large volume of air in the Long Room that facilitates heat dispersion and thus reduces the influence of thermal loads in the room.

Fig. 7-26 displays the T trends associated with identical loading scenarios described earlier for a one-week period in July in the Old Library Shop. In this case, mechanical heating is not supplied to the building. Comparing the T trends in Fig. 7-26 to those in Fig. 7-25, it can be seen that solar gains are contributing more significantly to the thermal environment in summer than in winter. This is not surprising considering the higher sunshine intensity observed in July when compared to January. Simulations of the no lighting and no solar T trends in July are comparable, as both scenarios appear to have a similar influence on the

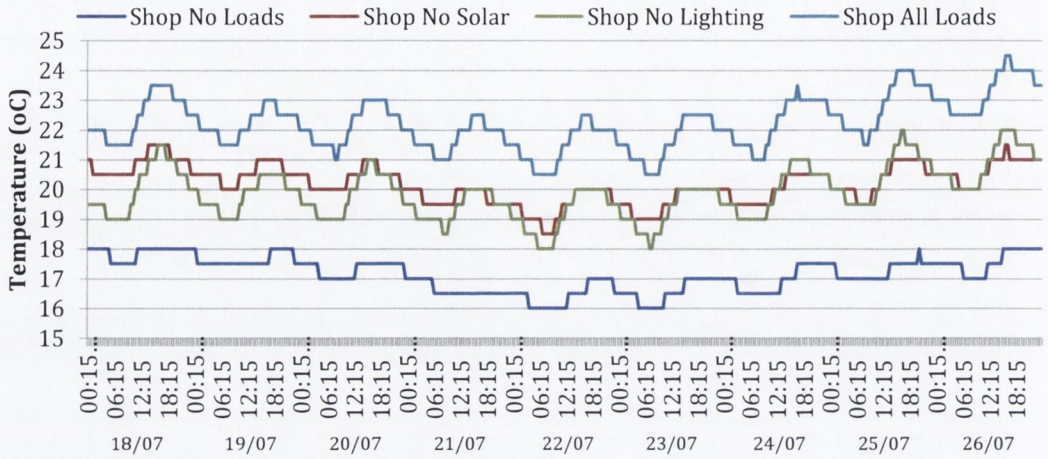


Fig. 7-26: Comparison of the effects of solar gains and artificial lightin on the thermal environment in the Old Library Shop during the month of July.

thermal environment. This observation contrasts with that modelled in January, where the removal of lighting resulted in a consistently lower T magnitude than when solar intensity is removed from the weather file, indicating that in July, heat loads associated with solar gains are more influential in determining internal thermal conditions when compared to January.

Similarly, solar gains in the Long Room in July contribute significantly more to the overall heat load than in January, as displayed in Fig. 7-27. In this case, the removal of direct radiation from the weather file lowers T values more than the corresponding effect of removing lighting alone. Based on this observation it can be concluded that solar gains provide a large portion of heat loads to the building during the summer period. Considering T trends simulated on 18/07 (circled in blue) illustrates the effect of solar gains in July.

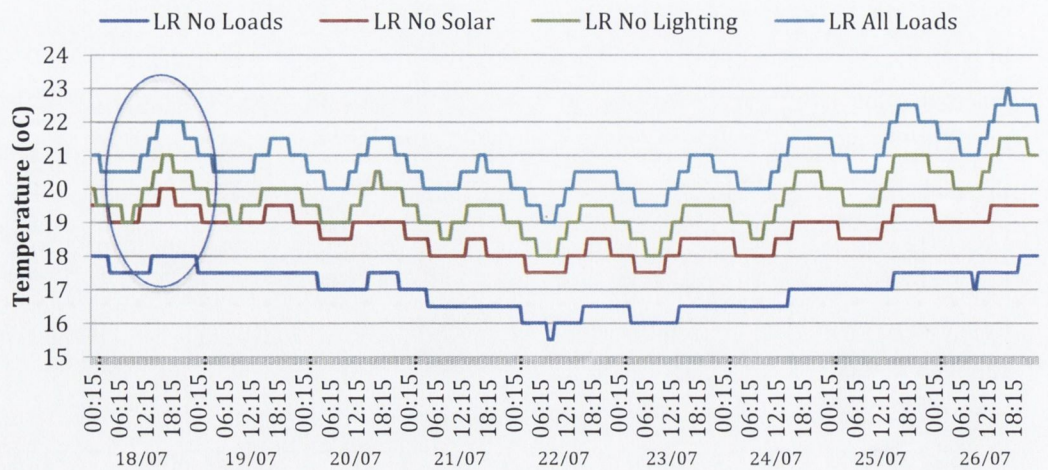


Fig. 7-27: Effect of solar gains and artificial lighting on the thermal environment in the Long Room during the month of July.

Maximum T values of 22°C are observed when all loads are included in the simulation. This value reduces to 21°C when lighting is removed and a further 1°C to 20°C when solar gains are not considered. This contrasts with the January simulations, which indicated that the removal of lighting is more significant than the removal of solar effects and indicates that the software is correctly modelling these loading scenarios as the trends are as expected. Furthermore, the large glazed area in the Long Room would mean that heat loads due to solar gains in this space are relatively large compared to those observed in the shop, a factor that is also suggested by the simulated trends for July.

In conclusion, the casual loads due to lighting have a discernible effect on the thermal conditions in the Old Library, as internal T values fall when this parameter is excluded from simulations. Lighting in the Old Library has a relatively large influence on the thermal conditions in the Old Library when compared to solar gains in winter, however, in summer, this trend reverses and the solar becomes equally significant in the Shop and more significant in the Long Room. In terms of H_{abs}, removal of lighting does not appear to have an influence on the moisture conditions in the building, although in reality, the change in T may alter the H_{abs} value in the building to some degree due to hygroscopic effects not modelled here.

7.3.3.5. Casual Loads due to People

The final loading scenario to be tested is the presence of people in the building. As aforementioned, actual visitor numbers have been incorporated into the model (see Appendix G for the loading numbers used). IESVE requires the specification of an activity load for people in the building and, given that the overwhelming majority of people in the Old Library are visitors who spend their time walking through the building, a degree of activity of *"walking slowly"* was selected from tables that accompany the software. This factor has a sensible and latent heat gain of 110W and 50W per person respectively. Simulations for July were used to assess the influence of people on the building, as it is the period of maximum occupancy and thus highest associated load. Fig. 7-28 displays the T variations simulated for all loading scenarios in the shop. Although all loads and no people simulations are the focus of discussions in this section, the remaining three loading scenarios are included on the chart for reference.

From the chart it is clear that, as suggested in previous discussions (Chapters 4, 5 and 6), the effect of people on the thermal environment is relatively small. This is apparent when considering the T change associated with the removal of people compared to the other loading scenarios that are considered. As expected, the lowest reduction in T is observed

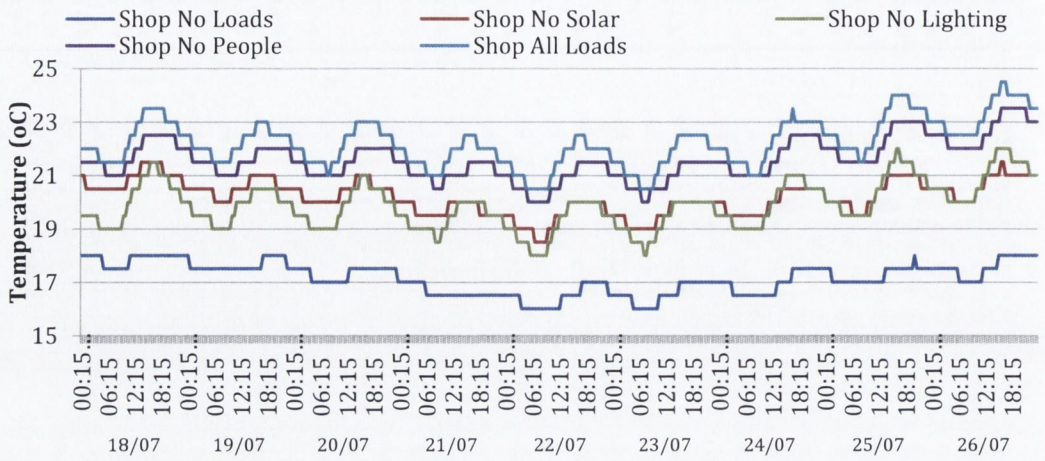


Fig. 7-28: The influence of people on the thermal environment in the Old Library Shop.

when people are removed from the building. Similarly, removal of people results in the smallest decrease in T compared to other loading scenarios in the Long Room, as illustrated in Fig. 7-29.

Considering the modelled trends for each loading scenario on 22/07 (blue region in Fig. 7-29), the effect of each casual load on the thermal environment can be assessed. Based on the models for each loading scenario it may be deduced that the removal of all casual loads from the building results in a T decrease of 19.5% in the Long Room. Removal of solar effects results in a 9.8% decrease in T, while the removal of lighting and people reduce T values by 4.9% and 2.4% respectively.

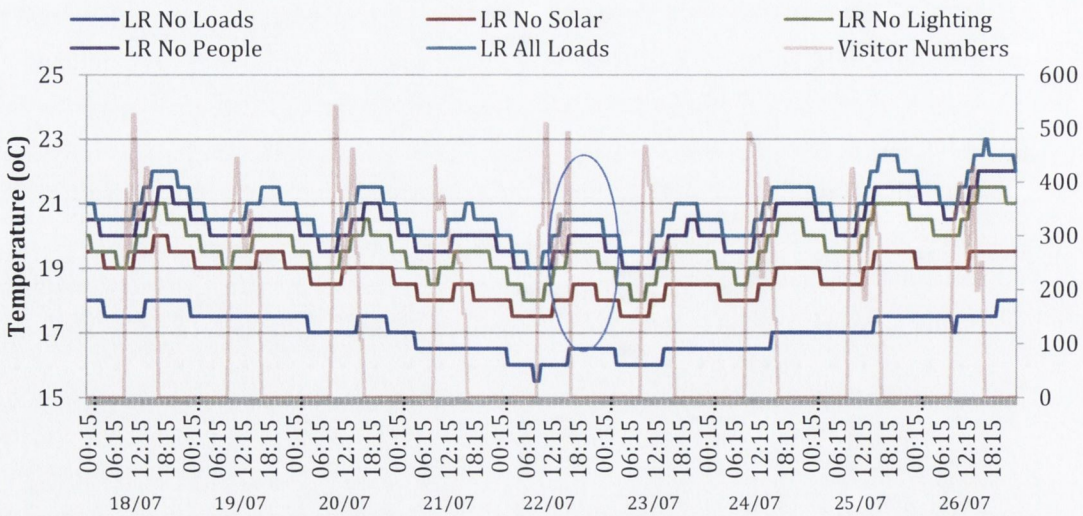


Fig. 7-29: Influence of people on the thermal conditions in the Long Room.

Accordingly, it may be concluded that the model is performing as expected regarding the effect of people on the thermal environment in the Long Room when the findings of the small-scale occupancy test (discussed in Section 4.6) are considered, as people are not expected to have a substantial effect on the T conditions in a large room. Furthermore, the removal of solar effects has the largest influence on thermal conditions in the Long Room.

In terms of H_{abs}, from Fig. 7-30, it can be seen that the presence of visitors is the determining factor for moisture conditions in the building during opening hours. Once more this finding is unsurprising from the signature studies because, excluding infiltration from the external environment, people are the only moisture load in the building. Evaporations and adsorption from hygroscopic materials has been discounted from this discussion since they are not modelled in IESVE and are likely to be small for low T changes.

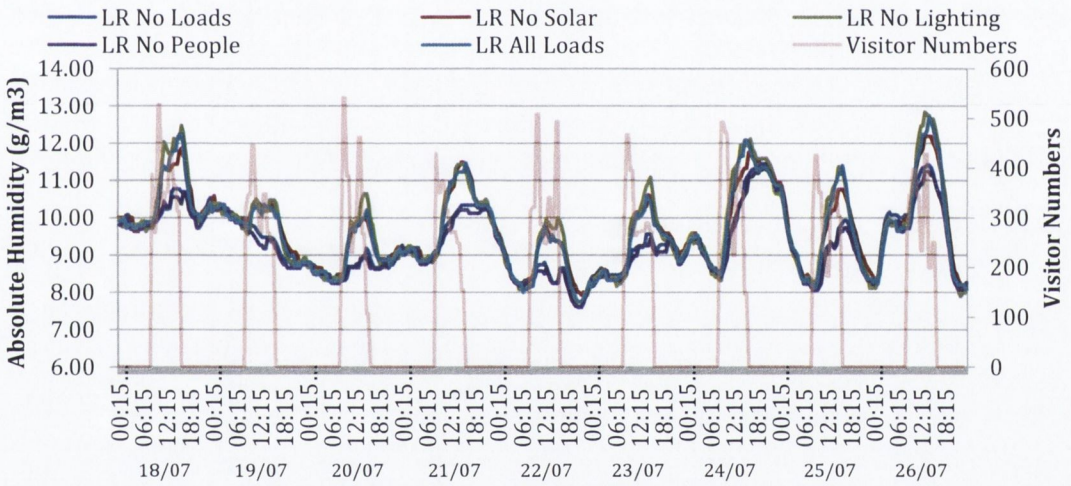


Fig. 7-30: Influence of people on the hygrometric environment in the Long Room.

Considering data simulated for 21/07, which is circled in blue on the chart, the effect of people on the hygroscopic environment can be clearly identified. In loading scenarios that include visitors, a large fluctuation in H_{abs} is observed. At approximately 09:30, H_{abs} begins to increase in the building corresponding to the building opening and the moisture load associated with visitors entering the Old Library. Over the course of the day, H_{abs} continues to increase in accordance with the moisture load due to the visitors until approximately 16:15, when the rate of people entering the building slows and the final visitors enter the building, resulting in a reduction in moisture in the environment. When the building closes at 17:00, H_{abs} decreases as the infiltration disperses and removes moisture from the building.

In contrast, removal of the people from the Old Library effectively eliminates any additional moisture loads (other than infiltration) from the building and results in the altered trend, which can be observed on the chart in Fig. 7-30. When the building is modelled without the casual people loads included, the peaks in H_{abs} no longer occur and, as a result, it may be concluded that the presence of people is a significant factor in determining the moisture conditions in the building, a conclusion that is consistent with actual observations and previous discussions.

7.3.3.6. Conclusions from Sensitivity Analyses

Based on the discussions of the sensitivity analysis outlined previously, the following conclusions have been made regarding the performance of the model:

- The overall trends simulated using an infiltration rate of 0ach are reasonably accurate, indicating that the model of the Old Library has been constructed to an acceptable accuracy in terms of geometry, constructions and loadings.
- Using a sensitivity analysis of the infiltration rates, it has been determined that the infiltration rate varies throughout the building and rates of 1ach and 0.15ach were deemed accurate.
- When the effect of mechanical heating is excluded from the model, the most influential load in determining the thermal conditions in the Old Library varies between seasons. During the summer, solar contributes largely to the T variations in the Long Room followed by artificial lighting and people. In winter, however, the role of artificial lighting increases in importance while solar is less effective. As is the case in the summer, people only have a marginal influence on the thermal environment. This suggests that lighting, solar gains and people are all essential elements in a predictive model.

Referring back to Fig. 7-20, the model with an infiltration rate of 0.15 and 1ach as well as the actual casual and mechanical heating loads are seen to model the thermal conditions in the Old Library well. This will thus be used as the base model and potential alterations to the building will be applied to this model. This model reasonably accurately simulates the infiltration and exfiltration effects arising from external condition as well as the moisture loads due to occupants, however, the effect of hygroscopic materials in regulating the hygrometric parameters is not accurately modelled by the IESVE software.

7.4. Potential Retrofit Options

Having compared and ensured the accuracy of the model through a number of sensitivity analyses, it is thence possible to simulate alterations to the building and their effect on the environment in the building. By conducting simulations of individual retrofit options, the building alterations that are most effective at improving the internal environment in the Old Library could be identified. Alterations will aim to fulfil one of two tasks, namely reduce heat losses from the building or to decrease the impact of current loadings on the environmental conditions. To achieve the former, alterations to the building fabric will be simulated, namely insulation of the roof, insulation of the walls, upgrades to the windows and removal of the central staircase. In terms of decreasing the impact of current loads, HVAC will be installed along the route visitors take through the building, the use of a low level heating system that is always on and the reduction of the visitor numbers to 100 per hour will be simulated. Although some of these measures may be unacceptable from a financial, technical or conservation viewpoint, they are simulated to assess the potential benefits of installation should the obstacles to their implementation be overcome. As a result of this analysis, it is then possible to develop a retrofit strategy for the building with the aim of reducing diurnal and seasonal fluctuations currently observed in the thermo-hygrometric environment of the building, thus extending the lifespan of the collections. In terms of assessing the influence of alterations to the building fabric, simulations from the Christmas vacation and subsequent heating up period will be discussed. The measures used to reduce loadings will be simulated for the summer period, as casual and solar loads are highest during this time.

7.4.1. Alterations to the Building Envelope

Referring to Fig. 2-4, it can be seen that typically the large majority of heat loss from a building occurs through the walls (35%) and roof (25%) of the building fabric. Accordingly, when undertaking a retrofit scheme, these elements of the building fabric should be the first focus for reducing heat losses and regulating the internal thermal environment.

When considering a retrofit scheme to reduce heat losses from a building, alteration of the building fabric through the installation of roof insulation is generally one of the first upgrades to be considered, owing to its relatively low cost, ease of installation and short payback time. Accordingly, roof insulation was the first alteration to be simulated for the Old Library. 250mm of natural insulation was installed above the Long Room and in the roofs of the East and West Pavilions.

Fig. 7-31 displays the T variations in the Long Room and Shop when 250mm of insulation is added to the roof. The T fluctuations simulated for the current building envelope are also plotted on the chart for comparison. From Fig. 7-31, it does not appear that insulation of the roof has a significant effect on the thermal environment in the building, although it does appear that marginally higher T values are observed in the building when the insulation is installed. This is observed on 26/12 (circled in blue) when minimum T values observed during the Christmas vacation are recorded. In the Long Room, the insulation of the roof increases the minimum T observed in the space by 0.5°C (6°C compared to 5.5°C). Similarly in the shop, the same trend is generally observed in the room, although a period is observed when minimum T values with and without the insulation are identical (7.5°C).

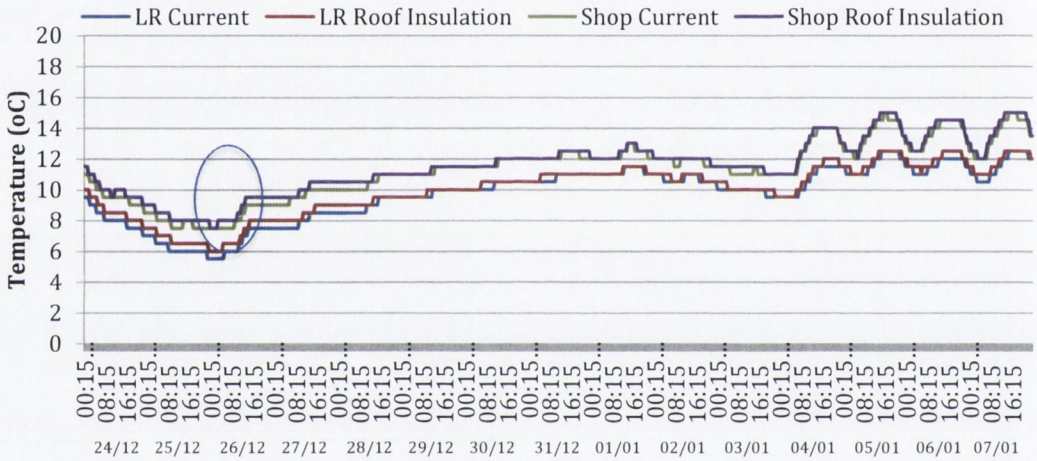


Fig. 7-31: Effect of the implementation of insulation on the thermal properties of the Old Library.

This magnitude of the improvement in T arising from the insulation of the ceiling is surprising as it would be expected that this alteration would have a relatively large impact in reducing heat losses and increasing T values in the Old Library. The reason for the small improvement is the low heat input to the building that means that there is little heat to retain in the building. If the heating scheme was improved, it is expected that the insulation of the ceiling would lead to a greater improvement in thermal conditions in the building.

When the building reopens after the Christmas vacation, the presence of insulation in the roof appears to slightly increase the rate at which the LR heats up over a number of days. The maximum diurnal T simulated in the Long Room, under current conditions, reaches 12.5°C on 05/01 and subsequently falls slightly to 12°C on 06/01. In the case of simulations of the roof being insulated, the maximum T value of 12.5°C is maintained on both days. Although the difference in values is quite small, this observation suggests that insulating the

room has some, albeit small, influence on the thermal conditions in the Long Room. A similar trend, however, is not observed in the Shop during this period.

Although the insulation of the Old Library roof did not lead to a substantial improvement in the internal T values observed during the Christmas vacation, when the geometry of the Long Room is considered, it may be unreasonable to expect better performance than that simulated. Given that the Long Room is a tall and long space with a relatively large external perimeter and glazed area, the majority of heat loss from the room may occur before heat has risen high enough to escape through the roof. In light of the previous discussion on the low heat input to the building, the insulation of a number of structural elements may be required to reduce heat losses from the building and improve the T conditions within. Accordingly, the installation of wall insulation on the external walls may prove more beneficial to the thermal conditions than the roof insulation.

Fig. 7-32 displays the T variations simulated when 250mm of insulation is retrofitted to external walls in the Old Library. The insulation is placed on the inside face of the wall and finished with a plasterboard layer and perlite plaster. In the Long Room, the insulation is placed behind the oak panelling so as to maintain the character of the space. While this measure may be impractical, it is important to understand the effect that walls have on the heat loss from the building. From Fig. 7-32 it can be seen that the insulation of the walls has a larger effect on the thermal environment in the building than the corresponding effect of insulating the roof as higher diurnal T values are observed in both the Long Room and Shop when compared to those obtained when no alterations have been carried out.

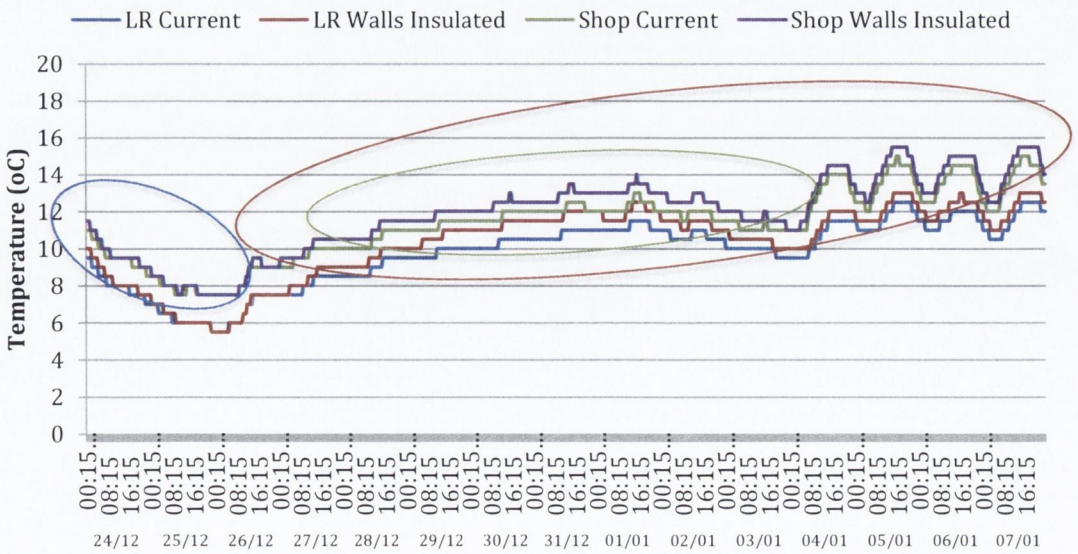


Fig. 7-32: Influence of wall insulation on the thermal conditions in the Long Room and Shop.

Between 24/12 and 26/12, circled in blue on the chart, it appears that the installation to the walls has little or no effect on the T conditions in the Old Library, as there is practically no difference in the simulated trends in both cases (wall insulation and no alteration). As the building heats up from 27/12 onwards (circled in red), however, the reduced heat loss across the building envelope is reflected in the T variations simulated in the Old Library as T values in the model with the wall insulation increase to a greater extent than observed for the current envelope. In the case of the shop, a difference in T of 0.5°C is generally observed for the remainder of the Christmas vacation (circled in green) as heat loss from the building is reduced. In the Long Room, the insulation of the wall has a more noticeable effect as a difference in T of 1°C between the two models is generally observed, although this falls to 0.5°C from 02/01 to 03/01. Based on this observation it may be concluded that, insulating the walls is not a worthwhile alteration for improving T conditions in the Old Library as heat losses from the building through the roof and windows eliminate any potential benefits arising from the wall upgrade.

When heating and casual loads are provided to the building from 04/01, the presence of the wall insulation again has an influence on the thermal environment in the building as larger diurnal maximum T values are observed in both the Shop and Long Room than observed in the model with no alterations. Furthermore, these maximum values are maintained for a longer period, indicating increased regulation of the thermal environment in the building, although diurnal T fluctuations in the shop remain relatively large despite this alteration.

Although insulation of the external walls has a measurable influence on the thermal conditions in the Old Library, it is not to the extent that may be expected. Considering that approximately 40% of the external wall area consists of glazing, it is clear that, despite the effect of insulating the walls, heat loss from the building can still occur at a relatively quick rate through the leaky, single glazed windows. Accordingly, upgrades of the windows in the building may lead to improved performance. For the purposes of simulations, the windows are upgraded to triple glazed windows with a hardwood frame and low emissivity coating. Referring back to Fig. 2-4 once more, it can be seen that typically only 10% of heat loss through a building occurs through the windows, though it may be larger here. As a result, upgrading the windows may have a relatively small effect on thermal conditions in the building, however, given that it is a common retrofit option and approximately 40% of external walls are glazed, replacement of the windows has been simulated and the results are displayed in Fig. 7-33.

