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A PARAMETRIC INVESTIGATION OF THE INFLUENCE OF ATRIUM FACADES ON THE DAYLIGHT PERFORMANCE OF ATRIUM BUILDINGS

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ABSTRACT

Daylighting is of decisive importance to the architectural experience. Atria have proliferated in a range of contemporary buildings and daylighting is perhaps their most valuable aspect. Daylight in an atrium and its adjoining spaces is affected by the atrium's characteristics, such as its roof, geometry and the surface reflectances of its walls and floor.

This thesis is an exploration of the effects of atrium facades on the daylight performance of an atrium and its adjoining spaces. It is proposed that the design of the atrium facades will affect the way in which daylight is reflected within the atrium space and the amount that reaches the atrium floor and its adjoining spaces. This study examines the effects of atrium wall surface reflectance distribution patterns, different surface types, i.e. diffuse and specular; and the location, size and proportion of fenestration and opaque areas in an atrium's facade on the daylighting conditions within an atrium and its adjoining spaces. It seeks to provide knowledge that would be most useful at the early design stages of a project.

The introductory Chapters Two and Three develop an understanding of the key daylighting concepts and the behaviour of daylight in atrium buildings before considering the specific daylight linked atrium parameters related to this study; atrium geometry and enclosing surfaces each of which is then examined through an extensive literature review.

The study uses the Daylight Factor (DF) and the Average Daylight Factor (ADF) to examine daylight levels in an atrium building. Daylight Factor is a ratio of interior to exterior illuminance under an overcast, unobstructed sky and is measured in a horizontal plane at both locations. While ADF, is the mean DF over a given area of the room, usually at the horizontal working plane. Therefore, although useful, ADF is a broad measure for assessing daylight levels in a room.

The main body of the thesis is structured around the key parameter of atrium surface reflectances which forms the focus of this study, beginning in Chapter Four which

demonstrates the effects of reflectance distributions and diffuse and specular surface types on the DFs across the atrium floor using physical scale models. Following this, in Chapter Five, the experiments undertaken in the previous chapter are repeated via RADIANCE and ECOTECT simulations and the results from the two methods are compared to establish their accuracies. ADF values, calculated using Littlefair's (2002) algorithm, are also compared with those obtained from the physical scale model and the RADIANCE experiments.

Building on the experiments of Chapter Four and Five, in Chapter Six, the range of well indices in which the surface reflectance distributions affect the DFs in an atrium building is established. This then informs the experiments undertaken in Chapter Seven where different facade compositions comprising varying fenestration versus opaque wall ratios are tested to ascertain their influence on the daylight availability in the atrium and its adjoining spaces. These include facades with a progressive increase in the fenestration from the atrium roof to its floor as well as those with even fenestration on all the floors.

To contextualise the work undertaken in this thesis, research findings are compared with previous studies and, where possible, with monitored data obtained from real buildings. Finally, in the concluding Chapter Eight, specific conclusions with regards to the effects of atrium facades on daylighting in an atrium building are drawn before more wide-reaching inferences are made.

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Forthcoming Book Chapter

1. SAMANT, S. 2011, Atria: A Vital Ingredient of a Sustainable Tall Building, **Book Chapter in The Tall Building Reference Book**, by Routledge and Council on Tall Buildings and Urban Habitat (CTBUH)

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This is for my parents…

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ADF: Average Daylight Factor

ADFs: Average Daylight Factor s

ADF_b: Average daylight factor at the base of an atrium

AHRAE: American Society of Heating, Refrigerating and Air-conditioning Engineers

AR: Aspect Ratio

ARC: Atrium Reflected Component

ARCs: Atrium Reflected Components

BMS: Building Management Systems

BRE: Building Research Establishment

BREEAM: Building Research Establishment Environmental Assessment Model

BRS: Building Research Station

BS: British Standard

CIBSE: Chartered Institute of Building Services Engineers

CIE: Commission Internationale de l'Eclairage

CU: Coefficient of Utilization

DC: Direct Component

DF: Daylight Factor

DFs: Daylight Factors

EC: European Commission

ERC: Externally Reflected Component

ETSU: Energy Technology Support Unit

FDF: Flux Transfer Daylight Factor

GDDM: Graphic Daylighting Design Method

IEA: International Energy Agency

IES: Illuminating Engineering Society

IESNA: Illuminating Engineering Society of North America

IRC: Internally Reflected Component

LBL: Lawrence Berkeley Laboratory

LCP: Laser Cut Panels

LI: Light index

LT: Lighting and Thermal

MDF: Medium Density Fibreboard

PAR: Plan Aspect Ratio

RI: Room Index

SAD: Seasonal Affective Disorder

SAR: Section Aspect Ratio

SBS: Sick Building Syndrome

SC: Sky Component

SI: International System of Units

SS: Single Stage

WI: Well Index

1 INTRODUCTION TO THE THESIS

1.1 INTRODUCTION

"*Although we do not mostly see light, we see the effects of light*" (Michel, 1996).

The poetic qualities of light and their instrumental role in the architectural experience, human behaviour and perceptions of space are central to the creation of a sustainable built environment.

Artificial lighting is one of the largest energy users in non-domestic buildings, despite the increase in luminous efficacy of light sources and considerable progress in control systems (Yeang, 1999). This is due to the fact that building forms are often not designed to use daylight effectively, artificial lighting is frequently being left on and control systems are not widely used.

Al-Sallal (2004) highlighted that "an office with simple daylight strategies (such as sidelights and light shelf) and fluorescent lighting system can achieve 60% total reduction of lighting energy and 51% annual electric energy savings". Typically, artificial lighting can be reduced through optimizing building configuration to admit natural light, and using efficient low energy lamps, better electronic ballasts and high quality fittings. Additionally, lighting switching systems coupled with the building management system (BMS) or local controls and ambient light sensors to adjust artificial lighting based on availability of daylight can also be used.

Post Industrial Architecture ignored the issues of resource consumption and their implications until the 1970s oil crisis and associated energy costs, when architects were forced to reconsider their design strategies and develop energy conscious architecture. However, with the advent of fluorescent lighting that reduced costs, heat gain and improved lighting efficacy, daylighting was largely ignored by designers even in the 1970s. Envelope design did not respond to the external environment but relied heavily on the artificial environment and air-conditioned offices with a focus on artificial lighting. Even where energy conservation measures were adopted, they resulted in poor daylight due to the use of fixed shading and tinted glass. This trend continued from the early 1970s for nearly two decades.

Since the 1990s climate sensitive environmental design has been the focus of many architects the world over, employing a range of passive strategies for lighting, heating, cooling and ventilation. Daylighting is increasingly used to address issues of quality in the indoor environments and the “Sick Building Syndrome” (SBS), which is predominantly associated with air-conditioned, deep plan buildings and lighting quality related to spectral composition, flicker and glare (Kwok, 2007). Additionally, Seasonal Affective Disorder (SAD) is related to light deprivation and can be avoided by use of daylight.

Edwards and Torcellini (2002) compiled a list of commonly cited literature and presented a summary of information from a noncritical literature review on the impacts of daylighting in buildings. The review concluded that natural light is of benefit to the health, productivity and safety of building occupants with the use of appropriately installed and maintained daylighting systems. In healthcare settings, natural light helps improve patient recovery rates, maintain their good health, and cure some medical ailments and present opportunities for improved vision for the elderly in assisted living facilities. Natural lighting also brings benefits to staff in terms of providing amiable working environments thereby affecting their mood and the care they provide and indirectly affecting patients’ recovery rates. Pleasant environments created as a result of natural light reduce stress and improve health of workers in office environments that consequently increase productivity and bring financial benefits to the employers. Day-lit classrooms in schools show links to improvement in students’ performance and health (due to increase in Vitamin D intake) and growth with fewer dental cavities due to access to full-spectrum lighting. In retail environments, daylighting and its even distribution improves colour rendering resulting in better working conditions for employees, whereby they can identify items faster, and better sales as customers stay in stores longer.

Fontoynont (1999a) edited the book, *Daylight Performance of Buildings* includes monitored data and objective assessment of 60 new and old European buildings of different typologies and scale undertaken over a three year period from 1994-1997. The study confirmed the outstanding potential of daylighting in terms of improving amenity and energy performance of buildings. However it was noted that daylighting opportunities were often missed and sometimes overestimated, and were combined with problems of overheating and glare. The book highlights the broad potentials of daylighting design and the importance of careful assessment and management of its side effects.

Given that daylighting is fundamental to the enhanced quality of the indoor spaces, to the creation of enjoyable and healthy environments that contribute to the well-being and productivity of building users and to the sustainability of the built environment, the current research investigates daylighting in atrium buildings, which is one of the key aspects of this typology. The thesis, in particular, explores the effects of atrium facades on the daylight performance of an atrium and its adjoining spaces.

In the following sections, after an introduction of the atrium concept and a brief historical review of its evolution, the diverse roles of atria in contemporary buildings are discussed. Several notable case studies are included to examine their uses: for aesthetic purposes, as circulation and amenity spaces, as urban connectors and their role in improving the environmental performance of buildings.

The next section focuses on the research area: daylighting in atrium buildings. It demonstrates the daylighting potential of atria in various buildings and the contributions they make to a building's aesthetics, experience and environmental performance. Subsequently, the atrium design parameters that influence the daylight performance of atria are identified.

Following this, the background to the study is presented and includes a summary of key investigations that examine the influence of atrium facades including their surface reflectances and glazing areas on daylighting in atria and their adjoining spaces. This then leads to the defining of the aims and objectives of the study followed by the overarching methodology adopted to undertake the research. The final section includes a description of the organisation of the thesis and outlines the contents of each of the Chapters.

1.2 DEFINITION OF AN ATRIUM

A courtyard is a space within a building or between buildings that is open to the sky. An atrium is a covered, enclosed courtyard. Bednar (1986) gave the definition "The new atrium is a centroidal, interior, day-lit space which organizes a building".

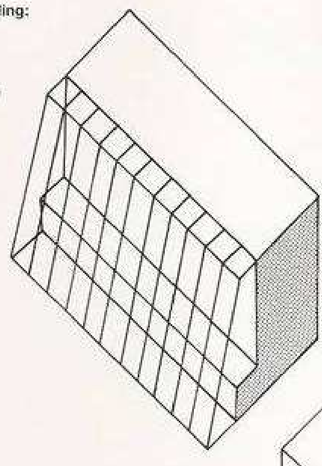
The word atrium has its primary roots in the archetypal ancient Roman house where the central courtyard was open to the sky. The courtyard concept was prominent in the dwelling as "climatically it has been a great source for the provision of natural light and air, wind protection, as a heat sink in winter and a cool, shaded place in summer" (Bednar, 1986). Some authors use the word atrium to include covered and uncovered spaces. The plural form 'atria' is occasionally used as an alternative to 'atria'. Since atrium is integral to its parent building, the term 'atrium building' is also widely used.

The historical context of atrium conflicts with how we might now describe the modern atrium as, with time, the atrium has significantly evolved in design with the advent of new materials and technologies. The modern atrium typically follows the description of a hall or multi-storey void enclosed by a structure or building, this in cases is further clarified by a proportion of access to natural light.

Saxon (1983) described five simple and four complex generic atrium forms with the understanding that more hybrid arrangements are possible through an adaptation of these generic forms as shown in Figure 1:1. The five simple atrium types include the single sided or conservatory atrium, the two sided atrium with two open sides, the three sided atrium with one open side, the four sided atrium with no open sides; and the linear atrium with open ends. Complex atria include the bridging atrium between multiple buildings, the podium atrium at the base of a tower, the multiple lateral atria and the multiple vertical atria. With the difficulty of bringing light into the atrium, a simple four-sided, top-lit atrium with no open sides is the worst case scenario and forms the focus of this study.

Generic forms of atrium building: simple types

Single-sided or conservatory atrium



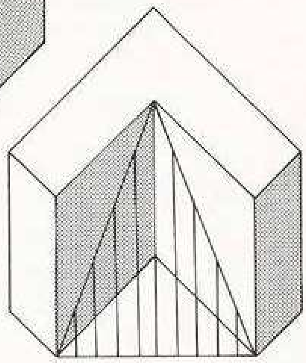
Examples:

Irwin Bank, Columbus, Indiana, Roche and Dinkeloo

Truman's Brewery, London, Arup Associates

Law Courts, Vancouver, Arthur Ericson

Two-sided atrium (two open sides)



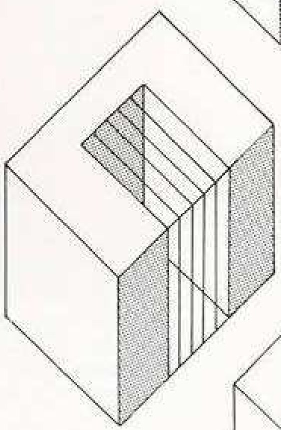
Examples:

Ford Foundation, New York, Roche and Dinkeloo

History Library, Cambridge, James Stirling

Holiday Inns Holidomes (several)

Three-sided atrium (one open side)



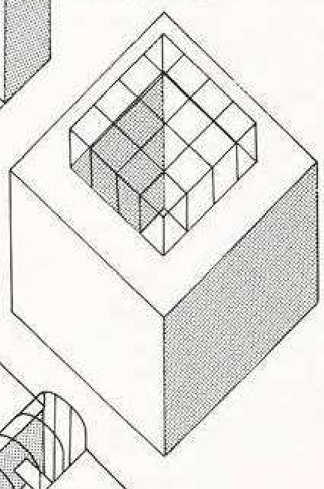
Examples:

Children's Hospital of Philadelphia, H2L2

Hyatt Reunion Hotel, Dallas, Welton Beckett

C D Howe Building, Ottawa, Adamson Associates

Four-sided atrium (no open sides)



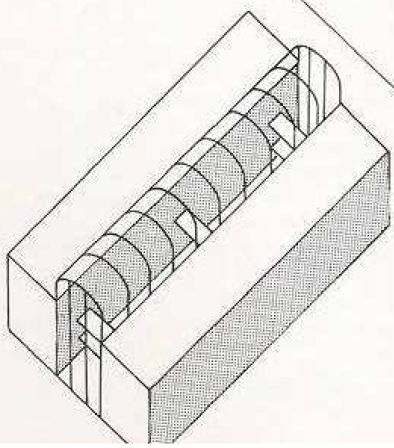
Examples:

Regency Hyatt Hotels, Atlanta and Chicago, John Portman

IMF Headquarters, Washington DC, Vincent Kling

Welsh Office, Cardiff, Wales, Alex Gordon and Partners

Linear atrium (open ends)



Examples:

Hennepin County Courthouse, Minneapolis, John Carl Warnecke

Rustoleum Headquarters, Chicago, Murphy/Jahn

Decker Building, Corning, NY, Davies, Brody

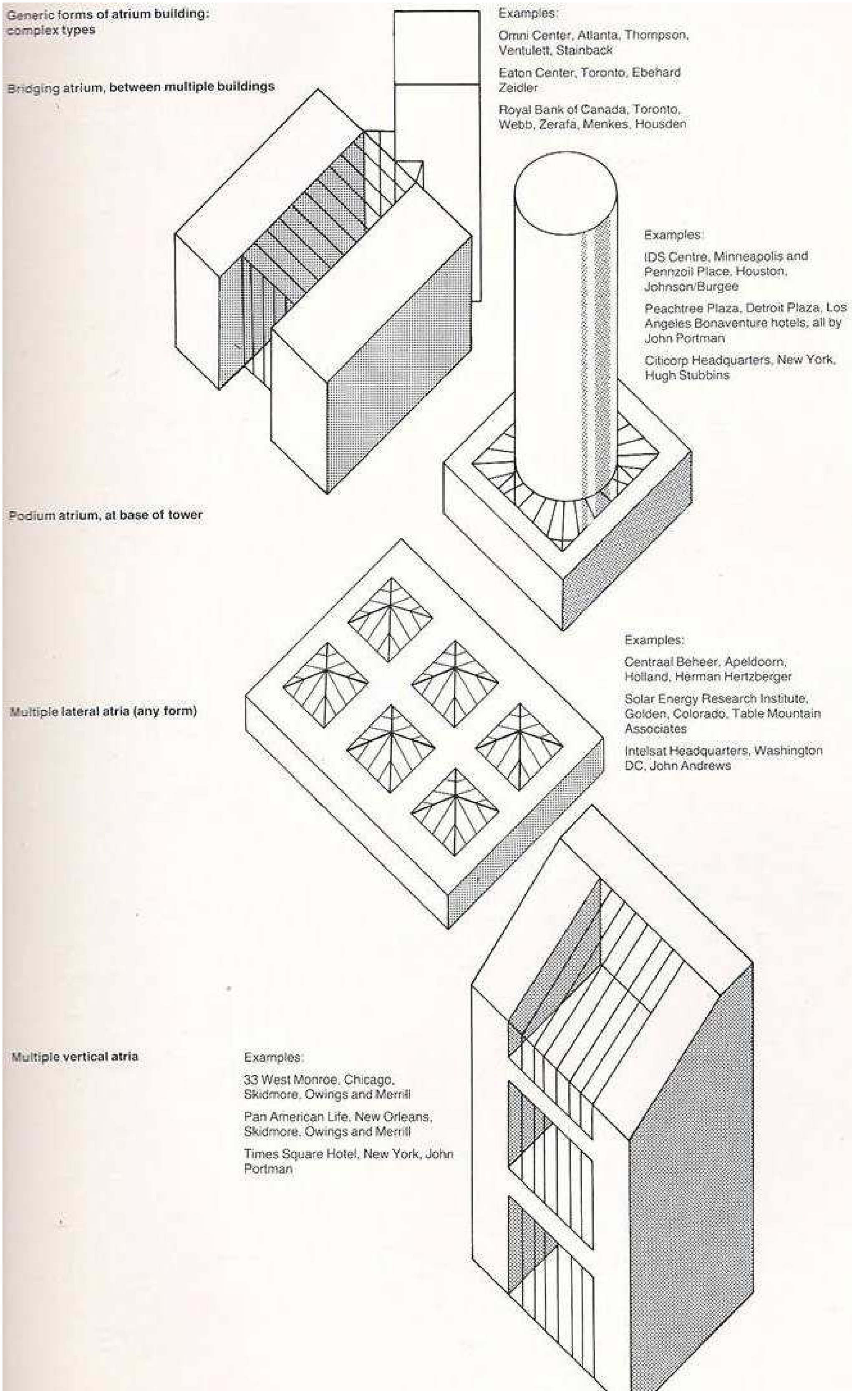


Figure 1:1 Generic Forms of Atrium Buildings: Simple and Complex Types (Saxon, 1983)

1.3 A BRIEF HISTORICAL OVERVIEW

Atrium spaces, in the form of grand entrance spaces, courtyards and sheltered semi-public areas, have been around for about 2000 years (Saxon, 1983). Due to the versatile nature of the atrium form, it has been used in different climates (hot-dry, temperate, and warm-humid) and found in Greece, Italy, India, Latin America, China and many Islamic countries (Bednar, 1986).

Iron and glass technology of the industrial revolution in the 19th century led to the covering of large courtyard spaces with significant improvements to the climate achieved. This technology saw its use first in the greenhouses of the 19th century and allowed for the garden courts to become indoor saloons and therapeutic gardens, a strategy employed in the Reform Club (1837) and the Crystal Palace (1851). This technology also proliferated in a variety of public buildings; market halls, museums, arcades, bandstands, factories, small bridges and most notably in the great enclosures of railway stations and exhibition buildings produced by the Victorian glasshouse technology (Saxon, 1983). In hotels, shopping centres and office buildings, atria were surrounded by iron galleries from which rooms could be accessed. Circulation stairs/stair-towers and elevators, plants and trees were also prominently located in the atrium spaces, which were now much taller and formed the social hub of the building in the latter part of the 19th century (Figure 1.2) (Saxon, 1983).

Atria were an essential feature of the early tall buildings in New York and Chicago and were used to admit daylight to provide adequate levels of ventilation and to draw away fumes from the oil and gas fired lamps. Although few architects used this concept in a more restrained manner, by the First World War the development of this concept steadily declined (Saxon, 1986). Changed regulations in New York, of larger floor spaces on small blocks, made the use of the atrium spaces obsolete and led to the rise of the second generation of dispersed and fully glazed Modernist towers of North America and Europe. While the fully glazed facades were adopted to bring in light and air in buildings, the use of heavy tint on the glass to prevent excess solar gains provided poor natural lighting conditions and resulted in mechanically conditioned and predominantly artificially lit environments.

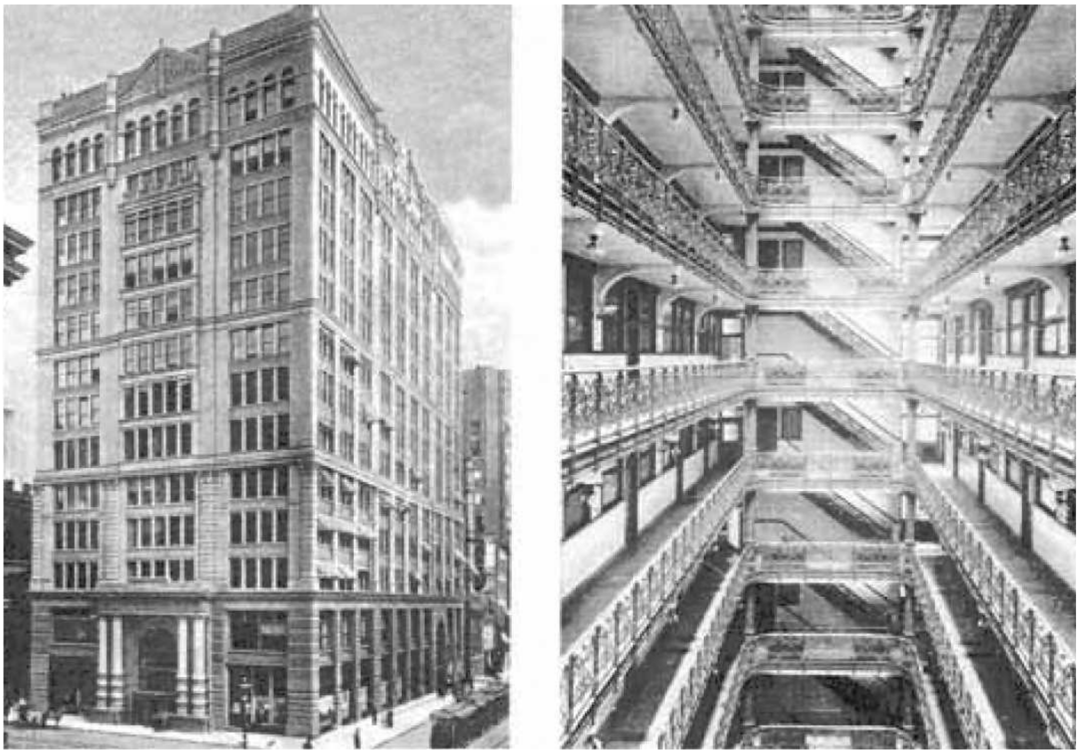


Figure 1:2 Chicago Chamber of Commerce, 1890 (Willis, 1996)

Although many pioneers, including Frank Llyod Wright, pushed forward the atrium concept, it was not used before its revival in the late 1960s (Saxon, 1983). The use of atria as iconic design features, combined with landscape, water and dramatic rising elevators to create attractive public spaces by John Portman in the Hyatt Regency Hotels in USA and particularly in Atlanta in 1967, saw the resurgence of the atrium concept in North America. “Mainstream commercial development in Canada and the USA adopted the atrium and galleria concepts universally and proved their economic value and their technical feasibility” (Saxon, 1994).

Tall buildings are often preoccupied with making landmark public statements through iconic forms and soaring heights. However, the latest generation of tall buildings have made admirable progress in their response to the environment and embraced designs that are embedded in their physical, environmental and cultural context (Wood, 2004), often with the use of atria.

As Bednar (1986) summarises in the first chapter of his book, “The New Atrium”, “This third epoch, of the new atrium, which began in the 1960s, continues through the present day”. Atria have now become a dominant feature in contemporary architecture and have spread to the far corners of the globe, transcending climates and cultural contexts. The atrium concept has significantly evolved in design with the advent of new materials, glazing and structural technologies and advanced computational capabilities.

1.4 FUNDMENTAL USES OF ATRIUM SPACES

Atria have been widely incorporated in a range of building types due to their ability to contribute to several aspects of a building: they bring about social, functional and spatial order and coherence in buildings and create a strong identity and marketability for the building (Bednar, 1986).

Saxon (1994) discussed the development of the atrium concept in the 1980s, particularly in terms of its contribution to urban design, its use in building conservation and recycling of old buildings, and its role in energy conservation. He also highlighted the significant opportunities presented by the atrium concept in terms of refining structural and envelope design. He observed that “…although atria cannot make a poor location prime, and although poorly designed atria make very little economic contribution, in general atria have given a strong return on investment, raising values and occupancy rates. The unquantifiable return, noted in public and corporate buildings as well as commercial development, has been the fostering of community values through the availability of a public realm in which the occupiers can be more aware of each other and occasionally share events” (Saxon, 1994). Furthermore, day-lit office spaces and pleasant views are associated with improved productivity and occupant well being. If these are considered alongside the energy efficiencies that could be achieved as a result of daylighting and natural ventilation aided by atria, they have the potential to offer significant economic benefits.

Saxon (1994) discussed the role and design of atria in different building typologies; hotels, shopping and leisure, offices, public buildings such as government, education, health and art galleries/museum and mixed use buildings. He includes a gazetteer of notable atrium buildings in the UK, France, Scandinavia, USA, Canada, Australia, Hong Kong and Japan. What is evident is that the use of atria can vary greatly in different building typologies influencing the combination of strategies that may be used and the resultant design. Therefore, the following sub-sections discuss the various roles of contemporary atria.

1.4.1 Identity, Aesthetic and Iconic

An atrium can be a powerful iconic space which lends a strong identity and an architectural presence to a building and becomes a feature that forms popular recognition. Soaring atrium spaces lend a sense of delight and excitement to the building due to the heightened contrast of the atrium space extending over numerous levels with its surroundings. The height and sheer scale of an atrium, particularly in tall buildings, can create a monumental sense of awe as seen in the Jin Mao Tower in Shanghai (Figure 1:3).

Figure 1:3 Jin Mao Tower, Shanghai, 1999, SOM
(http://meiguoxing.com/blog/wpcontent/uploads/2010/02/JinMaoTower_Shanghai.jpg)

Atria are often animated by the different uses and the vertical and horizontal circulation they may encompass. They are frequently incorporated in hotels, offices and recreational buildings as an expression of wealth, extravagance, power and grandeur. This effect is often achieved through the use of rich materials, colours and other features such as art installations, planting, waterfalls, sculptures and lighting.

Corporate buildings may use an atrium to reflect the organisation's ethos and identity. Deutsche Post AG tower Bonn, Germany (Figure 1:4) by Murphy & Jahn successfully employed an atrium to express transparency and sustainability within their head offices. The iconic Greater London Authority building by Norman Foster and Partners, completed in 2002, on the south bank of the Thames is an important landmark for the city (Figure 1:5). Foster's website states that, learning from the Reichstag project, this building "expresses the transparency and accessibility of the democratic process…" (Foster and Partners, 2011).

Figure 1:4 Deutsche Post Tower by Murphy & Jahn, 2002 (http://archrecord.construction.com/features/aiaAwards/04architecture.asp)

Figure 1:5 The Greater London Authority, Foster & Partner, 2002 (http://www.fosterandpartners.com/Projects/1027/Default.aspx)

1.4.2 Circulation, Entrance and Lobby Areas, Social and Amenity Spaces

One of the predominant uses of an atrium is to provide a welcoming entrance and circulation space. An example of a top-lit atrium, which has been effectively designed and used for its circulation potential, is the Guggenheim museum in New York by Frank Llyod Wright. Visitors entering on the ground floor are taken through into the glass dome roofed atrium which is defined by a helical, spiral ascending pathway on its periphery extending the height of the building and taking visitors to collections housed within the museum (Figure 1:6).

Atria can become significant nodes ensuring appropriate circulation, orientation and way-finding in educational buildings, which are often characterised by large circulation areas and somewhat illegible layouts. Here, atria can serve as vital assembly and spinal spaces that aid circulation (Saxon, 1994). The Business Academy Bexley adopts an open-plan compact design based around three atria that were dedicated to the disciplines of business, art and technology. These atria visually and functionally link teaching spaces of the different educational disciplines on different levels (Figure 1:7).

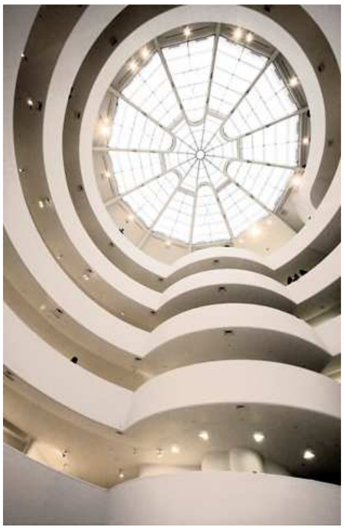


Figure 1:6 Guggenheim Museum, New York by Frank Llyod Wright (http://www.jmg-galleries.com/blog_images/121506_guggenheim_III_520c.jpg)

Figure 1:7 Atrium space of the Business Academy Bexley (http://arts.guardian.co.uk/pictures/image/0,8543,-10505012002,00.html)

The concept that “medical care cannot be separated from the buildings in which it is delivered,” and that “the quality of space in such buildings affect the outcome of medical care” is gaining increasing attention (Gross et. al, 1998). Effective healing environments have been proven to produce quantifiable effects on the patient experience, including reduced pain medications, shortened lengths of stay, decreased operational expenses, enhanced patient satisfaction, higher staff retention and increased and recaptured market share (Tidwell and Sowman, 2002). In this context, atria are used in a range of healthcare settings to provide daylight in typically deep plan buildings; to improve way finding, legibility and orientation; to aid circulation and provide visual access and importantly to create an uplifting and healing environment. Naturally lit, centrally located atria are often used to pull together complimentary yet diverse functions of primary and community healthcare, social care and community services, forming the vital heart of these buildings as shown in the example of the Knockbreda Centre in Belfast (Figure 1:8).

Figure 1:8 The Knockbreda Centre Atrium (http://www.penoyre-prasad.net/)

Increased urban densities and inner city living in the 20th Century has led to the increase in high-rises and collapse of the public realm and public spaces (Pomeroy, 2007) that are now being reinterpreted in vertical structures through sky-courts, sky gardens and atria (for example, the Commerzbank in Frankfurt discussed later in the Chapter). In tall buildings, in particular, an atrium may soften the transition between the building’s height and the ground, and may act as an invitational mechanism for drawing people into the building. Such spaces could embrace a multitude of functions, act as breathing transitional and social amenity spaces at height, improve visual links and create lively and sustainable mixed use vertical communities.

1.4.3 Extensions, Refurbishments and Conservation

Architects and conservationists have used atria to revive deep plan historic buildings, to resolve difficult sites and sympathetically link existing and new buildings with the intention of refurbishing, extending, accommodating new uses or giving a new life to an existing building. The glass canopy over the Great Court at the British Museum in London has enabled the sensitive refurbishment of this very important structure, its facades, character and function (Figure 1:9). The atrium roof floats above the structure admitting abundant daylight whilst providing weather protection to the public spaces housed within the atrium space (Anderson, 2005). The Manchester Art Gallery project by Hopkins Architects employed an atrium to link the new wing of gallery space with the former City Art Gallery and Athenaeum (Figure 1:10). Several perimeter block developments with a central courtyard typically of varying merits and with multiple owners are joined together by a central atrium space (Saxon, 1994).

Figure 1:9 Great Court, The British Library in London by Foster and Partners (http://www.tiredoflondontiredoflife.com/2010/03/admire-british-museums-great-court.html)

Figure 1:10 Atrium of the Manchester Art Gallery by Hopkins Architects (http://www.superstock.com/stock-photos-images/1801-18377)

1.4.4 Urban Connectors

Saxon (1994) notes “exterior and interior public space, defined by built form, is the foundation of good urban design”. Atria enable transition between the public and private realms and are often used to connect buildings to their context (the urban fabric, infrastructure and the wider city) and to create pedestrian routes and sympathetic building masses in cities. At Scotia Plaza, headquarters of the Bank of Nova Scotia in Toronto, a striking 11 storey atrium is used as an entrance connecting a 68 storey office tower with the historic limestone bank headquarters building and with the below ground level pedestrian concourse which links this development to Toronto’s PATH system of retail and subways (Figure 1:11). The DZ Bank HQ in Frankfurt by Kohn Pedersen Fox is a mixed use project which responds to its low rise office and residential neighbourhood by surrounding its office and residential tower with a low rise office and retail podium comprising a central atrium winter garden (Figure 1:12). Here, the atrium helps “to moderate the scale transition” (Brown and DeKay, 2000) making the building compatible with its neighbours.

Figure 1:11 Scotia Plaza by WZMH Partnership (http://www.manhattanarts.com/readingroom/ ezine/CreativeProcess/Rubin_Toronto.htm)

Figure 1:12 DZ Bank HQ in Frankfurt, Germany by Kohn Pedersen Fox (http://www.kpf.com/project.asp?R=3&ID=21)

A notable feature of the atrium of the Bullring in Birmingham is that it builds on the existing historic street patterns of the city to create vibrant, day-lit internal streets that now form part of the wider network of public spaces of this city (Figure 1:13) (Benoy, 2011).

Figure 1:13 The Bullring, Birmingham by Benoy Architects
(http://www.facadeds.co.uk/projectportfolio/bullring-birmingham.ashx)

1.4.5 Environmental Atria

With the onset of climate change, energy crisis and consequently more energy consciousness, the design of the modern atrium is being reconsidered, often with the rationale of climate modification and energy-efficiency. Baker and Steemers (2000) stated "Accepting the atrium is now a very common feature in large public and commercial buildings; it becomes all the more important to ensure that it does not commit the building to a lifetime of high energy consumption". Potential reduction in a building's energy dependency with the use of an atrium is achieved mainly through optimising daylight and reducing the use of artificial lighting, the thermal buffering effect that it creates, and passive solar heating and cooling. Figure 1:14 shows the environmental functions of an atrium as presented by Terry Farrell and Ralph Lebens (Saxon, 1986).

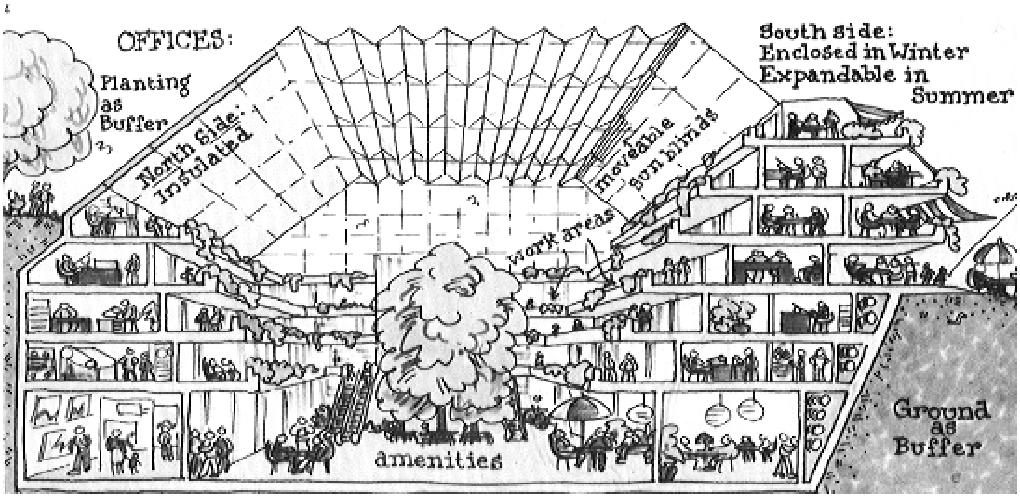


Figure 1:14 The Sheltering Atrium from Terry Farrell and Ralph Lebens' Thesis 'Buffer Thinking' (Saxon, 1986)

The Buffer Effect

Since the late 20th century, atria have become extremely common as buffer spaces (Saxon, 1983) between the exterior and interior in large scale urban architecture that may not be fully conditioned but bring in the daylight while excluding the wind, rain and temperature extremes. As buffer spaces with temperatures higher than the outdoor temperatures, they reduce heat losses in winter but they are prone to overheating in summer and require appropriate ventilation and shading.

Heat flow through walls is a result of difference in temperature between two sides of the wall; the rate of flow is slowed when the atrium temperature is between that of the inside and the outside. This effect is maximised and is successful in energy terms when an atrium space is not fully conditioned to provide full comfort (similar to the adjoining space), and when the ratio of exposed surface to interior surface is at its lowest. Therefore, when the occupied spaces are heated or cooled, the atrium reduces heat gain or loss through the buffering effect.

Passive Heating and the Greenhouse Effect

Atrium aids passive solar heat collection and pre-warming of trapped air reducing the use of mechanical heating and conserving energy. In office buildings, the heating load is much less than cooling and lighting loads because much heat is provided by the occupants, equipment and artificial lighting. However, in cold climates, in winter, or other building types such as hotels, housing or museums, heating considerations become more significant. Considering the climate and thermal nature of the building's form and use, it is necessary to decide between an atrium that collects heat (the warming atrium), one that rejects heat (the cooling atrium), and one which attempts to do both depending on the season (the convertible atrium). Additionally, it is vital to determine comfort requirements of the atrium space as this would inform the relationship between the atrium and its adjoining spaces, atrium envelope design, and the air-handling concepts that can be considered as follows (Saxon, 1983):

- "Complete separation between occupied space ventilation and the atrium
- Intake of primary air via the atrium, the rest separate
- Exhaust of used, clean air into the atrium, the rest separate
- Use of the atrium as a supply air plenum to occupied spaces
- Use of the atrium as a return air plenum"

Most atria function in the direct gain mode when heat is retained due to the greenhouse effect allowing short-wave solar radiation to enter through the glazing and warm interior surfaces but not allowing the longer wavelength re-radiated heat to pass through the glass (Bednar, 1986; Saxon, 1983). To store heat from direct sun, the atrium surfaces should be of dark colour, low-reflectance, dense mass, which is contrary to the needs of distributing daylight and therefore other surfaces are required to assume the role of thermal mass storage elements.

Ideally atria should be used as unconditioned transitional/circulation spaces that require no net energy expense. This captured direct heat gain in the atrium space in addition to heat stored in thermal mass, additional heat gains from adjoining spaces depending on the nature of the thermal separation between the two and recirculation of warm air from the top of the atria can provide heating in winter (Bednar, 1986).

The atrium space can also effectively function like a sunspace of an isolated gain system where solar energy is collected and stored in the atrium space with provision for transfer to the adjoining spaces either naturally or mechanically (Bednar, 1986). For this, the atrium requires direct, glazed southern orientation, high thermal mass storage located in the atrium space (walls, floor) or linked thermally to it (remotely located pools of water or rock beds). The isolated gain passive solar heating approach is inefficient due to the use of large volume of air as a solar collector. Therefore a more efficient and economical approach is to use it to augment mechanical systems typically used in large scale buildings.

The atrium also acts as a return air plenum whereby heated air from the adjoining spaces is reused to heat the atrium. This return air can be partially reheated along with the fresh air introduced in the atrium by solar radiation through the atrium glazing. The air will stratify and can be drawn from the top of the atrium space and recycled through the heating system, in the process exhausting stale air from the building and adding fresh air into the building as necessary.

In the northern hemisphere, cool climates, a south facing atrium with sunshades can be designed and oriented to admit low angled winter sun but keep out the high angle solar penetration. Appropriate orientation and proportioning of the atrium space including the skylight is vital to maximise the solar potential of the southern exposure whilst not reducing daylight. North/south oriented atriums are preferred in comparison to east/west oriented glazed walls because of the problems of controlling low angled sun (Bednar, 1986).

Proportions/aspect ratio of an atrium will determine the amount and location of solar radiation and daylight that reaches atrium surfaces and therefore influences passive solar design. With this in mind, the Section Aspect Ratio (SAR) is more important than the Plan

Aspect Ratio (PAR) (Bednar, 1986). High SAR means that solar radiation does not reach the lower levels and the atrium floor. However, intense solar radiation at the atrium top would result in higher stratification and therefore higher convective flows useful for passive cooling. On the other hand, low SAR atrium would be useful for daylighting, passive heating, and radiative cooling.

Since atria are highly glazed spaces, conserving heat is an important consideration and can be achieved through use of insulating glazing, low emissivity (passage of radiant heat energy) but high transmittance glazing (passage of visible light), highly insulated opaque roof and facade elements, and appropriate thermal breaks in the window and skylight systems. The nature of the atrium wall surfaces will depend on the degree of thermal uncoupling determined by the energy strategy of the building. If the atrium is unconditioned, atrium walls can be treated as external walls with similar insulating properties and infiltration. However, these walls also admit daylight into the adjoining spaces and require significant amount of glazing in them. Therefore, trade-offs between these different requirements have to be considered.

Early examples such as the Children's Hospital in Philadelphia uses south facing court with heavily insulated outer walls but light and highly glazed partitions between the atrium and its surrounding spaces. The building uses atrium as a return-air plenum and passive solar winter collector with summer sun avoided using ventilation and shading to the roof and south facade.

Passive Cooling

Atrium buildings are usually used during the hottest part of the day and as a result they are thermally heavy, i.e. have high internal heat gains, making cooling necessary. "Cooling requires a higher level of energy expenditure per degree of temperature reduction than does heating per degree of temperature increase" (Bednar, 1986). Therefore, daylighting is critical to energy efficiency as it not only reduces energy consumption for lighting but also reduces cooling loads for the heat generated by artificial lighting.

In atrium buildings, passive cooling techniques include control of solar heat gain through shading, use of thermal mass, radiative cooling and convective cooling. However, even a combination of the different passive cooling techniques may not be enough for a large scale, enclosed atrium and may require some form of mechanical aid.

Atrium Shading: The atrium is likely to be free-running in summer and may be prone to overheating due to a combination of excessive solar radiation and heat gains from surrounding spaces. Although the atrium will enable self-shading of interior surfaces, some form of shading to the atrium roof may be required to keep the heat out. Solar orientation is an important aspect for shading the atrium walls and floor. High SAR atriums with skylit roof top can be effective in terms of shading. In climates where it is hot in summer and cold in winter, southern orientations should include horizontal sunshades whereby high angled summer sun is kept out while the low angled winter sun is admitted. Adjustable control elements can be added to the roof and wall surfaces to avoid overheating and loss of daylight.

Thermal Mass: The use of high thermal mass in the form of exposed concrete in the atrium can absorb heat in the day. This can be coupled with night-ventilation where cool night air is used to reduce the temperature of the high thermal mass components to form an effective cooling strategy.

Radiative Cooling: For radiative cooling of the building, the cold night and polar sky can be used in the day as a heat sink enabling heat flow from warmer atrium to cooler sky. This strategy is most effectively achieved through unobstructed, horizontal roof surfaces, the least through vertical surfaces while the atrium floor achieves only indirect radiative cooling (Bednar, 1986). The radiative potential of the sky reduces as the humidity and cloud cover increases.

Convective Cooling: Thermally driven convection is the most direct of the cooling techniques, particularly in high SAR atria. The greenhouse effect in an atrium causes highly buoyant warm air to stratify in the tall atrium volume. Vertical pressure differential is created due to this air stratification (as a result of different air temperatures and densities) causing stack effect whereby air moves from lower openings to higher ones in an enclosed volume. Hot air escapes from the vents/louvers in the atrium roof; this is replaced by cool air from the bottom of the atrium and the adjoining spaces causing convective flows.

Convective cooling is most effective at night when cool air is used to regulate temperatures in the building interior. During the day convective air movement and evaporative cooling can be used to reduce skin temperature and aid user comfort. Thermally driven convective cooling can be aided through use of exhaust fans at the top of the atrium to draw warm air from the adjoining spaces in the atrium space, which acts as a heat sink before exhausting it.

Whilst naturally ventilated atria are usually designed for stack effect, wind induced convections for cooling can be very effective. Whether thermally driven or wind-induced convection strategy is used, location and size of the vents remain the same with exhaust vents located at the highest point in the atrium, on the leeward side if it is wind-induced. The atrium roof could be raised above the rest of the roof to create a hot air reservoir above the occupied areas of the building while the cool air should be drawn from as low level as possible (Bednar, 1986).

Despite the energy potential of atria, atrium buildings are often inefficient due to the constraints presented by particular site characteristics, construction economics and a building's programme, including its pursuit of iconic architecture whilst disregarding the environmental aspects. While considering the energy strategy of an atrium building, Bednar (1986) highlighted the key factors that should be assessed as the local climatic and site conditions, daily and seasonal building and energy use patterns, the use of the atrium and the degree of comfort and conditioning required in it, and economics i.e. capital cost versus operating cost, fuel costs and availability.

With dynamic climatic changes it is difficult to develop architectural solutions that meet optimum requirements under all conditions. Heating and cooling requirements can vary during the day and for different areas of the building, and daylight availability and performance varies with changing sky conditions and sun positions. Passive design strategies such as appropriate orientation and building fabric as well as advanced glazing technology can be used to respond to these varying conditions. Moreover, mechanical controls in the form of movable shading devices, adjustable artificial lighting systems, sophisticated fire and smoke control, and air handling equipment can be employed to improve the environmental performance of atria.

Therefore, while an atrium building as a generic spatial type has the potential for energy conservation, realisation of the environmental (thermal, ventilation and daylight) benefits relies on the thorough evaluation of all the various contrasting performance variables and the complex trade-offs between them to achieve an optimised solution whilst retaining the design integrity and its inherent architectural merits.

In the 57 storey triangular plan, Commerzbank in Frankfurt, the arrangement of a central full height atrium, flanked by 16.5 metres shallow office spaces on its two sides, and a series of four storey 450 m^2 sky gardens on its third side enable daylight and natural ventilation in the offices (Figure 1:15) (Zaknic, et al., 1998). The offices and sky-gardens rotate around the central atrium at every four storeys forming a spiral of landscaping and vertically stacked 12 storey clusters of offices. The design allows light to penetrate the building from different directions with those working close to the atrium receiving light from the glass roof above and the sky court across (Figure 1:16). In winter, light is admitted into the office spaces horizontally penetrating deeper through the glazed facades and sky gardens. In summer, when the sun is higher up, light is reflected by the atrium facades to reach the adjoining offices (Pepchinski, M., 1998). To improve daylight conditions, reflective materials have been used and although this has led to higher light levels, it has also increased glare and consequently resulted in the incorporation of anti-glare devices, additional costs and potential loss of thermal mass/free heat (Volker and Fruneish, 1997).

The atrium itself has horizontal transparent glazed screens every 12 storeys for fire safety, to help control strong upward drafts within the atrium space and to avoid thermal stratification (Zaknic, et al., 1998). Cross-ventilation is also a strategy employed by the Commerzbank Tower. In a typical 12 storeys cluster of offices, warm air from the offices rises through the atrium and is exhausted from operable panels in the topmost sky-garden, while for additional cooling in summer, panels from the lowest sky-garden are opened to draw in cool fresh air (Pepchinski, M., 1998). This strategy allows 12 storey clusters of offices to be controlled independently based on the readings from their own weather stations (Evans, 1997).

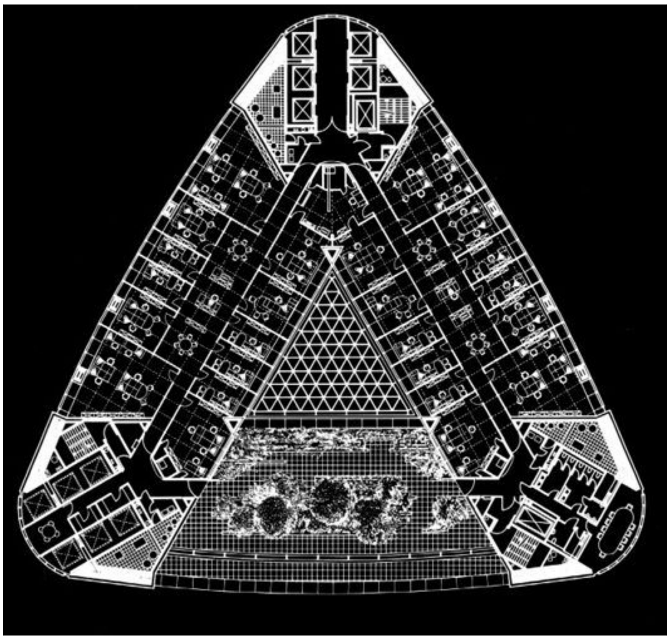


Figure 1:15 Commerz bank, Frankfurt: Plan
(http://www.fosterandpartners.com/Projects/0626/Default.aspx)

Figure 1:16 Commerz Bank, Frankfurt and its sky-garden
(http://www.fosterandpartners.com/Projects/0626/Default.aspx and
http://www.siteselection.com/ssinsider/snapshot/sf020429.htm)

Creative environmental solutions and improved energy efficiencies are also a result of technological advances and often complex geometries that are realised due to advanced computational capabilities that can be applied to the design and analysis of building structures. Although this has resulted in performance based design approaches and cost effective solutions, it requires early collaboration with environmental engineers.

Deutsche Bank Place - 126 Philip Street, Sydney is a premium sustainable mixed use tower by Foster and Partners and Hassell Pty Ltd which is a result of extensive whole building energy modelling and a meticulous and transparent process of measurement and assessment. This 31 storey building consists of three components: large, flexible column-free office floor plates; an offset core that houses building services and vertical circulation; and a transitional zone with a full-height atrium between the two (Figure 1:17). The atrium is used to admit daylight into the offices and to the lower reaches of the building. It also acts as a buffer zone to the possible heat transmission and solar radiation to the office floor plates. Finally, as part of the building's mechanical system, controlled exhaustion of the heat and smoke from the office floors is also made possible up through the atrium space (Foster and Partners, 2003). To ensure that the aesthetic, environmental, technical, fabrication and installation requirements were met, different facade typologies were developed. Mock ups of facade prototype test panels were manufactured and tested for the building's external and atrium facades to ensure high levels of light penetration into the atrium and the office floor plates (Bressi, 2005).

Figure 1:17 Deutsche Bank Place - 126 Philip Street, Sydney (http://www.skyscrapercity.com/showthread.php?t=349895 and http://www.papertopaper.com.au/admin/site/thumbs/30_30_30_Deutsche_Bank_Place_126_Phillip_St.jpg)

1.5 RESEARCH AREA

The previous section demonstrated that the potential use of atria to successfully address social, economic and environmental issues has made a compelling case for their incorporation in buildings.

The focus of this thesis is to examine the daylight potential of atria as it is recognised to be one of the key aspects of the atrium form, contributing to a building's aesthetics, experience and environment.

Atria allow for the adjoining spaces to have larger windows to admit daylight without considerable heat losses or heat gains. This potentially increases the amount of occupied space that can be naturally lit, and replaces artificial lighting which is typically the primary cause of energy consumption in commercial and office buildings, particularly when its associated cooling load is considered.

Within an atrium, daylighting helps to define the atrium space and animate it. In the adjoining spaces, daylighting can improve illuminance distributions, thereby reducing the problem of brightness imbalance which can occur in unilaterally glazed rooms in deep plan buildings, and reduce the use of artificial lighting. If the requirement is to save energy in adjoining spaces by displacing electric lighting, then even higher levels of daylight may be required in the atrium, bringing with it the risk of glare and unwanted heat gain and/or loss consequently resulting in an increase in the energy consumption. The successful design of an atrium is therefore a fine balance between interdependent factors such as daylighting, heating, cooling and ventilation, as well as taking into consideration aesthetic and functional aspects.

Goncalves (2007) highlighted the use of different types of atria as one of the key strategies that have led to the improved daylighting in office buildings.

The Lloyds register of Shipping in London by Richard Rogers has two glazed atria slotted between the radiating 14 storey office wings allowing daylight to penetrate the office spaces, providing views in and out of the building and acting as a thermal buffer between the offices and their external environment. Atrium's glass balustrades, and glazed and light opaque atrium facades and the floor act as light reflectors enhancing the lighting conditions and lending transparency to the atria (Figure 1:18) (Rogers Stirk Harbour + Partners, 2011).

In the Century Tower in Tokyo by Foster and Partners, the strategy of a top and side lit atrium with highly reflective surfaces combined with shallow adjoining floor plates and column free double height office spaces with suspended mezzanine floors that are open to the atrium create a day-lit environment (Figure 1:19) (Foster, 1992).

Figure 1:18 Atrium in the Lloyds Register of Shipping, London. (Photo by: Katsuhisa Kida / FOTOTECA)

Figure 1:19 Century Tower in Tokyo by Foster and Partners (http://www.fosterandpartners.com/Projects/0409/Default.aspx)

The Evelina Children's Hospital in London, by Hopkins Architects, is characterised by wards on its one side and the giant roof of the atrium which is essentially a big, curve of glazing that meets the atrium floor (Figure 1:20). This arrangement, along with the use of highly reflective surfaces brings daylight to the atrium and importantly into the adjoining ward spaces.

Figure 1:20 Evelina Children's Hospital, London by Hopkins Architects (http://www.hopkins.co.uk/projects/6,9/)

The Swiss RE HQ in London, designed by Fosters and Partners, is a circular plan 41 storeys building which has six triangular shaped atria carved out from the plan's edges on each floor; these are joined vertically and spiral up the facade with a five degree shift on each floor (Figure 1:21). These triangular atria create six rectangular modules of office spaces; the atria are enclosed at every sixth floor and are essentially social/meeting spaces (Zukowsky and Thorne, 2000). The tower's diagonally braced structural envelope creates column-free floor spaces and enables a fully glazed facade, which along with the atria enable daylight penetration and views (Foster and Partners, 2011).

Figure 1:21 30 St Mary Axe, London
(http://www.fosterandpartners.com/Projects/1004/Default.aspx)

The Heron Tower, in London, implements atria in its design by vertically sub-dividing the 36 storey building into three storey separate 'blocks'/villages, where each village is connected by a three storey atrium space on its glazed north elevation (Figure 1:22). The two upper floors on each sub-divided 'block' are recessed at the centre allowing daylight to flood the internal spaces and reduce their dependency on artificial lighting. The considered orientation of the building and the atria cuts out any need for solar shading. This solution addresses the problem of unequal daylight distribution characteristic of tall atrium spaces (Slavid, 2006).

Figure 1:22 Three Storey Atria in the Heron Tower, London (Photo by: Kohn Pedersen Fox Associates PC)

1.5.1 Atrium Design Parameters

Daylight performance of an atrium is complex and depends on the predominant sky conditions in which the building stands, the nature of its roof and fenestration system, atrium orientation and geometry, design of the atrium facades including reflectance of its walls (glazed and opaque areas) and floor surfaces, and the characteristics of the adjoining spaces.

Climate and the sky conditions have a great influence on the way light behaves in an atrium. Consequently varied approaches are adopted to suit the different climatic conditions. For the temperate climate of Britain and the rest of Northern Europe, daylighting expectations are based on overcast skies. The ideal atrium in these circumstances is largely top-lit, and with a clear, unobstructed glazed roof to achieve the maximum transmission of light. The roof configuration not only dictates how much light enters the atrium but can affect its direction in a significant way. The fenestration system will control the intensity and spatial distribution of light entering the atrium. The net transmittance of the fenestration will vary with glazing system, geometry, glazing orientation and type, shading system and the illuminance conditions.

Although it is the transmittance of the roof structure that determines how much daylight enters the atrium, it is the design of the atrium wall surfaces and their reflectance properties that dictate how daylight is distributed about the atrium and its adjoining spaces, which this study examines in a four-sided, top lit, square shaped atrium. In addition to the atrium boundaries, the size of an atrium and its configuration, known as the atrium type, can affect the amount of daylight that penetrates it and its distribution. In general, the shallower and wider the atrium space, the better the contribution of direct daylight to the adjoining spaces.

Although the daylight potential of an atrium has been recognised widely, atrium buildings have a tendency to not utilise daylight successfully in spaces adjoining the atria. Daylight levels within the atrium space are generally sufficiently high. However, this may not be the case for spaces adjoining the atrium, where daylight varies significantly with every floor level. Rooms on the top floors can be over-lit and suffer from glare while daylight levels on the lower floors can be low, particularly in tall/deep atria. One of the key parameters which plays a fundamental role in the way in which light is distributed within the atrium and its adjoining spaces is the atrium facades that this study aims to investigate. A brief review of this subject area is outlined in the next section from which the thesis aims are drawn.

1.6 BACKGROUND TO THE STUDY

Over the past three decades, extensive research on atrium buildings has been undertaken and resulted in peer-reviewed publications, conference proceedings, research reports and handbooks. Most notably, Richard Saxon's books "Atrium Buildings: Development and Design" (1983) and (1986), and "The Atrium Comes of Age" (1994) present a historical development of the modern atrium and include notable case studies. Furthermore, Michael Bednar in his noteworthy book "The New Atrium" (1986) illustrates the role of atria in key building types: hotels, shopping and leisure developments, office buildings, public buildings and multi-use structures; and discusses key design aspects of atria including environment, structure, vertical transport and economics. Glazed spaces have been studied in detail by Chartered Institute of Building Services Engineers (CIBSE), the International Energy Agency

(IEA), the American Society of Heating, Refrigerating and Air-conditioning Engineers, Inc. (ASHRAE) and the Building Research Establishment (BRE) that have resulted in guidelines on the design of atrium buildings.

The importance of daylight in an atrium's environmental performance has led to several investigations of daylighting in atria and their adjoining spaces. Case studies, scale models, simple formulas and computer programmes have been used by various authors to provide design aids and simple guidance quantifying the effects of varying daylight linked atrium parameters.

In an atrium well, Daylight Factor (DF) comprises of the sky component (SC) and the internally/atrium reflected component (IRC/ARC) from the atrium's enclosing surfaces (walls and floor). Therefore, wall reflectance has a direct and significant impact on the inter-reflectance occurring inside the light well and determines the distribution of light in the space, and the amount of light that reaches the adjoining spaces.

1.6.1 Atrium Surface Reflectances

Letherman and Wright (1998) highlighted the increasing impact that the internally reflected component of daylight has in deep atria. Mabb (2008) confirmed that light levels in the adjoining spaces are affected by the geometry, reflectivity and glazing of the atrium and its adjoining space. For design calculation purposes, the range of reflectances in an atrium is usually represented in terms of a single, area-weighted mean reflectance for estimating the average daylight factor (ADF) (Littlefair and Aizlewood, 1998), or the ARC of the DF (BRE Digest 310, 1986). Although this approach simplifies the calculation procedure, it does not help in identifying how the different distributions of reflectances around an atrium that are evident in real buildings actually produce different values of daylight factor (DF) or atrium reflected component (ARC). Most atria will consist of bands of different reflectances, both in value and in surface properties.

Letherman and Wright (1998) suggest that the influence of surface reflectances on daylight levels in atria and their adjoining spaces is complicated to model mathematically and most standard daylight calculation techniques do not transfer easily to atrium buildings. Consequently, many studies on this subject have been carried out using physical scale models or computer simuations. Oretskin (1982); Willbold-Lohr (1989); Navvab and Selkowitz (1984); Cartwright, (1986); Aschehoug, (1986); Liu et al., (1991); Baker et al. (1993); Iyer (1994); Boubekri (1995); Aizlewood et al. (1996); Aizlewood et al. (1997); Clarke et al. (1999); Matusiak et al. (1999); Fontoynont (1999a); Calcagni and Paroncini (2004); Mabb (2008); Lau and Duan (2008); and Du and Sharples (2009b) demonstrated that higher atrium wall reflectances improve daylight levels in an atrium building.

Aizlewood et al. (1996) carried out parametric physical model studies of the atrium surface characteristics, the atrium geometry and the geometry of the adjoining spaces. An approximate analytical expression for the atrium reflected component, ARC, was also developed. Comparison between predicted and measured ARC values suggested that the analytical expression had the correct general form, but that it underestimated ARC values for high reflectance surfaces. In a second paper Aizlewood et al. (1997) performed a similar study but now also compared their data with predictions from the computer program, RADIANCE. Sharples and Lash (2007) in their review paper observed that "Despite the simplicity of their models Aizlewood et al., (1997) failed to correlate measured ARC values with calculated values, demonstrating the complex and as yet poorly understood behaviour of reflected flux, particularly when highly reflective surfaces are used".

Fontoynont (1999a) confirmed that indoor finishes and glazing materials contribute to illuminance levels in buildings and in particular they can be major contributors to the daylight availability in areas that are further away from the apertures. For atria of several different well indices, Calcagni and Paroncini (2004) evidence that whilst increase in the wall reflectance increases the DF, it does not produce a significant improvement in the DF on the ground floor due to the large, high transmittance glazed areas typically seen on this floor, thereby reducing the amount of opaque surfaces that can reflect light. One feature of most of the above studies is that the effect on the atrium reflected component (ARC) of varying the distribution of the reflectances around the atrium well was not investigated. Reflectance patterns are altered by introducing bands of openings, this inevitably produces changes in the area-weighted reflectances of the atrium surfaces. Most atria will consist of bands of different reflectances both in value and in surface properties. This is due to the fact that atrium facades comprise of a sequence of horizontal bands of glazed openings and opaque surfaces that correspond to the several floors of the adjoining spaces they envelope.

This study investigates how the different reflectance distribution patterns, for the same overall area-weighted reflectance value, affects DF and ARC in a simple four sided, top lit atrium model using physical scale models. The experiments are repeated using the computer simulation program, RADIANCE, to justify its use for the subsequent experimental work undertaken in this thesis.

Well Index (WI) is an indicator of the geometrical proportions of an atrium space, where a higher well index means the atrium space is deep and narrow. Conversely, a low well index indicates that the atrium space is shallow and wide. Letherman and Wright (1998) state that as the WI decreases, the ARC potentially increases due to the increase in the relative size of the atrium walls with respect to the atrium floor. However, the view factor between the atrium's walls and sky vault is small resulting in a lower wall luminance. As the WI becomes very low however, the ARC would be expected to decrease, due simply to the fact that the opportunity for inter-reflectance is reduced significantly. However, it is vital to understand how the atrium geometry influences the ARC and therefore DFs in an atrium building and to establish the range of well indices over which reflectance distributions can affect the daylight levels. Willbold-Lohr (1989); Baker et al. (1993); Boubekri (1995); Boubekri and Anninos (1996); Aizlewood et al. (1996); Aizlewood et al. (1997); CIBSE (1999); Calcagni and Paroncini (2004); Mabb (2008) and Du and Sharples (2009b) have examined the influence of both atrium geometry and atrium enclosing surface reflectances, on the daylighting conditions in atrium buildings. While Oretskin, 1982; Willbold-Lohr, 1989; and Baker et al. 1993 show that the wells of square plans receive better illumination than rectangular/linear plans at a given level, Liu et al. (1991), Matusiak et al. (1999), Calcagni and Paroncini (2004), Lau and Duan (2008) and Du and Sharples (2009a) demonstrate that whilst keeping height the same, increasing the length of the atrium increases the light-admitting area (or reduces WI) and consequently the DFs. Therefore, there is a lack of agreement in the findings of the previous studies in relation to the atrium well indices and geometries in which the DFs are affected due to the atrium wall surfaces. Additionally, these studies do not examine the effects of varying reflectance distributions on DFs in atria of different well indices.

1.6.2 Fenestration

Several authors (Willbold-Lohr, 1989; Cole, 1990; Aschehoug, 1992; Szerman, 1992, Iyer, 1994; Boubekri 1995; Matusiak et al., 1999) suggest that the proportion of window area feeding light into the adjoining spaces should vary between the floors of the atrium. Since most daylight is available at the top of the atrium, adjoining spaces need the smallest windows to achieve desired daylight levels. A progressive increase in the amount of openings from upper to the lower floors can lead to higher DFs available at the bottom of the atrium. Willbold-Lohr (1989) studied different facade apertures in square shaped atria and demonstrated that at the base of the atrium, in comparison with white facades, facade aperture with 50% window openings reduced the ARC by half, and with 100% glazing the ARC reduced to third and was mostly dependant on the skylight. While Cole (1990) concluded that variable openings in atrium facade with 100% opening on the first floor, 80% on the second, 60% on the third, 40% on the fourth and 20% on the top floor was most effective in terms of bringing daylight on the lower floors adjoining a square atrium in comparison with a 100% glazed and a 50% glazed atrium facade. Aschehoug's (1992) recommended optimum glazing ratios for a glazed street of infinite length of 100% on the first floor, 70% on the second floor, 60% on the third floor and 50% glazing on the fourth floor to give quite similar daylight conditions in the adjoining spaces on all of the floors.

Undertaking physical model studies for a linear atrium, Matusiak et al. (1999) evidence that varying glazing area or glazing type results in a small but important increase in daylight on the atrium floor and improves the balance of lighting in the adjoining spaces. Equations were established to estimate the DFs in the adjoining spaces. Calcagni and Paroncini (2004) provided a relationship between the main architectural components of an atrium (geometry, material properties, fenestration system, atrium roof) and the daylight conditions in the adjoining space and on the atrium floor.

Whilst there is general consensus in terms of the positive influence of progressive increases in openings from the top to the atrium floor on the daylighting conditions in the adjoining spaces, an area of continued uncertainty is whether a particular incremental approach to fenestration from the roof to the floor of an atrium's facade might be advantageous in terms of improved daylighting in an atrium building.

Therefore, in summary, several studies have identified atrium surface reflectances as one of the key factors impacting on the daylight performance of atrium buildings; it is this parameter that the thesis concentrates on. It also seeks to gain a better insight on the effects of different fenestration distributions on the daylight conditions in an atrium and its adjoining spaces for an open, four sided, top lit, square atrium building under overcast sky conditions through a series of related parametric studies. The reflectances and well indices used in this study are representative of the built atria as identified by Liu et al.'s (1991) survey. The four-sided square atrium is chosen as it provides the least opportunity in terms of admitting daylight in comparison with a two-sided or a three–sided atrium, and therefore the study examines the worst case scenario and the possible improvements that can be achieved in it.

1.7 RESEARCH AIMS

With growing environmental concerns, architects are increasingly adopting passive design strategies to improve the buildings' performance. Considering the multiple and complex functions of buildings, this often involves intuitive and complicated design processes with little time and funds for detailed environmental analysis, particularly to test initial design solutions. Despite the widely developed and easily accessible computer simulation programs available for the assessment of daylight, ventilation and heating, it is often difficult, without bringing in environmental consultants, to test the performance of the design solutions that would inform the design process and its development at its inception. Therefore, an understanding of the general principles and developing of the design guidelines for the early stages of the design process would be useful for the architects and designers.

The decision to incorporate an atrium space, its relationship with the adjoining space, its geometry and envelope are some of the factors that are determined early in the design stage, which means that the daylight conditions as well as the energy requirements of the atrium and its adjoining spaces are also determined at this stage. Therefore it is vital to establish the influence of atrium facades on the daylight performance of an atrium and its adjoining spaces. In particular, how the different reflectance distribution patterns, and the diffuse and the specular surfaces evident in the atrium facades of a building affects the daylight availability in it. Whilst previous research recognises the influence of atrium facades, given that daylight will only travel up to a certain distance, it is essential to establish the range of well indices in which the atrium facade reflectance distributions may affect the daylight levels. Once this is ascertained it is also vital to establish for an atrium of such a proportion whether particular fenestration ratios using the strategy of a progressive increase in the fenestration from the top to the bottom floor might improve the daylighting conditions in the adjoining spaces.

Therefore, the primary aim of this study is to examine how atrium facades characterised by different surface reflectance distribution patterns, surface types and ratios of fenestration versus opaque areas affect the daylight performance of an atrium and its adjoining spaces under overcast sky conditions.

The findings from this study would enable an understanding of the influence of the atrium facades on the daylighting in atrium buildings and draw specific conclusions in the form of general principles. These could be usefully applied by architects in the preliminary stages of the design process for an improved daylight performance of atrium buildings under overcast sky conditions without entailing detailed calculations or parametric studies.

Having outlined the research aim, the following points summarise the major research objectives:

- To study parametrically the effects of different reflectance distributions in the walls enclosing an atrium on the daylight availability (ARC, DF, ADF) on the atrium floor
- To examine the effects of specular atrium wall surfaces on the DFs at the atrium floor
- To justify the use of RADIANCE for the experimental work, undertake a comparative analysis of the different daylight assessment tools (physical model, standard formula by Littlefair (2002) and RADIANCE simulation) used to calculate the DF and the ADF in atrium buildings and draw specific conclusions with respect to their use
- To investigate the influence of the atrium surface reflectance distributions in different atrium well indices on the DF at the base of the atria
- To understand the impact of atrium facade compositions with varied fenestration and opaque area distributions on the daylight availability in an atrium building. In particular, examine whether a particular incremental increase in fenestration from the top to the bottom floor and ratios of fenestration versus opaque areas might be adopted in an atrium's facade to improve the DFs in its adjoining spaces

1.8 METHODOLOGY

This section outlines the overarching methodology adopted in the thesis to achieve the stated research objectives.

The PhD has been undertaken on a part time basis alongside working as a full-time lecturer in an environment where there is a requirement to publish. Therefore the thesis essentially is a compilation of several small studies, the research outcomes of which have resulted in single authored and co-authored conference proceeding and international peer-review journal publications as the work evolved. Reference to these publications is made in the relevant sections below.

A detailed literature review which chronologically and thematically reviews 30 years of extensive published material of investigations particularly focussing on the influence of the atrium geometry and the atrium facades on daylighting in the atrium buildings is undertaken. Findings from the various studies are discussed and gaps in the research are identified which informed and defined the research focus for this thesis (Samant, 2007 and 2010). Following this, and due to the particular nature of the study, a four step methodology for the research undertaken is adopted as shown below, each of which is discussed in further detail in the relevant chapters.

Step 1: A physical scale model study is undertaken to investigate the effects of different reflectance distributions and surface types on the daylight levels, Daylight Factor (DF) and Atrium Reflected Component (ARC), at the base of a four-sided, top-lit, square shaped atrium. #Different reflectance distribution patterns are developed to reflect the horizontally banded atrium facades in real buildings, composed of glazed and opaque areas. This work was undertaken for the Masters Dissertation entitled “Daylighting in Atria: The Effect of Atrium Surface Reflectances” at the University of Sheffield in 1998. The work was subsequently developed into a journal publication for the International Journal of Lighting Research and Technology (Sharples and Samant, 1999) and formed the basis for the PhD and the subsequent experimental work undertaken.

Step 2: Comparison of the different daylight assessment methods: physical scale models, computer simulation and algorithm is undertaken to ascertain appropriate use of the computer simulation program, RADIANCE, in the subsequent parametric experiments. Due to the focus on parametric studies, undertaking field measurements in real buildings is not appropriate and therefore has not been considered in this thesis.

The physical scale model experiment is repeated via computer simulations using RADIANCE to undertake a comparative analysis of the DF results obtained by the two methods (Samant and Medjdoub, 2004).

Average Daylight Factor (ADF) across the atrium base is calculated from the DFs measured at the centre, edge and corner locations to understand the impact of distributions of light reflecting surfaces on ADFs in atria. ADF values obtained from the physical scale model and computer simulated studies are compared to the values obtained by Littlefair's (2002) formula for ADF at the base of an atrium, ADFb, which uses the area weighted reflectance concept (Samant and Sharples, 2003 and 2004; Samant and Medjdoub, 2006a and 2006b).

Step 3: As an extension of the previous experiments, a computer simulated parametric study using RADIANCE is undertaken. Parametric changes are made to the reflectance distributions in the diffuse atrium well surfaces in atria of WI 0.5, 1 and 2 to establish the impact of the surface reflectance distributions on daylight availability in atria of different well indices (Samant and Yang, 2007a and 2007b).

Step 4: Whilst the previous experiments are limited to the study of daylight levels on the atrium floor, using RADIANCE this final experiment investigates the influence of different fenestration distributions on the DFs in both the atrium and its adjoining spaces. It includes a parametric study of the effects of altered atrium facades composed of fenestration and opaque areas to understand whether particular fenestration ratios and an incremental approach to the fenestration in the atrium facades from the top to the ground floor improves daylight conditions in the spaces adjoining an atrium (Samant, 2010 and 2011).

Using secondary sources, and through a brief survey of specific atrium buildings, where possible, findings from the experiments undertaken in this study are compared with data obtained from real buildings.

1.9 THESIS LAYOUT

The thesis is organised in eight Chapters. Chapters Two and Three include an investigation of the key issues relevant to the current research i.e. daylighting concepts, introduction to the daylight design and performance of atrium buildings. They set the background and general context for the research area.

Chapters Four, Five, Six and Seven consist of the research methodology, analysis and interpretation/discussion of the results of the parametric studies of atrium facades from the physical scale model study and the RADIANCE simulations. Chapter Five includes a comparison of the DF and the ADF results from the different methodological approaches: physical scale model, RADIANCE and the ADF algorithm by Littlefair (2002).

The concluding Chapter Eight outlines key findings from the study and identifies important research areas for the future.

A more detailed presentation of the content of each Chapter is given in the following paragraphs.

Chapter Two starts with an introduction to the key daylighting concepts related to the study. The next section explains the Commission Internationale de l'Eclairage (CIE) Overcast sky which has been used for the experiments undertaken. Following this, an explanation of the DF and the ADF that have been primarily used to assess daylight levels in the atrium buildings for this study is provided. Finally, the Chapter focuses on fenestration to understand its impact on daylight performance of buildings.

Chapter Three provides background information on the research content: the atrium building and its daylight design. The chapter includes an introduction to the daylight linked atrium parameters and covers an extensive literature review of the prediction tools and of the key parameters related to this study: the atrium geometry and the atrium's enclosing surfaces (walls and floor).

The first part of Chapter Four highlights the importance of surfaces and their reflectances on how architecture and the spaces therein are perceived and experienced as elaborately described by Michel (1996). This is followed by detailed information related to the use of physical scale models in day-lighting studies. The final part includes the first parametric experiment which examines the effects of the different reflectance distributions and surface types (diffuse and specular) on the DFs on the atrium floor.

The aim of Chapter Five is to establish the accuracy of the different methods used to obtain the DFs and the ADFs on the atrium floor. To this end a comparative analysis between the physical model study and the RADIANCE simulation is undertaken. The ADF formula proposed by Littlefair (2002) is introduced and the ADF values obtained by the three different methods: physical scale model, algorithm and RADIANCE are also compared.

Chapter Six builds on the experiment undertaken in Chapter Four. It examines the effects of varying distributions of the atrium wall reflectances on the DFs and the ADFs in different atrium well Indices (WI 0.5, 1, and 2). This is undertaken to establish the range of well indices in which reflectance distributions affect the daylight levels. Where possible, data obtained from the RADIANCE models is compared with measured daylight performance data from real buildings available from Fontoynont's (1999a) book.

Having established the range of well indices within which the atrium reflectance distributions affect the DFs and the ARCs in the previous Chapter, Chapter Seven parametrically assesses the effects of different fenestration distributions on the DFs in the atrium and its adjoining spaces. Atrium facade compositions with a progressive increase in openings from the top to the bottom floor as well as those with even openings on all of the floors except the ground floor (100% opening) are tested and compared. This is undertaken to explore whether particular fenestration ratios and an incremental approach to the fenestration from the atrium roof to its floor improves daylight conditions in the adjoining spaces of an atrium building. This is followed by an analysis and discussion of the results and comparisons with monitored data in real atrium buildings, where possible.