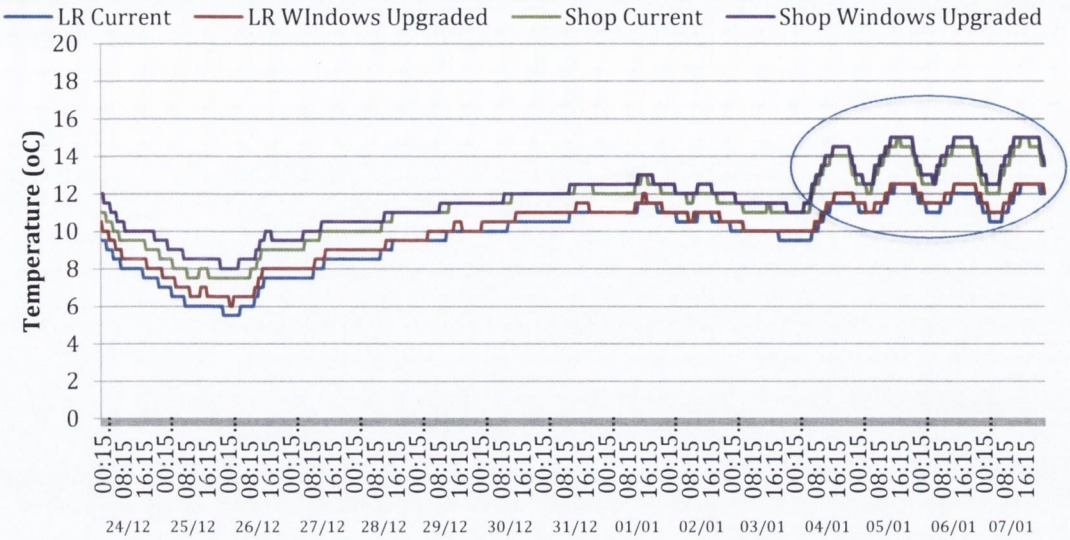


Fig. 7-33: Effect of upgrading the windows on the thermal conditions in the Old Library.

From Fig. 7-33 it can be seen that, as expected, upgrading the windows leads to a minimal improvement in the thermal conditions in the Old Library and the change in T trends are similar to those simulated when the roof of the building was insulated. Generally, the alteration of the windows would result in a 0.5°C difference in T compared to the current envelope in the period from 24/12 and 31/12 for the Long Room and between 24/12 and 28/12 for the Shop. The effect of the upgraded window is most noticeable between 04/01 and 07/01 (circled in blue) when the heating to the building has been turned on and the additional casual loads are present once again. Thermal conditions in the Long Room and, in particular, the Shop appear to observe a greater level of regulation with maximum T values being maintained for longer intervals throughout the day as heat loss from the building is somewhat reduced. Based on the results of this simulation, it may be concluded that upgrading of the windows alone, like insulating the roof, is not an effective measure in improving conditions in the Old Library but may be more useful as part of an overall building upgrade strategy.

One final potential alteration to the building envelope would be to remove the central staircase that links the Shop to the Long Room. Although this may require some additional alterations to the route that visitors use to pass through the building, it would significantly reduce heat flow between the Shop and Long Room, thus potentially regulating T conditions in the Long Room and increasing T values in the Shop. This would be beneficial in terms of providing improved comfort conditions in the Shop, while the smaller T fluctuations in the Long Room would prolong the lifespan of the collection.

Fig. 7-34 displays the change in T in the Shop and Long Room that may be expected if the central staircase was removed from the building. As can be seen, this alteration has a significant influence on the thermal conditions in the Old Library as a relatively large increase in T values in the Shop is noted following the alteration. Conversely, T conditions in the Long Room decrease in magnitude, indicating that heat flow from the Shop into the Long Room has a measurable influence on the thermal conditions in the Long Room.

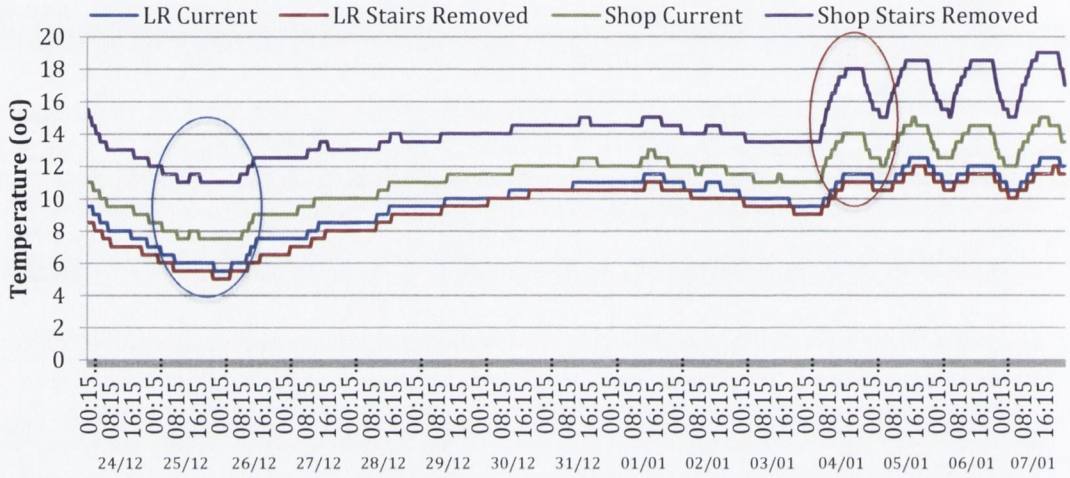


Fig. 7-34: Effect of removing the central staircase on the thermal environment in the Old Library.

Considering the Shop on 25/12 and 26/12, the effect of removing the staircase on T can be quantified. During this time period, which is circled in blue on Fig. 7-34, relatively stable T conditions are noted in the Shop. When the current envelope properties are simulated, the minimum value, which is maintained for a prolonged interval, is 7.5°C. Removing the central staircase and closing the void in the floor, however, leads to this minimum value increasing to 11°C, corresponding to a 3.5°C increase. The corresponding change in T in the Long Room values at this time differs noticeably from those in the shop. The reduction in heat infiltration into the Long Room from the Shop results in a decrease in T of 0.5°C.

When the building reopens on 04/01 (circled in red), the reactivation of mechanical heating and casual loads results in a large increase in T in the Shop, where a maximum value of 18°C is simulated, 4°C greater than that observed when the staircase is present. On 04/01, a relatively large rate of increase of T is observed as T changes from 13.5°C to 18°C at a rate of 0.44°C/hour. This contrasts from a rate of 0.33°C/hour that is currently observed. As well as observing a high diurnal rate of T change, it appears that the overall thermal conditions in the Shop are increasing at a quicker rate than when the central staircase is in place. In the Long Room, similar trends to those currently observed are simulated with the staircase removed, however, T values are generally 0.5°C lower.

Given that relatively low and stable T and RH values are preferable in terms of collection conservation, the removal of the central staircase could be the most effective fabric alteration in terms of regulating T values in the Long Room. Furthermore, the majority of Old Library staff that work in the visitor centre element of the building, (i.e. Shop, Exhibition Space and Long Room) spend most of their time in the Shop. The observed increase in T in this space (Shop) associated with the reduced heat loss would lead to improved comfort conditions in this area of the building. The small number of staff in the Long Room, however, would experience a marginal drop in T, which may not be acceptable.

Although removal of the staircase appears to be an effective measure for increasing T values in the Shop and reducing them in the Long Room, the relatively large T values and fluctuations observed between 04/01 and 07/01 in the Shop are cause for concern, as overheating could potentially occur during warmer weather conditions and in the summer season. Fig. 7-35 displays the T variations associated with removing the staircase in July. From Fig. 7-35 it can be seen that, in the summer season, closing the central staircase leads to regulation of the thermal variations in the Long Room, as more stable T values with smaller diurnal variations, varying between 0.5°C and 1°C are observed. Furthermore, the T magnitudes are reduced when compared to the current envelope, which suggests that removing the staircase has a positive effect on the thermal environment in the Long Room.

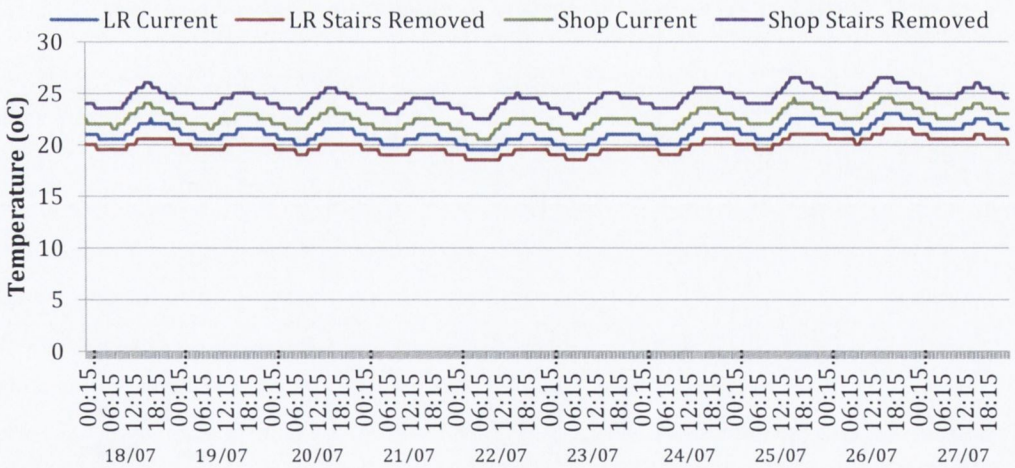


Fig. 7-35: Effect of removing the central staircase on the thermal environment in the Old Library in July.

In the Old Library Shop, however, the reduced heat flow between the Shop and Long Room leads to T values that are frequently in excess of 24°C during the time interval displayed on the chart, indicating that overheating is occurring in the room. Consequently, comfort conditions in the Shop are reduced. Accordingly it may be concluded that, although closing

the central staircase has a positive effect on the thermal conditions in the Long Room, the issue of overheating in the Shop means that it will have an adverse effect on comfort conditions in the Shop. In order for this retrofit option to be effective, measures to alleviate overheating in the shop must also be considered. Furthermore, since moisture, as well as heat, is transferred through the void in the ceiling, removal of this staircase will lead to higher H_{abs} peaks in the Shop, as illustrated in Fig. 7-36. Accordingly, this factor must also be considered when implementing plant to reduce the impact of this upgrade on the environmental conditions in the Shop.

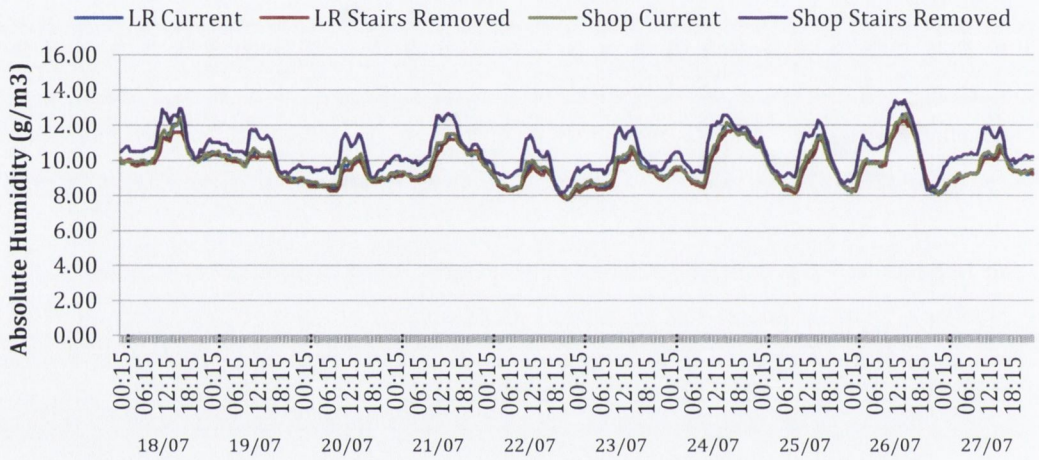


Fig. 7-36: Change in Habs associated with the removal of the central staircase.

Fig. 7-37 and Fig. 7-38 display the T change associated with each alteration in the Long Room and Shop. As can be seen from Fig. 7-37, it appears that insulating the external walls is the most effective measure for increasing T values in the Long Room. From Fig. 7-38, it is clear that closing the central staircase has a large influence on the thermal environment in the Shop, as a difference of approximately 4°C is observed between the T values in the simulations of this option when compared to the current envelope. Given the large number of visitors and staff located in this area, comfort conditions may be more relevant here than in the Long Room, although overheating of the Shop could become problematic, particularly in the summer season. Of the other three retrofit options (which were applied to the whole building) that were simulated, it appears that wall insulation is marginally more effective in increasing the T values in the Shop than either upgrading the windows or insulating the roof, which have a similar minimal influence on the thermal environment in the space.

The purpose of altering and upgrading the Old Library is two-fold. Firstly, alterations are required to improve the thermal conditions in the building by increasing the T values. Secondly, variations in T and RH and the range between maximum and minimum diurnal

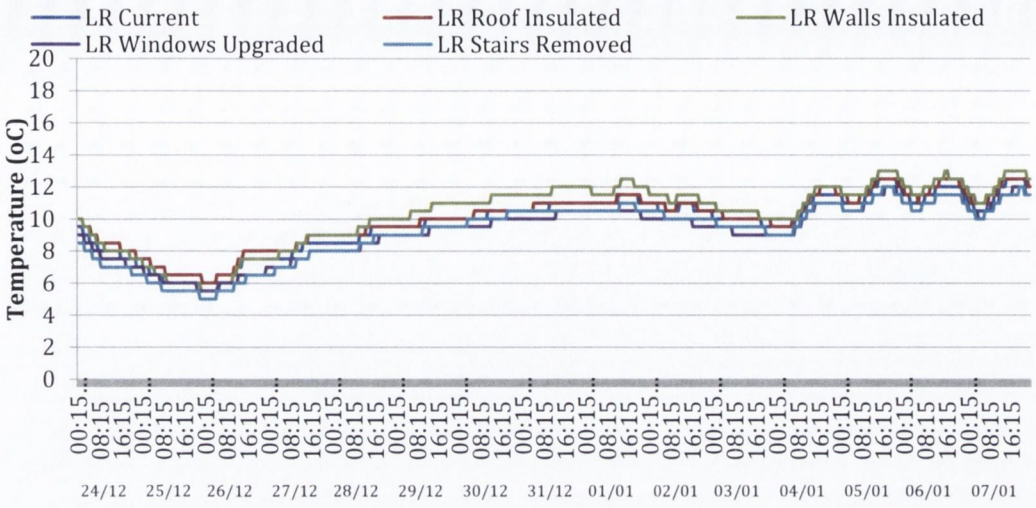


Fig. 7-37: T trends associated with each retrofit option in the Long Room



Fig. 7-38: T trends associated with each retrofit option in the Shop.

values should be decreased to improve the environmental conditions for the collect. A common observation in the trends simulated for each envelope upgrade, with the exception of removing the stairs in summer, is that the diurnal variations in T continue to occur, although the diurnal T magnitudes are increased. Accordingly, it is clear that, although fabric alterations have some influence on the magnitude of T values in the Old Library, they do not reduce the diurnal variations observed in the Long Room and, as a result, the implementation of plant is essential for reducing these variations. A number of changes to the current plant as well as the installation of additional plant will hence be simulated using IESVE.

7.4.2. Upgrade and Alteration of the Plant in the Old Library

As mentioned previously, alteration of the building fabric alone is not sufficient to improve environmental conditions in the Old Library, and so, upgrades of the current heating system and the implementation of supplemental systems such as HVAC, discretely implemented, and a Building Management System (BMS) may be required to supplement any fabric upgrades if the environmental conditions in the building are to be improved. Although such measures may have an on-going cost, such as energy use and maintenance in the case of the plant, it could prove to be important in extending the lifespan of the collection and would thus be a worthwhile exercise in the medium to long term.

The first upgrade option would involve altering the current heating schedules. The existing system of mechanical heating is switched on at full power for an average period of 12.5 hours per day. This method of providing heat results in large diurnal T variations that can cause damage to the collection in the Long Room. Furthermore, when the heating is deactivated, over the Christmas vacation for example, a large quantity of heat is lost from the building resulting in a significant drop in internal T values which prolongs the heating up phase when the mechanical heating is reactivated, a practice that is inefficient and leads to extended periods of thermal discomfort.

One alternative to the current heating regime would be to provide continuous low-level heating to the building over the winter season that will be regulated through the use of a thermostat. This in turn would reduce daily T fluctuations in the building, increase comfort levels and potentially reduce energy usage. For the purposes of modelling such an alteration to the heating system it is assumed that constant heat is provided to the building with the thermostat set at a lower limit of 14°C in the Long Room and 19°C in the Shop. The system would be turned on 24 hours a day from October until May, although only the Christmas vacations and subsequent heating up period is modelled here.

Fig. 7-39 displays the thermal conditions simulated for the alternative heat source as well as the current plant in the Old Library Shop and Long Room. From the chart it can be seen that the rate of change of T decrease observed during the first two days of the Christmas vacation (circled in blue) is less when the alternative heat system is used. Considering the Long Room, the rate of T reduction for the current heating regime is 0.11°C/hour as T decreases from 9.5°C to 6°C. Implementation of the alternative heat installation, however, reduces this rate to 0.07°C/hour, almost half that of the current system as T decreases from 11°C to 9°C. This drop in T indicates that this alternative method of providing mechanical heat to the Long Room may be effective in regulating the T variations within. Similarly in the Shop,

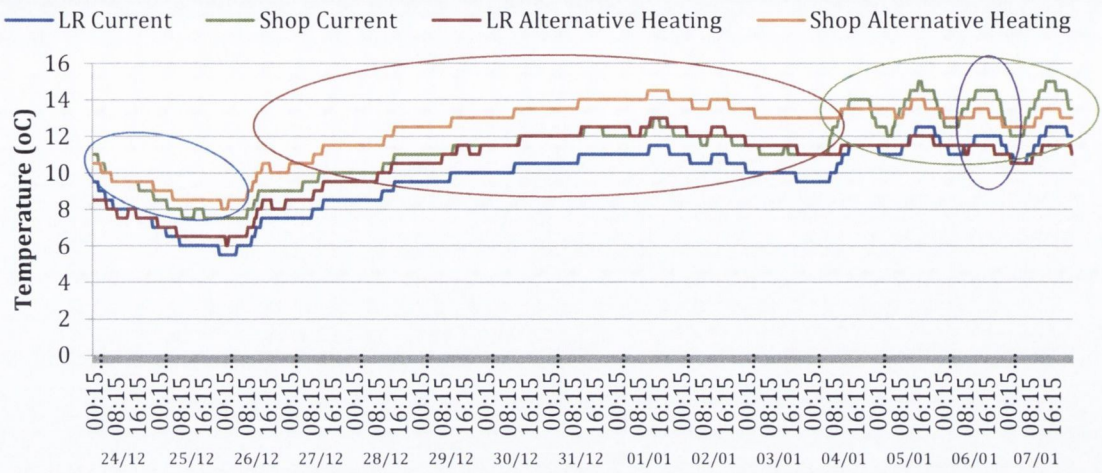


Fig. 7-39: Effect of altering the heating system on the thermal environment in the Old Library

more stable T conditions are simulated for the upgraded heating system when compared to the current installation.

In this case, a rate of T decrease of 0.07°C/hour is observed with the new system compared to 0.11°C/hour for the current system, again illustrating the benefits of low level continuous heating on the thermal environment in the Old Library. The fact that the T is decreasing in the building at this time is due to relatively large heat losses occurring according to the large thermal gradient between inside and outside and so, alteration of the heating regime should be implemented in tandem with measures to reduce heat losses from the building, such as the installation of ceiling insulation and upgrade of the windows.

For the remainder of the Christmas vacation (circled in red) the trends for the current and upgraded heating systems are comparable, although, since low level heat is continuously supplied to the building during this time interval for the upgraded system, T values simulated for the upgraded system are higher in magnitude than the current system, which is deactivated during this period. In the Long Room, the difference in the T values simulated for each scenario is approximately 0.5°C over the course of this time interval, compared to 1.5°C in the Shop. This is most likely due to the size of the Long Room, which has a large volume of air and thus a greater level of heat diffusion occurs in the space. Furthermore, the relative heat load in the Long Room is lower than the corresponding load in the Shop.

One of the issues that upgrading of the building fabric was unable to rectify is the relatively large diurnal variations observed when the building reopens after the Christmas vacation. From a conservation viewpoint, such fluctuations may be damaging to the collection and would thus be unacceptable in the Long Room. From Fig. 7-39, it can be seen that, when the

building reopens after the Christmas period (circled in green), the higher T values simulated for the alternative heat source coupled with the continuous and constant level of heating provided by the system, reduces the diurnal fluctuations observed in both the Shop and Long Room and lead to a more stable and regulated thermal environment. In the Long Room on 06/01 (circled in purple) for example, the current heating regime would result in an increase in T from 11°C to 12.5°C in the space, a 1.5°C variation. In comparison, the upgraded system relatively stable T value of 13.5°C with a 0.5°C fluctuation during the day. Furthermore, T conditions in the Shop will be more acceptable for comfort conditions as a 2°C improvement in T (increasing from 14.5°C to 16.5°C) is observed with the updated heating system, although this value remains below the required comfort conditions. The smaller fluctuation associated with the upgraded system would provide a more suitable thermal environment in the building as a whole, although the thermal environment in the Long Room would remain cold considering comfort conditions. Implementation of a BMS system with the heating system could lead to further stabilisation of the thermal environment in the building. Furthermore, the BMS could alter T values to regulate the hygrometric environment in the building and provide more stable moisture conditions to the Long Room. Based on the simulations displayed in Fig. 7-39, implementation of a constant, regulated, heating system could be extremely beneficial to the environment, particularly if installed with a BMS, and, as a result, increase the lifespan of the collection items stored in the Old Library. Unfortunately, the model did not indicate an improvement in the hygrometric environment in the building as a result of the upgrade. Accordingly, the implementation of HVAC may be required to stabilise moisture conditions in the building.

Currently in the Book of Kells' Exhibition Space, two small-scale HVAC elements are in place, each of which has a power output of 100W. Similar units will be implemented in the Shop (2 units) and the Long Room (12 units) to attempt to achieve environmental conditions within those specified by the Smithsonian Institute.

Fig. 7-40 displays the thermal variations simulated in the Long Room over an 8-day period in July for the current building as well as the two simulated HVAC schedules. As can be seen in the chart, the overall trends indicate a marginal difference in magnitude observed between the three simulations. T fluctuations are slightly smaller in magnitude when HVAC is on at all times, although maximum T values over the course of the week reaches a value of 24°C, the maximum specified T values according to the Smithsonian Institute's environmental limits. Over the course of the simulated interval, however, these environmental limits, which are indicated by the horizontal lines on the chart are not exceeded, nor do diurnal fluctuations in excess of 5°C occur, suggesting that HVAC may not be necessary in the building as a means for regulating the thermal environment. The actual

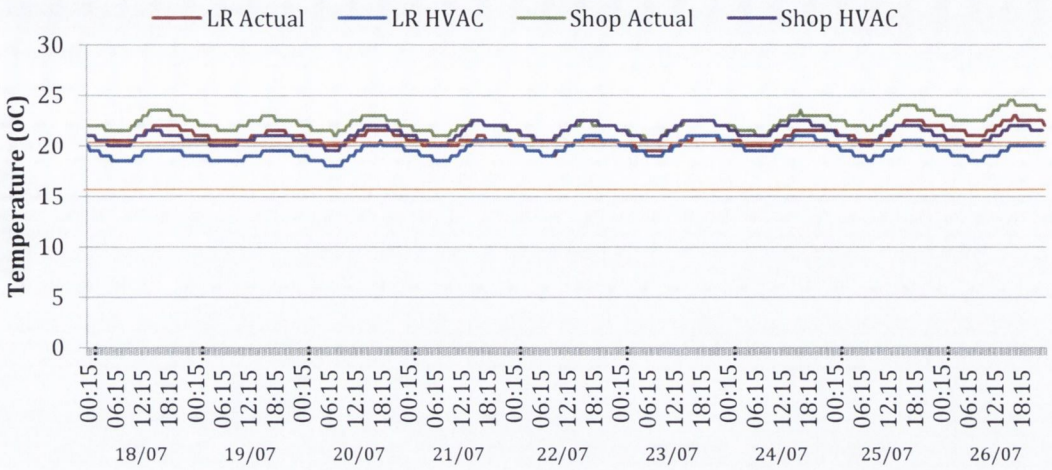


Fig. 7-40: Temperature variations associated with the implementation of HVAC in the Old Library.

purpose of the system, however, is to regulate the RH values in the building and, in particular, in the Long Room.

As well as examining the improvemnts in environmental conditions achieved using HVAC in the summer, it is also necessary to investigate its influence on the environment in winter. Fig. 7-41 displays the T variations associated with the introduction of HVAC in the Long Room during the Christmas period and subsequent heating period. As can be seen from the chart, the T improvements that result from the implementation of HVAC in the building are identical to those achieved through the implementation of the alternative heating system and, accordingly, will not be discussed in detail again.