In the concluding Chapter Eight, the findings are summarised and specific conclusions with reference to atrium facade design to improve daylighting in atrium buildings under overcast sky conditions are drawn. Conclusions regarding the use of different daylighting assessment tools are drawn and observations on the daylighting strategies used in practice are also made. The Chapter concludes with an outline of the research contributions of this study and its limitations. Finally, the Chapter identifies research gaps and the opportunities for future research.

2 DAYLIGHT IN BUILDINGS: AN UNDERSTANDING OF THE CONCEPTS

2.1 INTRODUCTION

This Chapter sets the scene for the 'daylighting' component of the thesis through an introduction to the key daylighting concepts and definitions including the direct and indirect sources of light; illuminance and luminance; and a detailed analysis of reflectance, absorptance and transmittance.

The second part of the Chapter describes the characteristics of the Commission Internationale de l'Eclairage (CIE) Overcast sky, and explains the concepts and definitions of Daylight Factor (DF) and Average Daylight Factor (ADF) including the methods of calculation that will be used in the subsequent Chapters.

Finally, the Chapter explores the behaviour of light as a result of fenestration in buildings through a focussed literature review; in particular it discusses the side and top lighting strategies and touches upon the glazing and roofing systems. The conclusion summarizes information related to daylighting in the context of the work which is subsequently undertaken in this thesis.

2.2 DAYLIGHTING CONCEPTS

2.2.1 Daylight Sources: Direct and Indirect Sources

Daylight sources are identified in two categories: direct (direct sunlight and diffuse skylight), and indirect "light from reflective or translucent diffusers that were originally illuminated by primary or other secondary sources" (Moore, 1991).

Direct Sources

Daylight consists of two elements: sunlight – the direct beam and skylight – the diffuse light scattered by the earth's atmosphere. Normal (perpendicular) surfaces are illuminated by direct sunlight with approximately 64,500 to 108,000 lux. Direct sunlight is excluded from buildings due to its thermal content and intensity resulting in problems of overheating and visual discomfort (as illumination is far higher than that required for task illumination). However, it also means missing valuable opportunity to create visually delightful and animated spaces where shades and blinds can be used to control glare. “Direct sunlight introduces less heat per lumen into a building than do most electric alternatives” (Moore, 1991) reducing the cooling loads associated with artificial lighting. Problems linked with direct sunlight can be addressed through the use of louvers, shades or translucent material on the building’s interior (reflecting, diffusing, and/or reducing the quantity of light and heat that penetrates) or exterior controls which can be more effective in terms of eliminating the undesirable aspects of the sun.

In cool, cloudy climates, south facing glazing can admit direct sunlight (which is absorbed and converted to heat) which is beneficial for winter heating and creating warmth and brightness. Additionally, a broad view of the sky brings in light from the diffuse sky into the buildings. Moore (1991) gave the definition for skylight and compared it with sunlight. “Sky light is diffuse light resulting from the refraction and reflection of sunlight as it passes through the atmosphere. Under clear skies, the very small size of the atmospheric particles causes only the wavelengths of light in the blue portion of the spectrum to be refracted, imparting a blue colour to the sky” (Moore, 1991). “Under overcast skies, the relatively larger water particles diffusely refract/reflect all wavelengths equally in all directions. This results in a white-coloured sky, about three times brighter at the zenith (directly overhead) than at the horizon” (Moore, 1991). “While sunlight is a point source of illumination, sky light is a distributed (area) light source” (Moore, 1991). Illuminance levels from the sky light are much less compared to the sun light (typically 5000 to 21,500 lux) for an overcast sky.

Whilst the position of the sun is determined very precisely, the relative intensities of the sunlight and skylight are not, as they are affected by weather, water vapour and the effects of pollution. In temperate and tropical humid climates with cloudy skies “daylight is effectively the subject of random variation” (Tregenza and Loe, 1998). Therefore forecasts of sunlight and skylight illuminances in cloudy climates are based on long-term measured statistics of daylight.

Indirect sources

“When a matte reflective (i.e., flat white) surface is illuminated by a primary source (sunlight or sky light), its resulting luminance makes it an indirect source of illumination” (Moore, 1991). For example, sunlight reflected from the ground and other buildings is the main source of interior daylight in hot-dry and Mediterranean summer climates.

2.2.2 Illuminance

“Light travels in a straight line until it is reflected, absorbed or refracted by a surface lying in its path. Illuminance is the light energy arriving at a surface at a certain rate” (Michel, 1996). “When luminous flux strikes a surface, that surface is said to be illuminated.” (Moore, 1991) Illuminance is the density of luminous flux incident on a surface and is measured in lux (lumens per square metre) (Figure 2:1). Illuminance is typically measured using a photocell which is colour corrected (“to duplicate the sensitivity of the eye in the radiation spectrum”) and cosine corrected (to “measure the illuminance in a flat plane and accurately respond to the cosine reduction at high incidence angles”) (Moore, 1991). Illuminance from sunlight is scattered as it passes through the atmosphere due to water droplets and airborne particles, even when the sky is cloudless affecting the illuminance. “The lower the sun in the sky, the longer the atmospheric distance traversed by the beam and so the greater the attenuation” (Tregenza and Loe, 1998).

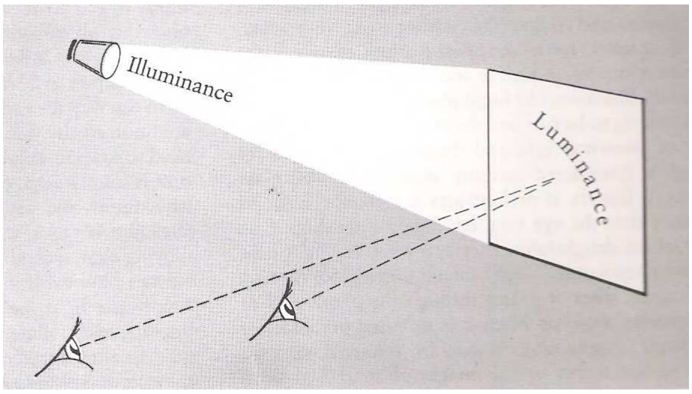


Figure 2:1 Illuminance and Luminance (Michel, 1996)

Tregenza and Loe (1998) explained the illuminance concept from skylight as “the light from the diffuse sky excluding the sun. The diffuse illuminance varies significantly with the sun’s height, and because light from diffuse sky can vary from one minute to the other and similar skies on successive overcast days can differ hugely in brightness”. The quantity of daylight falling at a point in a room depends more on the amount of visible sky luminance of the patch of the sky visible through the window than on the total illuminance on the ground. Illuminance is also affected by the angle of incidence, i.e. the angle at which light falls on a surface. Work desks nearer the window have the advantage of a larger visible sky zone, and receive light from the sky nearer to the zenith (which is brighter under overcast conditions) at an angle of about 30 degrees from the vertical resulting in higher illuminances. However, the angles of incidence increase as the distance from the window increases suggesting that the daylight illuminances on the horizontal working plane reduce significantly deeper into the room.

To show the daylight distribution patterns and illumination levels in a room, contours of equal illumination levels in lux or DF (called iso-illuminance diagrams/contours) can be used as shown in Figure 2:2. For example, 8600 lux from an overcast sky and a DF of 1% will result in an illumination level of 86 lux (i.e., 0.01 x 8600) on a horizontal surface indoors.

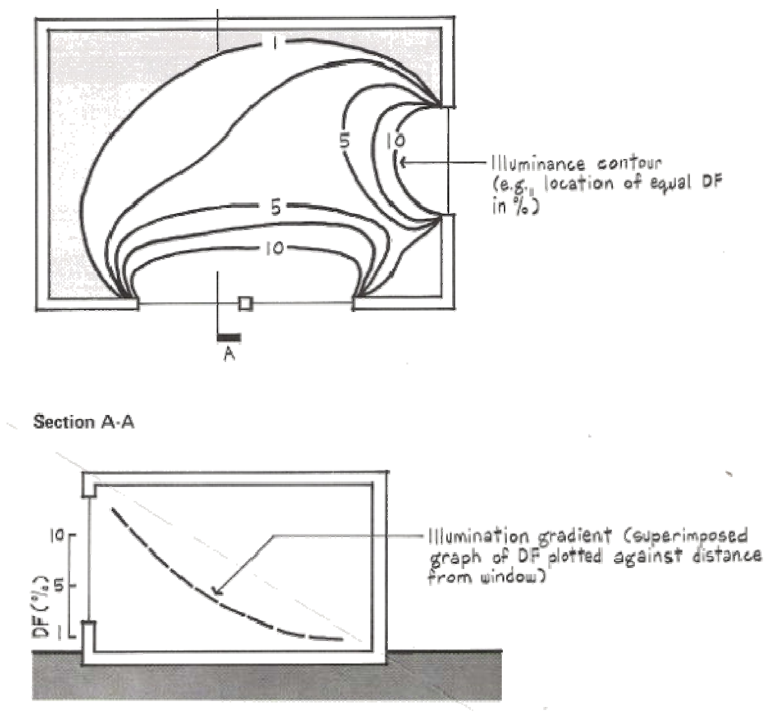


Figure 2:2 Illuminance Contour (Egan, 1983)

"In an area of room surface screened from direct skylight (and therefore lit only by reflection) the illuminance is typically less than one-tenth that of equivalent positions near a window" (Figure 2:3) (Tregenza and Loe, 1998).

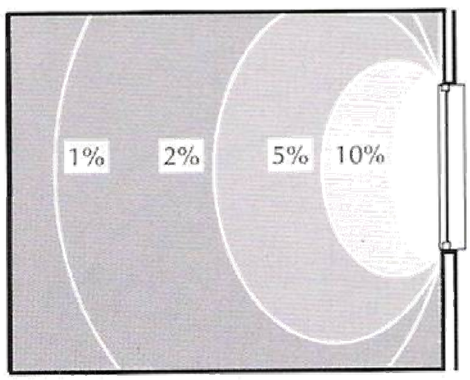


Figure 2:3 Contours of equal daylight factor from a side window (Tregenza and Loe, 1998)

Most codes of practice, such as the Chartered Institution of Building Services Engineers (CIBSE) Code for Interior Lighting in the UK or the Lighting Handbook of the Illuminating Engineering Society of North America (IESNA), provide recommended illuminance levels for different tasks and particular building typology. Typical recommended illuminances given by Tregenza and Loe (1998) are provided in Table 2:1.

Table 2:1 Typical Recommended Task Illuminances (Tregenza and Loe, 1998)

Task Requirements	Lux	Examples
General awareness of space; perception of detail is unimportant	50	Access route to service areas
Movement of people; recognition of detail for short periods; background lighting	100	Corridors, store rooms for large items, auditoria, bedrooms
Recognition of detail for short periods in areas where errors may be serious	150	Plant rooms, domestic bathrooms
Areas without difficult visual tasks but occupied for long periods: short-period tasks with moderate contrast or size of detail	200	General lighting in control booths, foyers, factory areas with automated processes
Tasks such as reading normal print (moderate contrast and size of detail) over long periods	300	Workshops for large items, general library areas, school classrooms, domestic kitchens
Tasks with some details of low contrast and moderate size	500	General offices, laboratories
Tasks with low contrast and small size	700	Drawing offices
Very small visual and low contrast tasks	1000	Electronic assembly, tool rooms
Tasks with extremely small detail and low contrast	1500	Fine work and inspection
Tasks with exceptionally small detail and very low contrast	2000	Assembly of minute mechanisms

2.2.3 Luminance

Reflected light that appears on a surface as seen by the eye is luminance; luminance refers to the light leaving a surface after it is reflected. Luminance is dependent upon the amount of illuminance reaching a surface and the reflectance quality of the surface material. Michel (1996) recommended “Design with luminance; do not design with illuminance.”

Moore (1991) defined reflected luminance as “the photometric measure of “brightness” of an illuminated opaque surface”. The SI unit of luminance is candelas per square metre (cd/m^2).

Reflected surface luminance is a function of the illuminance on the surface of the wall and the surface reflectance. For example, a grey surface having a reflectance of 30% and illuminated by 5000 lux would have a luminance of 1500 candelas per square metre (5000 x 0.30 = 1500). Luminance is usually measured using a colour-corrected photocell that is designed to receive light only within a very narrow angle of acceptance (typically one degree or less). The photocell is calibrated to measure surface luminance in candelas per square metre and it does so by aiming at the subject surface from an approximate direction.

2.2.4 Reflectance and Transmittance

"When light strikes a physical material, any or all of three surface actions will take place: (1) it can be absorbed by the surface, normally transformed into heat; (2) it can be reflected back into space in a direction other than that from which it came; or (3) it can be transmitted (refracted) through a medium to continue onward on the other side" (Michel, 1996).

Moore (1991) also defined these three concepts as "When luminous flux strikes an opaque surface, it is either reflected or absorbed. Reflectance is the ratio of reflected flux to incident flux. Absorptance, conversely, is the ratio of absorbed flux to incident flux". When surface is not opaque but is either transparent or translucent, some of the luminous flux is transmitted through the material and therefore "transmittance is the ratio of transmitted flux to incident flux" (Moore, 1991)

Reflectance

Egan (1983) gave the definition of Reflectance (P) as "the percentage of incident light that is reflected from a surface, with the remainder absorbed, transmitted, or both". Reflectance is denoted by the Greek letter rho (p), and is a value between 0 and 1; $p = 0$ if the surface is perfect black and absorbs all light; $p = 1$ if all incident light is reflected. In lighting calculations for buildings, the assumption is that diffuse reflection is dominant and describes the total reflectance of a particular material denoted by p. A white surface reflects about 85% of the light it receives = 0.85 reflectance or 85*%.*

The direction of reflected light is affected by the surface textures; matte surfaces will reflect light equally in all directions while specular surfaces will reflect light in one direction only and real surfaces are not perfect diffusers and would reflect light unequally in all directions. Moore (1991) stated that "The reflectance (and thus the luminance) of such a surface is dependent on the angles of incidence and reflectance and the surface's diffusion characteristics". The thesis examines the impact of atrium reflectances of both diffuse and specular surfaces on the daylight in an atrium building.

The reflective surfaces of the dominant enclosures in buildings play a fundamental role in the perception of the space; illuminating high reflectance surfaces can create an illusion in terms of the physical boundaries of a space. Indirect lighting is a method of reflecting illumination off the ceiling or other surface. If walls are over lit and of a large surface area, they can be too bright for work environments and may cause visual discomfort (Michel, 1996). For general room lighting, IESNA recommend walls to have 50 to 70% reflectance and vertical interior partitions to be of 40 to 70% reflectance as shown in Table 2:2 (Egan, 1983).

Table 2:2 IESNA recommended reflectances for matte or diffuse reflecting surfaces and finishes in offices and educational facilities (Egan, 1983)

Surface	Reflectance %	
	Classroom	Office
Ceilings	70-90	>80
Walls	40-60	50-70
Partitions (e.g., partial height barriers)	40-70	40-70
Floors	30-50	20-40
Furniture and machines	25-45	25-45
Desk and Bench tops	35-50	35-50
Walls containing windows should have high reflectance of >80% to reduce the contrast between bright glazing and surround. Window frame, sash, and glazing bars also should have a light-coloured matte finish.		
For floors, use surfaces with reflectance >25% for rooms where visual efficiency is a major concern but do not exceed 40% as reflected glare conditions would be critical.		

Reflected light is a significant component of the light indoors, particularly further away from the window and provides all the illuminance beyond the no-sky line (discussed later). Research investigating which surfaces in a room are most effective in supporting task level illumination as shown in Figure 2:4 demonstrate that “the ceiling is the most important surface in controlling the daylight coming into the room and reaching the task (Evans, 1981).

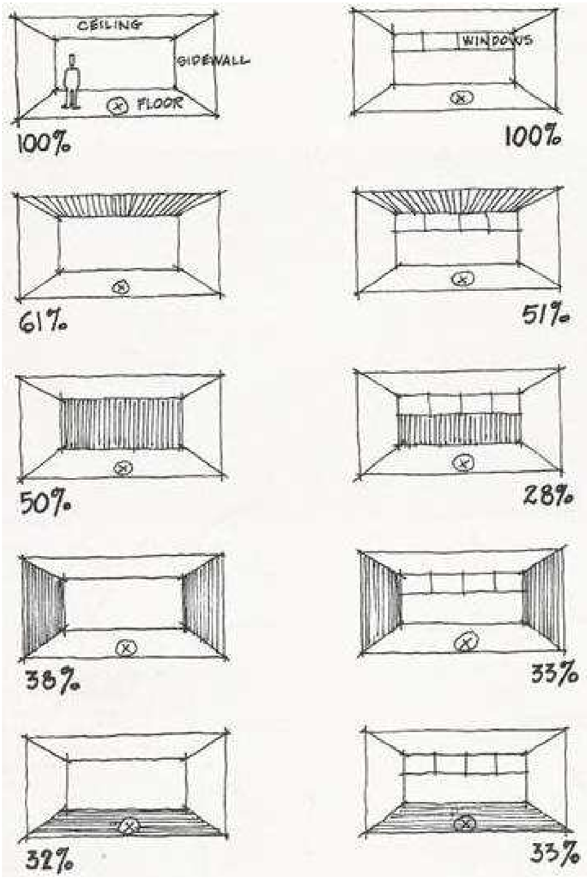


Figure 2:4 Reduction of lighting at a point due to painted black surfaces in a room indicating those that are most effective in supporting task level illumination (Evans, 1981)

Higher wall reflectances are also important in small rooms as they will enhance the illuminance on the working plane and increase the inter-reflected component, thus improving uniformity. While ceiling and walls of light colours increase most of the reflected light, a light coloured floor nearer to the window would also reflect direct high level light that strikes it from the sky. However, very light floors are difficult to maintain therefore usually the floors have low reflectances.

The reflectances used in the experiments undertaken in Chapter Seven are chosen due to the daylighting opportunities presented by higher ceiling and wall reflectances as identified in this section and are as per those recommended by IESNA.

Transmittance

Tregenza and Loe (1998) gave the definition of transmission as the fraction of light that passes through a material; it is denoted by the Greek letter tau (ح) and is a number between zero and one. “Light transmittance is the ratio of transmitted light to incident light (less than 1.0). Measured in footlambert, transmitted luminance is the product of illumination on the reverse side of a surface (measured in footcandles) and surface transmittance” (Moore, 1991).

Diffuse transmittance is the fraction of a beam that is uniformly scattered while regular transmittance is the fraction that remains as a geometrical ray. With glass, the fractions that are reflected or transmitted depend upon the angle of incidence. When a beam strikes a glass surface at a glancing angle it is mainly reflected while when it is perpendicular to the surface most of it passes through.

Transmittance of glass to light differs from the transmittance of solar radiation because of the fact that the transparency of glass varies with wavelength. Therefore, daylighting and solar gain calculations are undertaken using separate values. Whatever is the wavelength of the incident radiation, all absorbed energy results in an increase in temperature of the material. All the light that enters a room is absorbed by the surfaces and results in thermal gain. For simple calculations of window performance an average transmittance is used, a weighted mean over all directions of incidence. Littlefair (1996) gave transmittance values for different glazing types as shown in Table 2:3.

Table 2:3 Transmittance values for different glazing types (Littlefair, 1996)

Table 1 Approximate diffuse transmittances for various glazing types (when they are clean)	
Type of glazing	Transmittance
Clear single glazing	0.8
Clear double glazing	0.7
Low-emissivity double-glazing	0.65
Double glazing and internal light shelf	0.55
Double glazing, internal and external light shelf	0.4
Double glazing with coated prismatic glazing	0.3
Double glazing with prismatic film	0.55
Double glazing with solar control mirrored louvres5	0.3
Extra corrections for dirt on glass	
Horizontal glazing	0.7
Sloping glazing	0.8
Vertical glazing	0.9

The experiments undertaken in this study do not include window and atrium roof but consider an approximate loss due to them for the interpretation of the results and comparison of data obtained from real buildings.

2.3 COMMISSION INTERNATIONALE DE L'ECLAIRAGE (CIE) OVERCAST SKY

Whilst model studies can be carried out under real skies, i.e. outdoor conditions, real skies are complex and the variation in weather can present severe limitations. Artificial skies on the other hand overcome these difficulties; they simulate the standard overcast sky conditions, giving either uniform luminance or the CIE luminance distribution. Vitally, using a simplified model, experiments can be repeated and compared under the same sky conditions using an artificial sky.

Even though the sun affects the brightness of the clouds, under heavy cloud cover that is continuous, the sun is invisible. When there are several layers of clouds, the level of daylight is very low, and the brightness pattern found as a result of this is used for daylighting calculations in temperate climates under the CIE Overcast Sky. “In this, the luminance of any part of the sky in relation to the zenith luminance is independent of the sun’s position, and at a given elevation of view the sky is equally bright in every direction of azimuth” (Tregenza and Loe, 1998). From the horizon upwards, its luminance L increases with altitude Y in the sky according to the formula (CIBSE, 1999):

$$L_Y = L_z(1+2 \sin Y)/3\text{”} \qquad (1)$$

Luminance at horizon is a third of that of the zenith L_z. The CIE overcast sky represents a dull, heavily overcast day with assumed minimum illumination of 5,000 lux outdoors for more than 85% of the normal working day, averaged throughout the year (Bell and Burt, 1995). For daylighting studies, the CIE sky type is used in England and Europe and provides minimum daylighting conditions that will be experienced in a full-scale building.

Artifical skies are available in two forms; the hemispherical dome artificial sky (sky domes) and the rectangular mirror box artificial sky. Hemispherical dome artificial sky calibrated for the CIE standard overcast sky conditions are usually opaque white and illuminated by interior perimeter lights, which can be adjusted to give appropriate luminance distribution. The sky dome can be used to accurately simulate the lighting conditions within and around the scale models of the buildings being tested. Daylighting data can be obtained for all weather conditions, different seasons and locations taking into account the sun, the sky, the clouds and the reflections from ground and nearby the structures.

The mirror box artificial sky is a less expensive option and was originally developed by the BRE. It includes a luminous ceiling and mirrored vertical walls to create a sky with an infinite horizon due to the multiple inter-reflections between the parallel opposing mirrors. “Because some light is absorbed with each mirror reflection, this configuration tends to approximate naturally the luminance distribution of an overcast sky (brighter at the zenith than at the horizon). The height to width ratio of the box controls the actual luminance distribution” (Moore, 1991). While some boxes can be as large as a room, most are smaller with a mirrored wall and an opening to allow access for testing. In mirror box skies, multiple reflected images of the model are seen: this error can be reduced by having the exterior walls of the model white or covered in mirrors.

A mirror box artificial sky was used for the physical scale model experiments presented in Chapter Four.

2.4 DAYLIGHT FACTOR

The Daylight Factor (DF) method was first developed in the 1920s in England and is typically characterised by the overcast sky conditions. Interior illuminance values are dependent on the daylight availability and sky conditions. DF is used for the overcast sky conditions as its relative luminance distribution is constant and does not change with time. DF cannot be used for clear skies as it would vary when the sky luminance distribution changes with the changing sun position.

"The Daylight Factor is a ratio of interior to exterior illuminance under an overcast, unobstructed sky (measured in a horizontal plane at both locations and expressed as a percentage) and remains constant regardless of changes in absolute sky luminance" (Moore, 1991). 10% DF means that the given interior location receives 10% of the illuminance of that obtained under an unobstructed sky. Therefore, Daylight Factor D as presented by Tregenza and Loe (1998) is shown in equation 2:

$$D = E_i / E_{dh} \times 100\% \qquad (2)$$

E_i = Illuminance at a point in room

E_{dh} = Simultaneous Illuminance from the whole sky (the illuminance on an unobstructed horizontal surface outside).

DF is a ratio and not an absolute level of illuminance, and is calculated on the assumption of a particular sky luminance distribution. Tregenza and Loe (1998) showed that to estimate mean diffuse illuminance at a point in a room, an empirical orientation factor (f_o) which would account for the higher illuminances on the south-facing windows under all but very heavy clouded skies, can be introduced. Using values derived from long-term measurements and an orientation factor, the following Equation 3 for illuminance at a point in the room can be applied (Tregenza and Loe, 1998):

$$E = D\, f_o\, E_{dh} \quad (3)$$

Figure 2:5 shows how the DFs can be graphically represented in DF curves resulting from physical model studies of alternative window configurations. "Flat curves represent relatively uniform illuminance in the horizontal workplane at various distances from the window; steep curve slopes denote an abrupt illuminance gradient" (Moore, 1991).

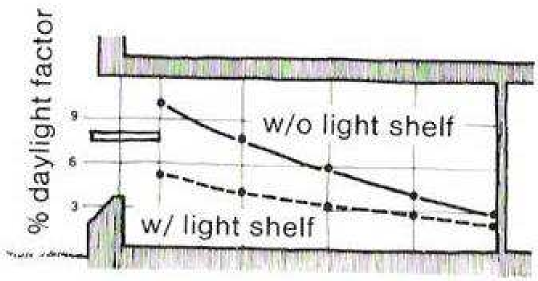


Figure 2:5 Section with the DF curves for alternative window configurations (Moore, 1991)

Moore (1991) outlined DF as a sum of three components (each of which is a % of the exterior unobstructed illuminance):

- Sky Component (SC) – the illuminance received at the interior reference point directly from the sky through the window or skylight
- Externally Reflected Component (ERC) – the illuminance received at the interior reference point from reflecting exterior surfaces above the horizon (surfaces below the horizon cannot be seen directly from the horizontal reference point)
- Internally Reflected Component (IRC) – the illuminance received at the interior reference point from all light reflected from the interior room surfaces

The uncorrected DF = SC + ERC + IRC, is multiplied with the following correction factors:

- Dirt Factor, which will depend on the slope of the glazing and the degree of atmospheric pollution (0.5 for industrial atmosphere to 0.9 for regular maintenance)
- Glazing Transmission (usually diffuse transmission), if other than clear single glazing
- Window frame and glazing bars (0.75 to 0.9) or (correction factor of 0.85 for metal frames and 0.75 for timber frames can be applied)

SC and ERC are calculated by several methods including the BRE's daylight protractors applied to scale plan and section drawings. IRC can be determined by the BRE's split flux formula (CIBSE, 1999).

DFs are widely used to calculate very simply daylight availability at a given location in buildings under a CIE overcast sky taking into account the building location, geometry and finishes including glazings and lead to design solutions of narrow floor plates, higher window head heights, surface finishes, high transmittance glazings that promote good daylighting generally. However, it is a static metric that does not take into account building orientations, different seasons, time in the day, direct solar ingress and variable sky conditions and therefore it is particularly unsuitable for assessing building performance under non-overcast sky conditions and its associated problems of glare and the need to develop different strategies for the different facades (Reinhart et al., 2006). On the other hand, dynamic daylight performance metrics take into account the variability that is created when these issues are considered.

Reinhart et al. (2006) compared static metrics with a range of dynamic daylight performance metrics such as 'Daylight autonomy', 'Useful daylight illuminance' and 'Continuous daylight autonomy' using the daylight analysis software, 'Daysim', for various design options. The variations included changes in the glazing geometries, shading devices and climatic conditions. The study showed that the use of static metrics can be misleading as they do not consider many of the variations made and that dynamic daylight metrics are much more useful for the decision making processes even though this may mean additional time and expense.

The use of Daysim may also be more useful for calculating annual daylight availability and glare analysis, and energy savings taking into climate data, consideration occupant behaviour and personal controls and automated lighting controls. Data in the form of "hourly schedules for occupancy, electric lighting loads and shading device status" is generated; this can be coupled with thermal simulation programs (TRNSYS, EnergyPlus etc) developing an integrated approach to lighting and thermal simulation (http://www.daysim.com/).

For the purpose of this parametric study under overcast sky conditions, the use of DF method was appropriate and is therefore adopted.

2.5 AVERAGE DAYLIGHT FACTOR

Average Daylight Factor (ADF) is the mean DF over a given area of the room, usually the horizontal working plane plus the wall surfaces below the mid-height of the window (Tregenza and Loe, 1998). It is defined as the ratio of the average internal illuminance E_i (a spatial average over the working plane) to the external unobstructed horizontal illuminance E_o. Although daylight availability in a room depends on the size of the window apertures, the amount of visible sky from the window and the surface reflectances, the ADF simplifies this in a single average daylight factor value for a room. Therefore, ADF is a useful yet broad measure for assessing daylight levels in a room. It is a valuable indicator of the daylit appearance of a space and is useful at an early design stage to estimate the amount of fenestration required to achieve good daylighting or can be calculated for windows in existing buildings. However, the distribution of light is also very important because even if the ADF is high, some parts of the room might be bright while others may look gloomy if they receive no direct light or if the room is too deep.

Tregenza and Loe (1998) and Philips (2000) suggest that 5% ADF results in a room that is well day lit while 2% suggests it is dull and might require supplementary artificial lighting for work spaces but is adequate for a domestic situation. ADFs higher than 5% are usually found in spaces such as conservatories and green houses that are not enclosed internal spaces (Tregenza and Loe, 1998). *The green studio handbook: Environmental Strategies for Schematic Design* (Kwok and Grondzik, 2007) suggests ADFs and minimum DFs under overcast skies as shown in Table 2:4.

Table 2:4 ADFs and Minimum DFs under overcast skies (Kwok and Grondzik, 2007)

Space	ADF	Minimum DF
Classrooms	5	2
Library	5	1.5
Gymnasium	5	3.5
General Office	5	2
Corridor	2	0.6

Tregenza and Loe (1998) gave room appearance and ADF values for temperate climates and some useful guidelines for the use of ADF as shown in Table 2:5.

Table 2:5 Room appearance and ADF values associated with rooms in temperate climates (Tregenza and Loe, 1998)

<table>
<tr><th colspan="2">Room appearance and ADF: values associated with rooms in temperate climates</th></tr>
<tr><th colspan="2">ADF</th></tr>
<tr><td>5% or more</td><td>The room has a bright daylit appearance
Daylight electric lighting is usually unnecessary
High levels of daylight may be associated with thermal problems</td></tr>
<tr><td>2-5%</td><td>The room has a daylit appearance but electric lighting is usually necessary in working interiors. Its purposes are:
• To enhance illuminances on surfaces distant from the window
• To reduce contrast with the view outside
The use of daylight with supplementary electric lighting is often the best choice for energy efficiency</td></tr>
<tr><td>Below 2%</td><td>Electric lighting is necessary, and appears dominant. Windows may provide an exterior view but give only local lighting</td></tr>
</table>

The ADF increases with higher room reflectances, increased window size in proportion to the room and if the window is clean and transparent and a large angle of open sky is seen from the window. The ADF equation shown by CIBSE (1999) is proportional to the window size and expressed as follows:

$$Df = TA_w \theta M/\{A(1-R^2)\}\% \qquad (4)$$

Note that window bars may considerably reduce the effective area of glazing

θ = the vertical angle subtended by visible sky is largely determined by the siting of the building and its relation with its neighbours

T = the diffuse transmittance of glazing material

A_w = *the area of glazing* R = the area weighted average reflectance

A = Total area of interior surfaces (ceiling + floor + walls, including windows)

M = the maintenance factor

For glazing transmittance, dirt correction factors and correction for frames the following tables 2:6, 2:7 and 2:8 from BS Daylight Code (1992) can be used.

The experiments undertaken in this thesis examine the effects of atrium surface reflectance distributions on the DFs as well as the ADFs on the atrium floor. However, the atrium models do not include a roof or windows. Hence, the DFs and ADFs obtained in this study will be typically higher than what would be expected in a real building. Therefore, correction factors are applied to the data obtained to take into consideration the roof and window glazing transmittance, dirt, window frames and the roof structure. This is vital for the data interpretation and its comparison with the data obtained from real buildings.

Table 2:6 Transmittance of glazing (BS Daylight Code, 1992)

Transmittance of glazing		
Type of glazing	Transmittance	Area of glazing needed %
Single	0.80	100
Double	0.65	125
Triple	0.55	140
Tinted*	0.39-0.66	120-210
Reflective +	0.15-0.26	310-530
*Body tinted single		
+double with one pane clear		

Table 2:7 Dirt Correction Factors (BS Daylight Code, 1992)

Dirt Correction Factors			
Type of location	Angle of glazing		
	∣	/	—
Clean	0.9	0.8	0.7
Industrial	0.7	0.6	0.5
Very dirty	0.6	0.5	0.4

Table 2:8 Corrections for Frames (BS Daylight Code, 1992)

Correction for Frames	
Type of window	Typical correction factor
Metal patent glazing	0.9
Metal frame: large pane	0.8
Wood frame: large pane	0.7
Wood frame: small pane	0.6

2.6 FENESTRATION

Fenestration is defined as “any opening or arrangement of openings (normally filled with media for control) for the admission of daylight” (Kaufman, 1981).

In addition to providing daylight, windows provide views and visual stimulation, act as noise barriers, insulators, glare protectors and assist with ventilation. Fontoynont (1999a) suggests that whilst increasing window areas will bring more daylight, they will also cause problems of glare and overheating and present constraints for the shading systems. Therefore integrated solutions for daylight, ventilation, solar gain, glare and noise are required.

"Decisions regarding the size and proportion of windows are clearly at the heart of daylighting and early preconceptions need to be constantly reassessed." (Philips, 2000) Once the size of the window is ascertained, it is important to consider the positioning and shape of a window. Al-Sallal (2004) also refers to "appropriate sizing and placing of the building openings" as one of the energy saving measures to improve daylight availability including counter balancing radiative, thermal, moisture and aerodynamic effects.

The thesis focuses on the atrium envelope and its reflectance properties including the extent of window openings and their positioning. Fenestration forms an integral part of an atrium's facade and affects the way in which light travels within the atrium and reaches its adjoining spaces. Whilst an atrium enables larger openings without the associated heat losses, due to the buffer environment it creates, very large openings can lead to overheating and glare. Whilst smaller openings higher up in an atrium combined with higher wall reflectances may increase daylight levels in the lower reaches of an atrium building, however, views to and the connectivity with the atrium may be compromised. Therefore, although the study focuses on the daylight improvements as a result of the atrium's facades, including the proportion of fenestration and opaque areas, it is recognised that the other roles of and benefits associated with window openings, including user preferences in relation to their size and positioning are also vital.

2.6.1 Sidelighting - Vertical and Horizontal Windows

Considering that the experiments in Chapter Seven examine the influence of different atrium facade compositions comprising of varied fenestration distributions on the daylight in the atrium's adjoining spaces, this section seeks to examine side lighting in buildings.

Fontoynont (1999a) suggested that the amount of natural light that enters a building depends on the sky luminance seen from behind the window, the associated solid angle of this section, window area and transparency, and the area and reflectance of the absorbing surfaces in comparison with the window area. Daylight penetration is also dependent on ceiling, depth of room, size/shape and the number of windows, and the spacing between them. In the case of an atrium building, daylight availability is determined by the atrium roof, geometry and reflectances of the atrium and its adjoining spaces, in addition to the size and positioning of window areas. This is discussed in further detail in Chapter Three.

Philips (2000) categorized windows that are greater in height than their width as vertical windows. Since sills for vertical windows are usually low and the window heads are high, they maximise distribution of light in the rooms and provide views out but the horizontal view is broken up due to the walls between vertical windows. For a window of equal area, daylight distribution of a tall window will be deepest while multiple window openings will be the widest. Although a vertical opening is more effective in provision of daylight and information about time and weather, a narrow vertical opening is found to be less desirable in comparison with a wide, short opening and a horizontal opening is considered to provide the best views (Keighley, 1973). Evans (1981) published results of the study undertaken at the Texas Engineering Experiment Station in 1950-51 to demonstrate the effect of changing window/ceiling height on illumination at the back of a unilaterally lit room. For this experiment, the top of the window was kept in line with the ceiling, and surface reflectances of 85% for the ceiling, 60% for the walls and 40% for the floor were used. In unilaterally lit rooms, illumination levels at the end of the room opposite to the window wall are reduced with increased room depth as the same amount of transmitted light is spread over a larger area, resulting in an increased diversity in the distribution of light (Figure 2:6) (Evans, 1981; Egan, 1983).

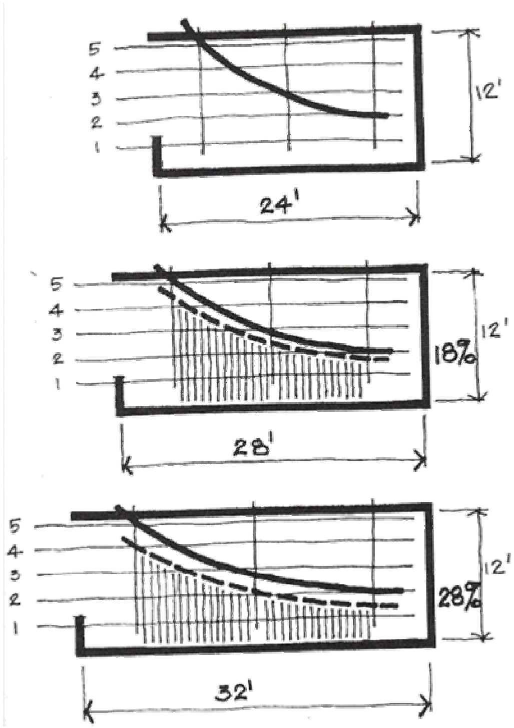


Figure 2:6 Effect of room depth on illumination in a unilaterally lit room (Evans, 1981)

Even if the ADF is adequate, if the room is too deep, it will be impossible to daylight those areas furthest away from the window. For unilaterally lit rooms, the room depth should not be much greater than its width and should not exceed 2.5h where h is the window head height from the floor (Evans, 1981; Bell and Burt, 1995; Egan, 1983). Al-Sallal (2004) recommends narrowing the floor plate to a width of approximately 14 metres (i.e., external wall to wall width) reduces the use of artificial lighting. A room with a height-to-depth ratio of 1:2 with 20% glazing of its external wall area allows good light penetration (i.e. 1.5-2% DF).

For uniform illumination, the area of window openings should be about one fo urth of the total floor area of the room (Egan, 1983). Additionally, ceiling and walls should be of high reflectance matte surfaces, including all surfaces at the back of the room. To assess whether daylight distribution is acceptably uniform the following two criteria need to be applied:

1. If a day-lit room has only windows in one of its walls, the depth of the room *L* should not exceed the limiting value given by the following equation (CIBSE, 1999):

$$L/W + L/H_w < 2\ (1 - Rb) \qquad (5)$$

Where*:*

L is the room length

W is the room width

H_w is the window head height above floor level

Rb is the average reflectance of surfaces in the rear half of the room (the value for a typical office is likely to be around 0.5; Bell and Burt, 1995)

"If L exceeds the limiting value, the rear half of the room will tend to look gloomy, and supplementary electric lighting will be required" (Lynes, 1979; BS 8206, 1992).

Table 2:9 gives maximum depth values for different room widths, window head heights and reflectances at the back of the room.

Table 2:9 Limiting depths of side-lit rooms (CIBSE, 1999)

Limiting depths of side-lit rooms (in metres) (CIBSE, 1999)						
Reflectance *Rb*	0.4	0.4	0.5	0.5	0.6	0.6
Room Width (m)	3	10	3	10	3	10
Window Head Height (m)						
2.5	4.5	6.7	5.4	8.0	6.8	10.0
3	5.0	7.7	6.0	9.2	7.5	11.5
3.5	5.4	8.6	6.5	10.4	8.1	13.0

The alternative uniformity criterion presented by Littlefair (1996) includes the following:

1 The ADF, or average illuminance, in the front half of the room should not exceed three times the ADF (or illuminace) in the back half (Lynes, 1979).

2 The minimum DF – or, for sunny locations, illuminance at the worst-lit point – should exceed 1% or 100 lux. Such a space will not have any particularly dark or gloomy areas. The minimum DF can either be measured or calculated.

Higher ceilings result in higher illumination and improved light distribution as shown in Figure 2:7. Although illumination levels are generally higher for the bilaterally lit room when compared with unilaterally lit room, with the drop in window head height, the intensity and diversity of the illumination decreases but not to the extent of the unilaterally lit room (Figure 2:8).

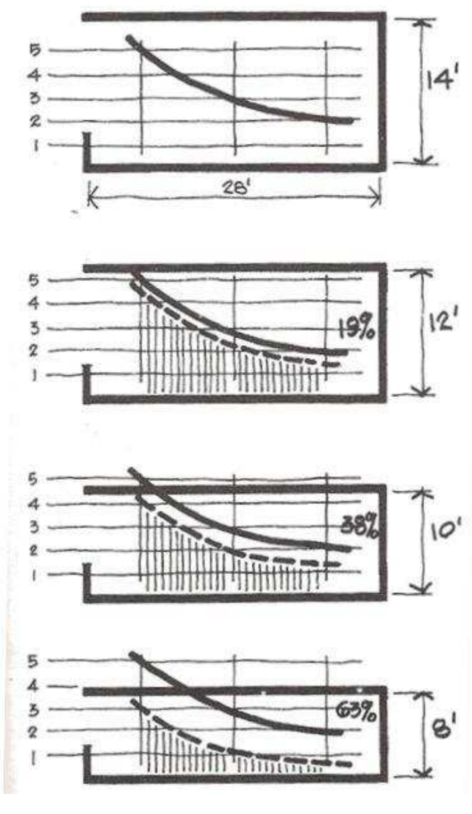


Figure 2:7 Effect of ceiling/window height on illumination in unilaterally lit rooms (Evans, 1981)

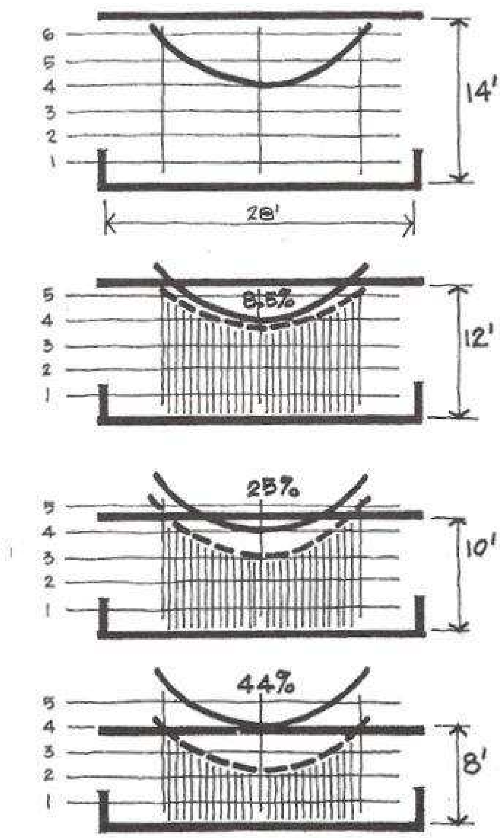


Figure 2:8 Effect of ceiling/window height on illumination in a bilaterally lit room (Evans, 1981)

CIBSE (1999) demonstrated the influence of different shapes and window positions on the daylight distributions in a room as shown in Figure 2:9

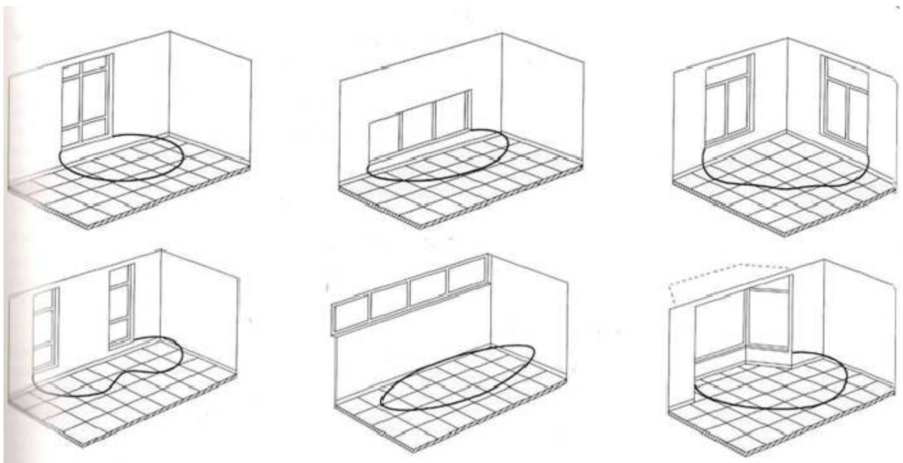


Figure 2:9 Influence of the different shapes and window positions on the daylight distributions in a room (CIBSE, 1999)

Bell and Burt (1995) also show the effect of different window patterns with the same total window area (20%) on the distribution of light and shadows in a room (Figure 2:10). It also shows comparison between the internal appearance and the contours of illuminance.

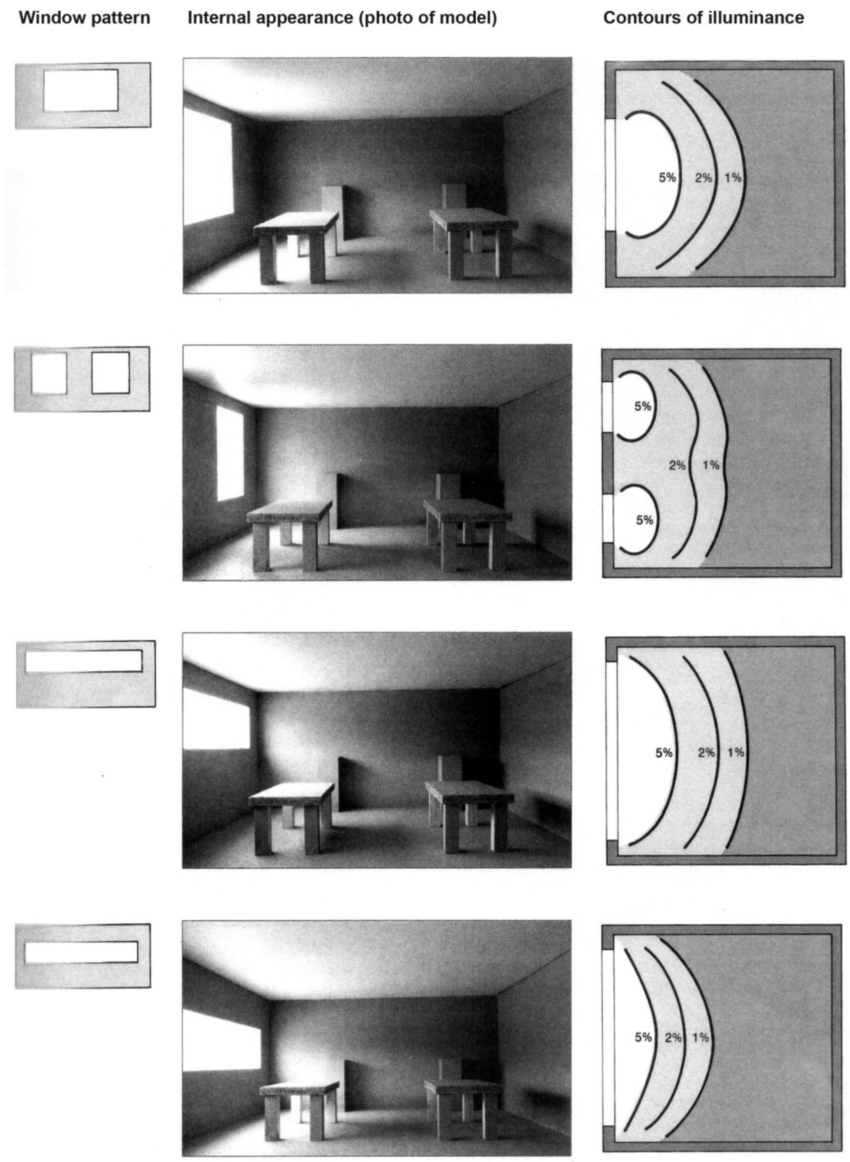


Figure 2:10 Effect of the different window patterns with the same total window area on the distribution of light and shadows in a room (Bell and Burt, 1995)

The study concluded that in unilaterally lit rooms, horizontal windows generally provide adequate daylighting depending on the ceiling height. Windows below working plane level transmit no direct light onto the desks. With windows just above the desk level, the DF is more than double for the front desk as the light is coming from a higher level and therefore brighter part of the sky. It also provides a view of the horizon from the seated and standing position. Moving the window further up, increases the DF even more, it will give deeper daylight penetration and light the ceiling from which light can be reflected increasing the DF at the rear desk; people can see some sky in this position but people seated do not have a view of the horizon and the brighter sky higher up can cause glare. Therefore, other windows at lower level may be required to provide views. Additionally, surfaces beneath a higher horizontal window can potentially appear dark and artificial lighting can be used to provide low illumination levels on this surface and reduce gloomy conditions. If the light is insufficient, rooms with horizontal windows can be supplemented with artificial lighting towards the rear or bilaterally day-lit.

While generally a higher window will increase the DF, raising the ceiling higher so that the same window can be placed even higher up will not improve the DF indefinitely. This position maximised direct light at the back desk but reduced it at the front desk as light is received at a more oblique angle. However, turning the same window in vertical position would result in good design whereby the head height is high and improves light levels, but it also improves views due to the lower sill where those seated and standing can see the sky and the foreground.

The character of a room will depend upon illuminances achieved at desktops in offices but also the total amount of light entering the room and the subsequent inter-reflections from the light coloured surfaces such as the walls, ceiling and floor. “Assuming that the total quantity of light admitted remains the same, distributing the interior fenestration over a larger area will (1) reduce shadows, contrast, and texture definition, (2) provide more uniform light distribution, and (3) reduce veiling reflections” (Moore, 1991).

This section demonstrated the impact of a room’s characteristics on daylight conditions. In particular, it identified the impacts of the room and window geometry, and window positioning on the daylight availability and its distribution in spaces. This section also enables an understanding of the behaviour of light in side lit spaces and what might be reasonably expected in the adjoining spaces of an atrium building that are also side lit but perhaps affected by the restricted sky component and the increased atrium reflected component depending on the atrium geometry and reflectances used within the atrium. This information informed the parameters that were chosen for the experiments of Chapter Seven that examined daylight availability in the adjoining spaces of an atrium building.

In the experiments, to understand the impact of daylight in the adjoining spaces from the atrium, the adjoining rooms were only unilaterally lit (from the atrium). The adjoining room depth of 12 metres and a room height of 3 metres were chosen, and the reflectances were generally high and representative of those found in real buildings. Importantly, the window head height was in line with the underside of the ceiling to enable deeper penetration of direct light in the room and to light the ceiling from which light can be reflected increasing the DFs at the rear of the room and providing uniform distribution of daylight.

No Sky line

A well daylit space requires an adequate amount of light and that it is well distributed. Often, lighting levels at the back of the room are much lower than positions near the window due to heavy obstruction to the window or because of the large depth of the room.

The no sky line effectively divides those areas of the working plane which can receive direct skylight from those which cannot receive any, and would appear gloomy and have to be supplemented by artificial lighting as shown in Figure 2:11 (Littlefair, 2002). The No Sky Line is useful in terms of describing how an atrium influences the daylight penetration and is a quick and effective way of estimating the daylight availability in the adjoining spaces.

The no skyline position can be altered to improve daylight by increasing the window head height or increasing the distance between the building facade and its obstructions, i.e. the atrium geometry. Daylight redirecting systems can be useful in improving the daylight distribution in a room. "Features such as light shelves, prismatic glazing, and higher reflectances on the ceiling and at the rear of the room will provide some redistribution of daylight to the back of the room" (CIBSE, 1999). Innovative daylighting systems can be used to lighten up walls and ceiling, which with even a small injection onto the upper room surfaces can lead to considerable improvement in the room appearance. However, the impact of these strategies is limited if the room depth, window head height and external obstructions are not appropriate. In an atrium building this relates to the atrium and the adjoining space geometry, and facade fenestration which this study investigates.

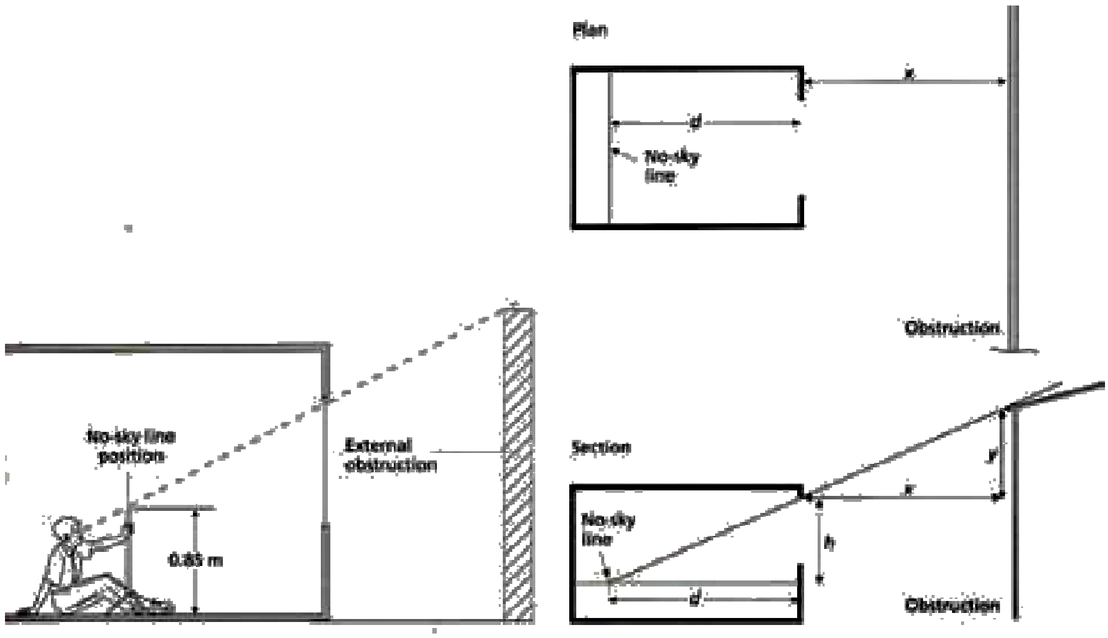


Figure 2:11 No Skyline Concept (CIBSE, 1999)

2.6.2 Top-lighting - Overhead Windows/skylights/rooflights

Skylights, in the form of domes and a variety of rooflights (monitor or saw tooth) are particularly useful to bring daylight into interior areas of deep plan buildings, top floors of multi-storey buildings or where perimeter windows are not possible. Indeed, skylights can be used to bring light to lower floors through the use of reflective devices. Since overcast skies are three times brighter at the zenith than at horizon, top lighting in the form of skylights and clerestories could be used to achieve effective distribution of daylight. Fontoynont (1999a) highlights that a strategy of simple, horizontal roof and facade apertures perform better than advanced facade systems with highly reflective surfaces that are designed to deviate diffuse daylight deep into the building and that their performance depends on maintenance and durability factors due to dust, condensation and surface deterioration reducing optical efficiency by more than 50%.

Atria use a range of roofing and structural systems including internal and external shading devices. For any situation, a system that effectively introduces daylight and controls heat transfer, and works for both day and night conditions is very useful. Maintenance, cleaning and heat loss/gain issues also have to be carefully resolved when using the different roofing systems.

In an atrium building, the atrium roof determines the quantity of light that is admitted and its distribution on entering the atrium space; this is discussed in a greater depth in Chapter Three. In addition to the external illuminance conditions, daylight will be affected by the roof structure and geometry, its orientation and type and the type of glazing or cover incorporated and its transmittance properties, and indeed the shading system it uses. Although, to understand the impact of atrium wall reflectances, the experiments undertaken in this thesis do not include the atrium roof, the results take into consideration the possible losses associated with the incorporation of atrium roofs.

Glazing Systems

When windows were first filled with glass, the panes were small and were secured by lead beading or leaded lights. Developments in glazing allowed for larger panes and today include a range of glazing systems that transmit diffuse skylight and control sunlight. Whilst clear single glass transmits light well, it transmits noise and heat too, and will result in heat loss from the interior space to the outside in winter. The cold glass surface will cause cool downdraught of air and condensation. These problems are reduced with double or triple glazing and can be enhanced even more if a double glazed unit incorporates a heat reflecting coating (CIBSE, 1999).

The use of clear glass is preferred as it admits more natural light. Whilst, tinted glass reduces thermal transmission to some extent, it conducts heat to the inside space after it absorbs it and also reduces the daylight significantly. On the other hand, solar-reflective glass reduces solar penetration without affecting the view. However, it also reduces light transmission (Al-Sallal, 2004). Low emissivity glass is highly recommended as part of a green strategy as it has the appearance of clear glass and it reduces direct heat gain by transmitting a greater proportion of light than heat allowing larger glazed areas in building. Recent intelligent glazing systems include photo-chromatics, phase-change materials, holographic and electrically responsive glass. Philips (2000) categorised glazing in four groups:

1. Systems used for daylight and views and at the same time control temperature and external noise

- Single glazing
- Double glazing – two layers of glass with air gaps with the possibility of placing acoustic absorption material at the reveals. Electrically controlled blinds between the two panes to control solar heat gain and glare.
- Triple glazing – similar to double glazing but with three panes and increased thermal and acoustic qualities

2. Special coatings to reduce solar gain into interior spaces but result also in reduced light transmittance and colour distortion of the view

- Glass coatings, usually dark, to reflect sun's rays and control solar gain and provide privacy to the interiors and alter the colour appearance of the exterior and interior, therefore diminishing the impression of daylight. An alternative to this is to use a glass that gives an impression of sunlight even on a dull day.

3. Intelligent systems that reduce solar gain but rely on a range of means of control that result in reduced daylight and views out. When electric controls are used, energy savings are also reduced.

- Light activated or photo-chromic glass- Due to receiving ultraviolet light from changing exterior conditions, light transmission to the interior is altered
- Heat-activated or thermo-chromic glass- change in exterior temperature alters the optical properties of glass and thus the daylight admission
- Electrically controlled or electro-chromic glass – formed of a series of glass layers and other elements where optical properties are altered by electric current

4. Shading systems, internal and external

- Simple internal or electrically controlled blinds are less successful in controlling solar gain due the fact that ultra violet rays have already entered the building. But this system can easily be controlled by the building occupants.
- Slatted or venetian blinds between two layers of glass – most appropriate for sun or sky glare but have issues of long-term maintenance and reduced view to the outside
- External shading – significantly reduce solar gains as they stop sun rays to enter the building, however they affect external building appearance, need to be weatherproof and robust in structure and finish, and can be prone to long-term maintenance issues.

ETFE (ethylene tetrafluoroethylene)

ETFE (ethylene tetrafluoroethylene) is a lightweight material; it takes the form of inflatable cushions comprising two or more sheets of foil that are laid on top of each other and joined at the edges with a constantly maintained air pressure between them. Due to its light transmittance (95%) and potential to improve energy performance by providing thermal insulation at reduced costs and structural support in comparison with glazed roof (Robinson, 2005), this material has been increasingly used in the roofing of courtyards and atria (Poiraziz et. al, 2009). However, it does not provide clear visibility typically expected in a clear glazed roof. While glazing is almost opaque to long wave radiation, ETFE transmits part of it (Salz and Schepers 2006). "The visual light transmittance of ETFE is 94-97% with ultraviolet transmittance being in the 83-88% range" (Poiraziz et. al, 2009). Salz and

Schepers (2006) compared the performance of insulated glazing units and ETFE cushions in terms of thermal transmittance (U value) and total solar energy transmittance (g value) as shown in Table 2:10. Both, the optical and thermal properties of an ETFE roof can be altered by the use of coatings, print, geometry etc. Frit is often introduced for shading and reducing the transmitted solar energy. The use of this material for roofing of atria is particularly suitable due to the daylighting and thermal benefits it offers over glazed units.

Table 2:10 Comparison between the performance of glazed units and ETFE cushions (Schepers, 2006)

Glazing and ETFE Cushions	U value (W/m2k)	g- value
6mm monolithic glass	5.9	0.95
6-12-6 Double Glazing Unit (DGU)	2.8	0.83
6-12-6 High Performance Double Glazing Unit (DGU)	2.0	0.35
2 Layer ETFE Cushion	2.9	0.71-0.22 (with frit)
3 Layer ETFE Cushion	1.9	0.71-0.22 (with frit)
4 Layer ETFE Cushion	1.4	0.71-0.22 (with frit)

Polycarbonate

Polycarbonate is essentially a transparent thermoplastic which is known for its exceptional strength under impact, its lightweight, high transparency, high light transmittance (0.7 - 0.8), durability, excellent fire performance, recyclability, good dimensional stability and heat resistance. This inexpensive material can be used for domed, flat, curved or pitched roofs including replacing vertical cladding and glazing. Its multiwall (approximately 4mm thick for twin wall to 55mm thick for ten wall) and corrugated constructions (0.8 mm - 2.0 mm) can be either transparent or translucent and come in different tints and colours to address issues of glare. Additionally, they may incorporate UV protection, an anti-drip layer to reduce condensation and solar heat reflection technology (solar inserts and laminates) to reduce overheating. The corrugated multiwall option, which prevents heat transmission while allowing visible light, is particularly useful for the roofing of atria.

Daylight will be reduced due to the incorporation of the atrium roof and glazing in the atrium's facades in addition to the losses due to the roof structure, window frames and the dirt factor. While developing an understanding of the effects of these elements is vital, they have been eliminated in the experiments in order to focus primarily on the assessment of the effects of different surface reflectance distributions in the atrium facades and the composition of the facades as a result of the disposition of the fenestration and opaque areas on the daylight availability in the atria and their adjoining spaces.

2.7 CONCLUSION

Daylighting is fundamental to the architectural experience and to the creation of energy efficient buildings. Whilst the potentials of daylighting in buildings are recognised, as pointed out by Fontoynont (1999a), daylighting opportunities are often missed and sometimes overestimated and are combined with problems of overheating and glare. This signal to the need for careful assessment and management of daylight design and its side effects

Daylighting in buildings has long been studied in detail and an understanding of the key concepts and definitions, particularly those of transmittance and reflectance, is vital to appreciate the behaviour of light and its influences on buildings and their internal spaces. Tregenza and Loe (1998) suggest that for simple calculations of window performance an average transmittance can be used, which is a weighted mean over all directions of incidence. Significant developments in glazing, ETFE and other roofing technology can be employed to contribute to the improved performance of buildings. Although an understanding of these is vital, roofs and windows are omitted in this study due to its focus on understanding the effects of different atrium surface reflectance distributions and atrium facade compositions as a result of the disposition of the fenestration and opaque areas on the daylight availability in atria and their adjoining spaces. Therefore correction factors are applied to the data obtained to take into consideration the roof and window glazing transmittance, the dirt, the window frames and the roof structure for the interpretation of the results and comparison of the data obtained from real buildings.

The reflective surfaces of the dominant enclosures in buildings play an essential role in the distribution of light within a building and consequently the perception of the space. They are critical for improving daylighting conditions in temperate climates, such as the UK. To this end, several studies (for e.g. IESNA) have recommended reflectances for matte or diffuse reflecting interior surfaces. The thesis examines the impact of atrium reflectances of both the diffuse and the specular surfaces on the daylight within atria and their adjoining spaces. The experiments use higher ceiling and wall reflectances to improve the daylighting and are as per those recommended by IESNA.

For daylighting studies, the CIE overcast sky is used in England and Europe and provides minimum daylighting conditions that will be experienced in a full-scale building. It represents a dull, heavily overcast day with assumed minimum illumination of 5000 lux outdoors for more than 85% of the normal working day averaged throughout the year (Bell and Burt, 1995). A mirror box artificial sky was used for the physical scale model experiments presented in Chapter Four.

Interior illuminance values are dependent on the daylight availability and the sky conditions. DF which is a ratio of interior to exterior illuminance is used for overcast sky conditions as its relative luminance distribution is constant and does not change with time. On the other hand, ADF is a useful yet broad measure for assessing the daylight levels in a room and is valuable at an early design stage to estimate the amount of fenestration required to achieve good daylighting. However, the ADF does not indicate how daylight might be distributed in a room. Several studies suggest ADF and minimum DF values for various rooms and building typologies, and the algorithms presented can be used to manually calculate the DFs and the ADFs in rooms. Experiments undertaken in this thesis examine the effects of atrium surface reflectance distributions on DFs as well as the ADFs on the atrium floor.

Several different fenestration types can be exploited to improve daylight and ventilation, and provide views and visual stimulation, whilst acting as noise barriers, insulators and glare protectors. Evans (1981) highlighted that in unilaterally lit rooms, illumination levels at the end of the room opposite to the window wall are reduced with increased room depth as the same amount of transmitted light is spread over a larger area, resulting in an increased diversity in the distribution of light. The thesis focuses on the atrium envelope and its fenestration which affects the way in which light travels within the atrium and reaches its adjoining spaces. Although bilaterally lit spaces will have better daylight levels and distribution, due to the focus of this study on daylight availability in the adjoining spaces from the atrium, unilaterally lit adjoining spaces have been used.

From the previous studies, it is concluded that an increase in the ceiling height, the window head height, the room and window widths, higher surface reflectances and the use of light shelves will improve daylight penetration in buildings. Therefore, these findings informed the characteristics of the key parameters, such as the atrium and the adjoining space geometry and their surface reflectances as well as the window sizes and their positioning, chosen in the experimental work. For example, to improve DFs at the rear of the room, the window head height chosen is in line with the underside of the ceiling enabling deeper direct light penetration and increasing reflected light from the ceiling. .

The key concepts and definitions described in this Chapter enable an understanding of the important daylighting strategies and their performance in the atrium building typology explored in the next Chapter. They inform the experimental work undertaken in this thesis and the interpretation of results and their comparison with data obtained from real buildings.

3 DAYLIGHT IN ATRIUM BUILDINGS: A LITERATURE REVIEW

3.1 INTRODUCTION

The importance of daylight in an atrium's environmental performance, particularly its potential to reduce electrical lighting and associated thermal loads, has led to several investigations of daylighting in atria and their adjoining spaces.

Daylight levels within the atrium space are generally sufficiently high. However, atrium buildings have been unable to successfully utilise daylight in the spaces adjoining the atria, where daylight varies significantly with the floor level. Rooms on the top floors can be over-lit and suffer from glare while the daylight levels on the lower floors can be low, especially in tall/deep atria.

The first part of this Chapter concentrates on the way in which light behaves in an atrium building. It discusses how light is admitted into an atrium building; how light travels and is distributed within the atrium space; and how light is collected by the occupied spaces adjoining an atrium.

Following an introduction to the daylight related atrium parameters, the second part reviews published literature on the available prediction tools. Given the focus of this research, the importance of atrium geometry and atrium surfaces (atrium walls and floor) and their reflectance properties in determining the daylight performance of an atrium building, this section chronologically and thematically reviews published literature of investigations focussing on their influence.

The conclusion highlights gaps in the knowledge base and the research opportunities, which form the basis for the work undertaken in the following Chapters. Therefore the Chapter concludes with the rationale for the research presented in this thesis.

3.2 DAYLIGHTING IN ATRIUM BUILDINGS

Glazed atrium spaces allow for the adjoining spaces to have larger windows to admit daylight without considerable heat losses or heat gains thus providing opportunities for the daylight to enter into the heart of a building and potentially increasing the amount of occupied space that can be naturally lit. Therefore, daylighting is one of the key advantages of the atrium form, as it replaces artificial lighting and its associated cooling loads. However, Fontoynont (1999a) showed that converting a courtyard to an atrium may reduce the daylight which reaches the windows of the atrium facades by 50%. Illuminance on atrium walls is much lower (third to a fifth) in comparison to that obtained on the external facades due to the high angle of incidence and resulting in a poor penetration of daylight, up to a depth of two metres, typically into the adjoining spaces. Furthermore, any shading devices either on the atrium roof or the walls will also affect the availability of daylight. Although the daylight availability from atria into the adjoining spaces might be low for particular tasks such as reading or writing, it might be generally enough as ambient lighting and is useful particularly in reducing the feeling of being confined and providing a perception of the outdoor environment through the atrium (Fontoynont, 1999a).

After passing through the atrium cover, a portion of the incoming daylight is directed towards the adjacent rooms, and the remainder is inter-reflected between the atrium surfaces and channelled downwards towards the lower floors. The amount of daylight reaching the adjacent spaces depends largely on how much light is transmitted from the outside, the size of opening within the atrium walls and the inter-reflection capability of the atrium (Boubekri, 1995). Atrium facades are usually made of interior materials and clear glazing to enable daylight and views, replacing expensive exterior walls. Thus the parameters that affect the daylighting of spaces adjoining atria are those to do with the adjoining room (room shape, reflectances, and fenestration) and the atrium itself (geometry, surface reflectances, roof structure). The atrium along with the fenestration in the building's exterior and atrium walls present opportunities for effective transmission of natural light and its balanced distribution in deep plan buildings.

Baker et al. (1993) proposed that the atrium's light system can be subdivided into two: light collecting system (atrium roof) and light guiding system (atrium space) whilst, both Saxon (1983) and Bednar (1986) extend it to the occupied adjacent spaces giving three important criteria for the analysis of daylighting in atria:

1. Daylight source: How is daylight admitted into the atrium?

2. Light box: How is daylight distributed within the atrium?

3. Illumination: How is the daylight collected and used in occupied spaces?

The following section examines in detail the three stages through which the daylight is admitted and travels through the atrium space and finally reaches the adjoining spaces.

3.2.1 Daylight Source/Admitting light into the Atrium

The predominant sky conditions, external daylight availability and local context are key factors for the use of daylight in buildings. The roof configuration dictates not only how much light enters an atrium but affects its direction in a significant way. The fenestration system will control the intensity and spatial distribution of light entering the atrium. Net transmittance of the fenestration will vary with the roof structure and geometry, roof cover and shading system - its orientation and type, and illuminance conditions (diffuse sky, direct sun).

Under cloudy or the CIE overcast sky, top-lighting which is non directional with clear, unobstructed glazed roof is most appropriate to achieve maximum light transmission allowing diffuse light from all parts of the sky to enter the atrium (Saxon, 1983) bringing with it direct heat gain in winter but also unwanted solar gains in summer (Bednar, 1986). Saxon (1983) suggested the use of a lantern light for cloudy temperate climates (Figure 3:1).

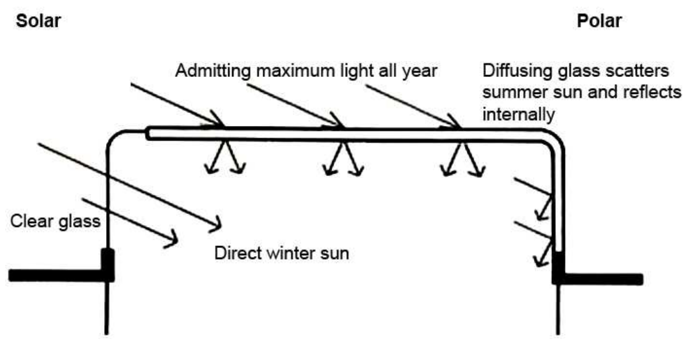


Figure 3:1 Light Collecting Atrium Roof Forms: Lantern light for cloudy temperate climates (Saxon, 1983)

To prevent overheating in summer or on sunny days, Saxon (1983) suggests that any shading under overcast skies should be limited to the atrium facades as shading the roof will result in significant loss in diffuse light transmission from the roof. Furthermore, fixed shading devices will reduce the light admitting area while movable shading such as fabrics and large highly reflective vertical baffles (trellises) that exclude sun but maximise the light admitting area are recommended (Baker et al., 1993). Dynamic systems that respond to the changing sky conditions such as motorized louvers over skylights that are automatically controlled can also be very effective.

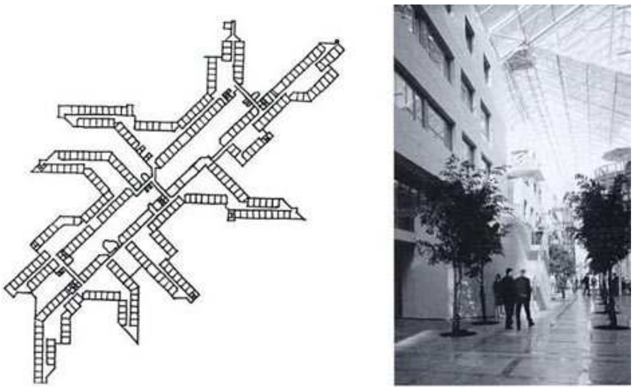
The optical properties of a roof cover, may it be glazing, ETFE or polycarbonate will determine the daylight quality and quantity, and consequently the energy savings associated with artificial lighting and cooling. High transmittance and increased light admitting area are vital to maximise light. Fontoynont (1999a) through monitoring of real buildings demonstrated that the covering of courtyards to make atria significantly reduces daylight availability in the atria. In the Berthold Brecht School in Dresden, converting the two courtyards into covered atria reduced the availability of daylight in the atria to one third (Figure 3:2). While the daylight from the courtyard contributed 80% of the total illumination in the deeper room areas of the ground and second floor, this is reduced to 50% with the addition of the atrium roof (Fontoynont, 1999a). In the Scandinavian Airlines System HQ outside Stockholm (Figure 3:2), the roof glazing reduced DFs in the atrium by 50% (Fontoynont, 1999a) while in St

Hubert Galleries in Brussels (Figure 3:2) although the semi-circular cast iron arches of the glazed roof created very little obstruction for the incoming daylight, DF was reduced by about 30% (Fontoynont, 1999a). This demonstrates the vital role of the atrium roof and indicates that when assessing the findings from model studies without a roof, reductions due to the roof should be taken into account. The extent of the DF reduction will depend on the roof geometry, structure, transmittance properties of the cover and shading devices and may range between 30 to 65%.

Berthold Brecht School in Dresden
http://www.annex36.com/eca/uk/03viewer/case_studies/de_2_user.html

Beresford Court atrium building in Dublin(Fontoynont, 1999a)

St Hubert Galleries in Brussels
http://www.flickr.com/photos/jaapwillem/4181690970/



Covered street/atrium of the Scandinavian Airlines System HQ
http://www.cityofsound.com/blog/urban_informatics/page/3/

Figure 3:2 Atria with different roof types

3.2.2 Light Box/Distributing Light within the Atrium

An atrium is a 'light box' with facade openings that act as outlets to admit light into the adjoining spaces. Atrium geometry and surface reflectances (walls and floor) are the two key parameters that determine daylight levels in an atrium building. The atrium geometry, size and relative proportions affect the amount of daylight which penetrates it and its distribution. Shallow, wide atria will generally have more daylight access than tall atria. The upper part of the atrium usually receives direct light from the sky while the lower atrium mainly receives the reflected light from the atrium walls and floor. Therefore, atrium walls and floor are fundamental in distributing light in the atrium and its adjoining spaces.

With the exception of the direct sky light (sky component SC), light travelling through the atrium space is either absorbed or reflected by the enclosing wall and floor surfaces before it enters the adjoining spaces as shown in Figure 3:3. Therefore, atrium surface reflectances including the design of an atrium's facades, their surface reflectances, window size and positioning, use of innovative daylighting systems (lightshelves, lightscoops) and atrium floor reflectances can impact daylight conditions significantly.