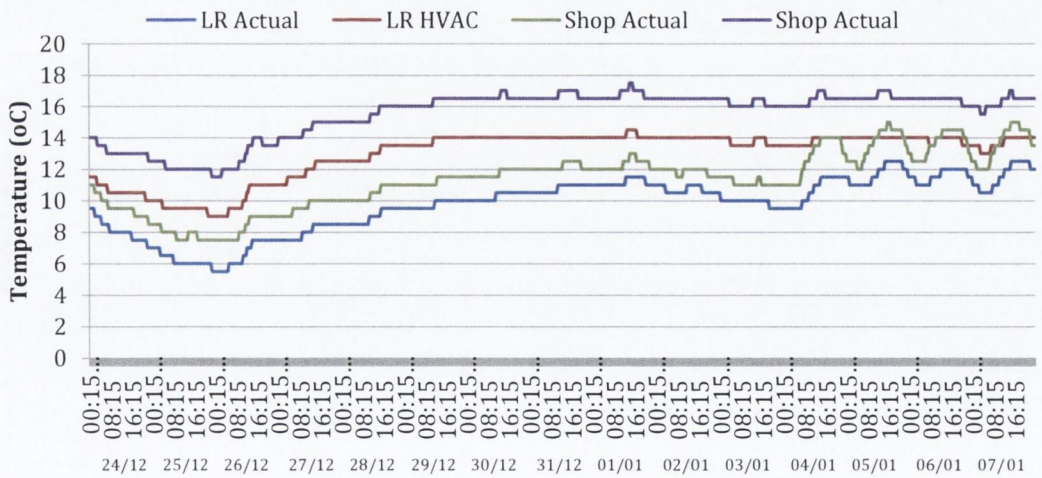


Fig. 7-41: Change in temperature observed following the implementation of HVAC in winter.

Of the two options outlined in this particular discussion, altering the heat and introducing a HVAC system appear to be effective methods of regulating the environmental conditions and

reducing diurnal variations in the Long Room. The introduction of a HVAC system, coupled with an effective BMS and some upgrade to the building fabric to reduce heat loss could be an effective measure in improving the thermo-hygrometric environment conditions, however issues such as cost and the potential loss of character to the building need careful consideration before undertaking such work. In terms of practicality, alteration of the heating system and implementation of a BMS for the building could be implemented relatively cheaply and would provide additional stability to the thermal environment in the building, as well as improving comfort conditions and reduce the fluctuations due to the current heating system. Implementation of the suggested heating scheme with some envelope upgrades to reduce heat loss from the building (such as upgrading the windows and insulating the ceiling) may also reduce the energy costs associated with the building in the long term.

7.5. Retrofit Strategies

7.5.1. Summary of Performance of Individual Measures

Based on the outcomes of the simulations of potential alterations discussed previously, it may be concluded that the implementation of a single upgrade in isolation to the building with the aim of improving the thermo-hygrometric environment in the Old Library may well be ineffective. The only change to the envelope that caused a relatively large change in T values in the building was when the central staircase was removed. Implementation of such a strategy, while improving the thermal conditions in the Long Room, would potentially give rise to additional issues not currently experienced in the building, such as overheating in the Shop. Accordingly, additional measures must be implemented to combat this undesirable effect and associated thermal discomfort for occupants.

In terms of the other three envelope retrofit options considered and simulated, namely roof insulation, insulation of the external walls and upgrading of the windows, they have a small influence on the thermal conditions in the building. Relative to the other two measures, which are comparable in terms of their influence on the environment, insulating the walls is the second most effective alteration option in terms of upgrading the building envelope. Based on the trends obtained from the model for the simulation of these retrofit options, however, the cost of installation of these measures in isolation may not be worthwhile considering the minimal benefit associated with each individual alteration.
In terms of plant alterations, upgrading the heating system to a low level continuous system, as compared to the current timed installation, could be beneficial in terms of reducing

thermal variations in the Long Room and providing a more stable thermal environment accordingly. Implementation of such a system, in conjunction with an effective BMS and one or more of the envelope upgrade measures could optimise the system and provide a suitable thermal environment to assist with the conservation of the collection. Simulations have also indicated that the introduction of a HVAC system to the building is effective in reducing RH variations over the course of the day without having an impact on the thermal conditions in the building. When implementing any alterations to the plant in a building, the associated maintenance and energy costs must also be factored and the design and selection of plant must be fit for purpose. In the case of the Old Library, however, based on the simulations conducted for the upgrade options suggested, a suitable strategy to improve environmental conditions in the building will most likely consist of both fabric alteration and implementation of plant.

7.5.2. Development and Simulation of Strategies

When developing any retrofit strategy for a building, and in particular a historic building, it is imperative that the requirements of the stakeholders as well as the constraints set by the building are considered at an early stage. In the case of the Old Library, the objectives and requirements for an upgrade of the building is to provide a stable and suitable environment to prolong the life expectancy of the collection. Furthermore, any retrofit option must be compatible with the current building fabric and have no adverse effect on the character of the building. Secondary to this fundamental requirement is the improvement of comfort conditions in areas of the building that are not used to store valuable collection items, such as the Shop and Long Room. Achievement of these objectives would increase the sustainability of the building from an environmental, social and economic viewpoint as the heritage and cultural value of the building and its contents are invaluable.

Although their impact on the thermal conditions in the Long Room were minimal when modeled individually, installation of roof insulation as well as upgrades to the windows and the implementation of the alternative heating regime as a combined strategy could be the most suitable retrofit proposal for the Old Library. This combination of measures is relatively easy to install, as well as being unobtrusive and, as a result, would have no negative impact on the character of the building, if carried out in a manner that is compatible with the building fabric.

In total four distinct building alteration strategies will be considered and simulated. Each of these will include some building envelope update as well as an alteration to the plant in the

Old Library. Strategy 1 will focus on the two most individual alterations that have the greatest potential to improve conditions in the building, namely removal of the central staircase coupled with the presence of a HVAC system. Strategy 2 will involve wall and roof insulation, window upgrade and the installation of a HVAC system. Strategy 3 is the most practical with the highest probability of being implemented as the roof would be insulated, windows upgraded and the alternative heating system would be installed in the building. Finally, Strategy 4 will involve the insulation of the ceiling, the upgrading of the windows, the isolation of the Long Room from the shop (through the installation of an insulated draught-lobby at the bottom of the central staircase) and the implementation of a new plant scheme that will control heating, cooling and moisture in the building. In this case the T range in the Long Room will be held between 15°C and 19°C , while the RH limits will be 37% to 53%, as specified by the Smithsonian Institute. Although the T range is lower than that specified previously, the variations between the minimum and maximum values are within the range specified by BSI and will be more achievable and efficient to achieve, particularly during the winter season, from an energy viewpoint. With the exception of Strategy 1 and Strategy 4, which will have thermal environment in both winter and summer discussed, winter simulations only will be considered as it is during this time that conditions are most likely to deviate from those recommended by the Smithsonian Institute. In each case the simulated environmental conditions arising from a particular strategy will be compared to the environmental conditions obtained from simulations of the building in its current state.

As mentioned previously, although removal of the central staircase from the building would have a positive influence on environmental conditions in the Long Room, potential overheating in the Shop was a potential issue with its implementation. Accordingly, HVAC plant was simulated in conjuntion with the envelope alteration to investigate whether this strategy would be beneficial to the environmental conditions in both the Shop and Long Room.

Fig. 7-42 displays the T variations simulated for the Long Room and Shop during the Christmas vacation and subsequent heating up period when Strategy 1 has been implemented. From the chart it can be seen that the implementation of Strategy 1, while not retaining T values within the 19°C to 23°C range required by the collection in the Old Library, provides a relatively stable environment in both the Long Room and Shop. Over the course of the Christmas vacation, T conditions in the Long Room are comparable to those simulated prior to the alterations, with a small difference in T, which is 1°C at a maximum,

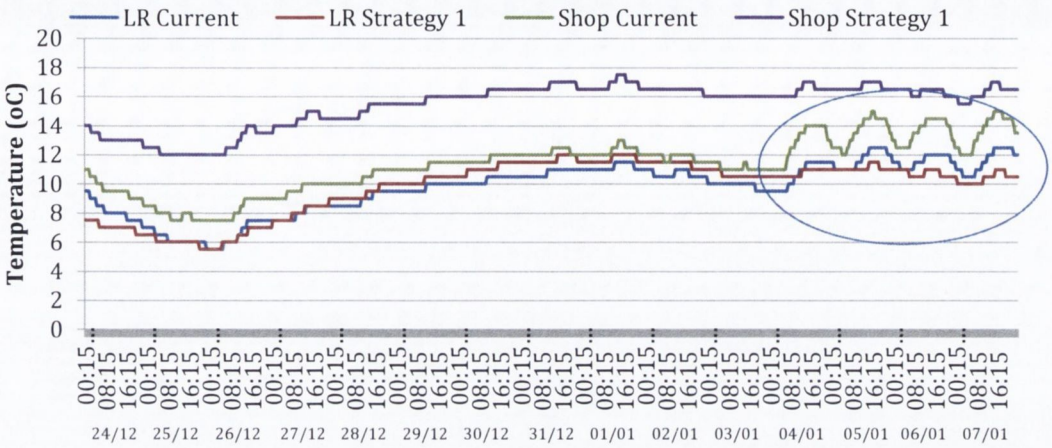


Fig. 7-42: Temperature values simulated for the implementation of Strategy 1 in the Old Library during the winter season.

occurring between conditions before and after the alteration. In the Shop, the reduced heat loss to the Long Room coupled with the installation of plant lead to a sizeable difference in conditions before and after alterations, with a difference of approximately 5°C between the trends being observed during the Christmas vacation.

When the building reopens (circled in blue), thermal conditions arising from the alteration are discernibly more stable than before the building upgrade. Diurnal fluctuations in the Long Room prior to the upgrade of the building range between 1°C and 2°C compared to fluctuations of 0°C to 1°C when Strategy 1 is implemented. In the Shop, the stabilisation of the thermal environment is greater as the diurnal changes reduce from a range of 3°C to 3.5°C to between 0.5°C and 1.5°C over the course of a given day. Although all current T fluctuations remain within the limits recommended by the Smithsonian Institute, reducing the magnitude of diurnal fluctuations will have a positive influence on both the condition of the collection and the comfort levels of staff and visitors, albeit slightly as T conditions remain significantly lower than those required for comfort, in the building despite the T range, especially in the Long Room, falling lower than the recommended 19°C to 23°C range.

Fig. 7-43 illustrates the T variations simulated for the Long Room and Shop during the summer season. From the chart it can be seen that, in terms of the Long Room in July, this particular strategy offers some, albeit small, improvement in the T conditions in the space as smaller variations are observed over the specified time interval. In the Shop, however, the introduction of the HVAC system is not sufficient to reduce the T values observed in the space and overheating continues to occur, with a minimum nightime T value of 24°C being observed, the upper limit for overheating. Accordingly, unless a more effective HVAC system



Fig. 7-43: Temperature variations in July following the implementation of Strategy 1.

could be implemented in the space to reduce the possibility of overheating in the summer, the removal of the staircase, despite its benefits on environmental conditions in the Long Room, may not be a suitable alteration for the Old Library.

As mentioned previously, Strategy 2 for improving conditions in the Old Library involves comprehensively insulating the roof and external walls and upgrading the windows to triple glazed systems with low emissivity glass, as well as installing a HVAC system. When these envelope alterations were modelled individually, the impact of each measure was reduced through continued heat loss through an alternative element. By insulating the entire envelope and upgrading the windows, it is anticipated that heat loss would be reduced and a more noticeable impact on the thermal environment would be simulated.

Fig. 7-44 displays the T variations in the Long Room and Shop before and after the implementation of Strategy 2. As expected, the reduced rate of heat loss from the building, following the implementation of Strategy 2, results in higher T values in the building compared to those currently noted in the Old Library. Considering the Long Room, the reduction in heat loss from the building equates to an increase in T of between 2°C and 3°C over the duration of the Christmas vacation, with similar improvement in T values also simulated in the Shop during this time interval. When the building reopens on 04/01, the extent of the variations in the building are greatly reduced.

In the Long Room, diurnal fluctuations of 0.5°C are noted indicating a very stable environment in the space. Similar conditions are observed in the Shop where slightly larger diurnal variations of 1°C are observed, compared to the fluctuations in the order of 3.5°C simulated prior to the upgrade. As with Strategy 1, although the values of T simulating during this time interval fall below those suggested by the Smithsonian Institute, the more

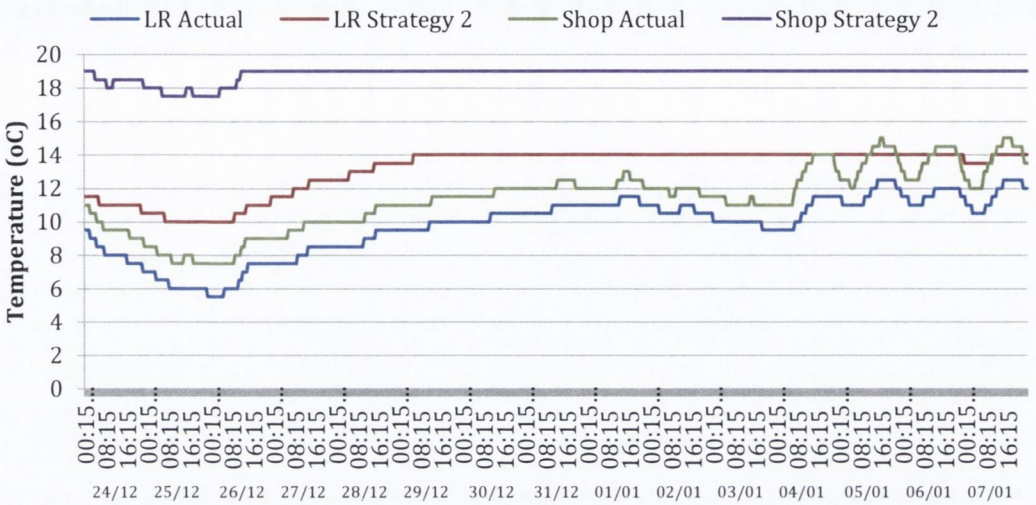


Fig. 7-44: Change in temperature conditions in the Old Library following the implementation of Strategy 2.

stable environment will be more beneficial for preserving the environment. The effect of this alteration strategy is expected to be similar to those achieved in Strategy 1, as an identical HVAC unit is installed with the envelope alterations.

Of the four upgrade scenarios modelled in IESVE, Strategy 3 is most likely to be implemented as if has the lowest potential to negatively impact on the character of the building. Strategy 3 involves the insulation of the roof, upgrading of the windows and installing the continuous heating system. Fig. 7-45 displays the T variations associated with Strategy 3 in the Long Room and Shop as heat loss from the building is reduced. This results in an increase in T of approximately 3.5°C in the Long Room and approximately 5°C in the Shop over the course of the Christmas vacation.



Fig. 7-45: Temperature variations associated with the implementation of Strategy 3.

As before, T variations when the building opens again in January, diurnal T fluctuations in the Long Room and Shop are again lower than the current conditions in the building, which indicates the benefit of implementing Strategy 3 in stabilising environmental conditions in the Long Room and Shop with stable T conditions being observed in the Long Room over majority of the time displayed in Fig. 7-45, indicating that this strategy may be effective in eliminating variations in the Long Room.

Strategy 4 represents the most desireable retrofitting scheme for implementation in the Old Library and involves insulating the stairs from the shop, upgrade of the windows, insulation of the roof and installation of a comprehensive HVAC system. In this case, a more powerful HVAC system is installed in the Shop (0.3kW) to combat the risk of overheating during the summer season. Fig. 7-46 and Fig. 7-47 illustrate the T variations simulated in the Old Library in winter and summer following the implementation of this strategy.



Fig. 7-46: Temperature trends simulated for the building before and after the implementation of Strategy 4 in summer



Fig. 7-47: Temperature trends due to the implementation of Strategy 4 in winter

This is a large improvement on the current system where seasonal fluctuations in typical T values could reach up to 11°C. Accordingly it may be concluded that the improvements in environmental conditions associated with Strategy 4 are significant in providing a more suitable thermal environment in the Old Library. Although T conditions in the Long Room in winter remain relatively low in terms of comfort (14°C), conditions are more stable and seasonal variations are reduced, a characteristic that is desireable in terms of preservation of collection items.

Thermal conditions in the Shop in summer continue to observe some overheating following the seperation of the stairs from the Shop, as T values during the day reach maximum values of 25°C despite the increased power of the HVAC system in the area. As a result, additional plant may be required in this space to reduce the maximum diurnal T values in summer. In winter, however, Strategy 4 has had a positive influence on T values in the Shop, which have increased significantly on the current conditions to observed stable conditions of 19°C. This is a large improvement in terms of occupant comfort as the previous range T values over the red region in Fig. 7-47 was 11°C to 15°C. As a result, comfort conditions for staff and visitors in the building has been greatly improved. Hence, the implementation of Strategy 4 in the building should be considered as it appears to offer the highest potential for environmental improvements in the Long Room in terms of both preservation of the collection and occupant comfort.

In terms of RH variations, Strategy 4 is effective in regulating the diurnal variations, as would be expected with the installation of a HVAC system. Accordingly, RH trends in the building closely resemble those observed when the HVAC alone is installed in the building and the RH charts associated with Strategy 4 can be found in Appendix H.

Although the three strategies outlined previously have a discernable influence on the thermo-hygrometric environment in the Old Library, all three may not be suitable for implementation in the building. Strategy 1, while causing preferable conditions in the Long Room, may result in excessive T values during the summer period, resulting in overheating and negatively impacting on the comfort conditions of visitors and staff in the area. Furthermore, removal of the central staircase would damage the character of the building as it is a key feature of the Old Library. Moreover, installation of the HVAC system in a manner that will not be visible in the Long Room would be difficult, impractical and costly.

Strategy 2 is also a difficult proposal to implement given the nature of the fabric of the building as well as the sheer area of external walls. Insulating these walls would require major construction work to the interior of the building, in particular the Long Room and the

risk of damage to the envelope while installing the insulation would be unacceptable. Furthermore the cost of implementing this strategy would be excessive given the difficulties associated with insulating the walls.

Strategy 3 is the most compatable with the building as, assuming the windows are altered to a high level and quality of craftsmanship, its implementation should have no influence on the character of the building. Although this strategy has the smallest relative improvement in conditions compared to the other options, the lower risk of damage to the building envelope associated with this strategy make it the most suitable for implementation in the building.

In terms of regulating environmental fluctuations in the Long Room, however, Strategy 4 is the most desireable alteration strategy as it greatly reduces the diurnal and seasonal thermo-hygrometric variations in the building and, as a result, will extend the permanence of the collection while simultaneously improve the comfort conditions in the building through the reduction in variations and the increase in the T magnitudes in the building. If the HVAC system could be installed in the building and the central staircase be isolated from the shop (by installing an insulated draught-lobby at the bottom of the stairs, for example) without negatively impacting the character of the Long Room, then Strategy 4 would be recommended for implementation in the building.

7.6. Conclusions and Recommendations

7.6.1. Performance of Model

- After running the model initially with an infiltration rate of 0ach, the overall trends that were simulated were comparable to those recorded in the building, indicating that loadings and envelope properties were defined in the software correctly.
- Based on a sensitivity analysis, it can be concluded that an infiltration rate of 1ach for the ground floor and 0.15ach for the rest of the building is appropriate.
- Although a good correlation between the simulated and actual thermal conditions was found, the difficulty in modelling the behaviour and effect of hygroscopic materials and surfaces on the moisture environment in the building means that the same level of accuracy as achieved in terms of T trends could not be attained for the moisture parameters in the IES.
- The HAMBase model of the Long Room indicated that the presence of the books in the space has a significant effect on the volume of water vapour in the air. Removal

of the books under current infiltration rate resulted in an average increase in H_{abs} of $0.69g/m^3$ over a five day simulation period.

- Upon completion of a sensitivity analysis on solar and casual loadings, it is concluded that, in terms of the thermal environment, the model is performing as would be expected.
- As well as the books playing a significant role in determining the hygroscopic conditions in the Long Room, the oak panels in the space were found to have a greater influence on the H_{abs} magnitude over the duration of the simulation period.
- The removal of both the books and the oak panels from the Long Room would result in an increase in the variability of the H_{abs} trends in the space.
- It has been shown that the books and oak absorb a lot of moisture but important to note that books cannot continue to absorb and desorb moisture

7.6.2. Performance of Individual Retrofit Options

- Installation of individual measures to reduce heat loss from the building (i.e. roof insulation, wall insulation, upgrade of the windows) have a limited effect on the thermal environment in the Shop and Long Room owing to the geometry of the Long Room (large external walled area with a large proportion of glazing).
- The most effective fabric alteration to regulate thermal conditions in the Long Room is the removal of the central staircase, which will reduce heat flow from the Shop to the Long Room. The risk of overheating and condensation (due to excessive moisture) resulting from this particular alteration means that some form of HVAC system must be installed in the Shop to overcome these issues.
- Replacement of the current heating system with a continuous low level heat source can significantly reduce thermal variations in the Long Room.
- The moisture conditions in the Old Library are influenced by the infiltration rate, the presence of people, the presence of the books and the presence of the oak panels in the Long Room. The current infiltrations rate, although relatively small is important for the removal of the moisture loads induced by people in the space. The books and oak panels work in tandem to regulate the hygroscopic environment in the space with the oak panels being the more effective hygroscopic material in the space.
- The most effective method of regulating moisture conditions is through the use of a HVAC system, although installation of such plant without negatively impacting on the character of the building, in particular the Long Room, may be challenging. The reduction of infiltration rates in the Long Room through the upgrading of the building envelope may lead to excess moisture loads due to the presence of people.

As a result, a minimum amount of HVAC may be required to remove these moisture loads and prevent damage to the collection.

7.6.3. Effect of Retrofit Strategies

- Despite leading to improvements to the environmental conditions in the Long Room, Strategy 1 may be unsuitable for the Old Library owing to the high probability of overheating during the summer months.
- Strategy 2 offers similar improvements to those observed following the implementation of Strategy 1, however, thermal conditions in the Shop are no longer likely to result in overheating over the course of the year meaning that Strategy 2 is more suitable than Strategy 1 for use in the Old Library.
- Strategy 3, which doesn't require the installation of new plant, may currently be the most compatible with the character of the building. Although it's implementation would improve the environmental conditions, it may not be effective enough in reducing RH variations when compared to the other strategies.
- Of the options considered in this research, Strategy 4, which involves installing HVAC, sealing the stairs and insulating and upgrading the ceiling and windows has the most potential to improve environmental conditions and reduce variations in the building. Although this strategy may be costly to implement initially, it would be advisable for preserving the collection contained within the Old Library if it would not have a negative impact on the character of the building.

8. Conclusions and Recommendation

8.1. Summary of Work Done

Upon completion of a review of the relevant literature, the thermo-hygrometric properties were determined to be of greatest interest in terms of assessing environmental quality owing to the influence of temperature and humidity on the environmental pollutants as well as their association with damage to heritage items. Accordingly, a number of OM-EL-USB-2-PLUS temperature and relative humidity data loggers were procured to enable data collection from the two case study buildings identified for monitoring.

Prior to carrying out any data-collection, the data recorded by each of the sensors was compared to the readings from each of the other sensors to ensure that discrepancies in the data could be minimised. This process involved placing the sensors in a drawer for a period of time, typically a day, to record the T and RH conditions in the microclimate. Once completed, the data was downloaded and collated in an Excel spreadsheet where the mean and standard deviation for each time interval (either 1 or 5 minutes depending on the length of the test) were calculated. When the loggers were returned after each test, a correction factor was applied to each sensor to facilitate accurate comparison between data. This process was carried out before each test or monitoring regime.

Although the literature had indicated the factors that may influence the thermo-hygrometric environmental properties, it did not necessarily indicate the extent to which each environmental stimulus affected the temperature and relative humidity. Accordingly, a number of small scale tests were devised to examine the influence of 6 stimuli on the indoor environment, namely a heating load, a moisture load, an increased ventilation/infiltration rate due to an open window, occupants with "dry" clothes and occupants with "wet" clothes. With the exception of the heat-loading test (which was conducted in a domestic oven), all small-scale tests were carried out in an unoccupied room in the basement of an office building. During these experiments, all sensors were placed at a height of 1.2m above the ground and this height was maintained, where possible, during all monitoring in the case study buildings. Prior to the testing, a data collection regime was carried out to obtain the baseline environmental conditions in the room to allow for greater ease of comparison of results after each test. As well as comparing temperature and relative humidity, the absolute humidity was also calculated and compared. This proved to be a useful parameter for understanding moisture movement as it accounted for the concentration of moisture in the

air and illustrated the moisture gradient between adjacent spaces as well as between inside and outside.

After the small-scale tests had been completed, the first case study building, namely the Museum Building, was monitored to determine whether the signatures associated with the environmental stimuli identified during the small-scale tests would be discernable in a large-scale historic building. Two monitoring phases were carried out in the Museum Building, the first of which was carried out over a four-month period during which four offices, four lecture theatres, the Atrium and the Civil Engineering Library were monitored. The second monitoring phase focused primarily on the thermo-hygrometric properties in the lecture theatres and additional sensors were placed in each of these rooms. As with the data collected during each small-scale signature test, data gathered from the Museum Building was downloaded and used to calculate the absolute humidity. The three parameters were then grouped using Excel and analysed for the trends observed during the small-scale tests as well as any additional factors that were not observed previously.

Upon completion of both phases of monitoring in the Museum Building, data collection in the primary case study building, namely the Old Library, could commence. As in the Museum Building, two monitoring periods were carried out in the Old Library, the first of which was approximately five months in duration and incorporated the Christmas vacation and the second, which studied the environmental conditions during the period of maximum occupancy (that is, July). For the first phase of monitoring sensors were placed along the path visitors take through the building as well as in the attic and three unoccupied rooms. As the second phase focused on the effect of people on the indoor environment, the sensors were removed from the unoccupied spaces and a greater number were placed along the route that visitors take through the building as well as in the Long Room. Data was collected at approximately 4-6 week intervals to ensure that the loggers were still working correctly but also to allow on-going analysis of the thermo-hygrometric properties in the building. Hourly visitor numbers were also collected during monitoring to allow for the exact effect of people to be determined.

The final aspect of the research project was to construct a computer model of the Old Library to determine the effect of any proposed alterations to the building on the internal environment. To achieve this, the software package <Virtual Environment> by IES was used in conjunction with AutoCAD drawings of the building. The composition of building elements as well as the mechanical loads in the building were obtained from staff in the Buildings Office in TCD and external weather conditions as well as visitor numbers that were recorded on-site were incorporated into the software model. Once the model had been calibrated, a

number of alterations were made to the building and simulations of the effect of each carried out. Based on this, a number of recommendations to improve the thermo-hygrometric properties of the building were proposed.