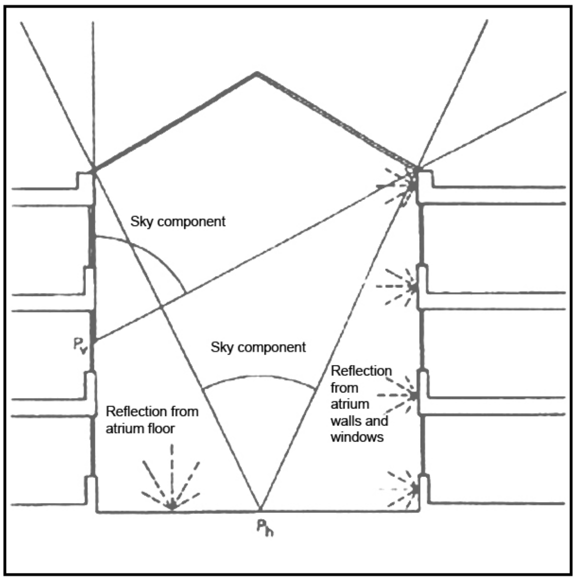


Figure 3:3 Daylight in the atrium (Baker et al.1993)

Skylights and clerestories can be used on the higher floors to admit light directly with smaller side/vertical windows for views. This would enable larger areas of opaque, high reflectance wall surfaces to reflect light towards the lower reaches of the atrium where light levels are typically low (CIBSE, 1999). Fenestration at each level should be altered so that the light at each level is drawn off as necessary with the rest allowed to be reflected for further transmission downwards. This will result in a progressive increase in the window sizes from top to bottom floors with completely glazed facades on the bottom floor (Saxon, 1983).

The quantity of the reflected light is a product of the average reflectance of the walls and the type of reflection; diffuse reflecting materials may reduce daylight quantity at the bottom of the atrium while specular surfaces may increase glare (Baker et al., 1993). Bednar (1986) and Saxon (1983) confirmed that opaque surfaces that are light in colour and smooth in finish are most effective in the distribution and diffuse reflection of daylight.

The lower storeys receive light reflected from the atrium floor and as a result it should have glossy finish or glossy floor material (such as marble). While light colour floor paving tiles and water pools at the atrium floor can be good reflectors of daylight, dark floors including dense planting can absorb light and reduce light reflection if planted too close to the walls. Therefore, plants should be placed at the centre of the atrium floor along with a band of highly reflective surface at the periphery to increase the light that can be reflected into the adjoining spaces (Baker et al., 1993).

3.2.3 Collecting Light in the Occupied Space

The most difficult task in atrium buildings is to admit daylight in the adjoining spaces. These spaces are illuminated by the sky component and the internally reflected component after light passes through the glazing between the atrium and the adjoining space. However, depending on the atrium geometry and the floor level of the adjoining space, daylight is either received directly from the sky and/or is reflected from the walls and the floor. A room near the roof receives light mostly from the sky while one near the atrium floor will mainly receive light reflected off the floor. Atrium wall and floor reflectances should be as high as possible so that the reflected light is optimised in many of the adjacent spaces that rely on it as seen in Figure 3:4. Furthermore, surface reflectances in the adjoining spaces should also be high. Atrium facades should be composed of high reflectance opaque surfaces and characterised by a progressive increase in the fenestration from the top to bottom floors, increasing the availability of reflected light further down the atrium where the daylight levels are typically low as stated earlier.

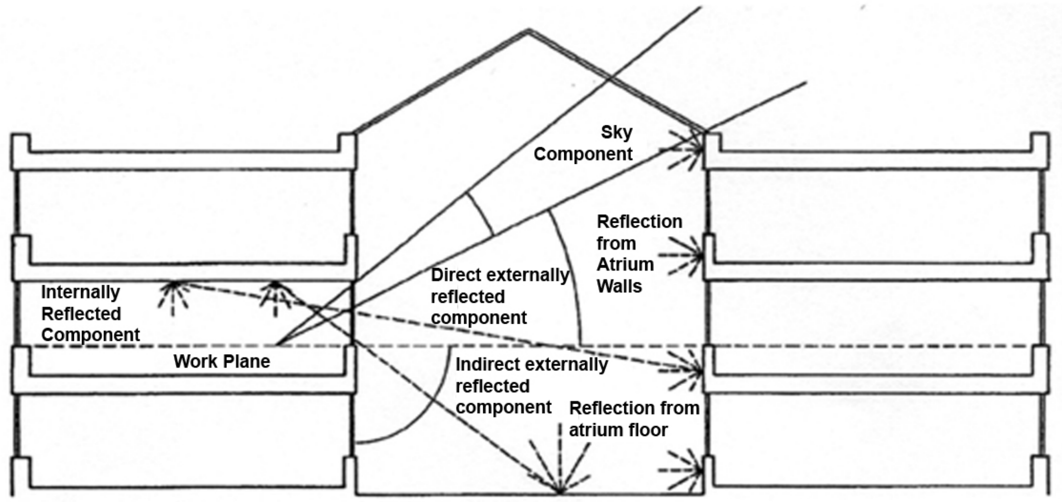


Figure 3:4 Atrium as a source of daylight for adjacent spaces (Baker et al., 1993)

As with a traditionally side-lit space, the daylight in an adjacent space will diminish as one proceeds away from the atrium into the adjoining space. Lighting in the adjoining spaces can be improved through designing an atrium as a daylight collector and distributor, and ensuring an appropriate arrangement and design of the adjoining spacesGenerally, daylight in the occupied spaces can be enhanced through shallow plans, increased floor to floor heights, appropriate window sizes, high surface reflectances, and incorporating light directing elements in the internal atrium and external facades.

Typically, light levels drop rapidly as one moves away from the window with very little useful light at between four and five meters in rooms with conventional windows and room heights. However, with an increase in the ceiling height from 2.7m to 3.6m, ambient light obtained can reach twice as far, up to 9 metres into the plan (Michel, 1996). Therefore, there is a trade-off between plan depth and storey height within the overall volume. Getting full benefit means reducing the depth or increasing the height of the occupied space until all useful areas can be naturally lit. With conventional floor-to-floor heights and window design this means space depths of about 12 metres. Such shallow plans do not require deep service voids and can be serviced from the perimeter while deeper floor plans would need increased height to draw daylight deep into the plan, and would reduce the number of floors and increase the in-between volume required to ventilate the space (Saxon, 1983). Deeper floor plans would need more artificial lighting resulting in additional heat being generated that could be used in the heat deficit perimeter. Rooms could be set back from the atrium to create a stepped section so that each floor has a view of the sky; however, this may also lead to deeper lower floors that will in part have to be lit artificially. If rooms are lit bilaterally, they will only have a small central zone that may require artificial lighting.

Thermal requirements demand a separating wall between the adjoining space and the atrium. Since the quantity of light received in the adjoining space is reduced by glazing transmittance properties and window frames, these aspects should be optimised (Baker et al. 1993). High windows that permit access to brighter parts of the atrium and roof aperture enabling the light to fall more perpendicular on horizontal working surfaces could be used (Michel, 1996). Light guiding systems such as the light shelves, reflectors and prismatic systems can be used at the atrium facade to reflect zenithal light from the atrium to the ceiling of the adjoining space from where it can be reflected deeper into the space (Baker et al. 1993).

In summary, the daylight performance of an atrium and its adjoining spaces is complex and affected by five key parameters which determine the amount of light that penetrates the atrium, and the way in which it travels through the atrium to reach the bottom floors:

- The predominant sky conditions and external daylight availability

- The roof configuration which dictates not only how much light enters the atrium but can affect its direction in a significant way
- The atrium geometry, size and relative proportions which affects the amount of daylight that penetrates it and its distribution
- The design of the atrium's enclosing surfaces (walls and floor) which determine how much light is going to be transmitted to the adjoining spaces, or reflected down towards the lower floors
- The design characteristics of the adjoining spaces

Daylight potential of an atrium has been recognised widely and the daylight levels within the atrium space are generally sufficiently high. However, atrium buildings have been unable to successfully utilise daylight in spaces adjoining the atria, where daylight varies significantly with every floor level. Rooms on the top floors can be over-lit and suffer from glare while daylight levels on the lower floors can be low, mostly in tall/deep atria. Therefore, it is vital to examine means by which this specific problem may be addressed. To this end, the next section examines the influence on daylight of two of the key parameters: atrium geometry and atrium enclosing surfaces (atrium walls and floor) including surface reflectances, glazing and fenestration. It includes a critical review of investigations undertaken over the past 30 years and an identification of the gaps in this knowledge that the thesis intends to fill.

3.3 A REVIEW OF DAYLIGHT LINKED ATRIUM PARAMETERS

Case studies, scale models, algorithms and computer programs have been used to provide simple guidance quantifying the effects atrium parameters have on the daylight performance in atrium buildings. Aizlewood (1995) undertook a detailed review of prediction methods that provide DF data for an atrium and its adjoining spaces whilst Littlefair and Aizlewood (1998) gave guidance for daylighting design in atrium buildings. Letherman and Wright (1998) in their review paper included analytical equations that predict the sky components (SC), the internally reflected components (IRC) and the daylight factors (DF). They concluded that "the poor daylighting performance of some atria may be attributable in part either to the poor availability of suitable daylighting design models or to the poor quality of information within such models" and that "the absence of complete sets of performance data within the literature justifies further research in this area" (Letherman and Wright, 1998). In 2002, Littlefair outlined guidance on daylighting design for atria and reviewed published techniques to evaluate the average daylight factor (ADF) at the atrium base, atrium walls and in the adjoining spaces. This study summarised that the penetration of daylight into the adjoining spaces can be improved by changing the roof profile to admit additional side light, higher head heights for openings in the atrium walls, higher reflectances in the atrium and its adjoining spaces and through the use of innovative glazing systems like the light scoops and shelves. Sharples and Lash (2007) reviewed research completed since 1990 on the way in which daylight is transmitted through the atrium roof structure, distributed in the atrium well by its geometric properties and surface reflectances and penetrates the spaces adjoining an atrium well.

3.3.1 Prediction Tools

Over the years, various lighting design tools have been developed to assess the interior daylight levels (DiLaura, 1978; Bryan and Clear, 1981; LBL, 1985).

The International Commission on Illumination (1970) developed the Commission Internationale de l'Eclairage (CIE) method to determine the DF at a specified reference point in rooms lit by vertical windows with and without external obstructions for certain room geometries, window sizes and glazing transmittance. This simple and easy method is not highly accurate but is commonly used to establish whether enough daylight is available in uncomplicated rooms under average conditions. However, BRE's tabular method is perhaps the simplest way of determining DF at a point indoors for windows with clear, vertical, rectangular glazing in conjunction with a CIE standard overcast sky (CIBSE, 1999).

Lynes (1979) devised a simple expression, for rooms illuminated by windows in one wall, which gave the ratio of average illuminance in the front half of the room to that in the back half. The study proposed that if this ratio has a value of less than three, the diversity of illuminance is likely to appear acceptable. CIBSE Code for Interior Lighting (1984) gave the limiting depth concept beyond which in a side-lit room, lighting in the depth of the interior may look very dull and can be calculated.

Degelman and Boyer (1986) show how the model for daylighting contribution into exterior perimeter offices follows the Illuminating Engineering Society (IES) Lumen Method that is used to calculate the light levels in a room taking into consideration the contributions of the skylight and the artificial light from the luminaires. It utilizes a Coefficient of Utilization (CU) to estimate the fraction of light that penetrates a space to varying depths. Factors influencing coefficient of utilization are the efficiency of the luminaire, the luminaire distribution, the geometry of the space and the reflectances of the room surfaces. Each luminaire will have its own CU table specific to that luminaire's light distribution and efficiency. CU values are available in tables for different room geometries and room surface reflectances.

The basic equation for the lumen method presented by Degelman and Boyer (1986) is:

$$E\ (tot) = E_{kw} \times A_g \times T_g \times C_s \times K_s \times V_s + E_{gw} \times A_g \times T_g \times C_g \times K_g \times V_g \qquad (1)$$

Where:

$E\ (tot)$ = the total illuminance on the work plane

E_{kw} = illuminance from sky onto the window

E_{gw} = illuminance on wall reflected from ground

A_g = area of glass transmitting the light

T_g = daylight transmissivity of the glass

C_s, K_s = Coefficient of Utilizations (CU)s for light from sky

C_g, K_g = Coefficient of Utilizations (CU)s for ground reflected light

V_s, V_g = Venetian blind factor or 1 if blinds are not present

While the CIE method accounts for SC, IRC and ERC (as described in Chapter Two) for conventional spaces, for an atrium Baker et al. (1993) quantified illumination using only two components of the DF:

Direct light from the sky reaching the atrium floor and walls D_s (sky component horizontal or vertical) and light reflected off the atrium walls and floor D_i (internally reflected component)

Szerman (1992) as shown in Figure 3:5 used a scale-model approach to develop a nomograph for the ADF at the working plane height in the adjoining spaces taking into account the shape of the atrium, floor level of the adjoining room, reflectance of the opaque atrium wall elements, the reflectance of the atrium floor, and the glazing types of the outside-atrium and the atrium-office boundaries.

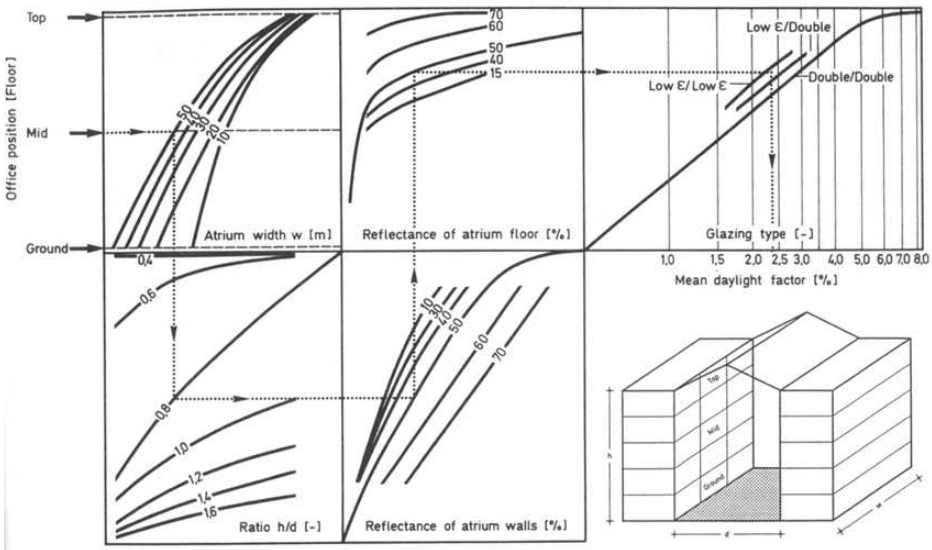


Figure 3:5 Nomograph for deriving mean daylight factors of rooms connected to atria (Szerman, 1992)

Hopkirk (1995) developed the “light index” (LI) equation specifying daylight availability in the adjacent offices as follows:

Light index (LI) = $t_a \times A_a \times P_{eff} \times t_{o,gl} \times A_{o,gl}$ (2)

Where:

t_a = atrium skylight glazing transmission coefficient (-)

A_a = atrium skylight glazing area relative to roof area (-)

P_{eff} = effective reflectance of all atrium walls (including all walls and fenestration) (%)

$t_{o,gl}$ = adjacent office interior window glazing transmission coefficient (-)

$A_{o,gl}$ = adjacent office interior window glazing areas relative to the facade (-)

The expression demonstrates that Hopkirk (1995) considered skylight and window areas with their respective transmissions and the atrium facade reflectances to be important parameters for daylighting in the adjacent offices. On the other hand and in agreement with Szerman (1992), Boubekri and Anninos (1996 a, b, c) identified wall reflectance and the geometric proportions of the atrium as the key parameters to impact the daylight performance. Boubekri and Anninos (1996c) gave the equation for calculating illuminance at a chosen point inside a four sided top lit atrium as follows:

$E_{sp} = E_e \times C_g \times DEF$ (3)

Where:

E_e is the exterior illuminance striking the horizontal glazing,

C_g is the glazing transmission factor, which represents the reduction in interior illuminance caused by the glazing transmittance, dirt and the framing factor of the glazing system

DEF (%) is the Daylighting Efficiency Factor at the chosen location which includes both the direct component from the glazing and the inter-reflected component

DEFs were provided for atria of Section Aspect Ratios (SAR) 0.5, 0.75, 1.0, 1.5, 2.0, 3.0 and 4.0; and Plan Aspect Ratios (PAR) 0.2, 0.4, 0.6, 0.8 and 1 with wall reflectance of 0.7, 0.5 and 0.3 and a constant floor reflectance of 0.3. DEFs for critical locations on the floor and vertical atrium walls were provided as shown in Figure 3:6 and Table 3:1 (for point P_8).

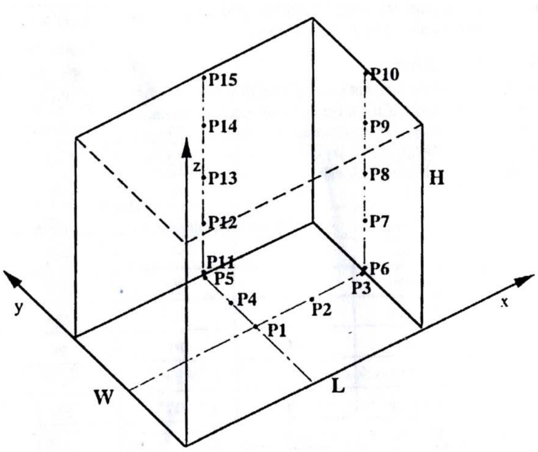


Figure 3:6 Critical locations inside a four-sided atrium where DEFs are tabulated (Boubekri and Anninos, 1996)

Table 3:1 DEF at Point P_8 (on the shorter atrium wall as indicated in Figure 3:6) (Boubekri and Anninos, 1996)

DEF at point P8 (on the shorter atrium wall) as indicated in Figure 3.

PAR	wall refl.	SAR						
		0.5	0.75	1.0	1.5	2.0	3.0	4.0
0.2	0.7	53.7	48.8	44.5	37.4	31.8	23.6	17.9
	0.5	49.1	42.8	37.7	29.8	24.1	16.6	12.0
	0.3	45.3	38.2	32.6	24.6	19.3	12.8	9.81
0.4	0.7	53.3	48.1	43.5	35.8	29.7	20.9	15.0
	0.5	48.6	42.0	36.5	28.1	22.1	14.2	9.48
	0.3	44.8	37.3	31.5	23.0	17.4	10.6	6.81
0.6	0.7	52.6	46.9	41.9	33.5	27.1	18.0	12.2
	0.5	47.8	40.7	34.8	25.8	19.5	11.6	7.23
	0.3	43.8	35.9	29.7	20.8	15.0	8.32	4.91
0.8	0.7	51.7	45.4	40.0	31.1	24.4	15.4	9.99
	0.5	46.6	39.0	32.7	23.3	17.0	9.44	5.56
	0.3	42.5	34.1	27.6	18.5	12.7	6.49	3.58
1.0	0.7	50.6	43.8	38.0	28.6	21.9	13.2	8.21
	0.5	45.2	37.1	30.5	20.9	14.7	7.71	4.33
	0.3	41.0	32.2	25.4	16.2	10.7	5.10	2.67

Whilst the DEFs might help to provide an indication of daylight availability in the atria due to the different wall reflectances, they do not take into account the wall reflectance distributions.

Furthermore, the equation does not enable estimation of the daylight availability in the adjoining spaces. CIBSE (1999) gave a two stage process for estimating daylight in spaces adjoining the atrium space. The first step is to calculate the ADF in the atrium space Df_a.

$$Df_a = TA_{wa}\ \theta/2A\ (1\text{-}R) \qquad (4)$$

Where:

A_{wa} = area of atrium glazing (m^2)

T = glazing transmittance

θ = angle of visible sky viewed from the glazing

A = total area of the atrium surfaces

R = atrium surfaces' average reflectance

The contribution from the atrium to the ADF in the adjoining space (Df_{sav}) is given by the equation:

$$DF_{sav} = 2A_wT_sDF_v\ /\ A_s\ (1 - R_s^2) \qquad (5)$$

Where:

A_w = the net area of glazing between the space and the atrium (m^2)

T_s = the diffuse visible transmittance of this glazing (for an open aperture with no glazing, 1.0 is used)

DFv = vertical DF

A_s = total area (m^2) of the room surfaces: ceiling, floor, walls and windows including those to the atrium

R_s = average reflectance of the room, for a light coloured space, typical value is 0.5

In addition to atrium roof glazing and transmittance, atrium geometry and surface reflectances, CIBSE's (1999) equation 4 highlights the influence of the adjoining room's geometry, surface reflectances, and the area and transmission of the glazing in an atrium facade on the ADFs in the adjoining spaces. When an adjoining room is also lit from the outside of the building, the ADFs from each set of glazing is added together.

Using a nomogram, De Boer and Erhorn (1999) also present relationship between fundamental design parameters of an atrium and the ADF inside its adjoining spaces while Liu et al. (1991) roughly estimated the extent to which the daylight penetrates into an adjoining space by the 'no sky line' concept from the glazed part of the roof (discussed earlier in Chapter Two) (Figure 3:7).

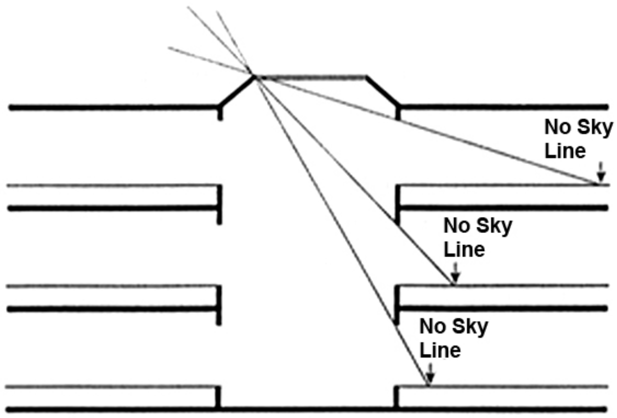


Figure 3:7 No skyline in an atrium building (Littlefair and Aizlewood, 1998)

In general, the various studies described here have developed tools by which the ADF and/or the DF in the adjoining spaces may be calculated, all of which highlight the influence of the atrium's and the adjoining space's geometry and reflectance, and of the glazing sizes and their transmittance on the daylighting conditions in the adjoining spaces.

3.3.2 Atrium Geometry

Well Index, Plan Aspect Ratio (PAR) and Section Aspect Ratio (SAR)

The geometry of an atrium is usually expressed through the plan aspect ratio (PAR) - width (w) to length (l) ratio, the section aspect ratio (SAR) – height (h) to width (w), and the Well Index (WI) where PAR and SAR are brought together as shown below (Bednar, 1986):

$$\text{Well Index (WI)} = \frac{\text{height x (width+length)}}{\text{2x width x length}} \quad (6)$$

The WI and SAR are some of the important factors that determine the amount of daylight that reaches the atrium floor and its adjoining spaces. In general, a high WI or SAR indicates that the atrium is narrow and the base of the atrium receives less light with little light penetrating the adjoining lower floors. Conversely, a low WI means that the atrium is wide compared with its height, and therefore the atrium and its adjoining spaces are likely to receive more light.

Cartwright (1986) concluded that “there is a simple relationship between the amount of light available in the spaces adjacent to an atrium and the ratio of the height to length of the atrium, irrespective of the actual size and depth of the well” i.e. the Well Index. Lau and Duan (2008) evidenced the importance of maintaining low SAR for improving daylight illuminance in the adjoining spaces. The geometry of an atrium can also be described by the Aspect Ratio (AR) (Equation 7) as shown below (Baker et al. 1993):

$$\text{Aspect Ratio (AR)} = \frac{\text{length x width}}{\text{height}^2} \quad (7)$$

Willbold-Lohr (1989) related DF to AR for three surface finishes. Reading data from the curves in Figure 3:8, the alternative parameters are approximately shown in equations 8, 9, and 10:

DF = 56.7 + 16.8 log AR for 100% white walls (reflectance 70%) (8)

DF = 44.3 + 19.2 log AR for 50% white/50% glass walls (reflectance 40%) (9)

DF = 39.7 + 19.0 log AR for 100 % glass walls (reflectance 10%) (10)

Where AR is the aspect ratio

Willbold-Lohr's (1989) three curves (10%, 40% and 70% reflectance) are plotted along with those given by Kim and Boyer (1986) for 30% wall reflectance, and Neal and Sharples (1992) for 45% wall reflectance. It is evident that agreement between the curves from the three studies is very good (Figure 3:8).

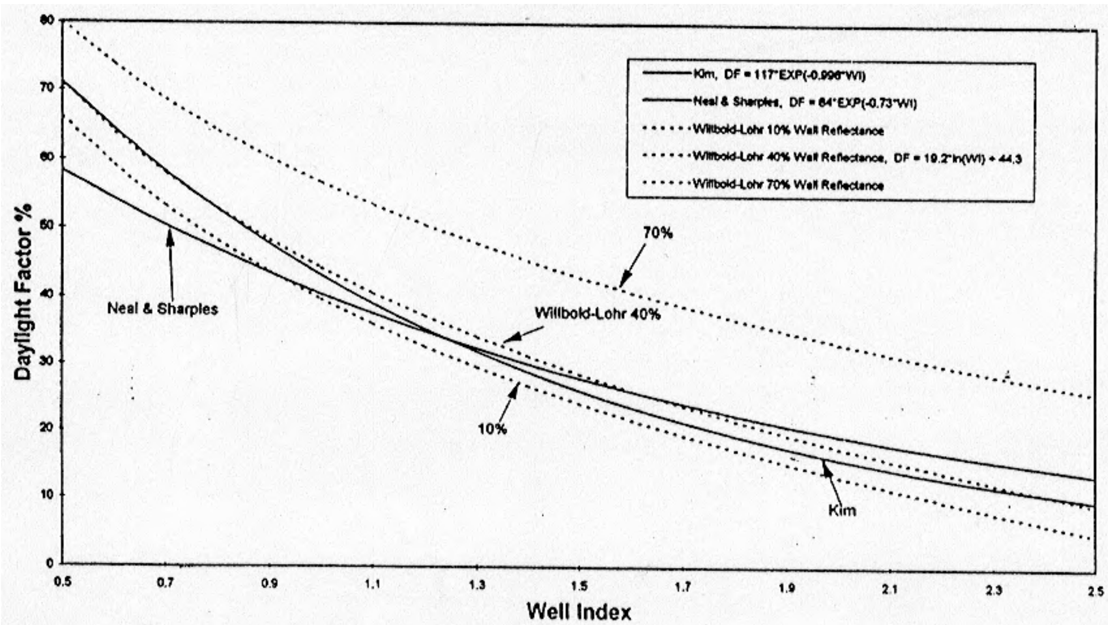


Figure 3:8 Daylight Factor at the Base of a Square Atrium (Aizlewood, 1995)

Atrium Shape

Using physical scale models, Kim and Boyer (1986) developed a relationship between the shape of the atrium (square, rectangular and linear) and the DF at the centre of an open atrium. The reflectance of the walls and floor was fixed at 0.3 and 0.1 respectively. DF at the centre of floor (DF_{cf}) of an open atrium was correlated as follows:

$$DF_{cf} = 117e^{-0.996\,WI} \tag{11}$$

The DF at the centre of walls (DF_{cw}) for a square open atrium was correlated as follows:

$$DF_{cw} = 44e^{-0.996\,WI} \tag{12}$$

Neal and Sharples (1992) show a linear relationship between log DF at the centre of the atrium floor and the WI for an open square atrium. Reading data from their curves, their equation would be approximately:

$$DF = 84\,e^{-0.73WI} \tag{13}$$

Two studies (Oretskin, 1982; Willbold-Lohr, 1989) show that the atrium wells of square or circular plans receive better illumination than the rectangular/linear plans at a given level and that elongated plans have a steeper drop in illumination, even though there is the potential for larger area for vertical fenestration. Willbold-Lohr (1989) demonstrated that a square shaped atrium with a height smaller than 0.75 times the width, i.e. of WI = 0.75, increases the quantity of light in the adjacent spaces. Although the quantity of light decreases in atria higher than 0.75 of their widths or with atria of higher WI, the quality of illumination is improved as the adjoining spaces mainly receive reflected light creating uniform illumination and reduced glare.

Cole (1990) shows the distribution of the DF within the adjacent space for atria of height/length ratios of 0.28, 0.82 and 1.36 (Figure 3:9). DFs in the adjacent space are reduced noticeably when the SAR increases from 0.28 to 0.82,

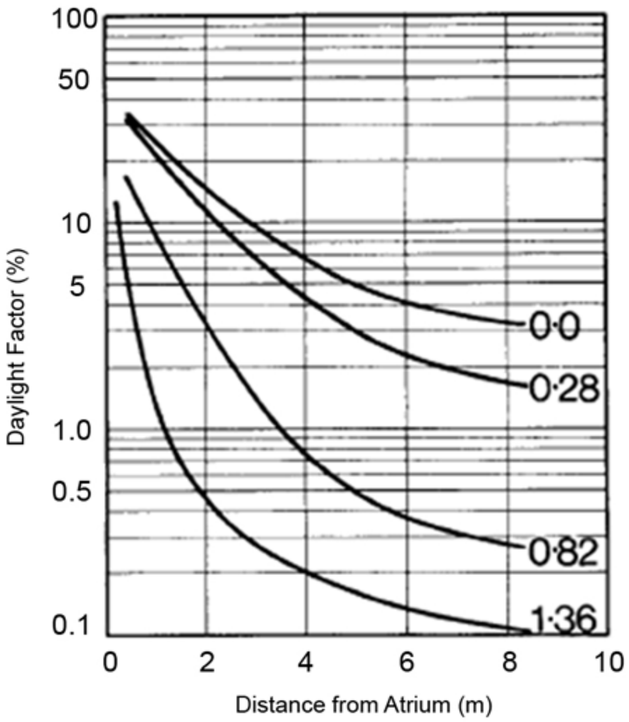


Figure 3:9 DF Distribution in an adjacent space to atria with height/length ratios of 0.28, 0.82 and 1.36; black atrium floor (15% reflectivity); 100%opening into the space (Cole, 1990)

Liu et al. (1991) conducted extensive research on the atrium shape and its influence on the daylight distribution in an atrium. This study showed that for a fixed section, whilst a quadrangular atrium provides four sides with roughly equal illumination, when the length of the atrium space is increased, daylight is also increased but is unevenly distributed across its width. In agreement with Kim and Boyer (1986), illumination levels were highest at the centre of the atrium well, with longer walls receiving higher values than shorter walls, followed by the corners receiving the least illumination. They demonstrated that built atria usually fall within the range of 0.1-1 PAR and 0.5-4 SAR. Typically, square atria would have PAR values between 0.9-1; rectangular atria would range between 0.4-0.9, whilst a linear atrium would have PAR values < 0.4 (Sharples and Lash, 2007).

Baker et al. (1993) examined the effect of atrium geometry and reflectances on the daylight quantity and distribution in atrium buildings under overcast skies. 1:50 scale models of square, triangular and rectangular shaped atria were analysed in an artificial sky. The square shaped atrium represented a 20m x 20m building with 3m high storeys and a maximum of 10 storeys; the section was manipulated by raising the floor of the atrium space. Completely white facade (reflectance 0.7), facade with 50% glazing/white wall ratio (average reflectance 0.4), totally glazed (average reflectance 0.1) and completely black facade (reflectance 0.05) with single glazing were tested.

Vertical illumination at the atrium walls (D), quantified by D_s (sky component) and D_i of Daylight factor D, (internally reflected component) determine the quantity of light that is available in the adjoining space. For the white walls and floors lower down the atrium, the contribution from the internally reflected component D_i to D at the atrium wall increases in comparison to the sky component D_s. However, nearer the roof, the reverse happens.

Horizontal illumination levels at the atrium floor of the square atrium were 10% higher for all the tested configurations when compared with those of the rectangular and triangular atria as shown in Figure 3:10.

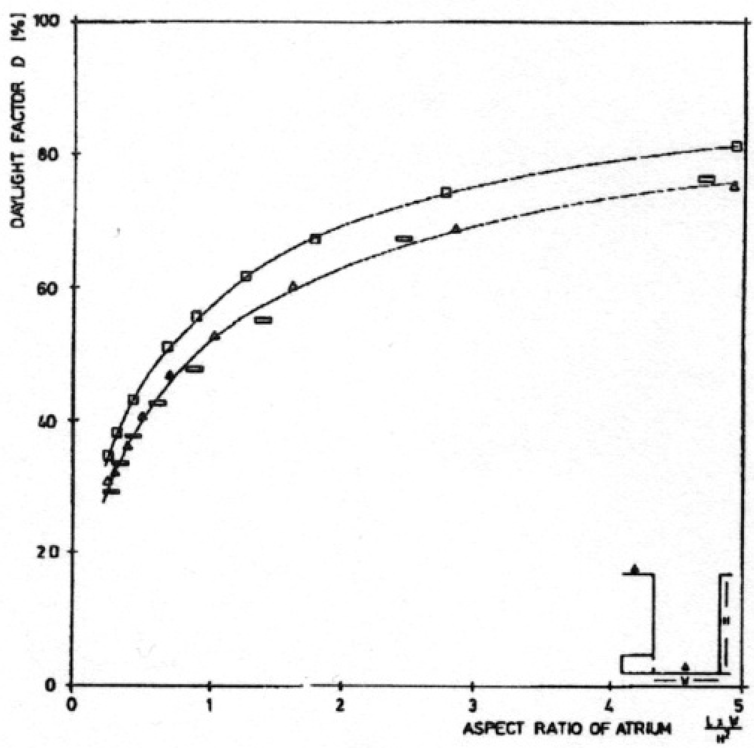


Figure 3:10 DF at the centre of the atrium floor for three atrium shapes; square atrium receives more daylight (Baker, et al. 1993)

Direct light coming from the sky was the main contributor to the light levels on the atrium floor and varied very little for the different shapes. Figure 3:11 shows the sky component of the vertical illumination, D_s, for atria with square, triangular and rectangular plan shapes. D_s increases with the AR of the atrium, and is generally higher for the square and triangular atria than for the rectangular shaped atrium. On the other hand, reduced atrium surfaces in the square shape in comparison with the rectangular or triangular atria reduced the internal reflections. This is not in agreement with the findings of Willbold-Lohr (1989) who evidences the vital role of the IRC in square atria of WI higher than 0.75.

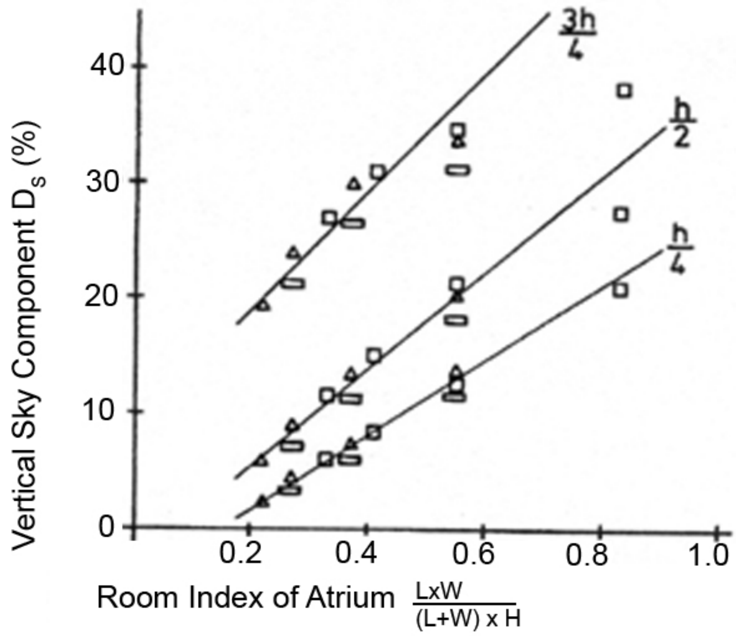


Figure 3:11 Sky Components of vertical illumination D_s at defined heights of various shaped atria (white walls and floor) (Baker, et al. 1993)

Figure 3:12 shows that in a square atrium with 50% glazing/white walls, as the AR increases, the ADF in the adjoining space also increases, however, this increase is more evident at half way up the atrium section and at the floor of the atrium than near the roof. Due to the higher position and consequent lack of opportunity for inter-reflectance to occur, surface reflectance has a minimal influence near the roof and therefore ADF values are not significantly affected by the higher wall reflectances.

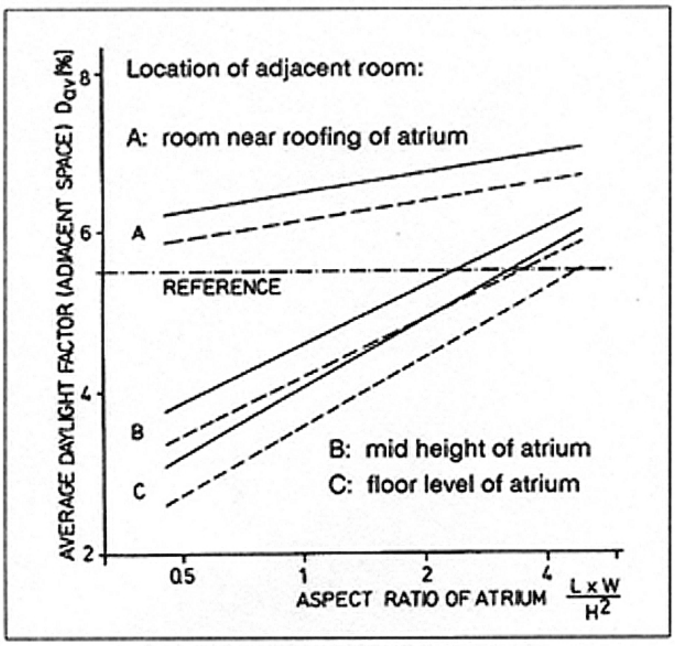


Figure 3:12 ADF in atrium-adjacent room as a function of AR for a square atrium with 50% glazing/white walls (Baker, et al. 1993)

Figure 3:13 shows that the atrium with the white facades provided more daylight to the adjoining spaces than that with the 50% glazing/white walls. Illumination at the desk level in an atrium-adjacent room, at 3m from window, related to different square atrium geometries, for the top floor and the ground floor rooms were compared. From Figure 3:14, it is noted that the influence of the atrium walls and floor reflectance on the total illumination in the adjoining room at the atrium's floor level is much higher in comparison to the adjoining room near the roof.