8.2. Principal Conclusions

The following signatures have been defined and verified for the specified environmental stimuli:

- Heat Loading: Assuming no change in moisture conditions in the air (that is, H_{abs}), when the T increases there is a corresponding decrease in RH. On the other hand, if there is moisture created or lost in the space it is possible that the RH will either increase or decrease in accordance with the H_{abs} change due to the change in moisture in the room. Therefore, it doesn't necessarily follow that if the RH changes in a room that there is a change in T present as it may be due to either a change in H_{abs} or a change in T, or a combination of both.
- Moisture Loading: The introduction of a moisture load into a room under constant T conditions results in an increase in both humidity parameters, which will exhibit similar trends. If T increases during the moisture-loading period however, the expected relationship between T and RH will not necessarily be observed, as it is possible that the extra moisture in the air will compensate for the increase in T and both RH and T will be observed to increase simultaneously.
- Open Window: The signature associated with an open window or external door is a rapid change in T and H_{abs} as internal conditions approach those observed externally, occurring throughout the room when the window/door is opened. The RH behaviour is influenced by both the T and H_{abs} variations depending on which is the most dominating factor. In this experiment, for example, the initial RH change (decreasing RH) due to the open window was driven by the H_{abs} variation before the decreasing T caused the RH to increase thereafter. When the window (or door) is closed once again, both T and humidity conditions stabilise before changing in accordance with loading conditions in the room.
- Occupancy: From this experiment it may be concluded that the environmental signature associated with the presence of occupants in a room is large perturbations in the humidity parameters about an existing general trend whereby the fluctuations in the general trend are exacerbated by the additional moisture load induced in the space by the metabolic processes of the people that were not previously present. The effect of people on the T conditions in the space is less pronounced. When

occupants are "wet", the increase in H_{abs} is more pronounced owing to the additional moisture load on the clothing and belongings of the occupants.

- Solar Gains: The signatures associated with solar gains are characterized by a sudden, relatively large perturbation in T about a general trend that is quickly dissipated when direct sunshine is no longer entering the room. Furthermore, a similar but opposite fluctuation in RH that is a result of the large increase in T is observed during the period of solar gain.
- Hygroscopic Surfaces: Relatively stable RH and H_{abs} conditions exist generally. When heating is then applied to the room, H_{abs} correlates very closely to the T variations as moisture is released into the air from the surfaces when T increases and then adsorbed when T decreases again.
- Library: It was seen that the books act so as to stabilize the environment in the library by acting as thermal mass and a hygroscopic material. Accordingly, a general background environment of relatively stable T and humidity parameter values would be expected in a library, which would undergo the fluctuations associated with the other stimuli when they are observed in the room or building.
- In the Museum building, the relative area of thermal mass and glazing are significant factors in determining the background T values during periods when the thermal gradient between the inside and outside is large. When this gradient is small however, solar gains and heat movement within the building determine the thermal behaviour of the rooms.
- Infiltration from the external environment, the hygroscopic properties of materials and the presence of people are the primary factors influencing the hygrometric parameters in the building.
- From the analysis of environmental conditions in the Museum Building it can be concluded that signatures defined in the small-scale experiments are generally observed in full-scale historic buildings, although, given the multiple stimuli that act simultaneously to define the environmental conditions in a building, some small alterations to the signatures may be required depending on the conditions in the building.
- The blinds on the external windows of the Old Library are effective in reducing the impact of solar gains on the thermal environment in the Old Library and in particular the Long Room.
- The presence of books, coupled with the thermal mass of the *"heavy"* walls in the Old Library, are effective in regulating the environment in the Long Room, resulting in the slow response to environmental stimuli in the space.

- The ineffective heating regime in the Old Library results in T and RH values in the Long Room falling significantly outside the range required for the preservation of the collection and comfort conditions throughout the winter season.
- When the building is unoccupied, diurnal environmental fluctuations fall within those specified for a historic museum, library or archive, however, seasonal variations are large and should be reduced to provide more adequate conditions for the collection.
- When the building is open to the public, the moisture load associated with the metabolic processes of people has a discernible impact on the RH and H_{abs} values in the building, particularly on *"wet"* days. These fluctuations may drive the internal hygrometric environment outside of the limits specified by the Smithsonian Institute and BSI and this must be addressed to prevent excessive and accelerated damage to the collection contained within the building.
- The use of signatures as a means of determining the dominating influences on the environmental conditions in the Old Library has been validated as signatures observed during the experiments. Subsequently refined in the Museum Building have also been noted in the Old Library under different boundary conditions and were used to define the dominating factors driving the environmental parameters in the building.
- Initial simulations of the computer model with an infiltration rate of 0 ach showed the simulated and actual environmental data for the Old Library to be correlating quite well indicating an accurately constructed model. A sensitivity analysis determined the actual infiltration rate to be 1ach for the ground floor and 0.15ach for the rest of the building.
- Although a good correlation exists between the simulated and actual thermal conditions, the difficulty in modelling the behaviour and effect of hygroscopic materials and surfaces on the moisture environment in the building means that the same level of accuracy as achieved in terms of T trends could not be attained for the moisture parameters.
- The HAMBase model of the Long Room indicated that the presence of the books in the space has a significant effect on the volume of water vapour in the air. Removal of the books under current infiltration rate resulted in an average increase in H_{abs} of $0.69g/m^3$ over a five day simulation period.
- As well as the books playing a significant role in determining the hygroscopic conditions in the Long Room, the oak panels in the space were found to have a greater influence on the H_{abs} magnitude over the duration of the simulation period.

- The removal of both the books and the oak panels from the Long Room would result in an increase in the variability of the H_{abs} trends in the space.
- Despite being perceived as having high infiltration rates, large historic building can typically have quite low infiltration rates in comparison to smaller or modern buildings.
- Upon completion of a sensitivity analysis on solar and casual loadings, it is concluded that, in terms of the thermal environment, the model is performing as would be expected.
- Installation of individual measures to reduce heat loss from the building (that is, roof insulation, wall insulation, upgrade of the windows) have a limited effect on the thermal environment in the Shop and Long Room owing to the geometry of the Long Room (large external walled area with a large proportion of glazing).
- The most effective fabric alteration to regulate thermal conditions in the Long Room is the removal of the central staircase, which will reduce heat flow from the Shop to the Long Room. The risk of overheating and condensation (due to excessive moisture) resulting from this particular alteration means that some form of HVAC system must be installed in the Shop to overcome these issues.
- Of the proposed retrofit proposals, Strategy 3, which comprises continuous low level heating coupled with insulation of the ceiling and upgrading the windows, is likely to be the most suitable for use in the Old Library as it is unlikely to negatively impact the character of the Old Library while still providing improvements to the environmental conditions in the building. Strategy 4, however, which involves installing HVAC, sealing the stairs and insulating and upgrading the ceiling and windows has the most potential to improve environmental conditions and reduce variations in the building. Although this strategy may be costly to implement initially, it would be advisable for preserving the collection contained within the Old Library if it would not have a negative impact on the character of the building.

8.3. Achievement of Objectives

Prior to outlining the manner in which each of the objectives, listed in Section 1.2, were achieved over the course of the project, it is first necessary to restate each of these aims. The four primary objectives of this research project are as follows:

1. To develop an understanding of the primary influences that determine the thermo-hygrometric variations in historic buildings by means of developing environmental signatures
2. To develop sensible restorative strategies based on best historic building practice
3. To assess the adaptability of this to other buildings.

The first of these objectives involved creating a number of small-scale, individual tests to examine the influence of four environmental stimuli on the thermo-hygrometric environment in a space. These stimuli were heat loading, moisture loading, increased infiltration rate due to an open window and the effect of *"dry"* and *"wet"* occupants. The heat-loading test was conducted in a conventional domestic fan-assisted oven, where a pair of sensors were placed inside and the T was increased. From this particular test it was found that, initially, the natural relationship between T and RH was not observed as evaporation from hygroscopic surfaces resulted in an increase in H_{abs} and, as a result, RH. This change was short-lived, however, and conditions in the microclimate of the oven quickly reverted to the expected T-RH relationship as the rates of evaporation and adsorption of the hygroscopic surfaces reached equilibrium.

The remaining small-scale tests were carried out in a basement room so that solar gains would not be a factor in the experiments. The moisture-loading test involved boiling a quantity of water in the test room to induce an additional moisture load in the room. The additional load was applied at a constant rate and minimal change in T was observed over the course of the loading process. Based on this experiment, the relationship between RH and H_{abs} was confirmed as similar trends were observed in each parameter as very little change in T (0.5°C) was observed.

The third of the small-scale tests aimed to determine the effect of an increased infiltration rate in a space arising from the opening of an external window or door. A number of sensors were placed in the test room, as well as an adjacent hallway and externally, to assess the initial conditions before the window was opened for a period of approximately 45 minutes. Data collection continued for a further 75 minutes after the window was closed to examine the effect of closing the window on the environmental conditions in the room. Based on this test, it was found that humidity parameters are more reactive to this environmental stimulus as H_{abs} conditions approached those exernally at a quicker rate than the corresponding T values as moisture diffused at a high rate in accordance with the moisture gradient between the room and the external environment. A similar observation was made for the T values, albeit at a slower rate. When the window closed, conditions were observed

to increase marginally as the rate of heat and moisture flow from the room was slowed. Thereafter, conditions stabilised, however H_{abs} values stabilised at a lower value due to the reduced concentration of moisture in the air in the room. A further finding from this experiment was that the open window also had an impact on the environmental conditions in an adjacent hallway, indicating that a change of conditions in one space can have a discernable impact on environmental conditions in another room.

The aim of the final small-scale test was to examine the effect of people and involved placing five sedentary people in the test room for a pre-defined period of time and was carried out in two stages to assess the impact of *"dry"* and *"wet"* occupants on the environment. In both cases, the presence of people had a significant impact on the hygrometric properties in the room and the extent of this influence was larger in the case of the *"wet"* occupants compared to the *"dry"* occupants. The effect of the people on the thermal conditions was relatively small in comparison to the corresponding impact on the humidity parameters.

Following on from the small-scale tests, it was necessary to establish whether the signatures associated with the environmental stimuli were applicable to a large-scale historic building and whether any additional influences that were not the subject of a small scale test were applicable to such buildings. To achieve this, the 155 year old Museum Building in TCD was identified as a suitable case study and a monitoring regime was designed and implemented in the building. Two data collection phases were conducted in the Museum Building over a combined period of approximately five months, namely over a Christmas period, when the heating and casual loads to the building were removed, and subsequent heating up interval and also during a college semester when occupancy levels were at a maximum. Four lecture theatres, four offices and a library were monitored and the environmental data associated with each room were collected and analysed using the knowledge gained during the small-scale tests to identify trends in the building. Overall, the signatures associated with the different stimuli were observed in the Museum Building, with two examples of this being observed in the manner that RH changes can identify the presence of people in a room and also the environment in M4, a basement theatre that, despite having a relatively stable thermal environment has a variable hygrometric environment due to an access door which is linked to an adjacent hallway that has variable RH and H_{abs} conditions. The study also illustrated the importance of solar gains in determining thermal and RH conditions in rooms, particularly those that are south facing. The study also demonstrated the influence of hygroscopic surfaces and materials in regulating the moisture environment in a room, as was observed in the GLT during the Christmas vacation. Furthermore, when the mechanical heating was applied to the space, H_{abs} variations corresponding to the change in T were observed indicating the importance of hygroscopic materials in regulating RH and H_{abs}

conditions in a room. Furthermore, through monitoring of the Civil Engineering Library, the thermal mass due to the presence of books in the room resulted in regulation of the thermal environment as diurnal fluctuations in the space were smaller compared to office rooms of similar size.

Having successfully defined the thermo-hygrometric signatures associated with a variety of environmental stimuli, the focus of the project shifted to the primary case study of the research, namely the, almost 300 year old, Old Library in TCD. As in the Museum Building, a data collection schedule was designed and implemented to obtain T and RH data for the building. Once more two data collection phases were conducted over a combined time interval of approximately six months. Monitoring of the Museum Building had demonstrated the usefulness of obtaining data over the Christmas vacation when the building was unheated and unoccupied and this was incorporated into the monitoring regime of the Old Library. Phase 1 of monitoring was carried out from September to January and focused on determining the primary factors that influence the thermo-hygrometric properties in the building. The data collected from this portion of data acquisition indicated that the large volume of visitors in the building had a large influence on the environmental properties in the building and, accordingly, the second data collection phase focused primarily on the route that visitors take through the building. Analysis of the data collected during both phases indicated that the presence of people during the day and infiltration from the external environment were the determining factor for the hygrometric conditions within the building. The effect of the presence of people was especially discernible on days where it was raining as the additional moisture load due to *"wet"* visitors had a greater impact on the environment than that on a dry day. Despite this, the presence of the books in the Long Room acted to regulate the environmental conditions in this space and a unique environment was observed in this area. Although diurnal variations in both T and RH were less than the limits specified by the Smithsonian Institute, seasonal variations were excessive and during the winter period, T values in the Long Room fell significantly short of the 19°C lower limit specified for the environment. Furthermore, similar values were observed in other areas of the building, indicating that poor levels of thermal comfort are being provided to the building by the current plant system. It was also noted from the data that the window blinds are having a positive effect in preventing solar gains influencing the thermal conditions in the building as there is little evidence of solar gains in the building, which is surprising given the area of external glazing. From the analysis of the building it was determined that the primary factors influencing the environmental conditions in the Old Library are the presence of people, infiltration from the external environment, heat loss through the fabric, the inadequate heating system and schedule.

The second objective of this research was to draft a building alteration strategy to reduce the environmental variations and thus improve conditions for the collection in the Old Library. Having identified the primary factors that are having an impact on the environment, a model of the Old Library was constructed in IESVE. After calibration of the model with the real data recorded in the building, a sensitivity analysis was conducted to ensure that the model was simulating conditions accurately. This analysis found that, although accurate variations for the thermal environment were obtained from the model, difficulties simulating hygroscopic surfaces meant that the moisture conditions in the building were not accurately modelled. Accordingly, an alternative software package, namely HamBASE, was used to model the hygrosopic environment in the Long Room. A number of building alterations that may be suitable for the building were simulated individually, using IESVE, and compared to the original values. The alterations in question were either building envelope or plant upgrades, although the reduction and regulation of the visitor load was also simulated. In general, it was found that the envelope upgrades, when simulated individually, did not lead to worthwhile improvements in the environmental conditions in the Old Library. Conversely, the plant upgrades, namely the introduction of HVAC and an alternative low power continuous heating system had a more noticeable influence on the environmental conditons in the building and reduced the diurnal variations in the building.

In total, four individual strategies were proposed to improve the environmental conditions in the Old Library. Strategy 1 involved removal of the central staircase linking the Shop to the Long Room and introduction of a HVAC system. Although this scheme offered more suitable environmental conditions in winter, the loss of character associated with the removal of the central staircase would mean such a measure would be unacceptable. Strategy 2 involved insulation of the roof and external walls, upgrade of the windows and installation of a HVAC system. This particular option offered similar benefits to Strategy 1 without the risk of overheating in the summer period and thus would be preferable to the previous suggestion. The technical difficulty of insulating the external walls without the loss of character or damage to the building envelope coupled with the difficulty in installing HVAC in the Long Room without having a negative impact on the character of the space again made this unsuitable for the Old Library. The third option, Strategy 3, was deemed to be the most suitable for implementation in the building. This proposal involve insulating the roof, upgrading the windows and installing the alternative heating regime. Although the environmental impact of this strategy is marginally less than the previous 2 strategies, given the lower risk to the character and envelope of the Old Library coupled with the measurable improvement on the current system means that Strategy 3 would be the most suitable for implementation in the building. Strategy 4, which involved entirely insulating the envelope, upgrading the windows, isolating the Long Room from the shop and the installation of plant,

despite requiring significant alterations to the envelope would have the most significant effect on the environmental conditions in the building.

8.4. Recommendations for Future Work

This study has made a contribution towards understanding the effect of thermo-hygrometric properties on the indoor environment of historic buildings. However, there is scope for further research in this area. Although this research projhect has defined the signatures associated with a number of environmnetal stimulo, the study could be extended to develop a full suite of environmental signatures that can be used as a resource for assessing the environmental conditions in buildings.

The study could be extended to other historic buildings of alternative use such as accommodation, a gallery or an office block. There is also the possibility to extend the study to incorporate chemical and biological pollution in each building. A further area of possible research could involve the implementation of a monitoring regime in the Museum Building to assess the effectiveness of alterations (i.e. HVAC in M17, new furniture and floor finishes in GLT) on the thermo-hygrometric properties in the rooms. These additional case-studies could further improve the signatures associated with environmental stimuli as well as further increasing the knowledge about how historic buildings function and how they can be upgraded and retrofitted to improve environmental conditions within.

Based on the findings from the computer model, a retrofit scheme could be performed on the Old Library involving insulation of the roof, upgrading of the windows and implementation of an alternative continuous low level heating system with the environmental conditions monitored before, during and after alterations to assess their effectiveness in regulating the environmental conditions in the building. Furthermore, the computer model could also be employed to model the Museum Building to determine the retrofit options that would be most effective in regulating the internal environment therein. Further development of the software package is required, however, as the simulation of the hygrometric environmental of the Old Library require refinement. Following such an upgrade to the moisture modelling ability of the <VE>, the Old Library should be siumulated again with particular attention given to the moisture conditions modelled using the software.

Accordingly, the use of the HamBASE software should be expanded to rigorously examine the effect of each retrofit option and strategy may have on the building. This would involve

the simulation of each individual retrofit option before simulating each strategy with a view to identifying the most suitable strategy in terms of regulating the hygrometric environment. Furthermore the study of the Long Room using the HAMBase software would require expansion to include the Old Library as a whole. This would enable the accurate assessment of airflow between the shop and the Long Room and lead to more accurate results. To fully achieve this, however, in excess of a full year worth of on-site weather data would be required to fully precondition the building.

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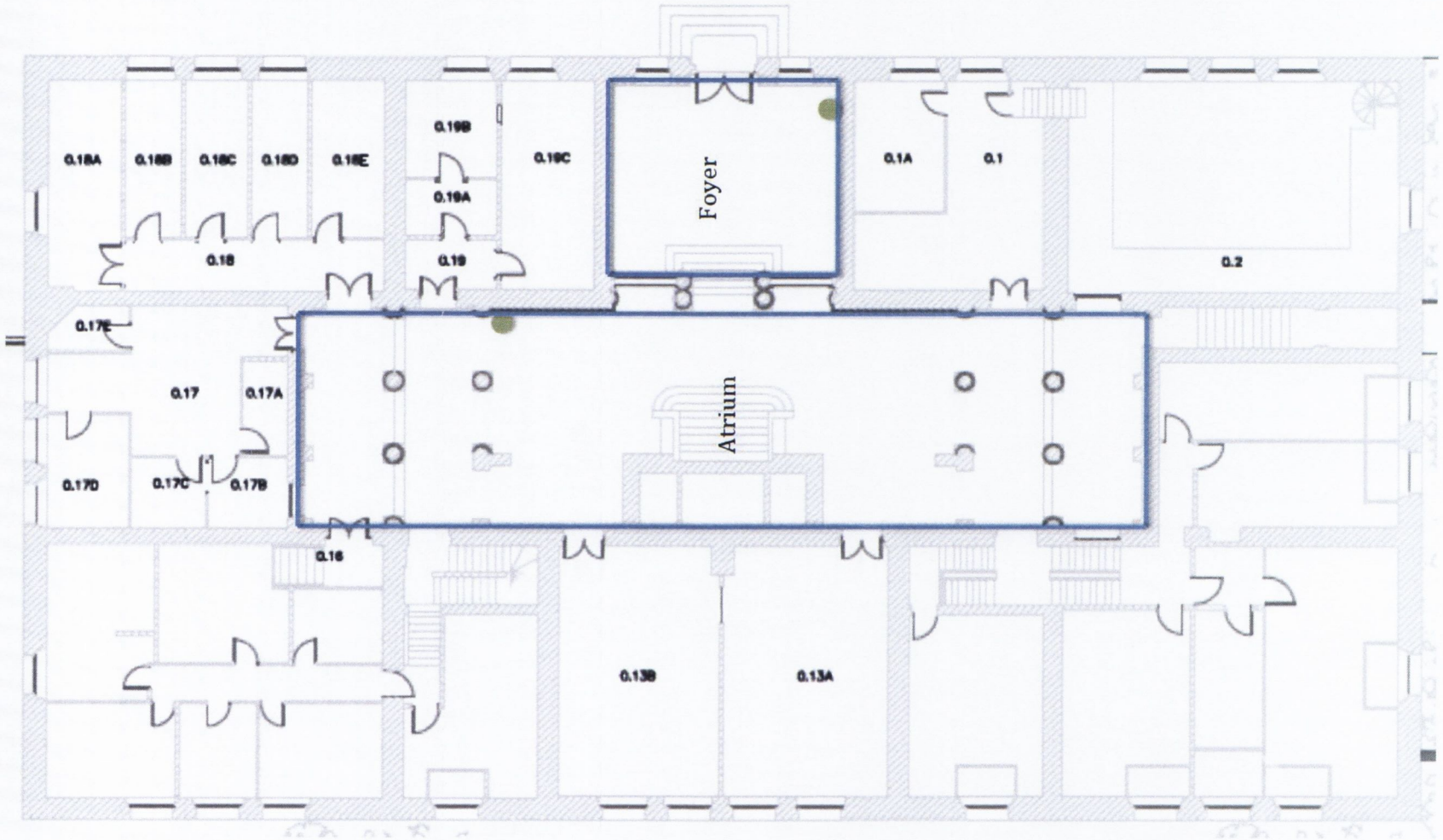
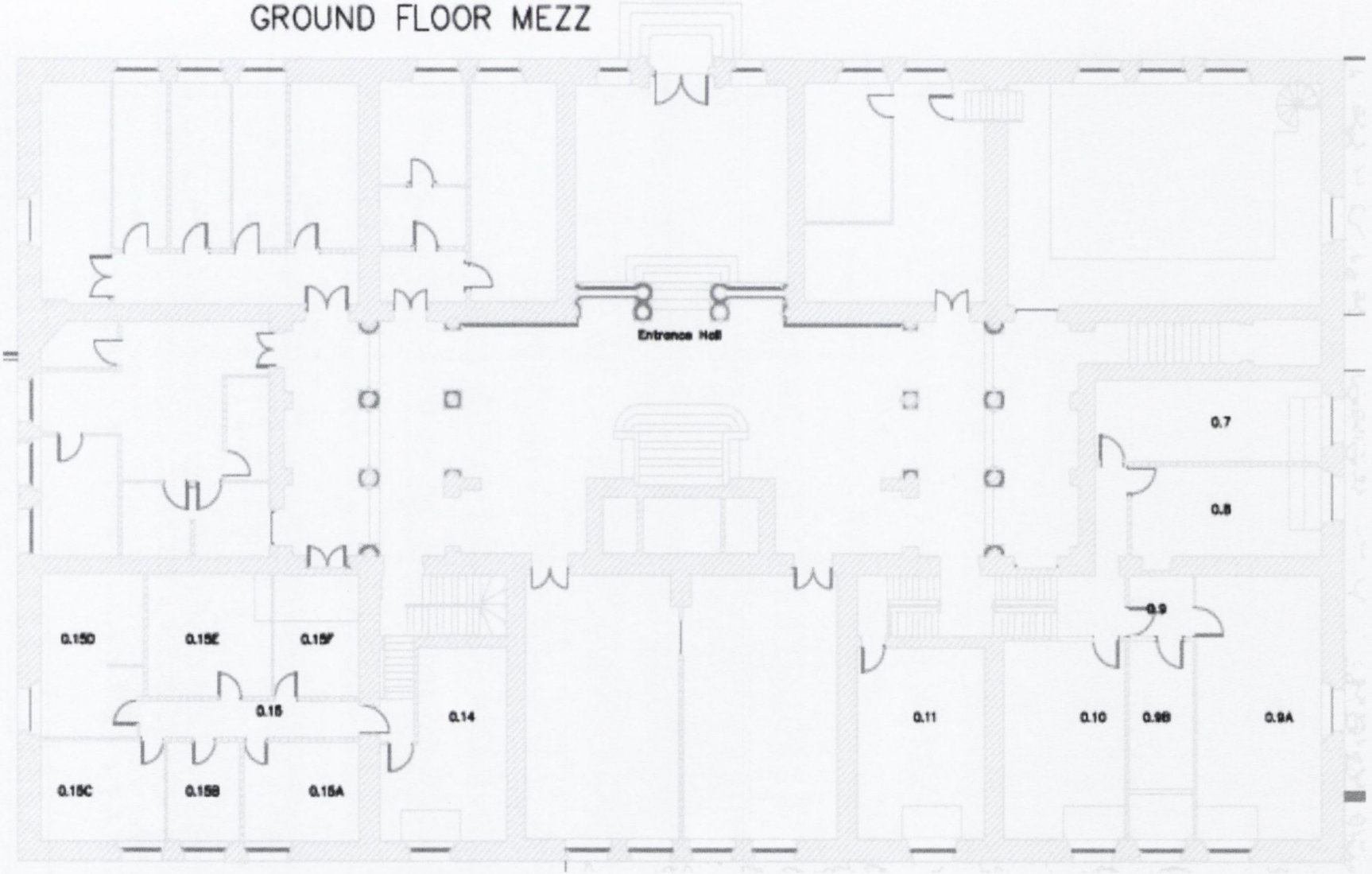
Appendix A: Floor plans of the Museum Building including the location of each monitored room together with the location of the data-loggers within. Green circles denote a sensor that was used in Phase 1 only, green with a red border is Phases 1 and 2 and a red only circle denotes Phase 2 only.

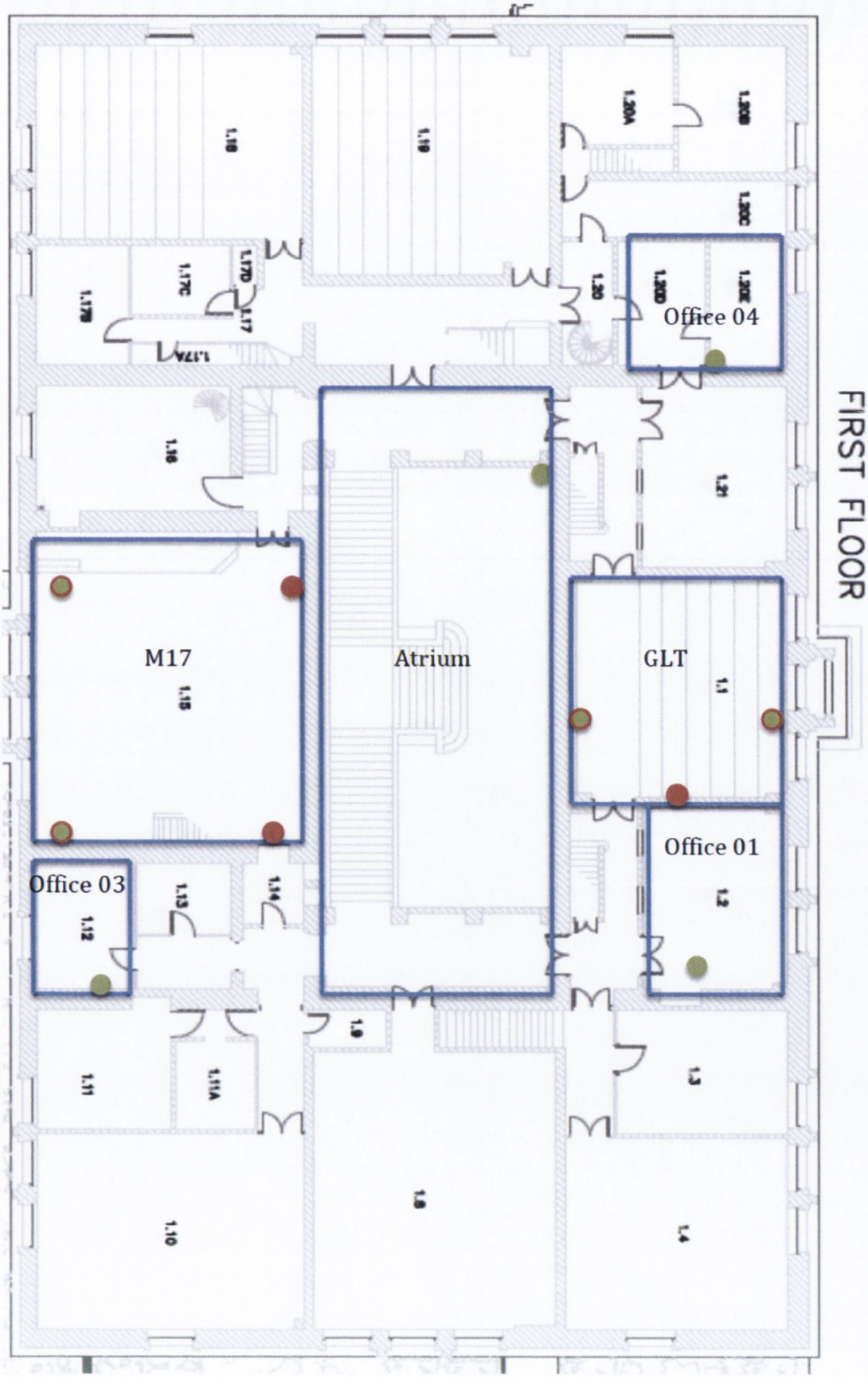


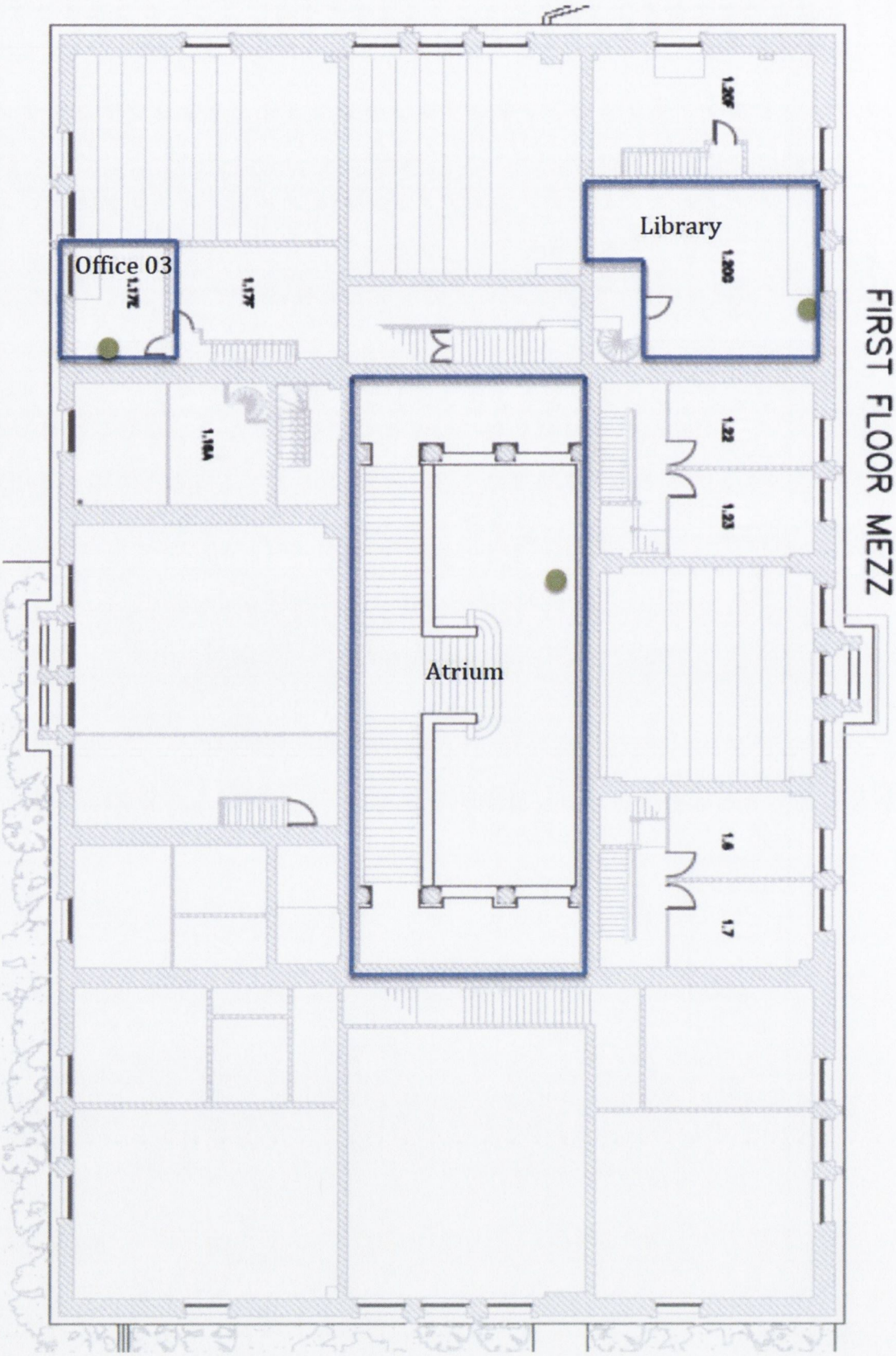
GROUND FLOOR

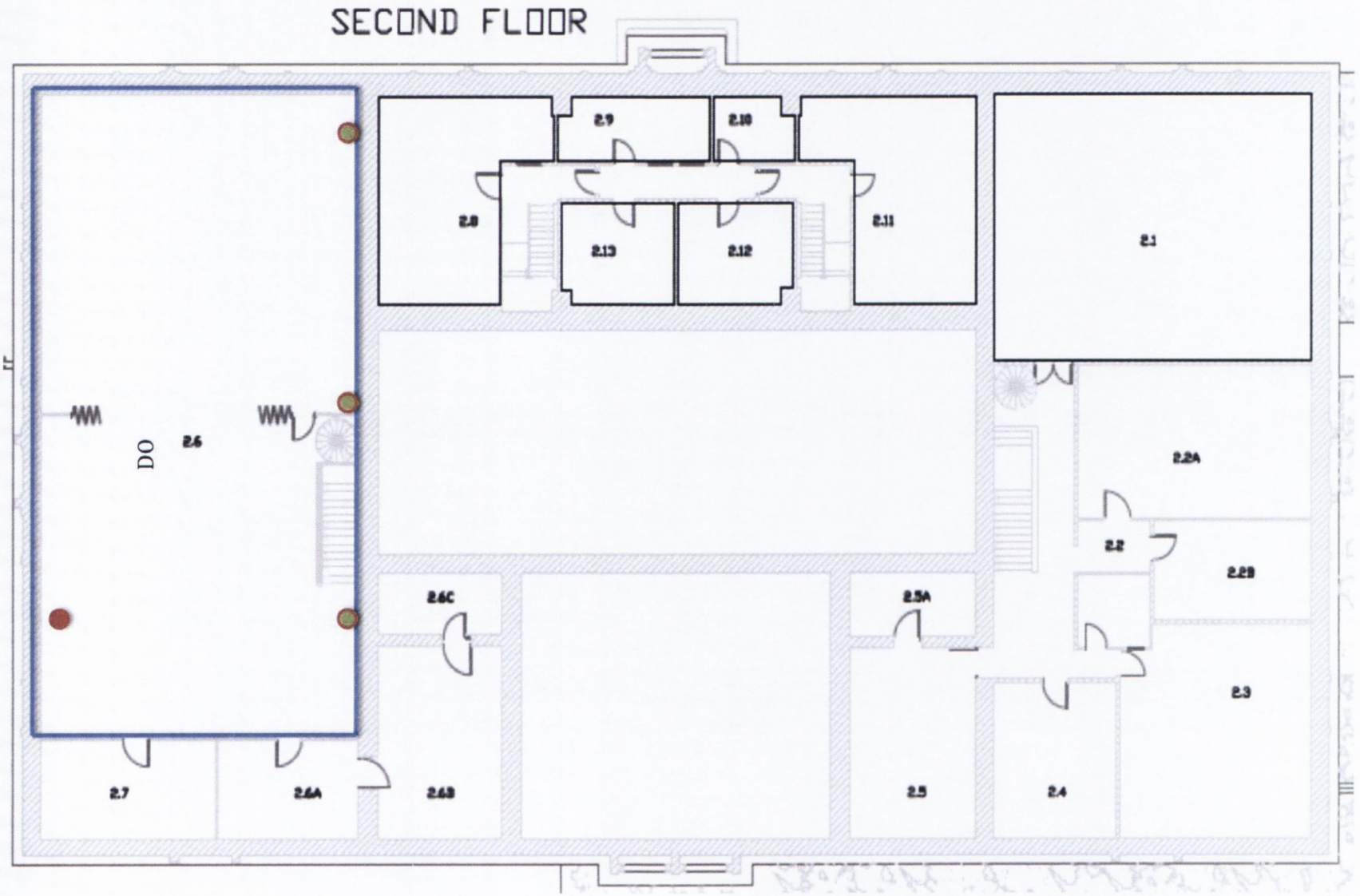


GROUND FLOOR MEZZ



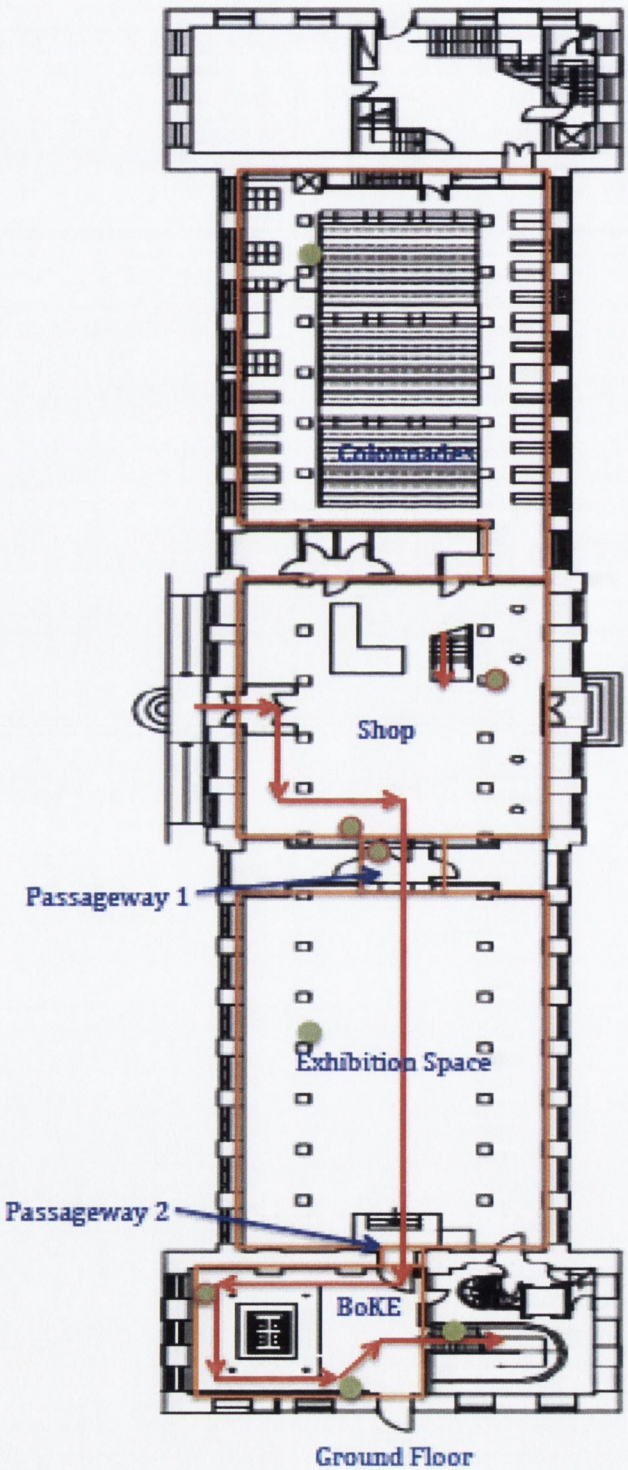

FIRST FLOOR
Office 04
M17
Atrium
GLT
Office 01
Office 03

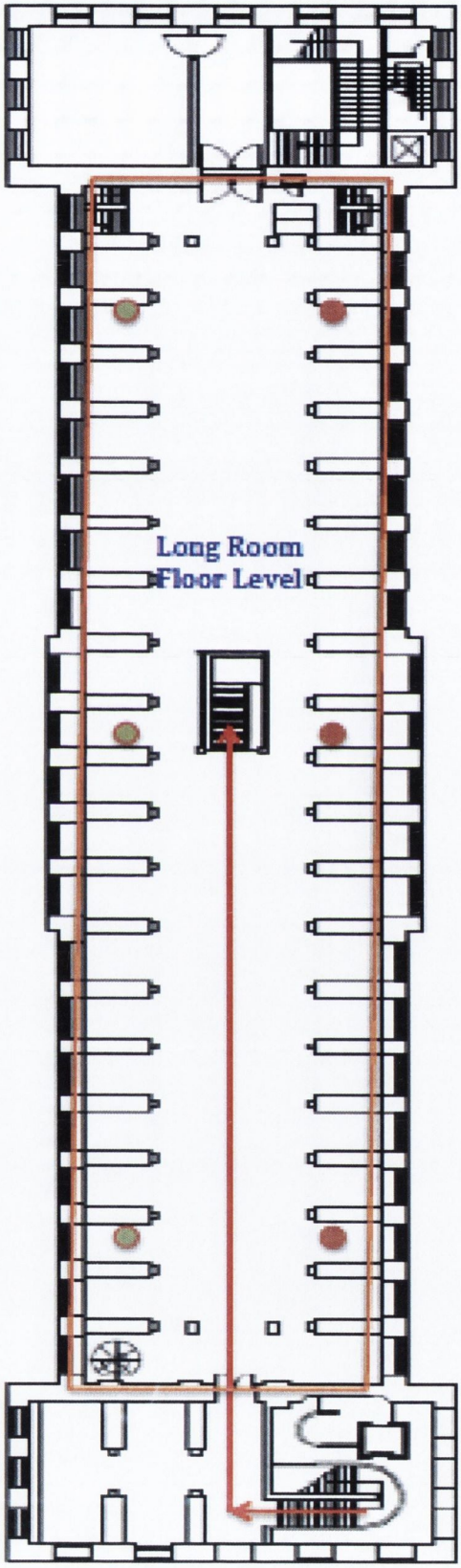

Office 03
Library
Atrium
FIRST FLOOR MEZZ


SECOND FLOOR
DO
2.6
2.9
2.10
2.8
2.11
2.13
2.12
2.1
2.2A
2.2
2.2B
2.6C
2.5A
2.3
2.7
2.6A
2.6B
2.5
2.4

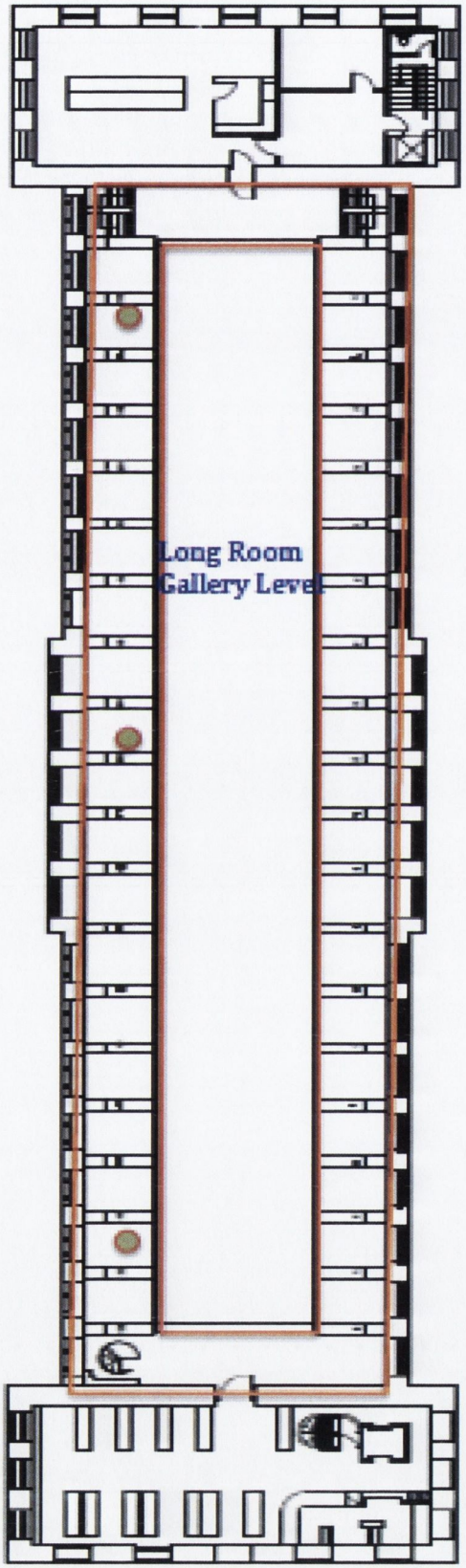
320

Appendix B: Floor plans of the Old Library including the location of each monitored room together with the location of the data-loggers within. Green circles denote a sensor that was used in Phase 1 only, green with a red border is Phases 1 and 2 and a red only circle denotes Phase 2 only. Route for tourists through the building is indicated in red.

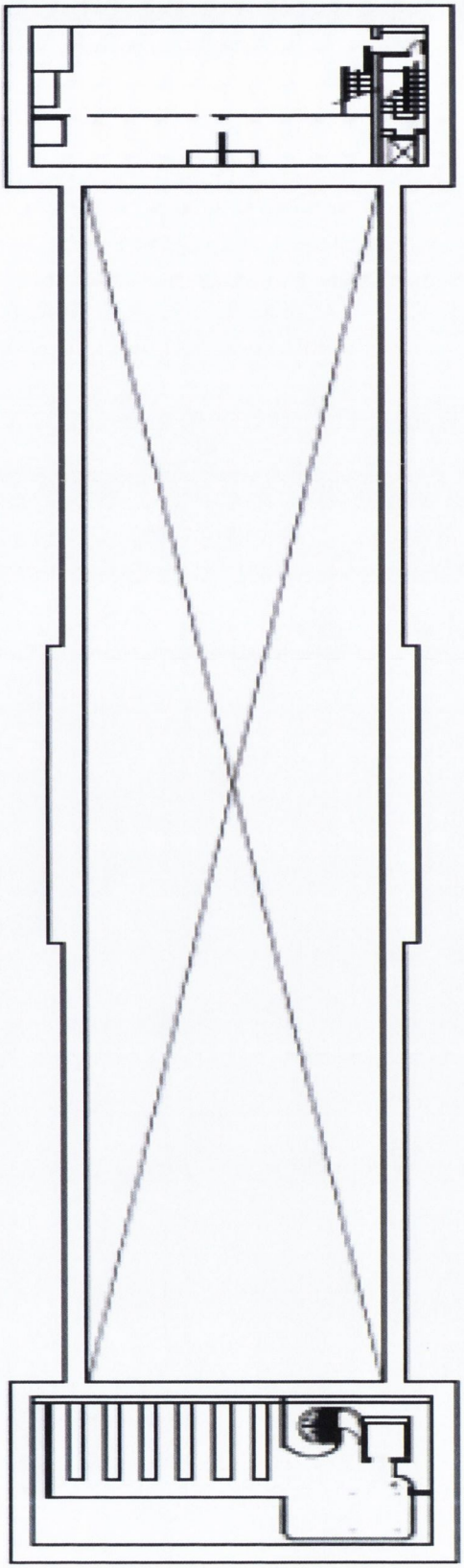




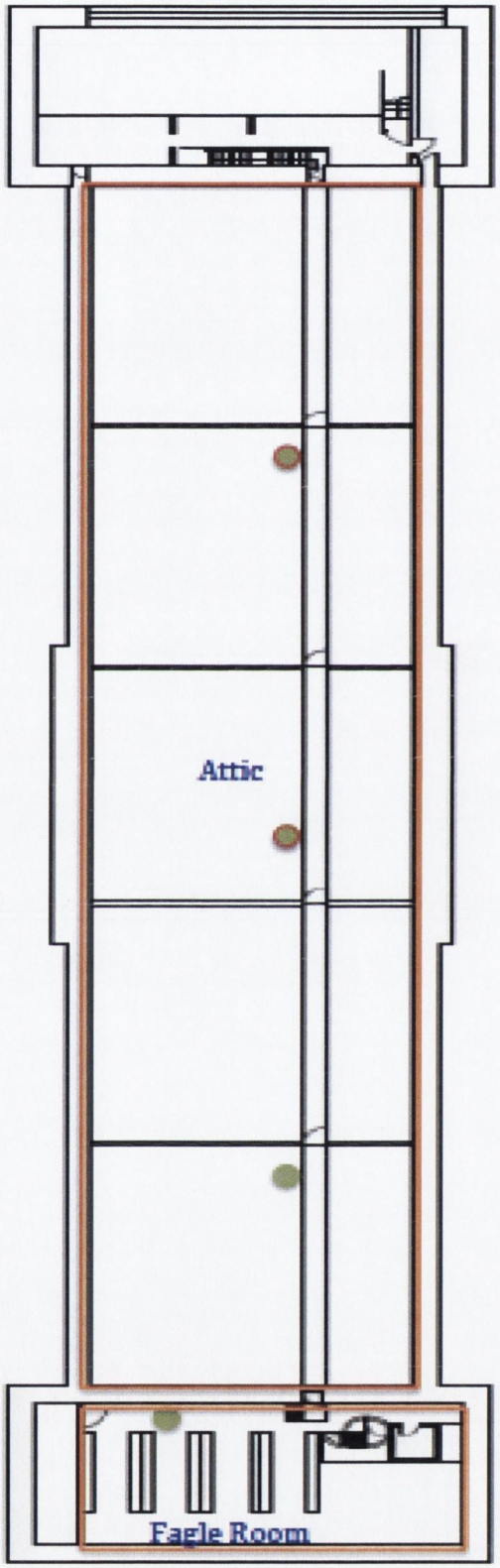
First Floor



Second Floor



Third Floor



Fourth Floor and Attic

Appendix C: Temperature trends observed in the Old Library on 19/11, 22/11, 21/07 and 26/04.

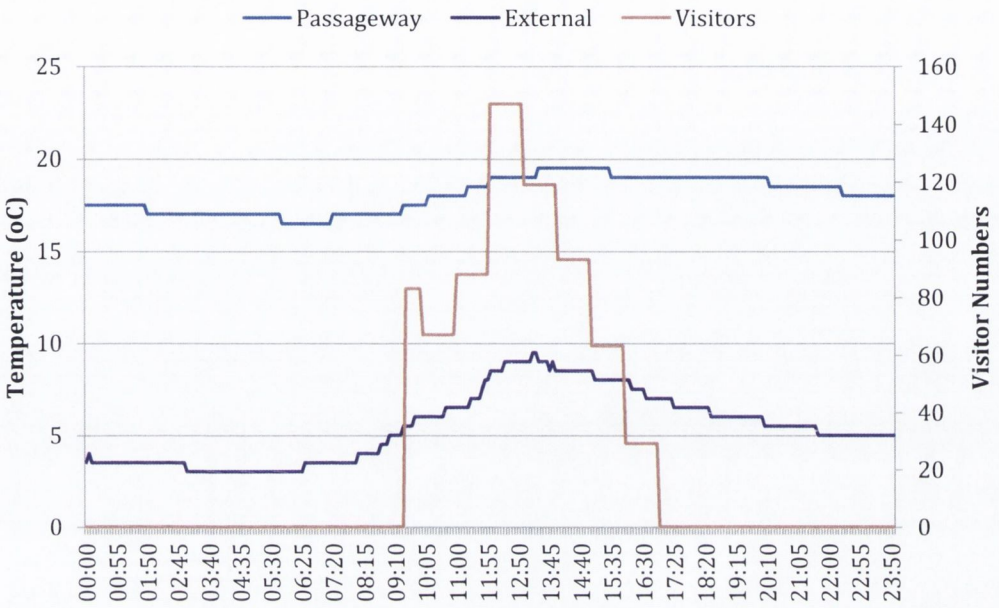


Fig. D- 1: T conditions recorded in the Passageway and externally, as well as visitor numbers, on 19/11.