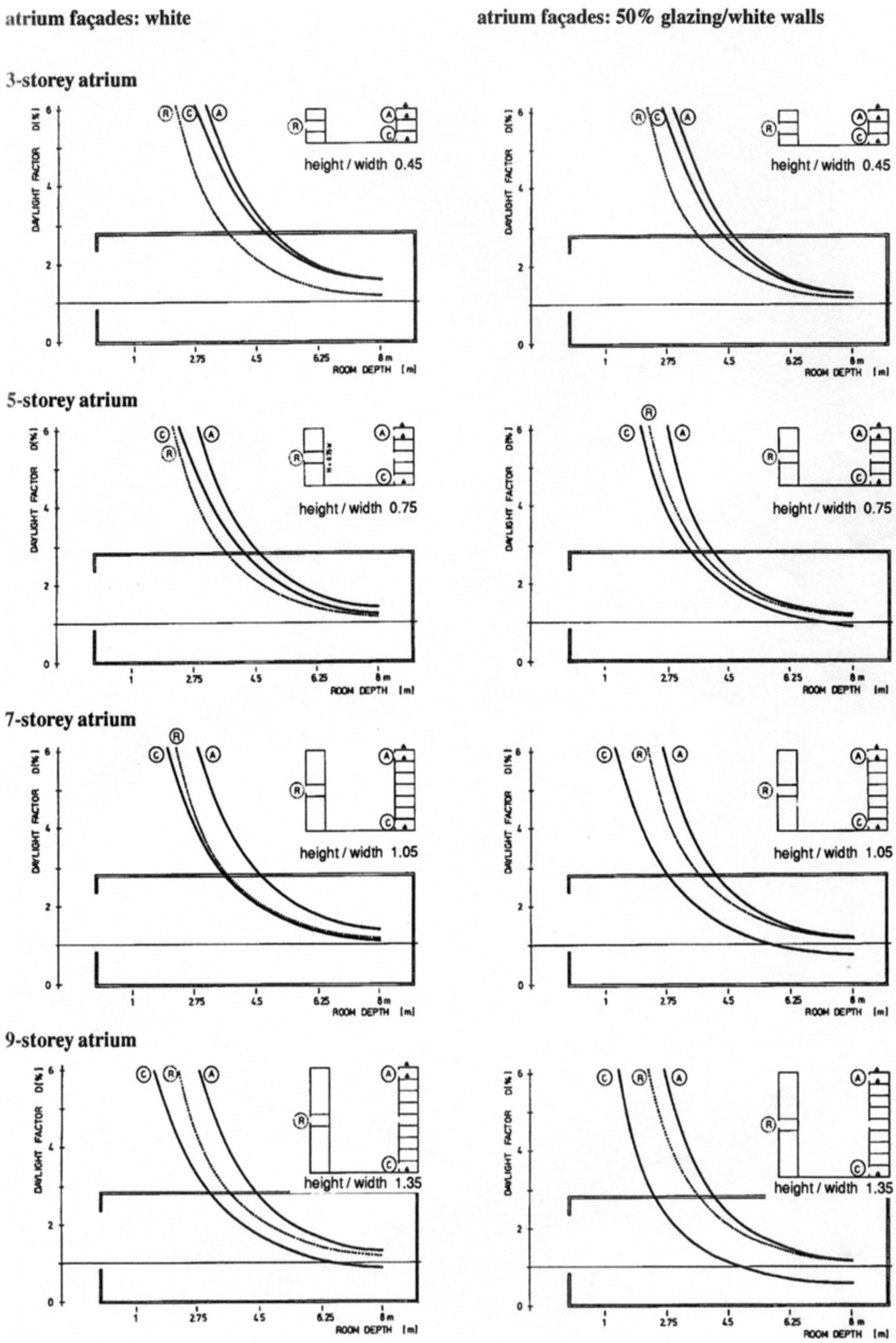
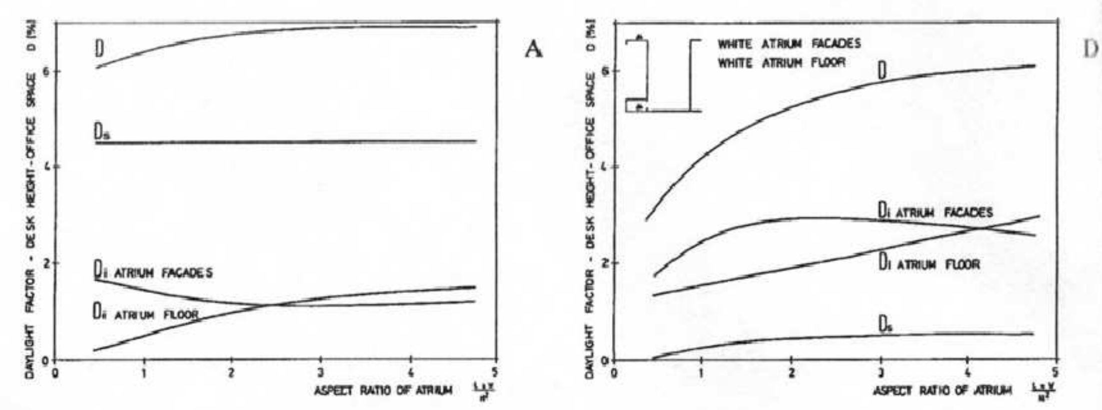


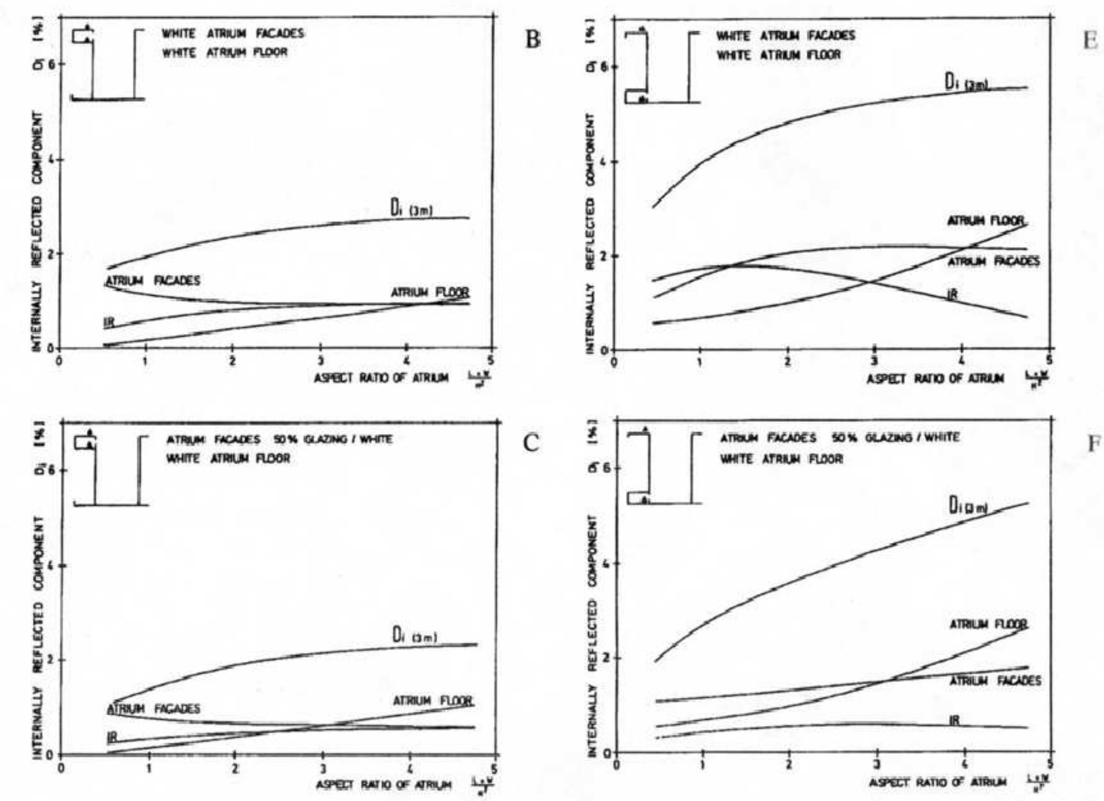
Figure 3:13 Daylight distribution in atrium-adjacent rooms A and C for different atrium reflectances – white atrium facades (left column), 50% glazing/white walls (right column). Also for reference room (R-dotted lines) with non atrium-facing glazing (Baker, et al. 1993)

Room located next to roofing of atrium | **Room located at floor level of atrium**



Components (D_s, D_i) of total Illumnination (D);
Di is split into $Di_{\text{atrium façades}}$, and $D_{i\ \text{atrium floor}}$,
(atrium: white façades, white floor)

Components (D_s, D_i) of total Illumnination (D);
Di is split into $Di_{\text{atrium façades}}$, and $D_{i\ \text{atrium floor}}$,
(atrium: white façades, white floor)



Components $D_{i\ \text{atrium façades}}$, $D_{i\ \text{atrium floor}}$ and IR of Internally Reflected Component D_i
(IR = interreflection between façades and floor)
B: atrium: white façades, white floor
C: atrium: 50%glaczing/white façades, white floor)

Components $D_{i\ \text{atrium façades}}$, $D_{i\ \text{atrium floor}}$ and IR of Internally Reflected Component D_i
(IR = interreflection between façades and floor)
E: atrium: white façades, white floor
F; atrium: 50%glaczing/white façades, white floor)

Figure 3:14 Illumination at desk level of atrium-adjacent room, at 3m from window, related to different aspect ratios, for top floor rooms (left) and ground floor (right) (Baker, et al. 1993)

Boubekri and Anninos (1996a, b, and c) carried out parametric studies using computer simulations for four, three and two sided (linear/open-ended) atria of PAR between 0.2-1.0, SAR from 0.5 to 4.0 and 0.3, 0.5 and 0.7 reflectance values. The study demonstrated that the influence of top aperture is reduced with the increasing depth of an atrium building and side-lighting can become very useful. The study showed that when one glazed wall is introduced in a four sided atrium illumination levels increase but the addition of a second glazed side does not prove to be as beneficial as the first one.

Letherman and Wright (1998) state that in atria of high WI, the relative surface area of the atrium's walls is high resulting in a higher potential for a large IRC. However, the view factor between the atrium's walls and sky vault is small resulting in lower wall luminance. As the WI decreases, IRC increases with increase in view factor with the sky vault. However, as the WI becomes very low, the wall area becomes too small and the IRC decreases. Therefore it is vital to establish the range of WI in which the IRC may be optimised.

In agreement with Liu et al. (1991), Matusiak et al. (1999) confirmed that a long glazed street atrium can receive up to 50% more daylight than a square atrium of the same depth, width and roof structure, and that the square atria also have the problem of low daylight levels in their corners. In congruence with Matusiak et al. (1999), Lau and Duan (2008) and Calcagni and Paroncini (2004) Show that when the atrium length is increased whilst maintaining the height constant, DFs also increase with an increase in the light-admitting area.

Calcagni and Paroncini (2004) provided a relationship between the main architectural components of an atrium (geometry, material properties, the fenestration system, roof) and the daylight conditions on the atrium floor and in the adjoining space. Eleven atrium (square and rectangular) cases with WI ranging from 0.2 to 1.47 and well reflectances of 10%, 30%, 50%, 70%, 90% were investigated under a CIE overcast sky. Simplified formulas (for atrium with and without roof) derived from RADIANCE were developed for preliminary prediction of the horizontal DF on the atrium floor and in the adjacent rooms at a distance of four metres from the atrium windows. Figure 3:15 shows that for the atrium with no roof, when the WI increases from 0.2-0.75 the DF values drop sharply, however when WI increases from 0.75 to 1.29, quite similar DF values are achieved suggesting that change in geometry within this range has limited influence on the DFs in spaces adjoining the atria.

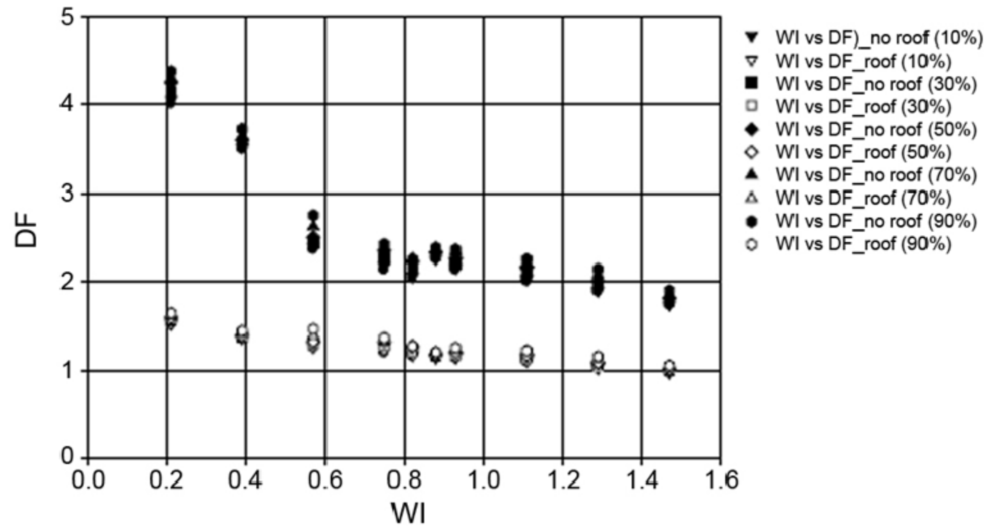


Figure 3:15 DF in the adjoining spaces for different reflectance values of the atrium walls (Calcagni and Paroncini, 2004)

The option with an atrium roof reduces illuminance in the adjoining spaces by about 45%, for several wall reflectances giving DF values of <2 (Calcagni and Paroncini, 2004). It is vital to consider this reduction when assessing results and predicting daylight availability based on experiments of atrium models without a roof, an approach that has been adopted in the experiments undertaken in this thesis.

Mabb (2008) compared the effect of varying dimensional ratios (WI 1, 1.5, 2, 3, 3.75), laser cut panels (LCP), glazing and surface reflectances on the daylight levels in the atrium and its adjoining spaces under clear and overcast skies. Illuminance levels were significantly higher for WI 1 than the other options tested but this atrium also saw the steepest fall in illuminance levels as shown in Figure 3:16. DFs in the adjoining rooms at the bottom of the atrium of WI 2 and above were too low, making artificial lighting necessary to meet the minimum standard lighting levels.

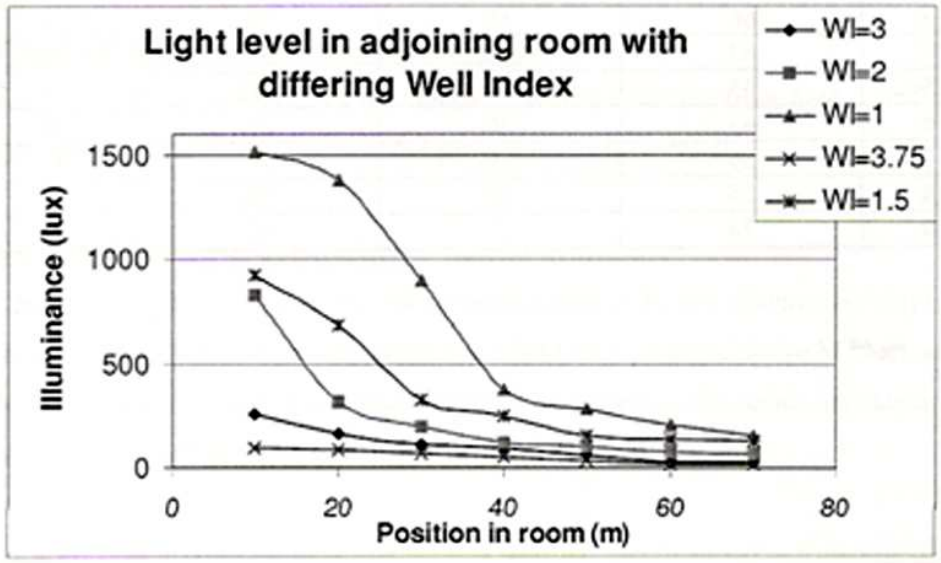
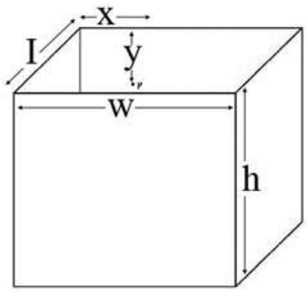


Figure 3:16 DF in the adjoining space for different WI (Mabb, 2008)

Aizlewood (1995) highlighted that daylight illuminances on the vertical atrium walls are vital as they can indicate the possible availability of daylight in the adjacent spaces from the atrium. However, very few investigations (Oretskin, 1982; Aizlewood et al., 1996; and Sharples and Lash, 2004) have focussed on daylight availability on the vertical surfaces in different atrium geometries.

While WI is a function of well length, width and height, well-indexed depth (WID) is used for the analysis of the vertical daylight levels (Du and Sharples, 2009a). WID takes into account the distance from the top edge of the atrium well as shown in Figure 3:17. Du and Sharples (2009a) investigated the effects of well geometry i.e. of square and rectangular atria on the vertical sky components under CIE standard overcast sky and concluded that for a given SAR, reducing the PAR will increase SC on the wall, particularly the lower parts of the wall which are still influenced by the sky light. This indicates that SC on the wall of a rectangular atrium will be higher than that of a square. The study also showed that the middle portion of an atrium wall between the two vertical lines at a distance of 30% of the atrium width from the atrium corner will have the highest SC and the most potential to influence daylight in the adjoining spaces. Furthermore, the area of wall from the top of the atrium up to a distance equal to the atrium width vertically down the atrium is mainly dominated by the SC.



$$WID = \frac{y\,x\,(w+l)}{2wl}\ \text{(rectangular atrium)}$$

$$WID = \frac{y}{w}\ \text{(square atrium)}$$

Figure 3:17 Definition of well index (WI) and well indexed depth (WID) as presented by Du and Sharples (2009a)

The findings of Liu et al. (1991), Matusiak et al. (1999); Calcagni and Paroncini (2004); Lau and Duan (2008) and Du and Sharples (2009a) are not in agreement with the previous studies by Oretskin (1982); Willbold-Lohr (1989); and Baker et al. (1993) which show that square atria receive higher illumination than rectangular/linear ones at a given level.

Stepped Section/Splayed Atria

Most atria tend to be built with straight or near-straight sides. Howeverincreased daylight and improved sky views can be achieved by splaying out the well walls away from the vertical. For sunny climates and those faces/floors that receive direct sunlight, it is possible to shade each floor of the atrium by having the one above it overhang it slightly. However, this may reduce daylight levels on the lower floors significantly. Bednar (1986) highlighted the effectiveness of a stepped section in terms of the daylight distribution in atria, where the atrium walls splay out from the ground to the top floors. However, it reduces the atrium floor area while making the adjoining spaces on the lower floors deeper and resulting in reduced daylight availability in these spaces.

Neal and Sharples (1992) showed DFs in the centre of the atrium and at three points in the adjoining spaces for a splayed atrium with SARs of 1.0, 2.0, and 4.0, and 0, 10, 20, 30 degree splay angles (Figure 3:18). For a relatively wide atrium (SAR 1), in comparison with an atrium with walls at right angles, there is an increase in the daylight levels of 40% at a 10 degree splay, increasing to 80% at a 30 degree splay. For a narrow atrium (SAR 4), increase in the DFs on the atrium floor appears to be more dramatic, ranging from a 300% for a 10 degree splay to more than a 1000% for a 30 degree splay (Figure 3:19).

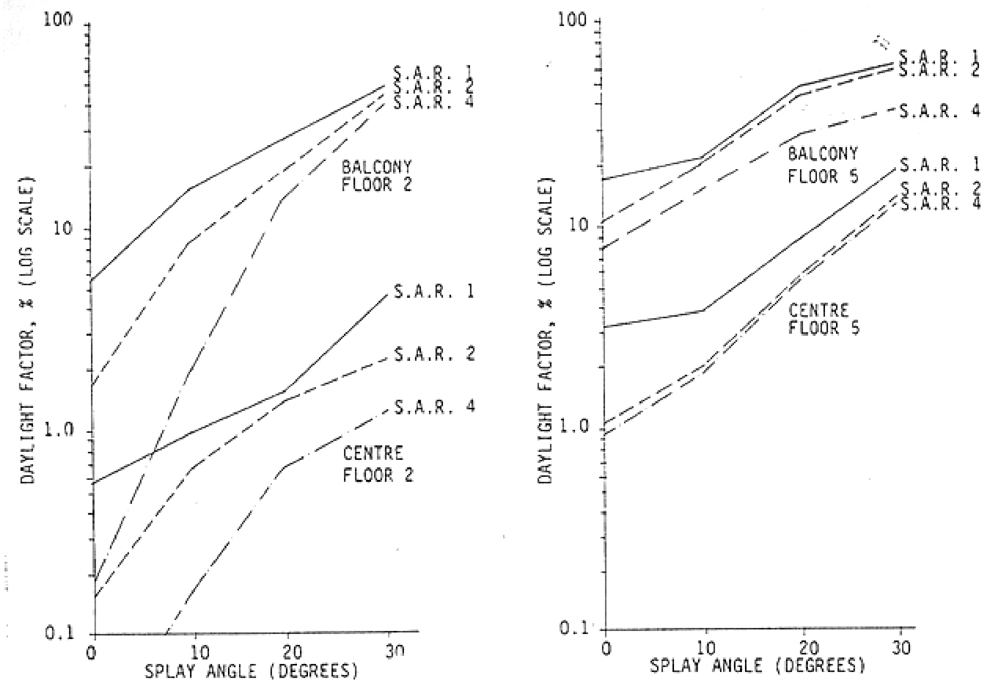


Figure 3:18 DF at 3 points in adjoining spaces (2nd and 5th floor – Balcony and Centre of the floor positions) for SARs 1.0, 2.0, 4.0, with 0, 10, 20, and 30 degree splay angles (Neal & Sharples, 1992)

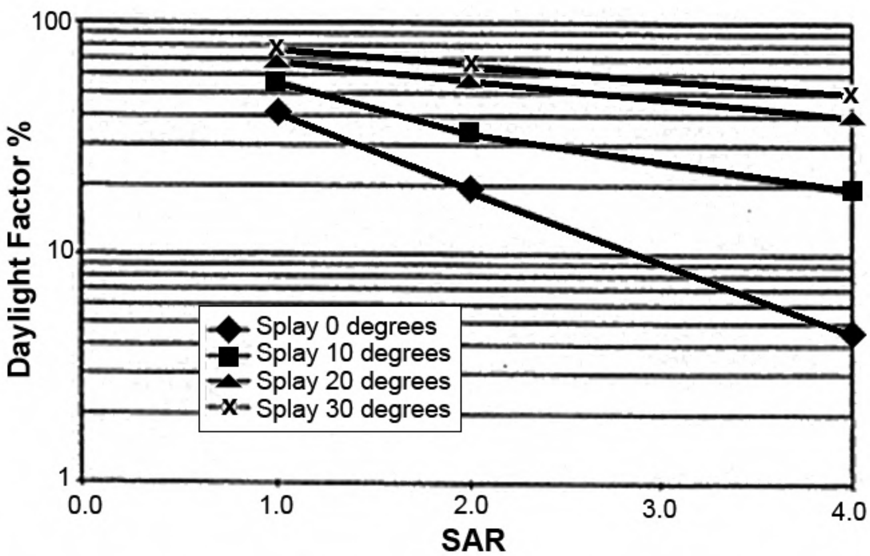


Figure 3:19 Daylight factor in a square atrium for different splay angles (Neal, & Sharples, 1992)

In agreement with Neal and Sharples (1992) and Iyer (1994), Baker et al. (1993), Tregenza (1997), Laouadi (2004) and Alraddadi (2004) suggest the use of splayed atrium walls to improve light levels in the adjoining spacesdemonstrated that the efficiency of an atrium well of WI 1 with 60 degree splayed enclosing surfaces was twice that of a well with no splays and the walls at right angles.

Whilst a stepped or splayed atrium might offer day-lighting benefits, the approach to whether the atrium steps in or out from the ground to the top level may vary under clear and cloudy sky conditions. Furthermore, the stepping will inevitably affect the spatial planning and use, the structure, construction and servicing of the atrium and its adjoining spaces and consequently the building's economic and environmental performance.

3.3.3 Atrium Wall Glazing and Reflectances

For a given size of atrium, the amount and distribution of light that reaches the lower levels and the adjoining spaces is primarily dependent upon the reflective characteristics of the surfaces that enclose the atrium as shown in Figure 3:20. The quantity of the reflected light is the product of the average reflectance of the walls and the type of reflection. Design of the facade including glazed screens, doors and windows, their size, positioning, transmittance and reflectance properties also influence daylight in the adjoining spaces. Fontoynont's (1999a) edited book *Daylight Performance of Buildings* obtained data from POE studies, observations, indoor luminous measurements for specific climates and calculation of performance indices for 60 new and old European buildings undertaken over a three year period from 1994-1997, many of which included atria. It was evidenced that higher atrium wall reflectances contribute significantly to daylight distribution within the atria and daylight penetration in the adjoining spaces (Scandinavian Airlines System HQ outside Stockholm; Sukkertoppen in Valby; the College La Vanoise in France).

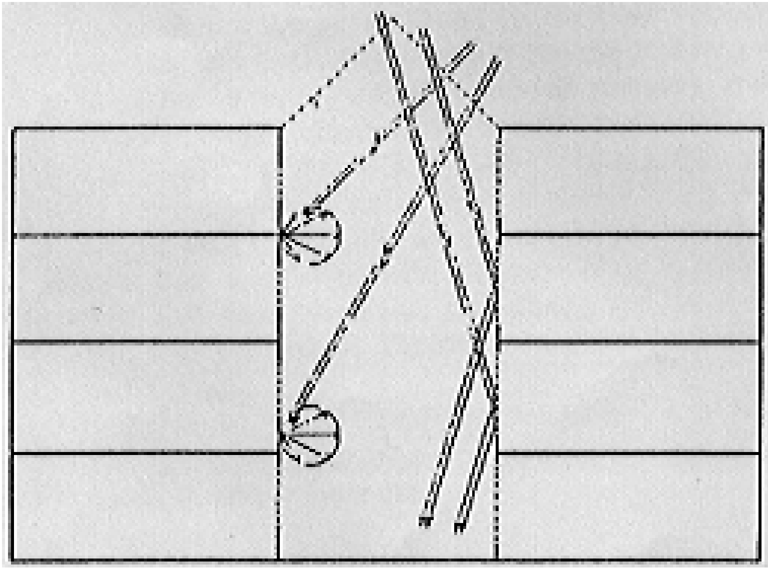


Figure 3:20 Penetration of daylight into narrow glazed atria: diffuse reflection from opaque facade surfaces, and specular reflection from glazing (Aschehoug, 1992)

CIBSE Code for Interior Lighting (1984) recommended that the reflectance of the atrium well facades should be as high as possible to improve daylight in the adjoining space. In general, several studies confirm that higher well reflectances increase the IRC and consequently the illuminance levels.

For atrium surfaces comprising of different materials, an area-weighted average reflectance is often used to calculate the ARC/IRC, where each material reflectance is multiplied with the area of its use and these figures are summed up and divided by the total area. Although this value gives an impression of the overall surface reflectance and possible resultant daylight availability, it does not indicate how daylight is distributed in the space due to the arrangement of the various materials and their reflectances within these surfaces. Whilst the ADF might be quite high, some areas may receive more light and others might be very dark. Therefore, the use of area-weighted reflectance can be problematic and it is vital to establish how reflectance distributions influence daylight distribution in an atrium and its adjoining spaces.

Oretskin (1982) showed the effect of 20%, 40% and 50% wall reflectances on the vertical illuminances as a function of WI. For WI 1.0, increasing the wall reflectances from 20% to

50% doubled vertical illuminance levels. Navvab and Selkowitz (1984) examined the effects of 15%, 50% and 86% atrium reflectances under uniform and clear sky conditions in 12 meters deep adjoining spaces of an open, four sided and five storey atrium building of WI 1.3. 1.2 metres high strip windows were also introduced in the atrium walls. Figure 3:21 shows the difference in the vertical DFs obtained indicating the importance of the inter-reflected component.

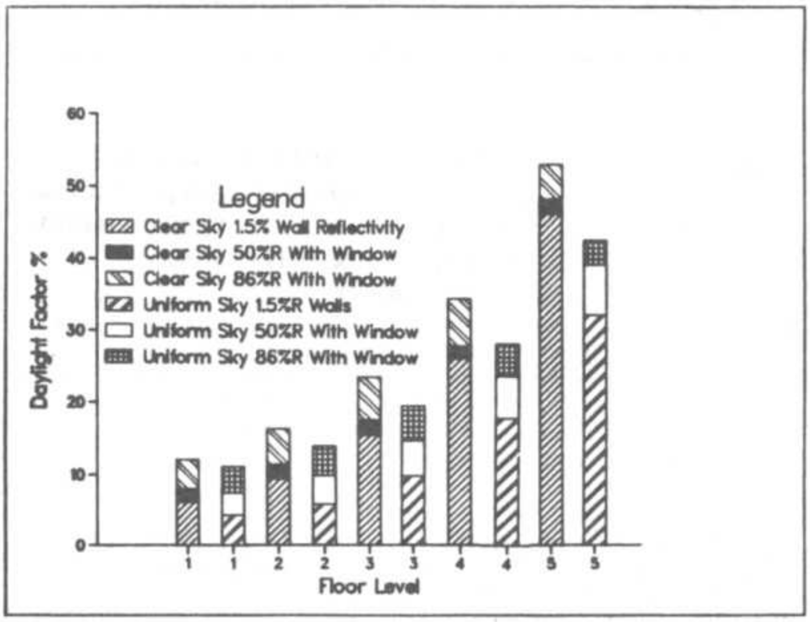


Figure 3:21 Vertical DFs at the window sill on the south-facing wall as a function of the floor level; uniform and clear sky conditions (Navvab and Selkowitz, 1984)

Several authors (Cole 1990; Aschehoug 1992; Boubekri 1995; and Matusiak et al.1999) recommend that daylight potential in the middle and lower floors can be enhanced by gradually increasing the proportion of opening to the reflective surface in the atrium walls from relatively small openings at the top to fully glazed openings at the ground level.

Willbold-Lohr (1989) studied different facade apertures in square atria of WI ranging between 0.5 and 2.0. Completely white facades (reflectance 70%), facade with 50% window/wall ratio (average reflectance 40%), only glazing (average reflectance 10%) and completely black facade (reflectance 5%) were tested. On the atrium floor, facade aperture with 50% and 100%glazing reduced IRC by half and to a third of the white facades respectively.

Cole (1990) used five storey open, square atrium (12.2m x 12.2m) models under real overcast sky conditions to examine the effect of varying atrium wall openings (100%, 50% and variable openings with 100% opening on the first floor, 80% on the second, 60% on the third, 40% on the fourth and 20% on the top floor) on the DF and its distribution in spaces adjoining the atrium (ground, third and fifth floor). The openings were not glazed and the wall surfaces had a reflectance of 0.8. The study demonstrates that the variable opening option is most effective in terms of bringing daylight onto the lower floors of adjoining spaces in atrium buildings, where it is most needed (Figure 3:22). This strategy also helps in controlling excessive brightness and glare, which is potentially found on the upper floors.

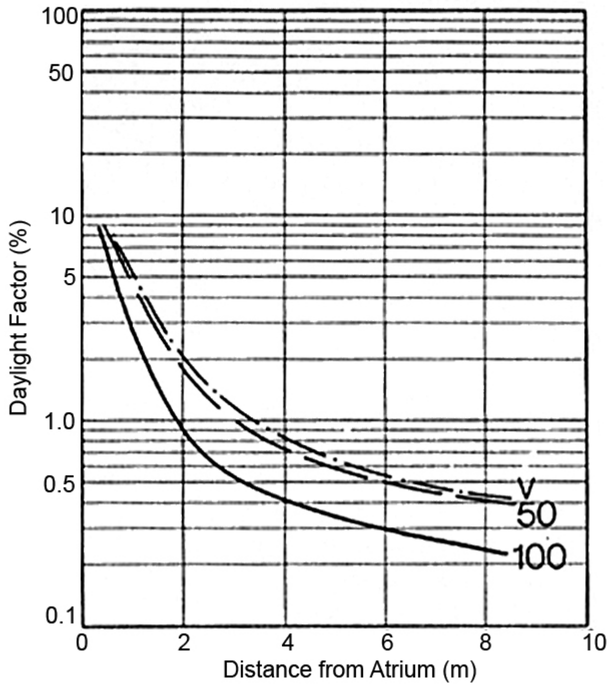


Figure 3:22 DF distribution on the ground floor adjacent to an open atrium 12.2 by 12.2 metres square in the centre of a 5 storey building for: 100%, 50% and variable openings (100% on the 1st floor; 80% on the 2nd; 60% on the 3rd; 40% on the 4th; 20% on the top floor) into adjacent spaces (Cole, 1990)

Liu et al. (1991) examined the effect of varying wall reflectances (30%, 45%, and 60%) on tDF at the base of four sided atria of different WIs (Figure 3:23). The study demonstrates that while higher reflectances give higher DFs, the influence of surface reflectance is mainly observed for WIs ranging between 1 and 2.

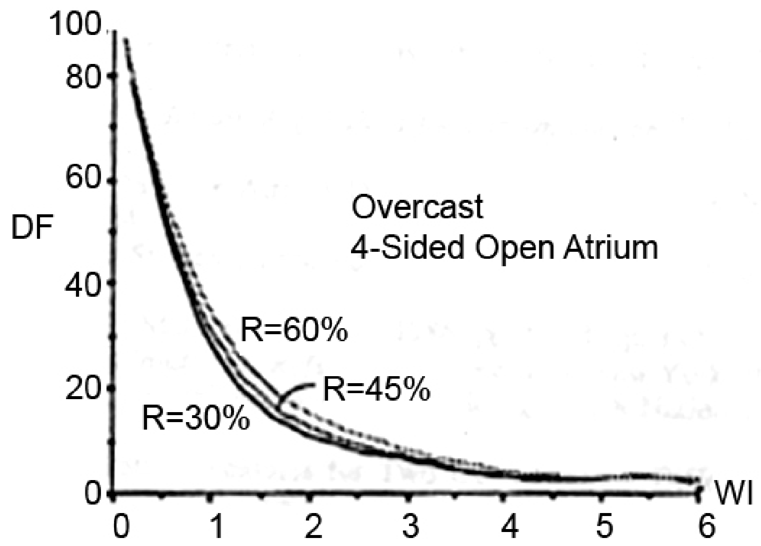


Figure 3:23 DF at the base of four sided atria with different WI and and varying surface reflectances (30%, 45%, 60%) (Liu et al.1991)

Aschehoug (1992) studied daylight distribution in the adjoining spaces of a glazed street of infinite length. Main parameters such as the street width/building height ratios, window sizes and facade reflectances were altered to present an "optimum" glazing percentage of 50% on the fourth floor, 60% on the third floor, 70% on the second floor and 100% on the first floor that provided quite similar daylighting conditions in the adjoining spaces on all of the floors. The study showed that "window glazing in very narrow and deep atria reflects daylight downwards in the same way as mirrors due to the glancing angle of glass incidence. Large windows in the upper floors therefore contribute more to daylight levels at the lower floors than normal average glass reflectants would indicate" (Aschehoug, 1992).

Baker et al. (1993) demonstrated that facade design influences illumination levels on the square atrium's floor due to the altered reflectance; high reflectance opaque facades improve IRC and therefore present opportunities to improve DFs in atrium buildings for a range of aspect ratios. Figure 3:24 shows DF (D), SC (D_s) and IRC (D_i) for white, 50% glazed/white and only glazed atrium facades for a range of aspect ratios. As the aspect ratio increases, the SC and the DFs increase, however the IRCs gradually decrease. The effect of

IRC is only noted for ARs below 1.5, after which its effect is steadily reduced with increase in the AR as shown in Figure 3.24.