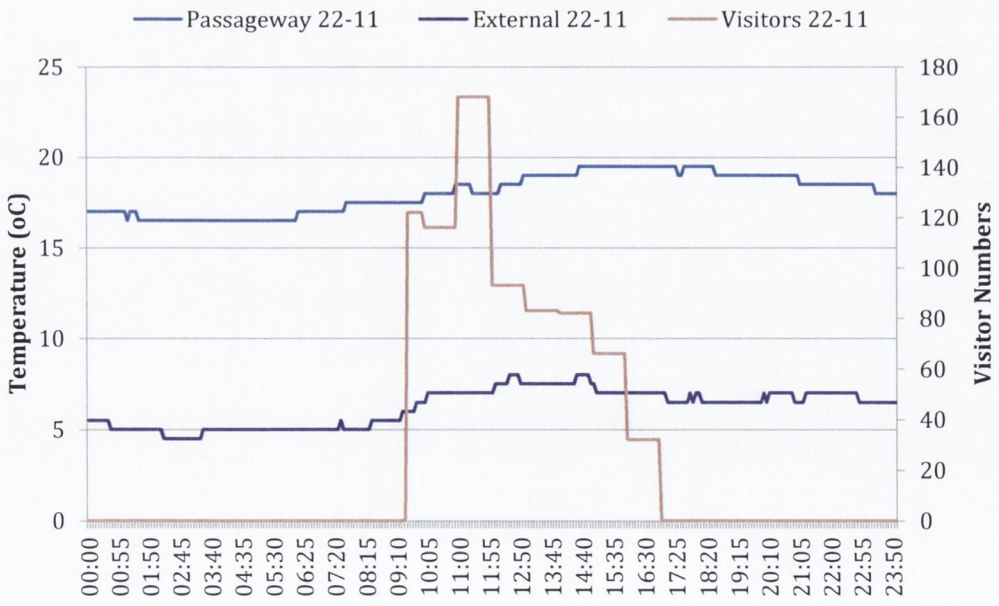


Fig. D- 2: T conditions recorded in the Passageway and externally, as well as visitor numbers, on 21/11.

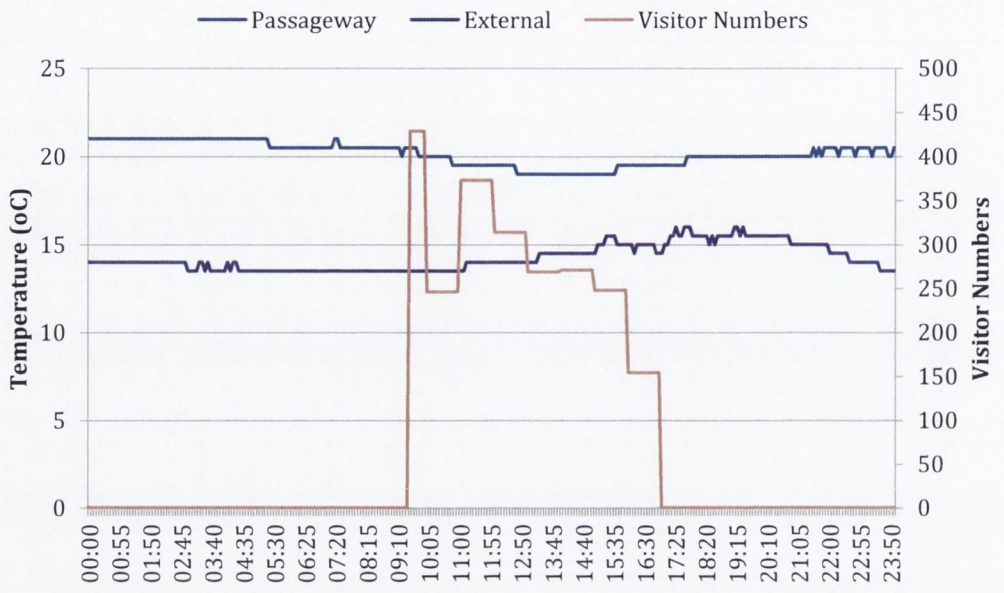


Fig. D- 3: T conditions recorded in the Passageway and externally, as well as visitor numbers, on 21/07.

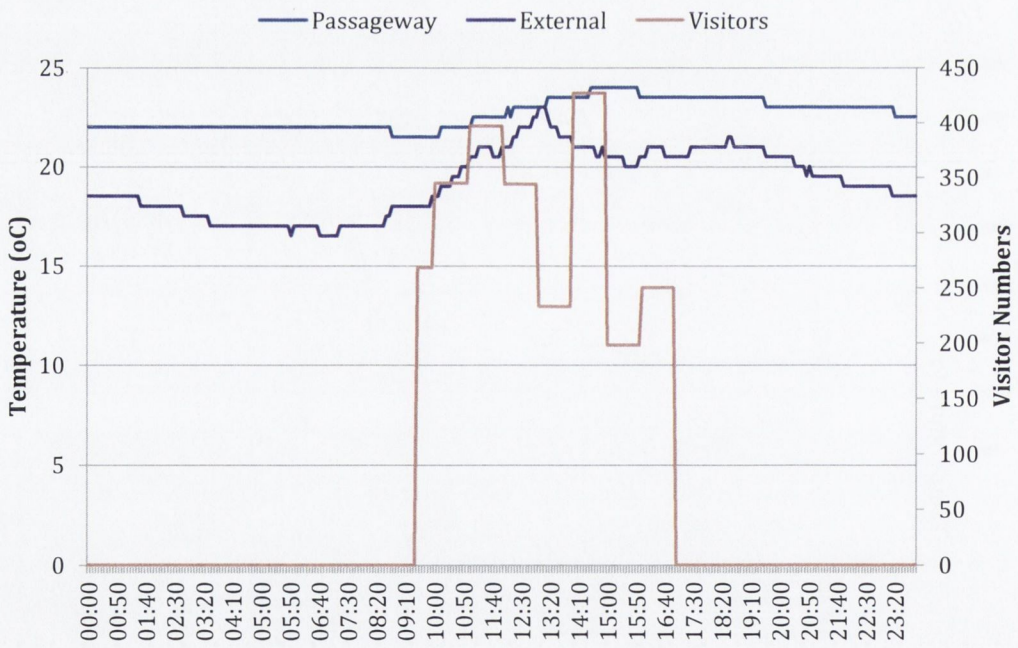


Fig. D- 4: T conditions recorded in the Passageway and externally, as well as visitor numbers, on 26/07.

Appendix D: Description of the physical models used by IES-VE as specified in IES (2011a).

Simulations in IES-VE are carried out by the ApacheSim package, a dynamic thermal simulation programme based on first principles mathematical modelling of the heat transfer processes occurring within and around a building (IES, 2011a). ApacheSim deals separately with each of the fundamental heat transfer mechanisms (conduction, convection and radiation) and control processes affecting building thermal performance. The methods used to model these processes are described in the following sections. For a more in depth description of the numerical and physical methods used to simulate thermal conditions the reader is reffered to the calculation guide provided by IES (2011a)

1. Heat Conduction and Storage

The time-evolution of the spatial temperature distribution in a solid without internal heat sources is governed by the following partial differential equations.

$$W' = -\lambda \nabla T \qquad (E - 1)$$

$$\nabla . W' = -\rho c \frac{\delta T}{\delta t} \qquad (E - 2)$$

where T(x,y,z,t) is the temperature (°C) in the solid ar position (x,y,z) and time t, W'(x,y,z,t) is the heat flux vector (W/m^2) at position (x,y,z) and time t, λ is the conductivity of the solid (w/m^2K), ρ is the density of the solid (kg/m^3) and c is the specific heat capacity of the solid (J/kgK).

Equations (E - 1) and (E - 2) are expressions of the principles of conduction heat transfer and heat storage repectively. The heat diffusion equation (in its most general form) in which λ, ρ and c may vary with position as follows:

$$\nabla . (\lambda \nabla T) = \rho c \frac{\delta T}{\delta t} \qquad (E - 3)$$

It is also necessary to consider heat storage in air masses contained within the building. The model of this process is:

$$Q = c_p \rho_a V \frac{\delta T_a}{\delta t} \qquad (E - 4)$$

where Q is the net heat flow into the air mass (W), c_p is the specific heat capacity of air at constant pressure (J/kgK), ρ_a is the air density (kg/m^3), V is the air volume (m^3) and T_a is the air temperature (°C).

In ApacheSim, conduction in each building element (wall, roof, ceiling, etc.) is assumed to be uni-dimensional. Furthermore, the thermo-physical properties (λ, ρ and c) of each layer of the element are assumed to be uniform within the layer. As a result, Equation (E - 3) may be written as shown in Equation (E - 5) as follows:

$$\frac{\delta^2 T}{\delta x^2} = \frac{\rho c}{\lambda}\frac{\delta T}{\delta t} \qquad (E-5)$$

The system of equations is closed by the application of boundary conditions and the stipulations that W is continuous ar the layer boundary.

Air gaps in both opaque and transparent constructions are modelled as pure resistances using Equation (E - 6).

$$W = \frac{(T_1 - T_2)}{R} \qquad (E-6)$$

where W is the heat flow across the gap, T_1 and T_2 are the temperatures at the air gap and R is the combined radiative/convective resistance of the air gap. The value of R is set as a parameter of the air gap layer.

The boundary conditions for conductive elements of the building ditated by conditions in the spaces either side of the element. These spaces may be internal or external. Where an adjacent room has been rendered inactive, the conditions on the far side are assumed to be identical to those on the rear side. In this way, the thermal mass of the element is taken into account, while the time-averaged heat transfer through it tends to zero.

The effect of heat storage in the furniture may be incorporated into the analysis. A facility is offered for modelling furniture on the assumption that its temperature closely follow that of the air. Under this assumption, its effect is to increase the effective thermal mass of the air by a factor, which is termed the furniture mass factor (f_f). In this case, Equation (E - 4) becomes:

$$Q = (1 + f_f)c_p\rho_a V\frac{dT_a}{dt} \qquad (E-7)$$

2. Convection Heat Transfer

Convection is the transfer of heat resulting from the flow of fluid over a surface. In this case, the fluid is air and the surface is an element of the building. If the convective air flow is driven by external forces (for example, wind or mechanical ventilation) it is referred to as forced convection. The term *"natural convection"* describes convection arising from buoyancy. It has been found, by experiment, that convective heat transfer can be accurately described by equations of the form:

$$w = K(T_a - T_s)^n \qquad (E - 8)$$

where W is the heat flux (W/m^2) from the air to the surface, T_a is the bulk air temperature (°C), T_s is the mean surface temperature (°C) and K and n are coefficients. For forced convection at sufficiently high air velocities, it is found that, to a good approximation, n = 1 and the process is thus linear.

For natural convection, although n is usually somewhat greater than 1, its value is often sufficiently close to 1 for the aproximation:

$$W = h_c (T_a - T_s) \qquad (E - 9)$$

where h_c is the convective heat transfer coefficient.

Convection occurrring at the external surfaces of the building is predominantly wind-driven forced convection. In ApacheSim, external forced convection is modelled with a wind speed dependent convective heat transfer coefficient as follows:

$$h_c = 5.6 + 4.0v \text{ for } v < 4.88 \qquad (E - 10)$$

$$h_c = 7.2v^{0.78} \text{ for } v \geq 4.88 \qquad (E - 11)$$

where v is the wind speed (m/s) read from the simulation weather file.

Interior convection can be modelled using one of four different options as follows:

- CIBSE Fixed Convection Coefficients

The CIBSE *"simple model"* for heat loss and heat gain calculations are based on a constant convection coefficient for internal surfaces of $h_c = 3.0$.

- CIBSE Variable Convection Coefficients

CIBSE Guide Volume C provides a procedure for calculating convection coefficients as functions of surface orientations, air-surface temperature difference ad mean room air velocity. Since these coefficients are dependent on air-surface temperature differences and other dynamically varying simulation variables they must be applied as part of an iterative calculation procedure. The convection coefficient is expressed as:

$$h_c = fC\Delta T^{n-1} \qquad (E - 12)$$

where $\Delta T = |T_a - T_s|$, C is a coefficient depending on surface orientation depending on mean air speed and n is an exponent (as in Equation (E - 1)). Values for C, n and f are taken from CIBSE Guide C Tables C3, 12 and C3, 13.

- Alamdari and Hammond Convection Coefficients

Alamdari and Hammond established, by empirical means, a procedure for calculating convection coefficients for internal surfaces. As they vary with temperature difference, these coefficients must be applied within an iterative calculation procedure. For vertical surfaces and horizontal surfaces for which the convective heat flow is upward, the Alamdari and Hammond expression is

$$h_c = \left[\left\{\alpha\left(\frac{\Delta T}{L}\right)^{\frac{1}{4}}\right\}^6 + \left\{b\Delta T^{\frac{1}{3}}\right\}^6\right]^{\frac{1}{6}} \qquad (E - 13)$$

where $\Delta T = |T_a - T_s|$, L is the characteristic length of the surface and a and b are coefficients.

- User-specified Fixed Convection Coefficient.

3. Heat Transfer by Air Movement

ApacheSim models the following types of air movement:

- Pre-specified air-exchanges. classified as infiltration, natural ventilation of mechanical ventilation.

- Air flows calculated by MacroFlo. MacroFlo calculates natural ventilation air flows arising from wind and stack pressure (buoyancy) as well as the flow imbalances generated by HVAC systems.
- Air flows specified or calculated by ApacheHVAC.

The rate of heat tranfer associated with a stream of air entering a space is specified in Equation (E - 14).

$$Q = mc_p(T_i - T_a) \qquad (E - 14)$$

where m is the air mass flow rate (kg/s), c_p is the specific heat capacity of air at constant pressure (J/kg/K), T is the supply temperature if the air (°C), and T_a is the room mean air temperature in the room (°C).

Equation (E - 14) assumes that the air displaced by the supple air is at the room mean air temperature, which is consistent with ApacheSim's stirred tank model of the room air.

4. Long-wave Radiation Heat Transfer

Building surfaces emit thermal radiation by virtue of their absolute temperature. For small surface element (dA) of a Lambertan emitter, the radiation flux emitted into a small solid angle (dω) lying in a direction making an angle θ to the surface normal is

$$dW = \frac{1}{\pi}\varepsilon\sigma\Theta^4 \cos\theta \, d\omega dA \qquad (E - 15)$$

where dW is the radiation flux (w/m^2), ε is the surface emissivity (W/m^2), σ is the Stefan Boltzman constant ($5.6696x10^{-8}W/m^2K^4$), Θ is the absolute temperature of the surface (K), θ is the direction angle measured from the surface normal, dω is an element of solid angle and dA is an element of surface area (m^2).

Integrated over solid angle, the total radiation emitted by a plane surface of area A is shown in Equation (E - 16):

$$W = \varepsilon A\sigma\Theta^4 \qquad (E - 16)$$

A variety of mean radiant temperature models have been proposed. In all such models the net radiant exchange between a surface and the rest of the enclosure is modelled with an equation of the form

$$W = h_f(T_s - T_{MRT}) \qquad (E\text{-}17)$$

where W is the net radiative loss from the surface, h_r is the surface heat transfer coefficient for exchange with the mean radiant temperature (MRT) node, T_s is the surface temperature and T_{MRT} is the MRT of the enclosure.

The various mean temperature models differ by small amounts in the values assigned to this coefficient. ApacheSim adopts the CIBSE mean radiant temperature model, which provides a good representation of radiant exchange where it can be assumed that the emissivities of the surfaces bounding the enclosure do not differ greatly from one another, which is almost always the case.

In the case of holes (openings) between spaces, the holes are treated as highly conductive surfaces with solar transmittance 1 and emissivity 1. The temperature of such a surface will equilibriate at a value near the MRT of its surroundings. This temperature will then, in turn, form part of the MRT calculations for the adjacent spaces.

Exterior building surfaces receive long-wave ratiation from the sky, the ground and other objects in the environment and also emit thermal radiation. The difference between radiation emitted and radiation absorbed constitutes the net long-wave gain. The model adopted by ApacheSim for the treatment of exterior long-wave radiation is specified by CIBSE Guide A as follows:

$$L^*(\beta) = \varepsilon_e\left[L_{sky}(\beta) + L_g(\beta) - \sigma\Theta_e^4\right] \qquad (E\text{-}18)$$

where $L^*(\beta)$ is the net long-wave radiation gain (W/m^2), ε_e is the emissivity of the external surface, $L_{sky}(\beta)$ is the long-wave radiation received directly from the sky (W/m^2), $L_g(\beta)$ is the long-wave radiation received from the ground (W/m^2) and Θ_e is the absolute temperature of the external surface (K).

5. Solar Radiation

ApacheSim is driven by actual weather recorded at hourly intervals and stored on a simulation weather file. The variables relating to solar radiation are direct solar radiation measures perpendicular to the beam (W/m^2), diffuse solar radiation measured on the horizontal plane (W/m^2) and solar altitude and azimuth.

The solar altitude and azimuth are calculated from the location of the site where the weather was recorded, and summertime clock adjustment information. This information is also used by the Suncast and Suncast Lite programmes to generate shading data for ApacheSim.

The components of incident flux are the direct solar flux and the diffuse solar flux. The direct solar flux (I_{dir}) is obtained using Equation (E - 19) while the diffuse solar flux has components radiated from the sky (I_{sdiff}) and the ground ($I_{g,diff}$) and are calculated using Equations (E - 20) and (E - 21).

$$I_{dir} = I_{beam}\cos(\theta) \qquad (E - 19)$$

where I_{dir} is the direct solar flux (W/m^2) incident on the surface, I_{beam} is the solar flux measured perpendicular to the beam and θ is the angle of incidence.

$$I_{sdiff} = I_{hdiff}\cos^2(\frac{\beta}{2}) \qquad (E - 20)$$

$$I_{gdiff} = \rho_g I_{hdiff}\sin^2(\frac{\beta}{2}) \qquad (E - 21)$$

where I_{sdiff} is the diffuse sky solar flux (W/m^2) incident on the surface, I_{hdiff} is the diffuse sky solar flux (W/m^2) on the horizontal plane, β is the diffuse ground solar flux (W/m^2) incident on the surface, ρ_s is the solar reflectance (albedo) of the ground and

$$I_{hglob} = I_{hdiff} + I_{beam}\sin\alpha \qquad (E - 22)$$

where α is the solar altitude.

This analysis covers the case where the sky diffuse radiation is assumed to be isotropic, the factors involving β arising from integration of this isotropic radiation over solid angle. If the user selects the anisotropic diffuse radiation model from the Simulation Opions menu, the calculation designates a portion of the diffuse radiation circumsolar, which it treats as if it

emanated from the sun position. The purpose of the diffuse radiation designated circumsolar varies with the intensity of the beam radiation, according to a variant of the method proposed by hay with adjustments applied for diffuse shading.

6. Casual Gains

Casula gains to rooms are specified in the Thermal View of the Virtual Environment. They are classified, for convenience, according to type as follows: fluorescent lighting, tungsten lighting, machinery, miscellaneous, cooking, computers and people.

Gains have, in general, both sensible and latent heat components. Each component of the gain is specified as a maximum value, modulated by a percentage profile. Sensible gains add sensible heat to the room (or remove it, if negative). A portion of this heat, dictated by the radiant fraction, is in the form of thermal radiation and the remainder , i.e. the convective portion, is input to the room air. The radiant portion is allocated to the room surfaces on an area-weighted basis.

Latent gains add water vapour ot the room air. All gains are expressed in terms of an energy input, the conversion factor between latent gain and water vapout addition being the latent heat of vaporisation of water.

7. Thermo-physical Properties of Air

The modelling of psychrometric processes in ApacheSim requires a set of calculation procedures for converting between such quantities as dry-bulb temperature, wet-bulb temperature, dew-point temperature, relative humidity, perventage saturation, humidity ratio, water vapour pressure, enthalpy, air density and atmospheric pressure.

For these conversions, ApacheSim uses the procedures published by Hyland et al. (1984).

The storage of water vapour in the room air mass is represented by Equation (E - 23)

$$w_a = \rho_a \frac{dg}{dt} \qquad (E - 23)$$

where ρ_a is the air density (kg/m^3), w_a is the net water vapour gain to the air (kg/s) and g is the room humidity ratio (kg/kg).

Appendix E: Thermal properties of materials used to model the Old Library as specified by CIBSE Guide A3 (Anderson, 2006)

Material	Density (kg/m^3)	Thermal Conductivity (W/mK)	Specific Heat Capacity (J/kgK)
Granite	2880	3.49	840
Limestone	2180	1.5	720
Slate	1600	1.44	1470
Rubble	1600	0.7	840
Masonry	1850	0.9	840
Concrete (cast)	2000	1.3	840
Concrete (l'weight)	870	0.25	840
Oak	720	0.16	1260
Plasterboard	950	0.16	840
Plaster (perlite)	720	0.22	1340
Books	350	0.05	1400
Acoustic Tile	290	0.057	1340
PVC	1380	0.16	1000
Roof Felt	960	0.19	840
Synthetic Carpet	160	0.06	2500
Glass wool	12	0.04	840

Appendix F: Specification of the materials for each of the primary structural elements in the Old Library from inside the building to the outside.

Element	**Materials**
Long Room External Wall	Oak
	Cavity
	Limestone
	Rubble
	Limestone
Shop and Exhibition Space External Wall	Granite
	Rubble
	Granite
Strong Room External Wall	Perlite Plaster
	Plasterboard
	Concrete
	Masonry
	Rubble
	Granite
Colonnades External Wall	Perlite Plaster
	Plasterboard
	EPS Slab
	Masonry
	Rubble
	Granite
Book Shelves	Books
	Cavity
	Oak
	Cavity
	Oak
	Cavity
	Books
Thick Internal East Pavillion Walls	Perlite Plaster
	Masonry
	Rubble
	Granite
	Plasterboard
	Perlite Plaster
Thick Internal Long Room Walls	Oak Panels

	Cavity
	Masonry
	Rubble
	Limestone
	Plasterboard
	Perlite Plaster
Long Room Roof	Oak
	Cavity
	Glass Fibre Insulation
	Felt/Bitumen Layers
	Slate
East Pavillion Roof	Perlite Plaster
	Plasterboard
	Insulation
	Cavity
	Felt/Bitumen Layers
	Slate
West Pavillion Roof	Perlite Plaster
	Plasterboard
	Cast Concrete
	Cavity
	Felt/Bitumen Layers
	Slate
Exposed Ground Floor Slab	Linoleum
	Cast Concrete
	GLASS-FIBRE SLAB
	London Clay
Long Room Floor	Perlite Plaster
	Plasterboard
	Glass Wool
	Oak
	PVC
Strong Room Ceiling	Perlite Plaster
	Concrete
	Synthetic Carpet
West Pavillion 2nd Floor Floor	Acoustic Tile
	Cavity

	Concrete
	Synthetic Carpet
East Pavillion Reading Room Floor	Perlite Plaster
	Plasterboard
	Glass Wool
	Cavity
	Oak
	Synthetic Carpet

December	9.30-10am	10-11am	11-12am	12-1pm	1-2pm	2-3pm	3-4pm	4-5pm
8th	0.036161335	0.087621697	0.125173853	0.069541029	0.061196106	0.089012517	0.063977747	0.033379694
9th	0.015299026	0.179415855	0.159944367	0.121001391	0.052851182	0.159944367	0.0945758	0.052851182
10th	0.029207232	0.121001391	0.157162726	0.127955494	0.105702364	0.186369958	0.090403338	0.04867872
11th	0.044506259	0.205841446	0.26147427	0.242002782	0.161335188	0.146036161	0.144645341	0.086230876
12th	0	0	0	0.201668985	0.101529903	0.0945758	0.146036161	0.006954103
13th	0	0.065368567	0.109874826	0.059805285	0.079276773	0.075104312	0.040333797	0.018080668
14th	0.004172462	0.058414465	0.076495132	0.033379694	0.045897079	0.077885953	0.045897079	0.026425591
15th	0.006954103	0.022253129	0.043115438	0.080667594	0.061196106	0.033379694	0.037552156	0.027816412
16th	0	0.027816412	0.091794159	0.075104312	0.098748261	0.036161335	0.02364395	0
17th	0.016689847	0.098748261	0.146036161	0.068150209	0.076495132	0.058414465	0.07093185	0.019471488
18th	0.031988873	0.146036161	0.211404729	0.134909597	0.123783032	0.090403338	0.101529903	0.038942976
19th	0	0	0	0.235048679	0.116828929	0.107093185	0.066759388	0.011126565
20th	0.013908206	0.100139082	0.105702364	0.11961057	0.087621697	0.083449235	0.147426982	0.038942976
21st	0.015299026	0.051460362	0.073713491	0.058414465	0.045897079	0.079276773	0.013908206	0
22nd	0.002781641	0.057023644	0.041724618	0.076495132	0.063977747	0.043115438	0.045897079	0.006954103
23rd	0.006954103	0.036161335	0.027816412	0.065368567	0.051460362	0.045897079	0.057023644	0.015299026
January								
4th	0.154381085	0.226703755	0.271210014	0.280945758	0.223922114	0.23922114	0.187760779	0.061196106
5th	0.062586926	0.101529903	0.140472879	0.152990264	0.115438108	0.115438108	0.122392211	0.054242003
6th	0.034770515	0.097357441	0.144645341	0.144645341	0.144645341	0.100139082	0.115438108	0.07093185
7th	0.011126565	0.159944367	0.173852573	0.127955494	0.169680111	0.180806676	0.140472879	0.086230876