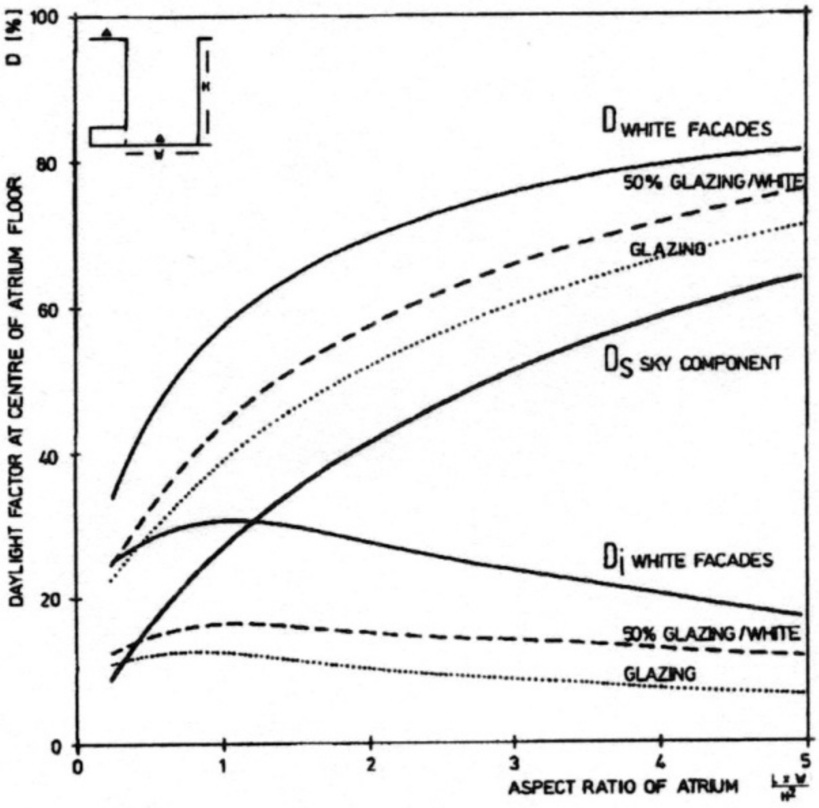


Figure 3:24 Impact of different atrium facades on the Daylight Factor at the centre of a square atrium (Baker, et al. 1993)

Iyer (1994) studied the effect of five wall reflectances (90%, 85%, 75%, 50%, 25%) in a rectangular top-lit atrium (WI=1.95) without any roof glazing for 25%, 50% and 75% openings in the wall (Figure 3:25). Additionally While larger openings gave greater illumination and a wide range of illumination values, there was a more uniform DF distribution in the adjoining spaces for 25% openings than 50% and 75% openings due to the increased inter reflectance of light down the atrium well and into the side spaces. . Therefore, to ensure higher illumination levels and uniform distribution, it is vital to have an appropriate balance between areas of opaque high reflectance surfaces and wall openings.

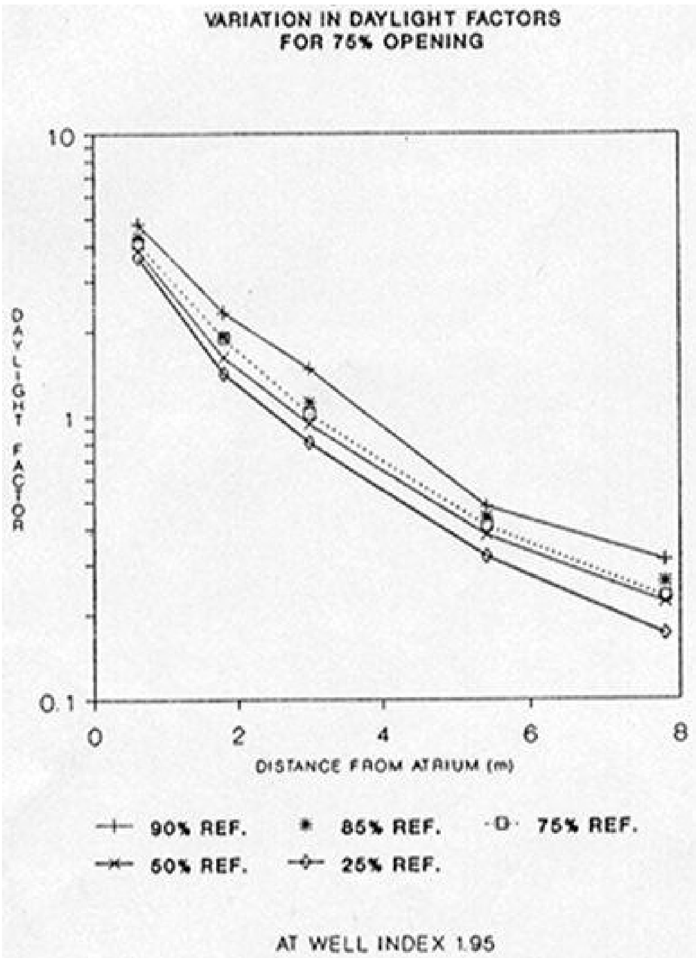


Figure 3:25 Variation in DF in the adjoining space for atrium with a WI 1.95 and wall reflectances of 90%, 85%, 75%, 50%, 25% with 75% openings (Iyer, 1994)

Boubekri (1995) examined the effect of wall reflectance (56%, 42%, 28% and 14%) on the daylight distribution under a horizontal glazed roof cover for a four sided, rectangular atrium building with a WI of 1.05. The glass to opaque wall ratio within the atrium walls varied from 0% to 75% with an increment of 25%. This corresponded to a weighted average wall reflectance of 56%, 42%, 28% and 14% respectively. As the wall reflectance increased from 14% to 56%, the overall DF on the walls at the upper level increased from 23% to 37% and from 11% to 23% at the lower level. Although the study confirms that there is a direct and positive relationship between the quantity of light reaching the walls and the wall reflectance, this effect is reduced because of the presence of openings resulting in a quadrupling of the reflectance values that led to only a doubling of the DF values on the atrium floor as shown in Figure 3:26.

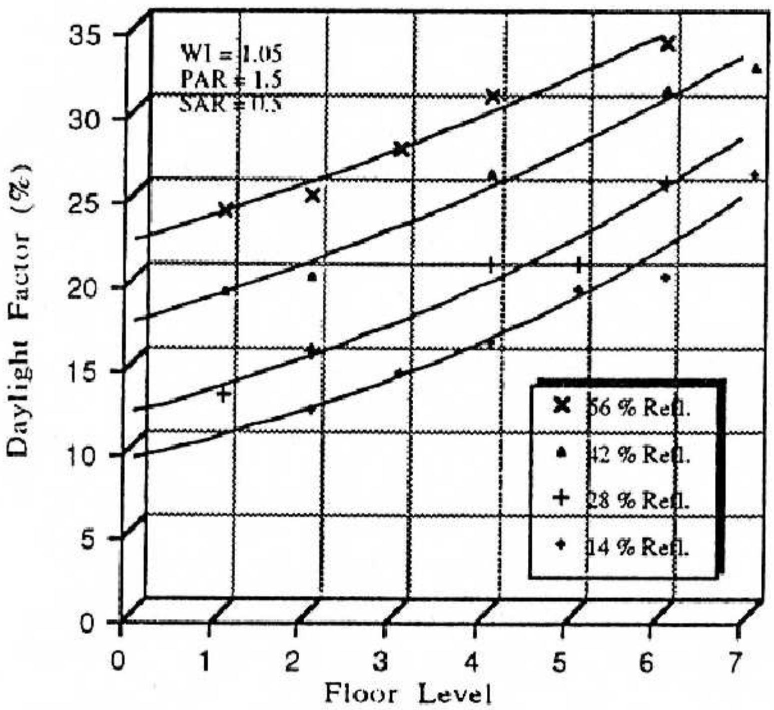


Figure 3:26 Effect of wall reflectance on daylight distribution along the walls of a four sided rectangular atrium of WI 1.05 (Boubekri, 1995)

Aizlewood et al. (1996) undertook parametric studies of atrium surface reflectances (White - 74%; Light Grey-47%; Dark Grey-33%; and Black-6%), and the geometry of the atrium and its adjoining spaces. The study concluded that the surface reflectances affect DFs in atria of WI ranging from 0.5 to 2. From Figure 3:27 it can be seen that for surfaces of lower reflectances fall in the DF at the atrium floor is rapid as the WI increases.

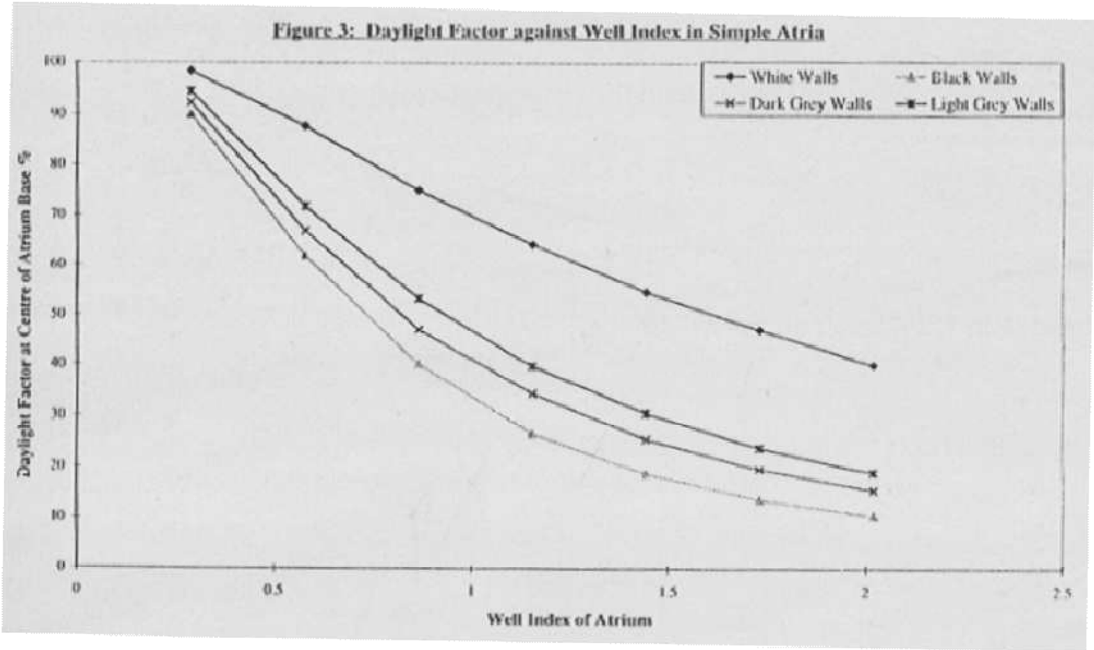


Figure 3:27 DF at the centre of the atrium floor for different Well Indices and surface reflectances (74%, 47%, 33%, and 6%) (Aizlewood et al. 1996)

An approximate analytical expression for ARC was also developed. Comparison between predicted and measured ARC values suggested that the analytical expression had the correct general form, but that it underestimated ARC values for high reflectance surfaces. In a second paper Aizlewood et al. (1997) performed a similar study and compared data with that obtained from RADIANCE. Despite the simple geometries involved, RADIANCE also underestimated the ARC for high reflectances, particularly for atria with a WI greater than 1.0 "demonstrating the complex and as yet poorly understood behaviour of reflected flux, particularly when highly reflective surfaces are used" (Sharples and Lash, 2007).

Fontoynont (1999a) recommended large windows, at least 50% of the wall surface, facing the atrium to achieve any significant daylight contribution in the adjoining spaces. He stated that the glazing ratio is the ratio of the glazed area in walls to the floor area and that typically 5% – 30% gives an idea of the general brightness of the space through the year. Of course, this is affected by the sensitivity of the space to the outdoor climatic conditions, transmittance of the glazing and the brightness of the finishes.

At the Beresford Court atrium building (Figure 3:2) in Dublin, due to the differentiated facade of 40% glazing on the top floor increasing up to 80% glazing on the lower floor, the building demonstrates a good use of the office space within three metres from the atrium facades and DFs of over 1% up to 6m into the adjoining spaces (Fontoynont, 1999a).

The Dragvoll University Centre in Trondheim, Norway consists of an 8.4 metres wide and 12 metres tall glazed street with three storeys of adjoining spaces on either of its sides (Figure 3:28). The strategy of progressive increase in openings from the top to the bottom floor, combined with white opaque wall surfaces, improves the DFs on the atrium floor and in the lower adjoining spaces (Fontoynont, 1999a).

Figure 3:28 Atrium of the Dragvoll University Centre in Trondheim, Norway
(http://wn.com/Malm%C3%B6_University)

Sukkertoppen in Valby, is an old sugar refinery whose two to three storey brick building (21% reflectance) was retrofitted and included an addition of a new white (86% reflectance), four storey office building to its south (Figure 3:29). The strategy of progressive increase in openings from the top (45%) to the bottom floor (90%) was also adopted. The new white building increased reflected daylight penetration in the old building, while the older brick building reduced the DFs across the atrium by 2% to 3% near its facade in comparison with the white facade (Fontoynont, 1999a).

Figure 3:29 Atrium of the Sukkertoppen in Valby
(http://www.arkitekturbilleder.dk/bygning_Sukkertoppen_$$516)

At St Hubert Galleries in Brussels (Figure 3:2), discussed earlier, high transmittance, cylindrical glazed roof and bright building facades with progressive increase in openings from top to the bottom floor are used. However, increasing obstructions of the opposite building facing the windows reduce vertical DFs rapidly from the top to bottom floor and cause shallow penetration of daylight where 2% DF reaches barely one metre into the adjoining spaces indicating larger windows may be necessary (Fontoynont, 1999a). The SAR is approximately 2 suggesting that in tall, deep atria/glazed streets of this nature, although the area weighted wall reflectance is high, due to the reduced view of the sky vault, DFs are low.

Clarke et al. (1999) also confirmed that non-specular and highly reflective finishes would improve daylight penetration in the atrium and in the adjoining spaces. Sharples and Shea (1999) demonstrated that the daylight penetration (amount and direction) in atria is significantly affected by the type, shape and position of glazing, including the frames, shading devices and external obstructions.

Whilst undertaking model studies for a linear atrium, Matusiak et al. (1999) evidence that a progressive increase in glazing or glazing type results in a small but significant increase in daylight on the atrium floor and improves the balance of lighting in the adjoining spaces. Horizontal DFs in the adjacent rooms will depend on the vertical DFs on the atrium facades (on the middle height of the window) and on the relation A_{gl}/A_{fl} where A_{gl} is the glass area and A_{fl} is the floor area of the room. The following rules of thumb for estimating the DFs in the adjoining spaces were given:

$$DF_{min}=0.25 \times DF_{vert} \times (A_{gl}/A_{fl}) \times (\tau/\tau_{clear}) \quad \text{rule 1} \tag{14}$$

$$DF_{mean}=0.5 \times DF_{vert} \times (A_{gl}/A_{fl}) \times (\tau/\tau_{clear}) \quad \text{rule 2} \tag{15}$$

The correction factor τ/τ_{clear} is used, where τ is the transmission factor of the actual glazing and τ_{clear} is the transmission factor of the clear double glazing. Comparisons between measured and calculated DFs show that the proposed rules of thumb give results with an accuracy of 30%.

Calcagni and Paroncini (2004) demonstrated that increasing the wall reflectance from 30% to 70%, increased the DF by an average value of about 4.8% in the adjoining spaces for the atrium of well indices ranging from 0.2 to 1.47. However, increase in the DF due to an increase in the reflectances is limited mainly due to the large windows that reduce the surfaces that could reflect light.

Lau and Duan (2008) examined the effect of different types and arrangement of specular surfaces of atria with WI 2.25, 3.0 and 6.0 on daylighting in the adjacent spaces. Adding different specular atrium parapet walls to the top level only resulted in a 25% increase in the DF at the atrium floor and in the ground floor adjoining spaces. The study concluded that in comparison to the strategy of altering atrium geometry, that adding specular atrium surfaces to improve DFs is less effective.

Du and Sharples (2009b) undertook RADIANCE simulations for square atrium models of WI 0.25 to 1.5 with various wall reflectances (0, 0.2, 0.4,0.6, 0.8) and a fixed floor reflectance 0.2 to analyse the impact of well geometry and wall reflectance on the vertical DFs in atria (Figure 3:30). The study demonstrated that for incremental increase in the atrium wall reflectance increases, vertical DFs on the atrium wall increase at a proportionally greater rate and that the magnitude of increase is bigger at higher and middle positions of an atrium in comparison with the lower positions.

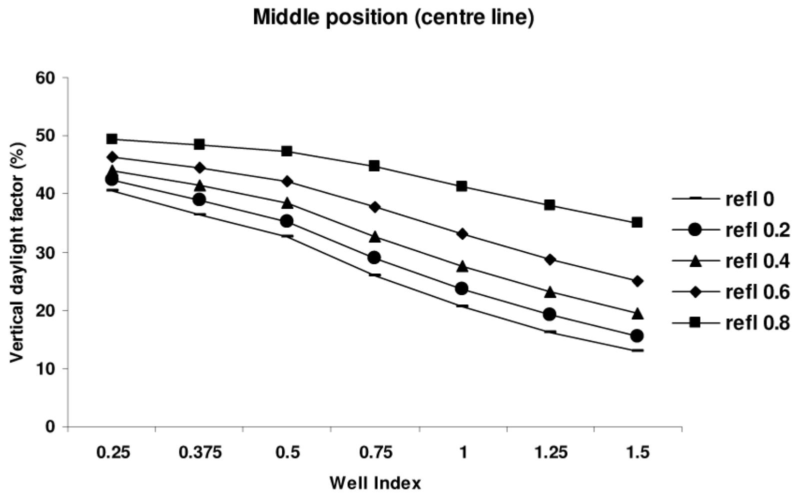


Figure 3:30 Vertical DFs at the centre line of the atrium half way down its depth for square atrium models of WI 0.25 to 1.5 for various wall reflectances (Du and Sharples, 2009b)

3.3.4 Atrium Floor Reflectances

The SC and the ARC reaches the atrium floor, a portion of which is reflected back towards the walls, if the floor reflectance is high. Therefore the atrium floor can influence the amount of light within the atrium and its adjoining spaces, particularly on the lower floors.

Cole (1990) examined the effect of atrium floor reflectance (Black – 15% and White - 80%) on DF on the top and ground floors and in agreement with Iyer (1994), Baker et al. (1993), Boubekri (1995), Fontoynont (1999a) and Lau and Duan (2008) concluded that the effect of ground reflectance is greatest on the lowest floors, becoming indiscernible by the fifth floor. This is because on the top floor the daylight levels are dominated by the sky component with some contribution from wall reflectance, while on the ground floor there is little sky component and the wall and floor reflections make dominant contributions to daylight levels.

To improve daylight on the ground floor adjoining spaces, large openings in the facades and increased floor reflectivity were recommended by Cole (1990). Figure 3:31 shows the effect of changes in the atrium floor reflectivity (from black to white surface) on the ground and fifth floors for 100% openings.

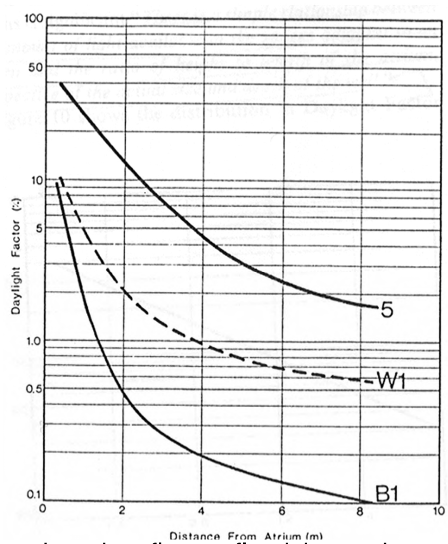


Figure 3:31 Effect of changes in atrium floor reflectivity on the ground (black, B1 and white, W1) & fifth (5) floors for 100% opening (Cole, 1990)

Baker et al. (1993) suggest that "natural illumination of most rooms facing the atrium, except the top floors, depends particularly on reflected light from the atrium floor" (Figure 3:32).

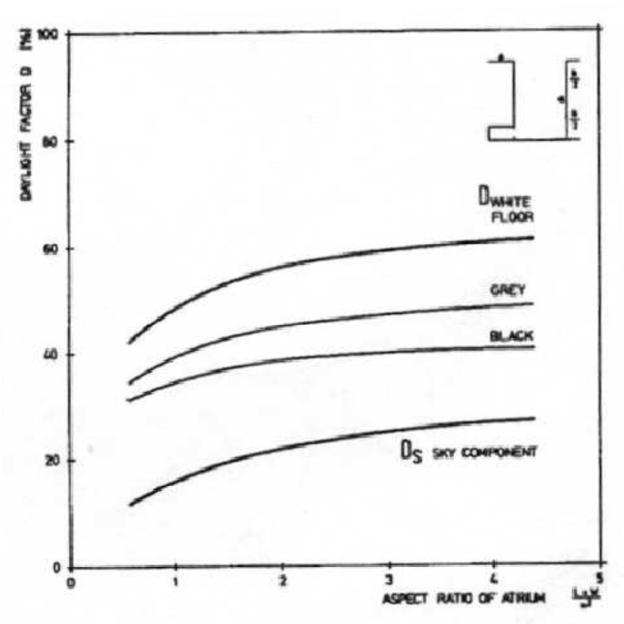


Figure 3:32 Vertical illumination at mid-height of atrium due to different floor reflectances (Baker et al. 1993)

Iyer (1994) examined the influence of white (90% reflectance) and black (5% reflectance) floors on DF at three metres in the adjoining spaces of an atrium of WI 1.95 and 25%, 50% and 75% openings (Figure 3:33). DFs increased by five times for the atrium facade with 75% opening when the floor reflectance increased from 5% to 90%. Iyer (1994) concluded that to improve DF and uniformity of light distribution in the adjoining spaces, plants which reduce ARC should generally be positioned in the centre of the space and the atrium floor reflectance should be high, particularly along its edges. However, the extent of high reflectance lined edges would depend on the size and location of the opening in the facade.

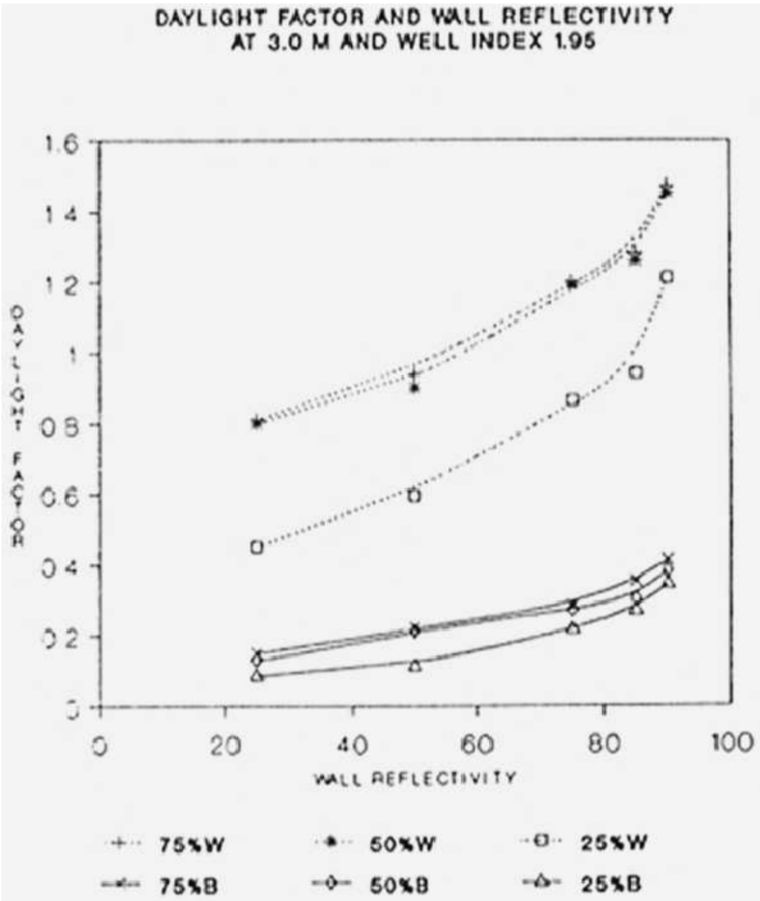


Figure 3:33 Daylight Factor at 3.0 metres in the adjacent space of an atrium (WI 1.95) with white (90% reflectance) and black floor (5% reflectance), and 25%, 50% and 75% openings in wall and different wall reflectances (Iyer, 1994)

This strategy is evident in the Domino Haus in Germany (Figure 3:34), a 4 sided, top lit atrium building where the stairs, glazed elevator and the gangways are grouped together in the centre of the atrium to reduce obstruction to daylight in the adjoining spaces (Fontoynont, 1999a). At the Beresford Court in Dublin (Figure 3:35), the atrium floor contributes to 85% of the daylight that reaches the adjoining space ground floor offices (Fontoynont, 1999a).

Figure 3:34 Domino Haus atrium, Reutlingen, Germany (Fontoynont, 1999a)

Figure 3:35 Atrium of the Beresford Court building in Dublin (Fontoynont, 1999a)

Boubekri (1995) examined the influence of 10%, 36% and 85% floor reflectance on DF on the atrium wall surfaces for a four-sided rectangular atrium with a WI of 1.05. The study evidenced that DFs near the bottom of the atrium doubled when the floor reflectance increased by eight times (Figure 3:36).

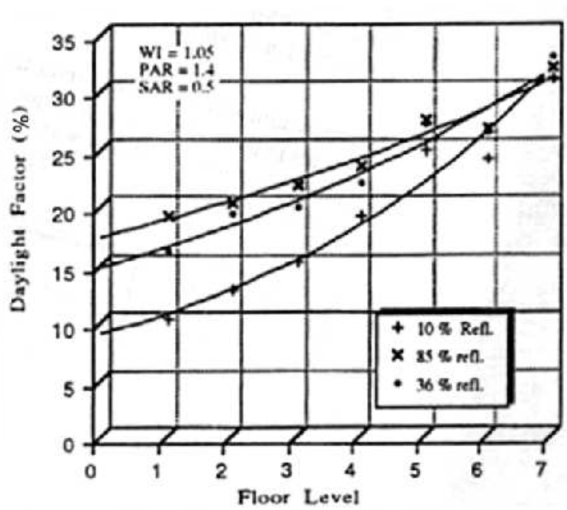


Figure 3:36 Effect of floor reflectance on the daylight distribution along the walls of a four-sided rectangular atrium with WI of 1.05 (Boubekri, 1995)

Fontoynont (1999a) recommended higher atrium floor reflectances to improve daylight conditions on the lower two floors of the adjoining spaces.While, Lau and Duan (2008) demonstrated that introducing high-reflectance floor to the atrium resulted in higher DFs, especially at the lowest floor level. Du and Sharples (2009b) showed that the floor reflectance mainly influences the daylight levels on the wall of lower atria or lower walls of deeper atria. They showed that in a square atrium with a WI of 1.5, up to a distance of ¾ of the atrium width from the top of the atrium, i.e. WID < 0.75, floor reflectances do not affect the vertical DFs on the atrium wall. It can be concluded that the atrium floor surface reflectances can be instrumental in improving the DFs in lower adjoining spaces. They work with the daylight reflected off the high reflectance atrium walls to improve daylight conditions within the lower reaches of an atrium building where the daylight availability is typically low.

3.4 CONCLUSION

Daylight potential of an atrium has been recognised widely and daylight levels within the atrium space are generally sufficiently high. However, atrium buildings have been unable to successfully utilise daylight in spaces adjoining the atria, where daylight varies significantly with every floor level. The upper part of an atrium usually receives direct light from the sky and can be over-lit, overheated and suffer from glare, while the daylight levels on the lower floors can be low particularly in a tall and deep atrium as it mainly receives reflected light from the atrium's walls and floor. Therefore, several studies have been undertaken to examine the means by which this specific problem may be addressed. In addition to the atrium geometry, the atrium walls and floor are fundamental in distributing light in the lower reaches of an atrium and its adjoining spaces; it is the atrium wall surface reflectances which forms the focus of the research undertaken in this thesis.

Surface Reflectances

The influence of surface reflectances on the daylight levels in atria and their adjoining spaces is complicated to model mathematically and most standard daylight calculation techniques do not transfer easily to atrium buildings (Letherman and Wright, 1998). Consequently many studies have examined this parameter using either physical scale models or computer simulation programs and demonstrated that higher atrium wall reflectances improve daylight levels in an atrium building.

Iyer (1994) showed that while large openings (50% and 75%) give greater illumination and a wide range of illumination values, 25% atrium wall openings provide more uniform distribution of DFs in the adjoining spaces due to the increased inter reflectance of light down the atrium well and into the side spaces. Boubekri (1995) showed that the rate of DF increase is not directly proportional to that of the wall reflectance where the reflectance quadruples before DFs double. Calcagni and Paroncini (2004) demonstrated that increasing the wall reflectance from 30% to 70%, increased the DF by about 4.8% in the adjoining spaces for the atrium well indices ranging from 0.2 to 1.47. On the other hand, Mabb (2008) demonstrated that increase in the atrium surface reflectances from 25% to 75% increased the illuminance levels by more than double at the bottom of a square atrium of WI 3.75. Lau and Duan (2008) evidenced that adding different specular atrium parapet walls only to the top level resulted in a 25% increase in DF at the atrium floor and in its adjoining spaces.

The review demonstrates a lack of consensus from the findings of the various studies in terms of the rate of improvement due to the reflectances. Furthermore, for atrium surfaces comprising of different materials, an area-weighted reflectance is often used to calculate the ARC. Although this value gives an impression of the overall surface reflectance and possible resultant daylight availability, it does not indicate how daylight (DF) is actually distributed in the space due to the arrangement of various materials and their reflectances within these surfaces. Whilst the ADF might be quite high, some areas may receive more light and others might be very dark. Therefore, the use of area-weighted reflectance to estimate availability of daylight can be quite problematic. It is vital therefore to establish how the distribution of reflectances influences the daylight distribution across the atrium floor. This forms the focus of the experiments undertaken in Chapter Four of the thesis. Taking into consideration findings from the above studies, a four sided top lit square atrium has been chosen as it allows the assessment of the impact of the atrium surface reflectance distribution on the daylight levels in the worst case scenario. To extend this work and develop a comprehensive study on the four sided atrium and to compare results from each set of the experiments, the square atrium has been investigated for the rest of the research undertaken in this thesis.

Atrium Geometry and Surface Reflectances

In congruence with previous studies (Cartwright 1986; Kim and Boyer 1986; and Cole 1990), Liu et al. (1991) confirmed that daylight within an atrium depends on its geometric proportions and that well index (WI) is a good indicator of the likely daylight availability in an atrium.

Letherman and Wright (1998) state that in atria of high WI, the relative surface area of the atrium's walls is high resulting in a higher potential for a large ARC. However, the view factor between the atrium's walls and sky vault is small resulting in lower wall luminance and DFs. As the WI decreases, with increase in the view factor with the sky vault the DFs increase. However, as the WI becomes very low, the wall area becomes too small and the ARC decreases.

Several studies have examined the influence of both, atrium geometry and atrium enclosing surface reflectances on the daylighting conditions in atrium buildings. While Willbold-Lohr (1989) evidences the vital role of the ARC in square atria of WI higher than 0.75, Baker et al. (1993) also showed that the influence of atrium facade was observed mainly for ARs between 0.5-2. Liu et al. (1991) suggest that the influence of surface reflectance is mainly observed for atria of WI ranging between 1 and 2 while Aizlewood et al. (1996) show this influence on WI ranging between 0.5 and 2. Calcagni and Paroncini (2004) showed that when the WI increased from 0.2-0.75 DF values drop sharply. However, when the WI increased from 0.75-1.29, quite similar DF values are achieved suggesting that increase in the WI within this range had a limited influence on the DFs in the spaces adjoining the atria. Du and Sharples (2009b) showed that the difference in the vertical DFs due to the altered reflectances is larger for atria of WI 1.25 and 1.5 than atria of WI 0.25, 0.375, 0.5, 0.75 and 1. The magnitude of increase as a result of higher wall reflectances was bigger at higher and middle positions of an atrium in comparison with the lower positions.

This review demonstrates difference in the findings from the previous studies of the effects of the atrium wall surfaces in different atrium well indices and geometries. Furthermore, these studies do not examine the effects of varying reflectance distributions on the DFs in the atria of different well indices, which this study examines in Chapter Six. The well indices (0.5, 1 and 2) chosen in the study fall within the range of the well indices identified by previous research in which surface reflectances affect DFs and are representative of the range of PARs and SARs identified by the survey of built atria that Liu et al. (1991) undertook.

Atrium Facades

Although daylight levels in an atrium might be adequate, they might be much lower in the adjoining spaces, particularly on the lower floors. Several studies recommend that Fontoynont's (1999a) edited book *Daylight Performance of Buildings* which includes monitored data from real buildings and several previous parametric studies show that daylight potential on the atrium floor and lower adjoining floors can be enhanced by higher atrium wall reflectances and gradually increasing the proportion of opening to reflective surface areas in the atrium walls from relatively small openings at the top to fully glazed openings at the ground level.

Cole (1990) concluded that the variable opening option (100% opening on the first floor, 80% on the second, 60% on the third, 40% on the fourth and 20% on the top floor) was most effective in terms of bringing daylight on the lower adjoining spaces in a square atrium building. Aschehoug (1992) on the other hand presented an "optimum" glazing percentage of 50% on the fourth floor, 60% on the hird floor, 70% on the second floor and 100% on the first floor to give quite similar daylighting conditions in the adjoining spaces of a glazed street.

To ensure higher illumination levels in the adjoining spaces, it is vital to have an appropriate balance between the areas of opaque high reflectance surfaces and openings in the atrium facades. Consequently the focus of the experiments in Chapter Seven is to investigate the influence of several atrium facades with different opaque and fenestration area ratios representing real buildings on the daylight levels in the atrium and its adjoining spaces. The objective is to assess whether a particular incremental approach in fenestration might be advantageous for improved daylighting in the adjoining spaces of a four sided, top lit, square atrium building with a medium proportioned atrium.

While previous studies show the potential of atrium floor in improving DFs in the lower adjoining floors, since the focus of the study is to examine the influence of atrium wall surfaces only, atrium floor reflectances have not been altered; the floor reflectances used are those recommended by IESNA (Chapter Two) and typically found in real buildings.

DFs obtained in a building will be affected by the external illuminance conditions and obstructions and reduced due to the roof geometry and structure, roof cover and window glazing transmittance, window frames and dirt factor. Calcagni and Paroncini (2004) demonstrated that an atrium roof reduced illuminance in the adjoining spaces by about 45%. On the other hand, Fontoynont (1999a) showed that the daylight levels within an atrium and its adjoining spaces were reduced significantly with the addition of a roof by approximately 30% to 65%. Therefore, an approximate 50% reduction is applied for interpreting the results, predicting the daylight availability in the atrium models and comparing the results with data obtained from real buildings in Chapters Six and Seven.

The role of the literature review undertaken in this Chapter has been to contextualise the area of study for the thesis and identify gaps in the research that this thesis aims to fill. The next Chapter includes first of the four parametric experiments undertaken in this thesis; the physical scale model study.

4 ATRIUM SURFACE REFLECTANCES: A PHYSICAL SCALE MODEL STUDY

4.1 INTRODUCTION

This chapter describes first of the experiments of this thesis.

The first part briefly highlights the influence of the surfaces and their reflectances on how architecture and spaces therein are perceived and experienced. While Chapter Three was a highly utilitarian description of the behaviour of light in an atrium due to its enclosing surfaces, what is covered in this section develops an understanding and an appreciation of the esoteric qualities of light and their interaction with building surfaces. Both these aspects are vital to the architectural experience. This provides an understanding of the broader qualities of light before focussing on the pragmatic aspects of daylight availability in atrium buildings as a result of its enclosing surfaces which the Chapter investigates parametrically in its latter section using physical scale models.

The second part examines in detail the physical scale model as a design tool for daylighting research.

The physical scale model experiment forms the third part of this Chapter and includes a brief introduction to the study, the methodology, the results and the conclusions. The aim of the experiment is to study parametrically the effects of different reflectance distributions and surface (specular and diffuse) types on the daylight levels at the base of a four-sided, top-lit, square shaped atrium under overcast sky conditions.

This experimental work pre dates the PhD and was used for the award of Masters in Architecture undertaken at the University of Sheffield in 1997-1998. However, this experiment forms the basis for the PhD and has been included here for completeness. It helps to contribute to the literature and provides a detailed description of the experimental techniques used in the subsequent Chapters.

4.2 SURFACES AND THEIR REFLECTANCES

The importance of building surfaces and their reflectance properties has been most elaborately and poetically depicted by Michel (1996).

"Throughout human history the treatment of surfaces forming architectural space has been a revealing manifestation of lifestyles and cultural values. Paleolithic cave dwellers of northern Spain and southern France transformed their habitats by painting on the irregular cavernous walls red and yellow ochre figures of themselves and animals of the hunt. Light from small stone lamps fuelled with tallow flickered across the natural stone surfaces enhanced by art, and gave visible shape to the space of communal shelter. What had begun was an irrepressible tendency to design the enclosing surfaces of the human environment. With the arrival of civilization sunlight described sculptural reliefs on temple walls, filtered through colonnades, illuminated the interiors of basilica halls, and reflected off mosaic floors in private houses. In the Middle Ages processions followed along ambulatories articulated by coloured light through stained glass, and in the Renaissance arcaded loggias cast rhythmic shadow patterns on the pavements of palace courts. During subsequent periods the boundaries of space became stuccoed, bricked, glassed, draped, muraled, painted, panelled, and papered" (Michel, 1996).

Illumination combined with light reflecting enclosing surfaces, shape and define spaces, make them visible, liveable and affect the quality of the architectural experience. In particular, visual environment and illumination is determined by the quantity and quality of the light that meets building surfaces, their surface materials and reflectances. This affects the way in which a space is perceived and creates different ambiences and moods that affect human feelings and behaviour, and their movement within spaces.

Michel (1996) described the atrium's spatial envelope/boundary to be stable and prominent in view and that it is a principle conveyor of the character of a space. Michel suggests that to maintain visual order, and the integrity and clarity of a spatial envelope it is vital to consider carefully the articulation of the vertical boundaries in co-ordination with the skylight and floor. Atria in multi-storey buildings require composition and detailing of their structural elements and atrium walls. Floor fascias alternating with voids above and below create horizontal lines while the piers and columns form the vertical lines and are referred to as spatial banding (Michel, 1996). They create linear patterns on the atrium's envelope defining and articulating the envelope and the atrium space.