July	9.30-10am	10-11am	11-12am	12-1pm	1-2pm	2-3pm	3-4pm	4-5pm
1st	0.344923505	0.564673157	0.570236439	0.449235049	0.339360223	0.350486787	0.511821975	0.197496523
2nd	0.414464534	0.589707928	0.489568846	0.456189152	0.389429764	0.559109875	0.410292072	0.230876217
3rd	0.183588317	0.435326843	0.570236439	0.317107093	0.225312935	0.344923505	0.744089013	0.114047288
4th	0.30876217	0.510431154	0.603616134	0.363004172	0.279554937	0.35744089	0.339360223	0.176634214
5th	0.337969402	0.353268428	0.456189152	0.337969402	0.21418637	0.191933241	0.385257302	0.297635605
6th	0.244784423	0.429763561	0.360222531	0.242002782	0.335187761	0.463143255	0.426981919	0.418636996
7th	0.421418637	0.574408901	0.470097357	0.358831711	0.283727399	0.397774687	0.379694019	0.23783032
8th	0.467315716	0.488178025	0.673157163	0.368567455	0.337969402	0.342141864	0.54659249	0.351877608
9th	0.414464534	0.467315716	0.436717663	0.414464534	0.276773296	0.397774687	0.386648122	0.368567455
10th	0.319888734	0.376912378	0.827538248	0.233657858	0.203059805	0.282336579	0.589707928	0.041724618
11th	0.42837274	0.463143255	0.628650904	0.337969402	0.339360223	0.585535466	0.375521558	0.215577191
12th	0.289290682	0.45340751	0.646731572	0.339360223	0.331015299	0.582753825	0.454798331	0.559109875
13th	0.346314325	0.545201669	0.620305981	0.363004172	0.329624478	0.579972184	0.33240612	0.321279555
14th	0.326842837	0.520166898	0.73852573	0.52294854	0.361613352	0.589707928	0.442280946	0.28511822
15th	0.290681502	0.559109875	0.559109875	0.367176634	0.40472879	0.560500695	0.389429764	0.290681502
16th	0.611961057	0.379694019	0.696801113	0.365785814	0.289290682	0.35744089	0.445062587	0.344923505
17th	0.26147427	0.443671766	1	0.354659249	0.311543811	0.470097357	0.663421419	0.235048679
18th	0.536856745	0.374130737	0.731571627	0.457579972	0.485396384	0.592489569	0.504867872	0.433936022
19th	0.443671766	0.481223922	0.617524339	0.450625869	0.375521558	0.482614743	0.374130737	0.346314325
20th	0.251738526	0.752433936	0.532684284	0.319888734	0.414464534	0.641168289	0.371349096	0.147426982
21st	0.596662031	0.485396384	0.518776078	0.436717663	0.374130737	0.376912378	0.344923505	0.21418637
22nd	0.433936022	0.445062587	0.706536857	0.399165508	0.343532684	0.472878999	0.367176634	0.684283727
23rd	0.414464534	0.648122392	0.54798331	0.367176634	0.376912378	0.379694019	0.401947149	0.376912378
24th	0.371349096	0.682892907	0.653685675	0.414464534	0.31015299	0.566063978	0.489568846	0.201668985
25th	0.447844228	0.591098748	0.486787204	0.325452017	0.251738526	0.445062587	0.489568846	0.421418637
26th	0.372739917	0.479833102	0.552155772	0.478442281	0.324061196	0.593880389	0.275382476	0.347705146

Appendix H: RH changes associated with the implementation of Strategy 4 in the Old Library

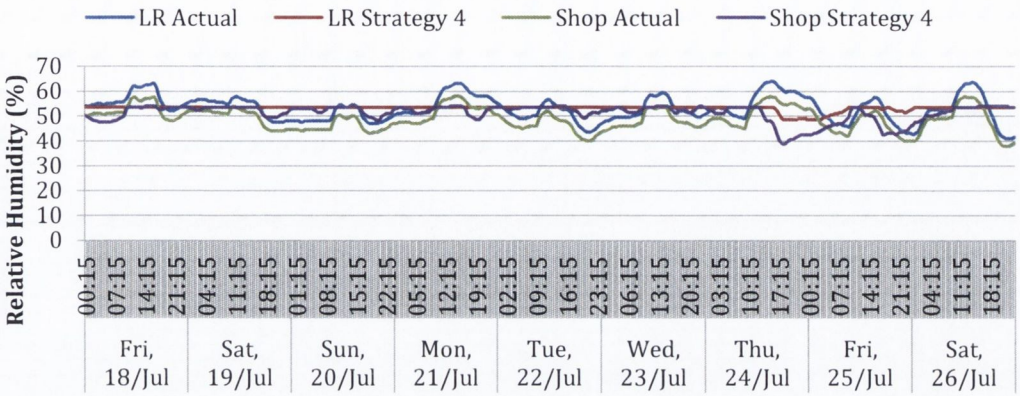


Fig. H- 1:Relative Humidity trends due to the implementation of Strategy 4in summer

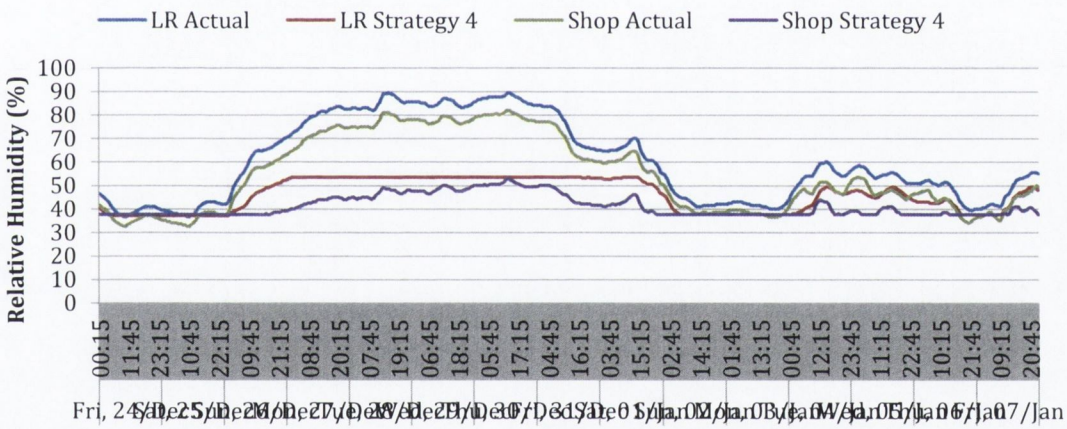


Fig. H- 2: Relative humidity associated with the implementation of Strategy 4 in winter

HAMBase consists of a number of different m-files that have been generated using the MatLab software package. The general structure of these files are presented in Fig. I - 1.

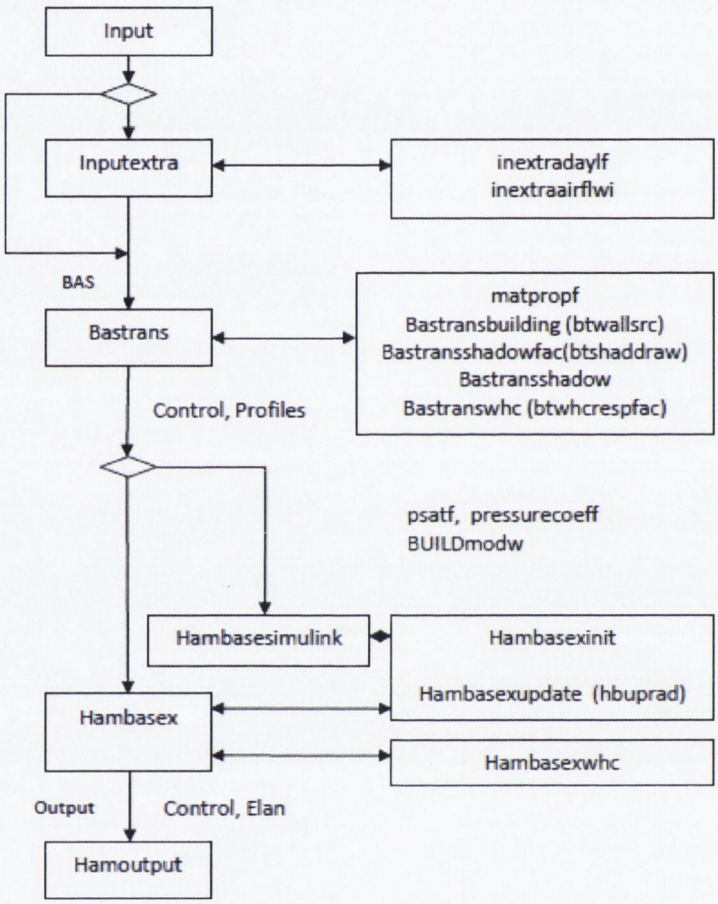


Fig. I - 1: General Structure of the m-files associated with the HAMBase computer package.

Each of these m-files is used for calculation purposes in HAMBase as follows (de Wit, 2006):

- Input: This is the standard input file of HAMBase with data for the building construction and orientation, the plant installation and the external environmental conditions.
- Inputextra: This file allows for the default values with regards advanced options and the more complex functions behind the calculations can be altered. The input is stored in a structured array BAS.
- Bastrans: This m-file allows for the BAS input to be checked for missing or incorrect data and generates warning and error messages. Moreover the files are transformed (e.g. arrays are renumbered to make them smaller) and stored in five different

structured arrays: Meteo (weather data for the calculation period), Building (data regarding the building), Elan (data regarding the thermal and hygric electric network model), Control (all controls) and Profiles (the use of the building).

  - In matpropf, material properties are stored.
  - In Bastrasbuilding and btwallsrc, the transfer coefficients and components of the electrical network are calculated.
  - Bastransshadowfac calculates the shadowed fraction of a window for the sunshine coming from each small element of the discretized sky and this can be plotted visually using brshaddraw.
  - Bastransshadow combines the shadow factors with the dependence of glazing transmittance on the incident angle of the radiations.
  - Bastranwhc and btwhcrepfac calculates the transfer function coefficients for wall heating.

- Hambasex: The output is calculated with Hambasex using Hambasexinit and Hambasexupdate, hbuprad (solar radiation calculation) and Hambasexwhc (for wall heating). This zone equations are solved with an hourly timestep.
- Hamoutput: In this m-file, the files Output, Control and Elan are used to generate plots.
- Hambasesimulink: If Simulink is used the clear all command and the removal of the figures at the beginning of the input cannot be used. The zone equations are solved by Simulink so Hambasex is not needed. Insteat the S-function Hambasesimulink is needed. Wall heating is currently not considered in the Simulink calculation process so only Hambaseexinit, Hambasexupdate and hbuprad are used.

The number of zones that can be generated using HAMBase is currently not limited but grouping of rooms with similar indoor climates into one zone is recommended to save time without an unacceptable loss of accuracy.

Appendix J: HAMBase code used to model the Long Room

```
%STARTEXAMPLE1
% ------------------------------------------------------------------------
%             HAMBASE
%
% HEAT And Moisture Building And Systems Evaluation
% ------------------------------------------------------------------------
% BUILDINGref
%
% Example input file to specify the building, profiles, systems are off
% The name of this m-file can be changed at wish.
% feb 2009

clear all
close all

% ------------------------------------------------------------------------------
%  PART 1 : THE CALCULATION PERIOD
% ------------------------------------------------------------------------

% FORMAT BAS.Period=[yr,month,day,ndays]
% yr        = start year
% month     = start
% month day = start day
% ndays     = number of days simulated

%BAS.Period=[1976,1,1,90,1];
BAS.Period=[2020,1,21,5];

BAS.station = [53.2, 6.15, -1, 0.2]; %Coordinates of the Long Room

% If BAS.DSTime=1 the EU daylight-savings time is taken into account. It starts on the
% last Sunday of March and ends on the the last Sunday of October (the total
% duration is 30 or 31 weeks). If there is no daylight-savings period BAS.DSTime=0
% If the daylight-savings period is different from the EU the starting and ending days
% must be given:
% BAS.DSTime(1,:)=[year,starting month,day,ending month,day];
% BAS.DSTime(2,:)=[year+1,starting month,day,ending month,day]; etc.

%BAS.DSTime(1,:)=[1987,4,28,4,29];
%BAS.DSTime(2,:)=[1988,4,3,4,3];
BAS.DSTime=1;

% ------------------------------------------------------------------------ ---
% PART 2 : THE BUILDING
% ------------------------------------------------------------------------ ---

%   ZONES NUMBERS [-] & VOLUMES [m3]
%
% A zone consist of a room or several adjacent rooms with oubout the same
% temperature and relative humidity and the same climate control e.g. a dwelling
% might have three zones: the ground floor (living room etc), the first floor
% (sleeping) and the attic (not heated). There is however no restriction in the
% number of zones that can be simulated. Example: three zones: BAS.Vol{1}=..;
% BAS.Vol{2}=..; BAS.Vol{3}=.. If alone 2: use '%' for 1 and 3 so only
% BAS.Vol{2} remains.
%
% FORMAT BAS.Vol{zonenumber}=volume (m3);
BAS.Vol{1}= 7128;
%BAS.Vol{2}= 3168;

% ** CONSTRUCTION COMPONENTS DATA **
%
% A construction component usually consists of different layers. The order of
% the input of the properties of these layers is standard from indoors to
% outdoors and for construction components between zones from the zone with the
% lowest zone-number to the highest so: 1->2,1->3,2->3etc..  The material
% properties of the component layer are inserted by a material ID-number. By
% typing 'help matpropf' a list of materials appear with a material ID-number.
```

```
% Also each different construction component gets a different construction
% ID-number: conID=1,2,....
%
% FORMAT BAS.Con{conID}=[Ri,dl,matID,...,dn,matID,Re,ab,eb].
% dn    = material layer thickness [m]
% matn = material ID-number.
% Ri = internal surface heat transfer resistance (for example Ri=0.13) [Km2/W]
% Re = surface heat transfer resistance at the opposite site (for example Re=0.04)
[Km2/W]
% ab = external solar radiation absorption coefficient [-] e.g.light ab=0.4, dark
ab=0.9.
% eb = external longwave emmisivity [-]. Almost always: eb=0.9

% BAS.Con{conID}=[Ri,  dl,matID,...        ,                                dn,matID,
Re,   ab,   eb].
%NEED TO CHECK ALL SURFACE RESISTANCES!!!!!!!!!!!!
BAS.Con{1} =  [0.13,    0.012,501,  0.005,001,  0.225,201,  0.75,205, 0.35, 201,
0.04,   0.9,    0.9]; %LR External Wall
BAS.Con{2} =  [0.13,    0.35,206,   0.3,205,    0.35,206,
0.13,   0.5,    0.9]; %Shop External Wall
BAS.Con{3} =  [0.13,    0.012, 367, 0.012, 387, 0.2, 342, 0.225, 239, 0.45, 205, 0.35,
206,                                                    0.13,   0.5,    0.9];
%Strong Room External Wall
BAS.Con{4} =  [0.13,    0.012, 367, 0.012, 387, 0.1, 453, 0.225, 239. 0.45, 205, 0.35,
206,                                    0.13,   0.5,    0.9]; %Colonnades
External Wall
BAS.Con{5} =  [0.13,    0.012, 367, 0.225, 239, 0.45, 205, 0.35, 206, 0.012, 387,
0.012, 367,               0.04,   0.9,    0.9]; %Thick Internal East Pav Walls
BAS.Con{6} =  [0.13,    0.012, 501, 0.05, 1, 0.225, 239, 0.45, 205, 0.35, 201, 0.012,
387, 0.012, 367,  0.04,   0.8,    0.9]; %Thick Internal Long room Walls
BAS.Con{7} =  [0.13,    .3, 504, 0.200,312,     0.080,456,  0.050,312,  0.3, 504,
1,      0.9,    0.9]; %Book Shelves
BAS.Con{8} =  [0.13,    0.002, 541, 0.5, 342, 0.2, 453, 0.75, 646,              1,
0.9,    0.9]; %Ground Floor Slab
BAS.Con{9} =  [0.17,    0.002, 601, 0.025, 501, 0.25, 1, 0.05, 403, 0.012, 387,
0.012,367,              0.1,    0.6,    0.9]; %LR Floor
BAS.Con{10}=  [0.17,    0.002, 562, 0.025, 501, 0.25, 1, 0.05, 403, 0.012, 387, 0.012,
367,                            0.1,    0.6,    0.9]; %East Pav Reading Room Floor
BAS.Con{11}=  [0.13,    0.125, 342, 0.01, 562,
0.04,   0.8,    0.9]; %West Pav 2nd Floor
BAS.Con{12}=  [0.13,    0.012, 367, 0.25, 342, 0.01, 562,
0.13,   0.6,    0.9]; %Strong Room Ceiling
BAS.Con{13}=  [0.17,    0.012, 501, 2.5, 1, 0.05, 403, 0.002, 625, 0.008, 639,
0.1,    0.6,    0.9]; %Long Room Roof
%BAS.Con{14}=  [0.13,   0.012, 367, 0.012, 387, 0.05, 403, 1.5, 1, 0.002, 625, 0.008,
639,                                                            0.04,   0.8,
0.9]; %East Pav Roof
%BAS.Con{15}=  [0.13,   0.012, 367, 0.012, 387, 0.2, 342, 1.5, 1, 0.002, 625, 0.008,
639                                                     0.13,   0.6,    0.9]; %West
Pav Roof
% Commments
% 1:  limestone,insulation,air gap,brick (external wall)
% 2:  plaster,insulation,plaster (internal wall)
% 3:  light concrete (internal wall, not used in this example)
% 4:  tiles, limestone (internal wall, not used in this example)
% 5:  limestone, insulation, air gap, hard brick (external wall)
% 6:  roof construction
% 7:  floor construction
% 8:  floor construction
% 9:  plaster, system floor, air gap, medium hardboard (floor between zones)
% 10: floor between zones
% 11: exterior door
% 12: interior door

% ** GLAZING SYSTEMS DATA**
%
% The solar gain factor of glazing depends on the incident angle of the solar
% radiation. The properties below are independent of this angle but if one wants
% to account for the incident angle this can be done with the shadow section
% (below). Each different glazing system gets an ID-number: glaID=1,2,.
%
% FORMAT BAS.Glas{glaID}=[Uglas,CFr,ZTA,ZTAw,CFrw,Uglasw]
%
% Uglas = U-value without sunblinds  [W/m2K]
% CFr   = convection factor without blinds [-]
% ZTA   = Solar gain factor [-] without blinds
```

```
% ZTAw  = Solar gain factor [-] with blinds
% CFrw  = convection factor with blinds [-]
% Uglasw = U-value with blinds  [W/m2K]
%
%BAS.Glas{glaID}=[Uglas,    CFr,        ZTA,        ZTAw,       CFrw,   Uglasw]
BAS.Glas{1}=        [5.7,       0.01,       0.0,        0.0,        0.34,       3.2
];
% Glazing 1  single glazing with interior sunblinds

% ** ORIENTATIONS **
%
% For each surface of the building envelope (exterior walls) the tilt and the
% orientation with respect to the south has to be known. Each different
% orientation gets a different orientation-ID-numbernumber: orID.
%
% FORMAT  BAS.Or{orID}=[beta gamma]
% beta  = tilt (vertical=90,horizontal=0)
% gamma = azimuth (east=-90, west=90, south=0, north=180)
%
%BAS.Or{orID}=[beta,    gamma];
BAS.Or{1}= [90.0,       180 ]; %north wall
BAS.Or{2}= [90.0,       90  ]; %west wall
BAS.Or{3}= [90.0,       -90 ]; %east wall
BAS.Or{4}= [90.0,       0.0 ];      % south wall
BAS.Or{5}= [0.0,        0.0 ];      % horizontal roof

% **SHADOWING DATA**
%
% For each vertical window the shadow by exterior obstacles can be accounted
% for. The obstacles can have any combination of blocks, cylinders and spheres,
% provided some limitations regarding the positioning: The position of the
% blocks is such that two planes are horizontal, two vertical and perpendicular
% to the window pane and two parallel. The axis of the cylinder must be
% vertical. E.g. a tree is a cylinder and a sphere. If two equal windows with
% the same orientation and zone have a different shadow they cannot be added to
% one window (with the sum of the surface areas) anymore. Each shadow situation
% gets a shadow ID-number:shaID.
%
% FORMAT BAS.shad{shaID}= [
% typenr, size1, size2, size3, x, y, z, extra;
% ......,......,......,......,..,..,..,......;
% typenr, size1, size2, size3, x, y, z, extra;
% typenr, size1, size2, size3, x, y, z, extra;]
%
% x,y,z are Cartesian coordinates where z is vertical and x is horizontal and
% perpendicular to the window plane. Left means left when facing the window from
% outside. The sizes are always positive numbers.
%
% typenr=1 (window):size1=depth (=distance glazing to exterior surface), size2=
%   width, size3=height of the window
%   [x,y,z] = the coordinates of the lowest window corner at the left side
%   extra   = elevation-angle of the horizon in degrees to account for far-away
%   obstacles.
% typenr=2 (block):size1= width(in x-direction),size2=length(in y-direction),
%   size3=height(in z-direction)
%   x,y,z] coordinates of the left block corner closest to the window
%   extra= solar transmission
%   factor (0 opaque)
% typenr=3 (tree):size1=radius crown,size2=radius trunk (e.g.1/20*radius crown),
%   size3=height center of crown
%   [x,y,z]: coordinates of the bottom of trunk.
%   extra=solar transmission factor of crown (0 opaque). In winter(120<iday< 304)
%   this is higher than in summer. e.g. winter extra=0.8, summer extra=0.35
% typenr =4 input for incident angle dependency of transmittivity of glazing.
%   Perpendicular (angle=0) always 1 and for 90 degrees (parallel) always 0. So
%   there is no need for an input for these angles! First row [4, incident
%   angle1,..,incident angle7], second row [5, transmittivity1,..,transmittivity7]
%
% Example input
%
BAS.shad{1}=[
    1  0.07     5        1.6          0        0.5000         0.7   3;...
       2  0.1      5.1      3.0000       17.00    0.0000         0     0;...
       2  17.00    0.1      3.0000       0        5.1000         0     0;...
       2 17.00     0.1      2.0000       0        0.0000         0     0;...
       2  0.5      24.00    9.2000       34.10   -9.0000         0     0;...
```

```
        3  1.25     1.25/7   2.75          15.50    0.0            0     0;...
        3  1.50     1.50/7   1.50          12.70    1.50           0     0;...
        4 0 10 20 30  50 60 90;...
        5 1 0.9 0.8 0.7 0.6 0.5 0.4];

BAS.shad{2}=[
    4 20       30          40         50           60       70       80      ;...
        5 787/789 784/789 775/789 754/789   700/789     563/789 302/789];

% Changing below '0' into '1' below, gives a drawing of the
% obstacle geometry for ShaID.
if 1==0
    shaID=1;
    figure(1)
    shaddrawfl101(BAS.shad,shaID);
end

% ------------------------------------------------------------------------
% A building is an assembly of different construction components. The input here
% is about the size, place in the building and ID of these different components
% (for convenience called walls and windows i.e. also if doors, floors or roofs are
meant).
% They are divided into 5 groups:
% I.   Constructions separating a zone from the exterior climate: EXTERNAL WALLS
% II.  Windows in external walls I
% III. Constructions separating a zone from an environment with a constant
%   temperature e.g. the ground: CONSTANT TEMPERATURE WALLS
% IV.  Constructions separating a zone from an environment with the same
%   conditions: ADIABATIC EXTERNAL WALLS
% V.   Constructions between and in zones: INTERNAL WALLS
% For external walls and constant temperature walls the heat loss by thermal
% bridges can be accounted for if the extra steady state heat loss in Watt per 1K
% temperature difference across these bridges is known. These values can be
% obtained by thermal bridge software or a approximate methods. Use '0' if not
% known.
% ------------------------------------------------------------------------

% I. EXTERNAL WALLS
%
% For each wall ID-number exID=1,2,...
%
% FORMAT BAS.wallex{exID} = [zonenr,surf,conID,orID,bridge];
% zonenr    = select zone number from ZONES section
% surf      = total surface area[m2] including the windows surface area.
% conID = select construction ID-number from CONSTRUCTION section.
% orID  = select orientation ID-number from ORIENTATIONS section
% bridge= the heat loss in W/K of the thermal bridges (choose 0 if unknown)

%BAS.wallex{exID}=  [zonenr, surf, conID,   orID,   bridge]
BAS.wallex{1} =         [1,      594.0,    1,           1,     0]; %LR North
BAS.wallex{2} =         [1,      594.0,    1,           4,     0]; %LR South
BAS.wallex{3} =         [1,      792.0,    13,          5,     0]; %LR Roof
BAS.wallex{4} =         [2,      264.0,    2,           1,     0]; %GF North
BAS.wallex{5} =         [2,      264.0,    2,           4,     0]; %GF South
BAS.wallex{6} =         [2,      792.0,    8,           5,     0]; %GF Slab

% II. WINDOWS IN EXTERNAL WALLS
%
% Each external wall can have one or more windows. The surface area is the area
% of the transparent part. If the surface is curved the effective area for solar
% radiation is needed. The U-value must be increased in such a way that the
% heat loss per 1K temperature difference equals the one for the curved glazing,
% e.g. a glazed dome in a flat roof has an orientation with tilt=0, surface
% area=pi*r^2 and U-value=Uglazing*2*pi*r^2/pi*r^2.
% If a wall has 100% glazing use an EXTERNAL WALL that is slightly larger than
% the window area. Each window gets an ID-number winID=1,2,...
%
% FORMAT window{winID} = [exID, surf,glaID, shaID];
% exID  = select external construction ID-number from CONSTRUCTIONS section
% surf   = surface area of the glazing [m2]
% glaID  = select glass ID-number from GLAZING section
% shaID  = select ID-number of shadow from SHADOW section, no shadow: shaID=0
```

```
%BAS.window{winID}= [exID,    surf, glaID,   shaID]
BAS.window{1} =         [1,             252,        1,        0];
BAS.window{2} =         [2,             252,    1,        0];
BAS.window{3} =         [4,             126,    1,        0];
BAS.window{4} =         [5,             126,    1,        0];

% III. CONSTANT TEMPERATURE WALLS
%
%  Each constant temperature wall gets an ID: i0ID=1,2,...
%
% FORMAT walli0{i0ID} = [zonenr, surf, conID ,temp];
% zonenr    = select zone number from ZONES section
% surf      = total surface area [m2]
% conID     = select construction ID-number from CONSTRUCTION section.
% temp      = constant temperature [oC],e.g ground = '10'
% bridge   = the heat loss in W/K of the thermal bridges (0 if unknown)

%BAS.walli0{i0ID}=  [zonenr, surf,   conID,         temp,    bridge]

% IV ADIABATIC EXTERNAL WALLS
%
% Each adiabatic wall gets an ID: iaID=1,2,...
%
% FORMAT wallia{iaID} = [zonenr,surf,conID];
% zonenr    = select zone number from ZONES section
% surf      = total surface area in m2
% conID = select construction ID-number from CONSTRUCTION section.

%BAS.wallia{iaID}=  [zonenr, surf,      conID]
BAS.wallia{1} =         [1,      108.0,     6 ];
BAS.wallia{2} =         [1,      108.0,     6   ];
BAS.wallia{3} =         [2,      48.0,  5   ];
BAS.wallia{4} =         [2,      48.0,  5   ];

% V. INTERNAL WALLS BETWEEN AND IN ZONES
%
% Also here all different internal walls get an ID-number: inID.
% If there are 3 different walls (or floors) between zonenr1 and zonenr2, the
% input is BAS.wallin{1}=[1,2,...  t/m BAS.wallin{3}=[1,2,.... If the 4th
% construction is completely in zonenr2 the input is consequently:
% BAS.wallin{4}=[2,2,... The first layer (Ri) of the construction component is
% in the zone that comes first. If instead BAS.wallin{3}=[2,1,.... is used the
% construction is reversed and Ri is in zonenr2. The surface area is the surface
% area of one side of the wall also for walls that are completely in the same
% zone.
%
% FORMAT wallin{inID} = [zonenr1,zonenr2,surf,conID];
% zonenr1   = select zone number from ZONES section
% zonenr2   = select zone number from ZONES section
% surf      = total surface area [m2]
% conID     = select construction number from CONSTRUCTION section.

%BAS.wallin{inID}=  [zonenr1,   zonenr2,    surf,       conID   ]
BAS.wallin{1} =         [1,             2,          792.0,          9   ];
BAS.wallin{2} =         [1,             1,          25.0,       7   ]; %bookshelves
BAS.wallin{3} =         [1,             1,          25.0,       7   ];
BAS.wallin{4} =         [1,             1,          25.0,       7   ];
BAS.wallin{5} =         [1,             1,          25.0,       7   ];
BAS.wallin{6} =         [1,             1,          25.0,       7   ];
BAS.wallin{7} =         [1,             1,          25.0,       7   ];
BAS.wallin{8} =         [1,             1,          25.0,       7   ];
BAS.wallin{9} =         [1,             1,          25.0        7   ];
BAS.wallin{10} =        [1,             1,          25.0,       7   ];
BAS.wallin{11} =        [1,             1,          25.0,       7   ];
BAS.wallin{12} =        [1,             1,          25.0,       7   ];
BAS.wallin{13} =        [1,             1,          25.0,       7   ];
BAS.wallin{14} =        [1,             1,          25.0,       7   ];
BAS.wallin{15} =        [1,             1,          25.0,       7   ];
BAS.wallin{16} =        [1,             1,          25.0,       7   ];
BAS.wallin{17} =        [1,             1,          25.0,       7   ];
BAS.wallin{18} =        [1,             1,          25.0,       7   ];
BAS.wallin{19} =        [1,             1,          25.0,       7   ];
BAS.wallin{20} =        [1,             1,          25.0        7   ];
BAS.wallin{21} =        [1,             1,          25.0,       7   ];
```

```
BAS.wallin{22} =        [1,             1,      25.0,       7   ];
BAS.wallin{23} =        [1,             1,      25.0,       7   ];
BAS.wallin{24} =        [1,             1,      25.0,       7   ];
BAS.wallin{25} =        [1,             1,      25.0,       7   ];
BAS.wallin{26} =        [1,             1,      25.0,       7   ];
BAS.wallin{27} =        [1,             1,      25.0,       7   ];
BAS.wallin{28} =        [1,             1,      25.0,       7   ];
BAS.wallin{29} =        [1,             1,      25.0,       7   ];
BAS.wallin{30} =        [1,             1,      25.0,       7   ];
BAS.wallin{31} =        [1,             1,      25.0        7   ];
BAS.wallin{32} =        [1,             1,      25.0,       7   ];
BAS.wallin{33} =        [1,             1,      25.0,       7   ];
BAS.wallin{34} =        [1,             1,      25.0,       7   ];
BAS.wallin{35} =        [1,             1,      25.0,       7   ];
BAS.wallin{36} =        [1,             1,      25.0,       7   ];
BAS.wallin{37} =        [1,             1,      25.0,       7   ];
BAS.wallin{38} =        [1,             1,      25.0,       7   ];
BAS.wallin{39} =        [1,             1,      25.0,       7   ];
BAS.wallin{40} =        [1,             1,      25.0,       7   ];
BAS.wallin{41} =        [1,             1,      25.0,       7   ];
BAS.wallin{42} =        [1,             1,      25.0        7   ];
BAS.wallin{43} =        [1,             1,      25.0,       7   ];

%------------------------------------------------------------------------ --
% PART 3 : profiles for internal sources, ventilation, sunblinds and free
% cooling
% ------------------------------------------------------------------------ ---
%
%
% **PROFILES**
%
% Profiles are related to the use of a zone: office, living room, school etc
% Each day of a week can have a different profile e.g. weekends are different.
% Here the profiles are defined and given an ID-number; proID.
% For each day up to 24 different periods can be defined with different data. period1:
% start time = hrnr1 and end time = hrnr2; period2: start time = hrnr2 and end
% time = hrnr3; last period: the hours that are left on the same day.
% for example [1,8,18] means period1: 1h till 8h, period2: 8h till 18h, period 3:
% 24h(==0h) till 1h and 18h till 24h. (3 periods are often used).
% The inserted hours are the clock time.
% The profile allows for free cooling i.e. above a certain threshold Tfc (oC)
% the ventilation is increased from vvmin to vvmax: e.g. vvmax=3*vvmin. So if
% vvmin=vvmax there is no free cooling. The temperature Tfc is also used for the
% control of blinds: if the solar irradiance on the window is higher than Ers
% and the indoor temperature higher than Tfc the blinds will be down. This means
% that if there is no free cooling the temperature Tfc is still necessary for
% the control of blinds. Ers is the same for all zones. A number often
% encountered for Ers is 300W/m2.
%
% BAS.Ers{proID}     = irradiance level for sun blinds [W/m2]
% BAS.dayper{proID} = [hrnr1,hrnr2,hrnr3], the starting time of a new period
% BAS.vvmin{proID} = [.  .  . ], the ventilation ACR [1/hr], for each period
% BAS.vvmax{proID}  = [.  .  . ], the ventilation ACR [1/hr] in case free cooling
% BAS.Tfc{proID}    = [.  .  . ], treshold [oC] for free cooling, for each period
% BAS.Tsetmin{proID}= [.  .  . ], setpoint [oC] switch for heating, (in case of
%   no heating choose -100)
% BAS.Tsetmax{proID} = [.  .  . ], setpoint [oC] switch for cooling, (in case
%   of no cooling choose  100)
% BAS.Qint{proID}   = [.  .  . ], internal heat gains [W]
% BAS.Gint{proID}   = [.  .  . ], moisture gains [kg/s]
% BAS.RVmin{proID}  = [.  .  . ], setpoint [%] switch for humidification,(in case of
no
%   humidifcation choose -1)
% BAS.RVmax{proID}  = [.  .  . ], setpoint [%] switch for dehumidification,(in case
%   of no dehumidifcation choose 101)

% proID=1 Long Room on Jan 4th
BAS.Ers{1} =300;
BAS.dayper{1}=      [   0,  7,  9.5,10, 11, 12, 13, 14, 15, 16, 17, 17.5,   0   ];
BAS.vvmin{1}=       [   .1,     .1,     .1,  .1,  .1,  .1,  .1,  .1,  .1,  .1,  .1,
.1, .1        ];
BAS.vvmax{1}=       [   .3,     .3,     .3,  .3,  .3,  .3,  .3,  .3,  .3,  .3,  .3,
.3,  .3       ];
BAS.Tfc{1}=         [   1,  1,  1,  1,  1,  1,  1,  1,  1,  1,  1,  1,  1       ];
BAS.Qint{1}=        [   0, 0,   0, 8993, 12269, 14285, 14726, 12143, 12836, 10505,
4772, 0, 0   ];
```

```
BAS.Gint{1}=        [   0, 0,    0, 0.00237, 0.00348, 0.004163, 0.004313, 0.003437,
0.003672, 0.002882, 0.000939, 0, 0   ];
BAS.Tsetmin{1}= [   -100,  20,  20, 20, 20, 20, 20, 20, 20,20, 20, -100, -100   ];
BAS.Tsetmax{1}= [   100,  100,    100, 100, 100, 100, 100, 100, 100, 100, 100, 100,
100 ];
BAS.RVmin{1}=       [   -1, -1, -1, -1, -1, -1, -1, -1, -1, -1, -1, -1, -1      ];
BAS.RVmax{1}=       [   101,101,101, 101, 101, 101, 101, 101, 101, 101, 101, 101, 101
];

%proID=2 Long Room on Jan 5th
BAS.Ers{2}=300;
BAS.dayper{2}=      [   0,  7,  9.5,10, 11, 12, 13, 14, 15, 16, 17, 17.5,   0   ];
BAS.vvmin{2}=       [   .1,     .1,     .1,  .1,  .1,  .1,  .1,  .1,  .1,  .1,  .1,
.1, .1          ];
BAS.vvmax{2}=       [   .3,     .3,     .3,  .3,  .3,  .3,  .3,  .3,  .3,  .3,  .3,
.3,  .3         ];
BAS.Tfc{2}=         [   1,  1,  1,  1,  1,  1,  1,  1,  1,  1,  1,  1,  1       ];
BAS.Qint{2}=        [   0, 0,   0, 4835, 6599, 8363, 8930, 7229, 7229, 7544, 4457, 0,
0 ];
BAS.Gint{2}=        [   0, 0,   0, 0.000961, 0.001559, 0.002156, 0.002349, 0.001772,
0.001772, 0.001879, 0.000833, 0, 0 ];
BAS.Tsetmin{2}= [   -100,  20,  20, 20, 20, 20, 20, 20, 20,20, 20, -100, -100   ];
BAS.Tsetmax{2}= [   100,  100,    100, 100, 100, 100, 100, 100, 100, 100, 100, 100,
100 ];
BAS.RVmin{2}=       [   -1, -1, -1, -1, -1, -1, -1, -1, -1, -1, -1, -1, -1      ];
BAS.RVmax{2}=       [   101,101,101, 101, 101, 101, 101, 101, 101, 101, 101, 101, 101
];


%proID=3 Long Room on Jan 6th
BAS.Ers{3}=2000;
BAS.dayper{3}=      [   0,  7,  9.5,10, 11, 12, 13, 14, 15, 16, 17, 17.5,   0   ];
BAS.vvmin{3}=       [   .1,     .1,     .1,  .1,  .1,  .1,  .1,  .1,  .1,  .1,  .1,
.1, .1          ];
BAS.vvmax{3}=       [   .3,     .3,     .3,  .3,  .3,  .3,  .3,  .3,  .3,  .3,  .3,
.3,  .3         ];
BAS.Tfc{3}=         [   1,  1,  1,  1,  1,  1,  1,  1,  1,  1,  1,  1,  1       ];
BAS.Qint{3}=        [   0, 0,   0, 3575, 6410, 8552, 8552, 8552, 6536, 7229, 5213, 0,
0 ];
BAS.Gint{3}=        [   0, 0,   0, 0.000534, 0.001495, 0.00222, 0.00222, 0.00222,
0.001537, 0.001772, 0.001089, 0, 0    ];
BAS.Tsetmin{3}= [   -100,  20,  20, 20, 20, 20, 20, 20, 20,20, 20, -100, -100   ];
BAS.Tsetmax{3}= [   100,  100,    100, 100, 100, 100, 100, 100, 100, 100, 100, 100,
100 ];
BAS.RVmin{3}=       [   -1, -1, -1, -1, -1, -1, -1, -1, -1, -1, -1, -1, -1      ];
BAS.RVmax{3}=       [   101,101,101, 101, 101, 101, 101, 101, 101, 101, 101, 101, 101
];

%proID=4 Long Room on Jan 7th
BAS.Ers{4}=300;
BAS.dayper{4}=      [   0,  7,  9.5,10, 11, 12, 13, 14, 15, 16, 17, 17.5,   0   ];
BAS.vvmin{4}=       [   .1,     .1,     .1,  .1,  .1,  .1,  .1,  .1,  .1,  .1,  .1,
.1, .1          ];
BAS.vvmax{4}=       [   .3,     .3,     .3,  .3,  .3,  .3,  .3,  .3,  .3,  .3,  .3,
.3,  .3         ];
BAS.Tfc{4}=         [   1,  1,  1,  1,  1,  1,  1,  1,  1,  1,  1,  1,  1       ];
BAS.Qint{4}=        [   0, 0,   0, 2504, 9245, 9875, 7796, 9686, 10190, 8363, 5906, 0,
0    ];
BAS.Gint{4}=        [   0, 0,   0, 0.000171, 0.002455, 0.002669, 0.001964, 0.002605,
0.002776, 0.002156, 0.001324, 0, 0 ];
BAS.Tsetmin{4}= [   -100,  20,  20, 20, 20, 20, 20, 20, 20,20, 20, -100, -100   ];
BAS.Tsetmax{4}= [   100,  100,    100, 100, 100, 100, 100, 100, 100, 100, 100, 100,
100 ];
BAS.RVmin{4}=       [   -1, -1, -1, -1, -1, -1, -1, -1, -1, -1, -1, -1, -1      ];
BAS.RVmax{4}=       [   101,101,101, 101, 101, 101, 101, 101, 101, 101, 101, 101, 101
];

%proID=5 Shop on Jan 4th
BAS.Ers{5}=300;
BAS.dayper{5}=      [   0,  7,  9.5,10, 11, 12, 13, 14, 15, 16, 17, 17.5,   0   ];
BAS.vvmin{5}=       [   .1,     .1,     .1,  .1,  .1,  .1,  .1,  .1,  .1,  .1,  .1,
.1, .1          ];
BAS.vvmax{5}=       [   .3,     .3,     .3,  .3,  .3,  .3,  .3,  .3,  .3,  .3,  .3,
.3,  .3         ];
```

```
BAS.Tfc{5}=         [   1,  1,  1,  1,  1,  1,  1,  1,  1,  1,  1,  1,  1       ];
BAS.Qint{5}=        [   0, 0,   0, 10267, 11671, 12535, 12724, 11617, 11914, 10915,
8458, 0, 0  ];
BAS.Gint{5}=        [   0, 0,   0, 0.001016, 0.001491, 0.001784, 0.001848, 0.001473,
0.001574, 0.001235, 0.000403, 0, 0 ];
BAS.Tsetmin{5}= [   -100,  20,  20, 20, 20, 20, 20, 20, 20,20, 20, -100, -100   ];
BAS.Tsetmax{5}= [   100,  100,    100, 100, 100, 100, 100, 100, 100, 100, 100, 100,
100 ];
BAS.RVmin{5}=       [   -1, -1, -1, -1, -1, -1, -1, -1, -1, -1, -1, -1, -1      ];
BAS.RVmax{5}=       [   101,101,101, 101, 101, 101, 101, 101, 101, 101, 101, 101, 101
];

%proID=6 Shop on Jan 5th
BAS.Ers{6}=300;
BAS.dayper{6}=      [   0,  7,  9.5,10, 11, 12, 13, 14, 15, 16, 17, 17.5,   0   ];
BAS.vvmin{6}=       [   .1,     .1,     .1,  .1,  .1,  .1,  .1,  .1,  .1,  .1,  .1,
.1, .1          ];
BAS.vvmax{6}=       [   .3,     .3,     .3,  .3,  .3,  .3,  .3,  .3,  .3,  .3,  .3,
.3,  .3         ];
BAS.Tfc{6}=         [   1,  1,  1,  1,  1,  1,  1,  1,  1,  1,  1,  1,  1       ];
BAS.Qint{6}=        [   0, 0,   0, 8485, 9241, 9997, 10240, 9511, 9511, 9646, 8323, 0,
0    ];
BAS.Gint{6}=        [   0, 0,   0, 0.000412, 0.000668, 0.000924, 0.001007, 0.000759,
0.000759, 0.000805, 0.000357, 0, 0 ];
BAS.Tsetmin{6}= [   -100,  20,  20, 20, 20, 20, 20, 20, 20,20, 20, -100, -100   ];
BAS.Tsetmax{6}= [   100,  100,    100, 100, 100, 100, 100, 100, 100, 100, 100, 100,
100 ];
BAS.RVmin{6}=       [   -1, -1, -1, -1, -1, -1, -1, -1, -1, -1, -1, -1, -1      ];
BAS.RVmax{6}=       [   101,101,101, 101, 101, 101, 101, 101, 101, 101, 101, 101, 101
];

%proID=7 Shop on Jan 6th
BAS.Ers{7}=300;
BAS.dayper{7}=      [   0,  7,  9.5,10, 11, 12, 13, 14, 15, 16, 17, 17.5,   0   ];
BAS.vvmin{7}=       [   .1,     .1,     .1,  .1,  .1,  .1,  .1,  .1,  .1,  .1,  .1,
.1, .1          ];
BAS.vvmax{7}=       [   .3,     .3,     .3,  .3,  .3,  .3,  .3,  .3,  .3,  .3,  .3,
.3,  .3         ];
BAS.Tfc{7}=         [   1,  1,  1,  1,  1,  1,  1,  1,  1,  1,  1,  1,  1       ];
BAS.Qint{7}=        [   0, 0,   0, 7945, 9160, 10078, 10078, 10078, 9214, 9511, 8647,
0, 0  ];
BAS.Gint{7}=        [   0, 0,   0, 0.000229, 0.000641, 0.000952, 0.000952, 0.000952,
0.000659, 0.000759, 0.000467, 0, 0 ];
BAS.Tsetmin{7}= [   -100,  20,  20, 20, 20, 20, 20, 20, 20,20, 20, -100, -100   ];
BAS.Tsetmax{7}= [   100,  100,    100, 100, 100, 100, 100, 100, 100, 100, 100, 100,
100 ];
BAS.RVmin{7}=       [   -1, -1, -1, -1, -1, -1, -1, -1, -1, -1, -1, -1, -1      ];
BAS.RVmax{7}=       [   101,101,101, 101, 101, 101, 101, 101, 101, 101, 101, 101, 101
];

%proID=8 Shop on Jan 7th
BAS.Ers{8}=300;
BAS.dayper{8}=      [   0,  7,  9.5,10, 11, 12, 13, 14, 15, 16, 17, 17.5,   0   ];
BAS.vvmin{8}=       [   .1,     .1,     .1,  .1,  .1,  .1,  .1,  .1,  .1,  .1,  .1,
.1, .1          ];
BAS.vvmax{8}=       [   .3,     .3,     .3,  .3,  .3,  .3,  .3,  .3,  .3,  .3,  .3,
.3,  .3         ];
BAS.Tfc{8}=         [   1,  1,  1,  1,  1,  1,  1,  1,  1,  1,  1,  1,  1       ];
BAS.Qint{8}=        [   0, 0,   0, 7486, 10375, 10645, 9754, 10564, 10780, 9997, 8944,
0, 0 ];
BAS.Gint{8}=        [   0, 0,   0, 7.32e-5, 0.001052, 0.001144, 0.000842, 0.001116,
0.00119, 0.000924, 0.000567, 0, 0   ];
BAS.Tsetmin{8}= [   -100,  20,  20, 20, 20, 20, 20, 20, 20,20, 20, -100, -100   ];
BAS.Tsetmax{8}= [   100,  100,    100, 100, 100, 100, 100, 100, 100, 100, 100, 100,
100 ];
BAS.RVmin{8}=       [   -1, -1, -1, -1, -1, -1, -1, -1, -1, -1, -1, -1, -1      ];
BAS.RVmax{8}=       [   101,101,101, 101, 101, 101, 101, 101, 101, 101, 101, 101, 101
];

%proID=9 Building during Christmas vacation
BAS.Ers{9}=300;
BAS.dayper{9}=      [   0,  7,  9.5,10, 11, 12, 13, 14, 15, 16, 17, 17.5,   0   ];
BAS.vvmin{9}=   [   0.1,    0.1,    0.1,  0.1,  0.1,  0.1,  0.1,  0.1,  0.1,  0.1,
0.1,  0.1, 0.1      ];
```

```
BAS.vvmax{9}=       [   .3,     .3,     .3,  .3,  .3,  .3,  .3,  .3,  .3,  .3,  .3,
.3,  .3       ];
BAS.Tfc{9}=         [   100,    100,    100,  100, 100,  100,  100,  100,  100,  100,
100,  100,  100      ];
BAS.Qint{9}=        [   0, 0,   0, 0,0 , 0, 0, 0, 0, 0, 0, 0, 0 ];
BAS.Gint{9}=        [   0, 0,   0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0 ];
BAS.Tsetmin{9}= [   -100,  -100,  -100, -100, -100, -100, -100, -100, -100,-100, -100,
-100, -100   ];
BAS.Tsetmax{9}= [   100,  100,    100, 100, 100, 100, 100, 100, 100, 100, 100, 100,
100 ];
BAS.RVmin{9}=       [   -1, -1, -1, -1, -1, -1, -1, -1, -1, -1, -1, -1, -1      ];
BAS.RVmax{9}=       [   101,101,101, 101, 101, 101, 101, 101, 101, 101, 101, 101, 101
];

% THE PROFILES OF THE BUILDING
%
% FORMAT BAS.weekfun{zonenr} = [upnrmon, upnrtue, upnrwed, upnrthu, upnrfri,
% upnrsat, upnrsun]
% for each zone n=1.. number of zones,  select profiles ID-numbers for each
% day
% upnrmon = select profile ID-numbers for Monday from PROFILES
% upnrtue = select profile ID-numbers for Tuesday from PROFILES
% upnrwed = select profile ID-numbers for Wednesday from PROFILES
% upnrthu = select profile ID-numbers for Thursday from PROFILES
% upnrfri = select profile ID-numbers for Friday from PROFILES
% upnrsat = select profile ID-numbers for Saturday from PROFILES
% upnrsun = select profile ID-numbers for Sunday from PROFILES
%
% BAS.weekfun{zonenr} =[upnrmon,    upnrtue,    upnrwed,    upnrthu, upnrfri, upnrsat,
upnrsun]
BAS.weekfun{1}=         [1,         1,      2,          3,          4,          9,
9];
BAS.weekfun{2}=         [9,         9,      9,          9,          9,          9,
9];

%-------------------------------------------------------------------------- --
% PART 4 : Heating, cooling, humidification, dehumidification
% ------------------------------------------------------------------------ ---

% If the maximum heating capacity is known then that value can be used. If it is
% unknown  the value '-1' means an infinite capacity. The value '-2' can be used
% for a reasonable estimate of the maximum heating capacity. Cooling and
dehumification
% are negative! If there is no cooling the dehumidification capacity is '0'.
% For each zone :
%
% FORMAT BAS.Plant{zonenr}=[heating capacity [W], cooling capacity [W],
%  humidification capacity [kg/s],dehumidification capacity [kg/s]];

BAS.Plant{1}=[000,0,0.00,-0.00];
BAS.Plant{2}=[000,0,0.00,-0.00];

% The simulation program treats radiant heat and convective heat differently.
% For each zone:
%
% FORMAT BAS.convfac{zonenr}=[CFh, CFset, CFint ];
% CFh =Convection factor of the heating system: air heating CFh=1,
%       radiators CFh=0.8 floor heating CFh=0.5, cooling usually CFh=1
% CFset= Factor that determines whether the temperature control is on the air
% temperature (CFset=1), or comforttemperature (CFset=0.6),Tset=CFset*Ta+(1-CFset)*Tr
%
% CFint= is the convection factor of the casual gains (usually CFint=0.5)

BAS.convfac{1}=[0.8, 1, 0.5 ];
BAS.convfac{2}=[0.8, 1, 0.5 ];

% If a heat recovery from ventilation air is used the effective temperature
% efficiency 'etaww' and the maximum indoor air temperature 'Twws' above which
% the  heat exchanger will be by-passed must be known. In summer with cooling
% conditions this temperature is used to switch the exchanger on, e.g Twws=22oC
%
% FORMAT BAS.heatexch{zonenr}=[etaww, Twws];
```

```
%BAS.heatexch{1}=[0 22];
%BAS.heatexch{2}=[0 22];
%BAS.heatexch{3}=[0 22];
%BAS.heatexch{4}=[0 22];

% Real rooms are furnished. Furnishings are important for moisture storage.
% Moisture is released dependent on the change in relative humidity. Especially
% in zones with a lot of paper or textiles this can easily outweigh the moisture
% storage of the building. A value of '1' means that about the same amount is
% stored as in the air that fills the volume of the zone. The heat storage of
% furnishings is less important but by absorbing solar radiation and releasing
% that directly to the indoor air more solar energy is released in a convective
% way. A value for the convective fraction of 0.2 can be considered as
% reasonable.  For each zone:
%
% FORMAT BAS.furnishings{zonenr}=[fbv, CFfbi];
% fbv = Moisture storage factor
% CFfbi= The convection factor for the solar radiation due to furnishings.

BAS.furnishings{1}=[1, 0.2];
BAS.furnishings{2}=[1, 0.2];

% ------------------------------------------------------------------------
% PART 2 : THE BUILDING
% ------------------------------------------------------------------------

% Extra input for infiltration, shadow etc can be inserted in Inputextra.
% Without this m.file no extras are used
%Inputextra11a

% The input is now completely stored in the structured array BAS. By typing
% BAS in the command window, this input can be checked and changed
% At the end of Inputextra a function is called for that changes the input
% BAS to an input the simulation program WAVO needs:

[Control,Profiles,Meteo,Building,Elan]=Bastrans11a(BAS);

[Output,Control,Elan]=Hambasex11a(Control,Profiles,Meteo,Building,Elan);

Hamoutput11a
```