It is evident that the atrium's vertical surfaces play a critical role in the articulation of atrium spaces, including the way in which light is reflected about in the atrium space and results in daylight penetration in the adjoining spaces. An appreciation and understanding of the pragmatic and utilitarian role of the atrium's enclosing surfaces described in Chapter Three and the poetic role of the atrium surfaces as described by Michel (1996) are both vital to daylighting in the atrium buildings.

4.3 AN INTRODUCTION TO PHYSICAL SCALE MODELS

Scale models are very useful to study light as light behaves in the same way at the model scale as it would at full size (Philips, 2000). Unlike other physical models for thermal, structural, acoustic and ventilation analysis, daylighting models do not require scaling correction and are a means of accurately predicting interior daylight illumination (Moore, 1991). The wavelengths of visible light are short in relation to the size of the models and do not affect the behaviour of light. Any differences are not noticed by the human visual perception. The reflectance of surfaces and the room geometry can be duplicated to provide the same quality and quantity of illumination as that expected in real buildings. Visual impression of colours will be the same as an actual room if used in the model (Baker et al., 1993). Therefore, it has long been recognised that a model study, particularly at the design stage, is the most reliable, simple and versatile technique for daylighting studies (Evans, 1981). Although Cannon-Brookes (1997) highlighted that physical scale models can overestimate illuminance levels in buildings and affect the accuracies due to factors such as dimensional accuracy (particularly of the fenestration), simulation of photometric properties, surface reflectances, transmittance, and dirt and maintenance factors.

Scale models are simple design tools that can be easily built and understood, and can be used to investigate other design aspects along with daylighting. Even simple models can provide good and immediate results that are particularly useful at the conceptual design stage. Several design options can be tested and comparative studies can be undertaken cheaply and easily by changing components of the model. Notably, most designers are competent in making physical scale models and architects need to make only minor modifications to their architectural models to use them for daylighting studies. Simple instruments can be used to undertake quantitative studies rapidly along with identifying problems of glare and assessing whether electric lighting and thermal conditioning may be required. While at the same time, visual observations and photography can be used for the assessment of visual effects and qualitative data, enhancing the use of models.

Model studies can be carried out under a real or artificial sky. Additionally, “the dynamic play of light within the space can be observed using the scale model and a heliodon, a sky simulator or real sky in conjunction with a video recording system. Scale models are particularly useful for studying daylight performance in atria for pre-validation and evaluation of performance characteristics before transferring to computer programs.

Difficult geometries can be simulated easily but it is essential that the geometries are accurate. Construction materials should be opaque and joints should be covered with black tape to ensure no extraneous light is entering the interior space. Model reflectances should match those of the experimental set up. For quantitative studies and surfaces whose reflectance is not known, grey samples of different reflectances can be prepared and compared with a surface of known reflectance to establish its reflectance.

4.3.1 Glazing

Transmittance from glass varies with the incident angle of light. However, in relatively simple openings and in comparative model studies, clear glazing materials can be excluded in the model and a correction factor can be applied to the illuminance measurements obtained to allow for the angle of incidence, glazing transmission losses and dirt. For example, for typical single glazing, the glazing transmittance of 0.9 can be multiplied with a dirt factor of 0.9, giving a value of 0.81 as a correction factor that could be applied to the obtained illuminance values.

4.3.2 Model Scale

Where measurements are taken at a working plane height, the ability to add detail and the relative size of the photometric sensor should be considered when deciding the scale of the model. Very small models are not recommended as the photocell when placed in the model may cause excessive absorption and reflection and present difficulties in measuring daylight. Size of a model is usually selected taking into consideration the ease of use, the size of the model relative to the sensors, the construction materials used and the portability of the model.

Furthermore, highly detailed models can be expensive and may reduce their flexibility, which can be problematic for daylighting studies. It may be difficult to scale real building materials and the use of real materials can cause errors in the quantitative measurements. Quantitative analysis of electric lighting is not possible in scale models and the combination of electric and natural lighting requires testing of real mock-up rooms.

4.3.3 Measurement

Daylight levels can be measured in physical scale model experiments with the use of photocells that can be placed inside and outside the model at specific locations. Accurate and convenient measurement of interior and exterior model illuminances is very important in physical modelling and can be undertaken using a cosine and colour corrected photometer. Cosine correction is necessary to measure illuminance in a plane, while colour correction requires that the sensitivity of the photometer matches that of the human eye. Cosine correction is fundamental for lighting studies as photocells are subject to the "cosine law of illumination" whereby they do not record light striking the cell from a low angle as accurately as that from a high or more direct angle.

Photocells must be calibrated frequently and at regular intervals to provide true illumination at all levels as photocells are not always identical and their output is therefore not always directly proportional to the illumination incident on the cell. Additionally, multi-sensor photometers allow near simultaneous measurements to be made at several locations inside and outside the model, saving time and minimizing the effect of changing sky conditions.

4.4 THE EXPERIMENT

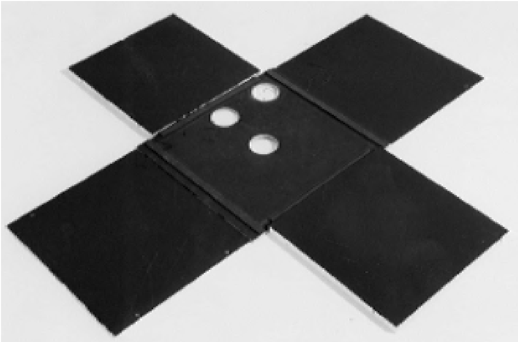
4.4.1 Introduction

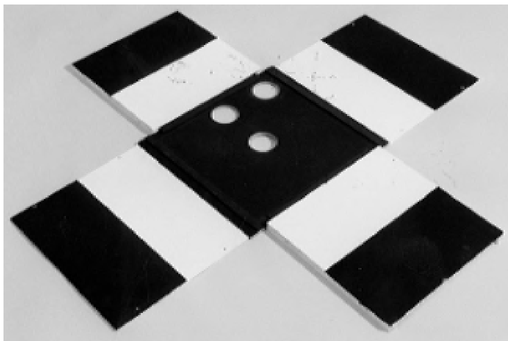
Letherman and Wright (1998) demonstrated that the influence of surface reflectances on the daylight levels in atria and adjoining spaces is complicated to model mathematically using analytical techniques and most standard daylight calculation techniques do not transfer easily to atrium buildings. Consequently, many studies have been carried out using either physical scale models or computer simulation programs to examine the effect of surface reflectances on the daylighting in atria and their adjoining spaces as discussed in Chapter Three. Reflectance patterns were also altered due to the introduction of bands of openings; however effect on the ARC of varying the distribution of the reflectances around the atrium well was not investigated in these studies.

For design calculation purposes the range of reflectances in an atrium is usually represented in terms of a single, area-weighted mean reflectance for estimating the average daylight factor, ADF (Littlefair and Aizlewood, 1998), or the atrium reflected component, ARC, of the daylight factor, DF (BRE Digest 310, 1986). Although this approach simplifies the calculation procedure it does not help identify how different distributions of reflectances around an atrium actually produce different values of the daylight factor or the atrium reflected component. For example, an atrium well that is painted with its top half white and its bottom half black would give the same area-weighted reflectance value and the same ARC value as an atrium with its top half black and its bottom half white. However, it would be expected that the actual daylight levels at the base of the two atria would be different. The above is an extreme case. Most atria will consist of bands of different reflectances, both in value and in surface properties. Whilst the overall area-weighted reflectance value of the atrium wall might be the same, it might be achieved through innumerable variations in the atrium's facade composition achieved through different sizes and location of openings and opaque surfaces affecting the daylight levels on the atrium floor. Therefore, this study sought to investigate how the different reflectance distribution patterns, for the same overall area-weighted reflectance value, affect the ARC and the DF in a simple atrium model. In particular, the parametric experiment examines the effects of the different reflectance distributions and surface (specular and diffuse) types on the daylight levels at the base of a four-sided, top-lit, square shaped atrium under CIE overcast sky conditions.

4.4.2 Methodology

For the purpose of this study, atrium wall surfaces were painted either completely in black or white or in various, systematic patterns of alternate horizontal bands of black and white representing the horizontal bands of the openings and the opaque wall surfaces in real buildings (Figure 4:1). However, the bands are not representative in terms of their scale or proportions. In the first set of measurements, the daylight was to be measured at three points across the atrium floor, in the centre, half way along the edge and at the corner position for the diffuse surfaces with various bands of paints. 2mm sheet of single glazing was then fixed onto the inner atrium diffuse painted wall surfaces and a second set of measurements was made, but this time with observations limited to the centre of the atrium floor. Glazing was fixed on to the models to assess if the addition of the specular surface improved DFs on the atrium floor.


Model 1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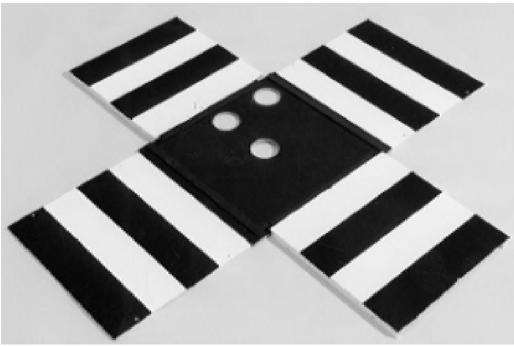
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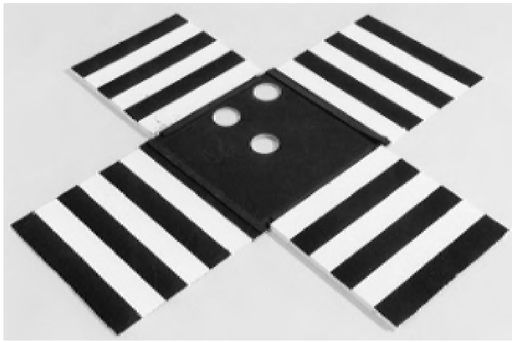
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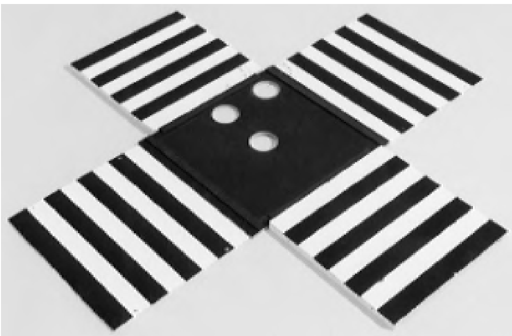

Model 5

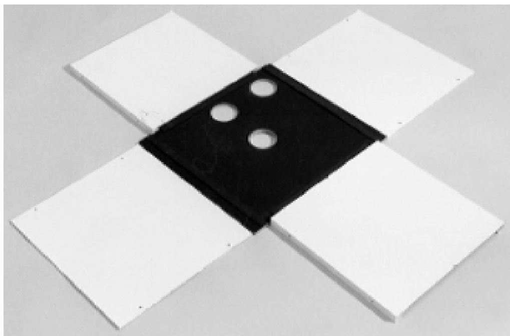

Model 6

Figure 4:1 Atrium Well Surface Patterns

The experiments were conducted in a mirror box type of artificial sky capable of reproducing a CIE overcast sky luminance distribution as shown in Figure 4:2. The artificial sky measured 1.5 metres in length, 1.2 metres in width, and 0.6 metres in height. Light levels inside the sky were kept constant by the use of an independent reference photocell positioned in one corner of the sky which was used to ensure that the light levels were maintained.

Figure 4:2 Mirror Box Artificial Sky (University of Sheffield)

The atrium models (walls and floor) were constructed from MDF (medium density fibreboard) which made them opaque as well as reasonably lightweight. Any joints in the models were sealed with an opaque tape. The selection of the model scale was governed by two opposing limitations. The models could not be too small, due to the difficulties in making accurate measurements inside the models using the available size of photocell. Conversely, the models could not be too large as they could create photometric errors in the artificial sky conditions due to the inter-reflection obstructions in the sky simulator.

The models were constructed to a scale of 1:100 and measured 240 x 240 x 240 mm. The test models therefore simulated a square, four sided top-lit atrium with full-scale dimensions of 24 x 24 x 24 metres high. These dimensions represented an atrium building of WI 1.00, a plan aspect ratio (PAR) of 1.00, a section aspect ratio (SAR) of 1.00 and an aspect ratio (AR) of 1.00 as shown in Figure 4:3. The atrium is representative and falls within the usual range of built atria (0.1-1 PAR and 0.5-4 SAR) as highlighted by the survey undertaken by Liu et al. (1991) and due to the fact that surface reflectances were shown to have affected the DFs in a WI of 1 by Aizlewood et al. (1996). The four-sided atrium is chosen as it provides the assessment of the impact of atrium facades and the internally reflected component on the daylight levels in the worst case scenario in comparison with a two-sided or a three–sided atrium.

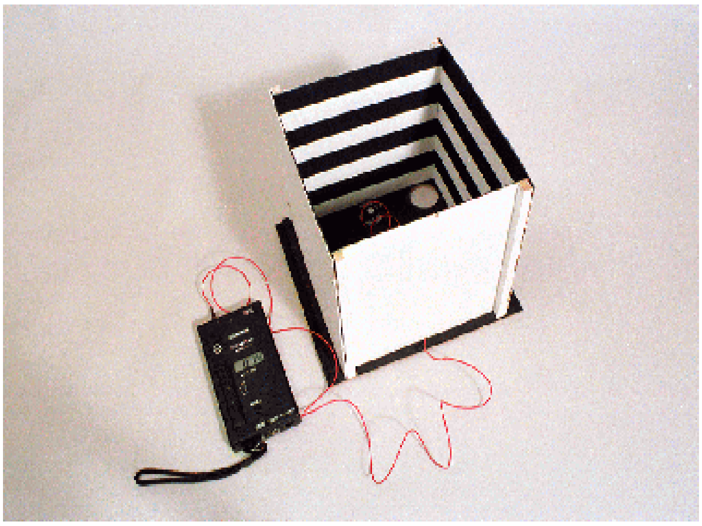


Figure 4:3 Atrium Model, WI = 1, PAR = 1, SAR = 1, AR = 1

All dimensions were defined in terms of their interior envelope dimensions. No roof elements were used over the atrium well in order to reduce the number of variables under consideration. The illuminance measurements were made with a high quality, newly calibrated luxmeter (A Hagner Model E2-X) with photopic and cosine correction (Figure 4:4). The diameter of its face was 45 mm and the diameter of the light-sensing diffuser on top of it was approximately 10 mm. To undertake horizontal daylight factor (DF) measurements on the atrium floor, three measurement points, the centre of the atrium, halfway along the atrium wall's edge, and atrium corner position, were selected. When the luxmeter was aligned with model's wall edges (for the edge and corner positions), the sensor was 22.5 mm away from the atrium walls. Holes were made in the floor of the atrium to fix the photocell in these positions. The actual height of the cell was 14.5 mm while the thickness of the model base was 6mm; this allowed the photocell to protrude through to a height of 8.5 mm above the well floor level achieving a working plane height of 0.85 metres.

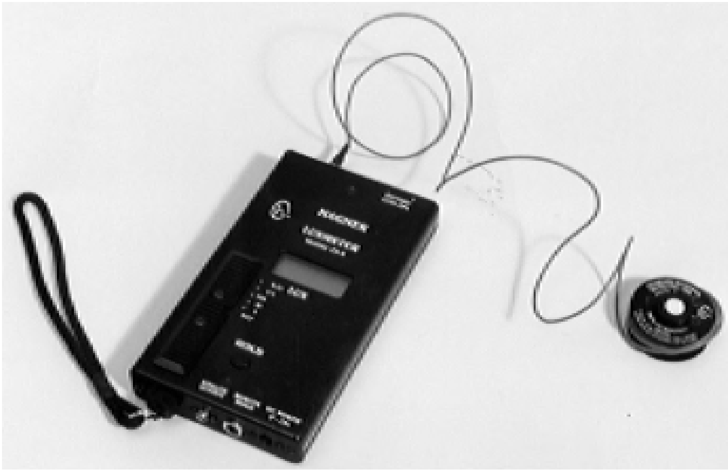


Figure 4:4 Hagner (E2-X) Photocell

Six scale models were painted with various configurations of white and black paint, simulating different wall reflectance distributions as shown in Figure 4:1. However, for each model the overall split of the total white atrium wall surface area to the total black atrium wall surface area was 50:50. The surfaces were painted with diffuse matt paints of known reflectances. Two coats of white matt paint (British Standard colour BS 00 E 55) were used for the white surfaces. The black surfaces used a specialist primer base coat and a specialist topcoat of velvet finish black paint. The floor of the atrium was given the same black paint finish for all of the experiments.

The reflectance values were measured by placing a sample of the material next to a white tile sample of known reflectance (0.87) in an area of relatively uniform illuminance. The ratio of the luminances of the samples (measured with a luminance meter) is the ratio of their reflectances. Measurements were repeated to check the uniformity of the illuminance.

Reflectance of the known surface (white tile) $\rho_k = 0.87$

Reflectances of painted white and black surfaces used in the model (ρ_u)

$$\text{Luminance of known surface } L_k = \frac{E_{\rho k}}{\pi}$$

$$\text{Luminance of unknown surface } L_u = \frac{E_{\rho u}}{\pi}$$

where *E* is the illuminance

Hence:

$$E = \frac{Lk}{\rho k} = \frac{Lu}{\rho u} \qquad (1)$$

$$\rho u = \frac{\rho k \text{ x } Lu}{Lk}$$

$$\rho u = \frac{0.87 \text{ x } Lu}{Lk}$$

This gives a reflectance of 0.83 for the painted, white surfaces and 0.02 for the black surfaces as shown in Table 4:1.

Table 4:1 Reflectances of Black and White Painted Surfaces

COLOUR	L_u (cd/m^2)	L_k (cd/m^2) tile	$\rho_u = 0.87x\ L_u/L_k$
White surface	234.2	244.2	ρ white =0.834
Black surface	6.68	244.2	ρ black =0.023

The atrium well surfaces were painted with alternating bands of white and black, and configured to give the arrangements shown in Figure 4:1 and specified in Table 4:2. Table 4:2 also gives the area weighted average reflectance, R, of all the atrium surfaces (note that in calculating the area weighted average reflectance the non-existent roof was allocated a surface area equal to the floor area and a reflectance value of zero). Because the ratio of the white to the black is constant for models 2a, 2b, 3a, 3b, 4a, 4b, 5a and 5b, the area-weighted average reflectance remains the same.

Table 4:2 Classifications for atrium configurations and reflectances

Model No.	Atrium Configuration	Area-weighted average reflectance *p*
1	All surfaces painted black	*p* = 0.02
2a	1/2 black at the top	*p* = 0.29
2b	1/2 white at the top	*p* = 0.29
3a	1/4 black on top	*p* = 0.29
3b	1/4 white on top	*p* = 0.29
4a	1/6 black on top	*p* = 0.29
4b	1/6 white on top	*p* = 0.29
5a	1/8 black on top	*p* = 0.29
5b	1/8 white on top	*p* = 0.29
6	All walls painted white	*p* = 0.57

For every set of measurements, the readings were taken at the centre of the artificial sky without the atrium model to find the unobstructed outdoor illuminance. Each model was then immediately placed over the photocell to measure the obstructed indoor illuminance. Positioning the model over the photocell took only a few seconds, thereby ensuring that the observed external illuminance would not change significantly before the internal illuminance was recorded as shown in Figure 4:5.

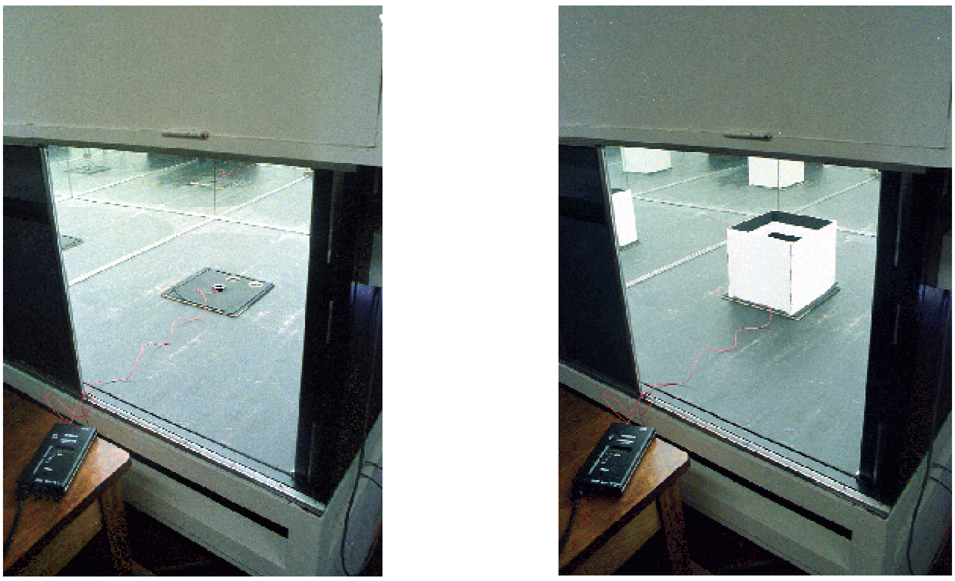


Figure 4:5 Measurement of indoor and outdoor illuminance in the artificial sky

Each set of readings was repeated four times and an average of the readings was taken. Readings were taken systematically, starting with the all-black surfaces, increasing gradually the number of alternate horizontal black and white bands from 2 to 4 to 6 to 8 to the last model with all white wall surfaces. Measurements were also taken by turning the model upside down and having the bands in the reverse sequence. So, for a model with surfaces painted 1/2 black and 1/2 white, one set of measurements was taken with the white band on the top and then another set of measurements was taken with the black band on the top. In a final set of experiments a 2mm thick sheet of clear glass was attached onto each surface of the atrium well for all of the model patterns given in Table 4:2. This will affect the specularity and reflectance due to the transition of light through the glass and then returning back again. Daylight Factor measurements were again made, but were this time limited only to the centre position on the atrium floor.

4.4.3 Results and Discussion

The data presented and its analysis focuses on absolute data, i.e. any changes in the DFs described in the text relate to absolute differences with relative values shown in italics in brackets, where appropriate. Relative values can be important depending on the magnitude of the absolute values and the difference between them. However, it is vital to remember that whilst the relative values may appear to be large, in many cases, this is due to the fact that they are a big proportion of a small value, which may not be perceived in real life. Therefore relative values/changes could be misinterpreted and should be used in conjunction with absolute data. Moreover, if typical recommended task Illuminances set out in Table 2.1 (pg. 71) are considered and related to DFs, for example, for an external illuminance of 8000 lux a school classroom which requires 300 lux would need a DF of 3.75% (300x100/8000 = 3.75%).

While the tables show more specific values, figures are used to discuss the results and to provide an overall impression of the DFs obtained and to compare the results. Table 4:3 shows results from this study for the three measured points; centre, edge and corner positions across the atrium floor and the six configurations of wall reflectance distributions. For Model 1 (the all-black model), the reflectances were so low that the DFs could be taken, without serious error, to represent the SC of the atrium model. ARC for the black models is assumed to be zero. If this assumption holds, subtracting Model 1 values from DFs for the other models gave ARC values for the remaining models and allowed an analysis to be made of how the changing distributions of reflectances affected the individual ARC values. These derived values of ARC are also shown in Table 4:3.

Table 4:3 Daylight factors measured in the atrium model at the three positions and six model configurations

Model Type	Position	External Illuminance (lux)	Internal Illuminance (lux)	DF (%)	ARC (%)
Model 1	Centre	7885	2890	36.6%	0.0%
(All Black)	Edge	8065	2390	29.6%	0.0%
p = 2%	Corner	8080	1980	24.5%	0.0%
Model 2a (Halves)	Centre	7790	3360	43.1%	6.5%
p = 29%	Edge	8172	3255	39.8%	10.2%
White bottom	Corner	8170	2960	36.2%	11.7%
Model 2b (Halves)	Centre	8185	4040	49.3%	12.7%
Black bottom	Edge	8157	3175	38.8%	9.2%
p = 29%	Corner	8175	2590	31.6%	7.1%
Model 3a (Quarters)	Centre	7657	3340	43.6%	7.0%
White bottom	Edge	8235	3190	38.7%	9.1%
p = 29%	Corner	8255	2850	34.5%	10.0%
Model 3b (Quarters)	Centre	8245	3910	47.4%	10.8%
Black bottom	Edge	8250	3200	38.7%	9.1%
p = 29%	Corner	8245	2645	32.0%	7.5%
Model 4a (Sixths)	Centre	8135	3635	44.6%	8.0%
White bottom	Edge	7900	3030	38.3%	8.7%
p = 29%	Corner	7855	2630	33.4%	8.9%
Model 4b (Sixths)	Centre	8222	3810	46.3%	9.7%
Black bottom	Edge	8075	3130	38.7%	9.1%
p = 29%	Corner	8125	2685	33.0%	8.5%
Model 5a (Eighths)	Centre	8185	3670	44.8%	8.2%
White bottom	Edge	8240	3060	37.1%	7.5%
p = 29%	Corner	8235	2617	31.7%	7.2%
Model 5b (Eighths)	Centre	8205	3797	46.2%	9.6%
Black bottom	Edge	8277	3195	38.5%	8.9%
p = 29%	Corner	8235	2740	33.2%	8.7%
Model 6	Centre	8195	5337	65.1%	28.5%
(All white)	Edge	8240	4655	56.4%	26.8%
p = 57%	Corner	8260	4130	50.0%	25.5%

The Effect of the reflectance distributions on the DF

As seen in Figure 4:6, for the banded models 2, 3, 4 and 5, the DFs in the centre position for the models 2b, 3b, 4b and 5b were higher by about 1.2% *(relative increase of 3%)* to 6.2%*(relative increase of 13%)* than the models 2a, 3a, 4a and 5a for the centre position at the base of the atrium. This difference in the DF was most pronounced in model 2 since it had a large white band close to the top reflecting more light down towards the base of the atrium. As the number of bands increased, the width of the band decreased and DFs for the 'a' and the 'b' type models were very similar and differed by 1.4% *(relative difference of 3%)* to 3.8% *(relative difference of 8%)*. Therefore, reflectance distributions do influence the amount of daylight reaching the atrium base, but only significantly if the bands of diverse reflectances are very wide.

Figure 4:6 shows graphically the variation of DFs across the atrium floor at the centre and corner positions for the all-black and all-white models. Also shown are DFs for the four 'a' type models that had the white band at the bottom of the well adjacent to the atrium floor and the four 'b' type models that had the black band at the bottom of the well adjacent to the atrium floor. At the centre of the floor for the 'a' type models the DFs showed a small but consistent increase as the number of black and white bands increased. In the same position for the 'b' type models the DFs displayed a small but a consistent decrease as the number of black and white bands increased. For both sets of models the DFs had converged in Model 5 (four black and four white bands). The range of DFs measured in the eight configurations of banded models varied between 43.1% and 49.3% *(relative difference of 13%)*. This suggests that the DFs at the centre of the atrium well were affected to a limited degree by the distribution of the atrium wall reflectances. It should be recalled that calculations using simplified area-weighted average reflectance values for the atrium would have predicted the same value of DF for all the eight configurations of the banded models. For the corner position on the atrium floor, Figure 4:6 shows that for the 'a' type models DFs displayed a small but consistent decrease as the number of bands increased. For the 'b' type models there was a slight increase in DF values as the number of bands increased. Similar to the centre position, the effect of inverting the model was most notable in model 2 for the corner position. In model 2a, a large white band at the bottom resulted in higher light reflectance near the corner increasing the DF by 4.5% *(relative increase of 13%)* than model 2b. The range of DFs measured in the corner position of the atrium floor for the eight configurations of banded models varied between 31.6% and 36.2% *(relative difference of 13%)*. Therefore, DF values at the corners of the atrium floor were also affected by the reflectance distributions, although again the effect was small.

DFs for the edge position were very similar for all the six models including the 'a' and 'b' type models, differing at the most by only 1.4% *(relative difference of 3%)*. This demonstrates that the daylight levels are balanced by the SC and ARC in this position.

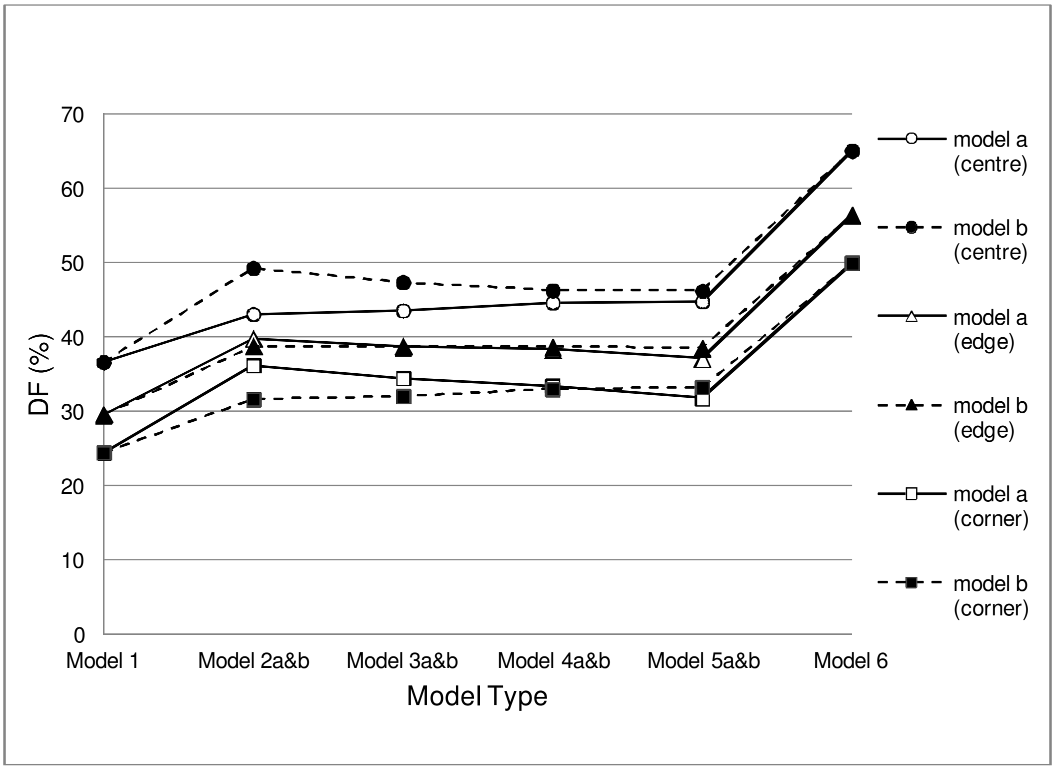


Figure 4:6 Comparison of DFs for a and b type models at the centre, edge and corner positions

The Effect of the reflectance distributions on the atrium reflected component, ARC

Aizlewood et al. (1997) developed an analytical approximation for estimating the ARC for an overcast sky. Their expression took the form:

$$\text{ARC} = (100 - \text{SC}).\left[\frac{W}{A-W} + \frac{WR_{fw}}{A(1-R)}\right].R_w.\frac{7}{(3+4\sin\Theta)} \qquad (2)$$

Where $\sin\Theta = \dfrac{WI}{\sqrt{(WI^2 + 1/\pi)}}$

Where:

SC = sky component

A = total surface area of atrium, including roof

W = area of atrium light admitting opening (i.e. roof)

R_w = area-weighted average reflectance of atrium walls (including apertures)

R = area-weighted average atrium reflectance (including roof and apertures)

R_{fw}=area-weighted average reflectance of roof and walls (including apertures)

WI = well index = H(D+L)/2LD

For this study, equation (2) predicts the following ARC values at the centre of the atrium floor:

All-white atrium walls with black floor: ARC = 25.6%

Half black, half white atrium walls with black floor: ARC = 8.3%

From Table 4:3 it can be seen that the measured ARC value for the all-white atrium was 28.5%, which is in good agreement with the value predicted by the analytical approximation.

Figure 4:7 shows the values of ARC derived from the current study at the centre of the atrium floor. The impact of the large white or black band on the ARC in Model 2 is evident. As the number of bands increases the ARC values for both the model configurations begin to converge. However, it appears from Figure 4:7 that further bands would need to be added to the model before the values would be identical and independent of the reflectance distribution. For Model 5 the ‘a’ type configuration with the white band at the bottom had an ARC value of 8.2% compared to 9.6 % *(relative difference of 15%)* for the ‘b’ type arrangement. Both the figures are close to the value calculated from equation (2). Indeed, the experimental data from this study are much closer to the expression developed by Aizlewood et al. (1997) than they themselves found from their own measurements. This may be linked to the different experimental techniques between the two studies. For example, the atrium opening was level with the bottom of the mirrored walls in Aizlewood et al.’s (1997) artificial sky while in this study the model sat on the floor of the artificial sky with the roof opening above the horizon created by the mirrored walls.

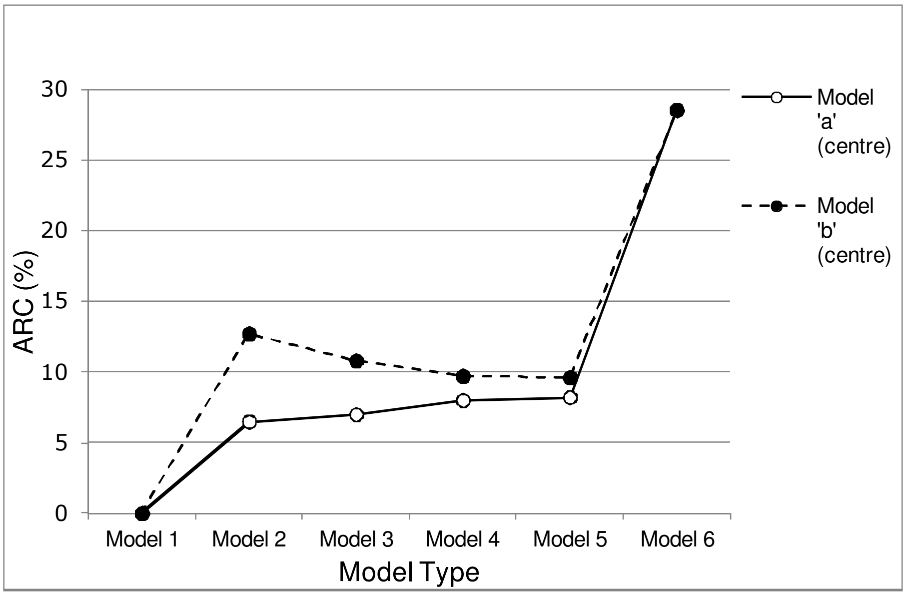


Figure 4:7 Variation of ARC at centre of atrium floor for ‘a’ and ‘b’ models

Results in Table 4:3 also allow the variation of ARC with the position on the atrium floor to be investigated. For all the banded 'b' type models (models 2, 3, 4 and 5), which always had the black band on the walls next to the floor, ARC was always highest in the centre, lower at the edge position and lowest in the corner. This is because very low reflectance of the black surfaces dominates the ARC values. For the banded 'a' type models 2, 3 and 4 which always had the white band on the walls next to the floor, the ARC was lowest in the centre, higher at the edge and highest at the corner position. This is because of the enhanced reflectance from the white bands adjacent to the photocell when the photocell is close to one (edge) or two (corner) of the walls. However, for the 'a' type model 5 the ARC pattern is reversed, with the corner site having the lowest value and the centre position having the highest value. It is suggested that this occurs because of the effect of the narrower bands found in model 5. The photocell adjacent to the lowest edge and corner white bands will 'see' much more of the first black band above the first white band in model 5 compared with the other models. For example, the lowest white band in model 4 has a width of 40 mm while the equivalent band in model 5 has a width of 30 mm. Therefore, the photocell, which is at a height of 8.5 mm, will 'see' the first 40 mm band in model 4 as a 31.5 mm white strip. In model 5 the first 40 mm of the wall above the floor will be 'seen' as a 21.5 mm white strip and a 10 mm black strip. Consequently, the average local reflectance very close to the photocell will be greatly reduced, thereby reducing the observed ARC.

The Effect of the reflectance distributions and specularity on DF and ARC

A set of measurements were made at the centre of the atrium floor for the six model types with 2mm sheets of clear glass overlaying the diffuse painted atrium wall surfaces. Table 4:4 lists the results for the DF and the ARC without glass and with the addition of glass (DF_g and ARC_g) and the ratio between the two options. ARC_g, were derived by subtracting from the glazed daylight factors, DF_g, DF for the all-black unglazed Model 1 (which has been taken as being equivalent to the SC).

Table 4:4 Effects on DF and ARC of adding glass surfaces to atrium walls

Model type and reflectance (*p*)	DF without glass, DF (%)	DF with glass, DF_g(%)	Ratio of DF_g/ DF	ARC without glass, ARC (%)	ARC with glass, ARC_g (%)	Ratio of ARC_g/ ARC
Model 1 (*p* = 2%)	36.6%	40.9%	1.12	0.0%	4.3%	_
Model 2 (*p* = 29%)	43.1%	46.8%	1.09	6.5%	10.2%	1.57
Model 2 (*p* = 29%)	49.3%	51.6%	1.05	12.7%	15.0%	1.18
Model 3 (*p* = 29%)	43.6%	46.9%	1.08	7.0%	10.3%	1.47
Model 3 (*p* = 29%)	47.4%	50.1%	1.06	10.8%	13.5%	1.25
Model 4 (*p* = 29%)	44.6%	47.2%	1.06	8.0%	10.6%	1.33
Model 4 (*p* = 29%)	46.3%	49.8%	1.08	9.7%	13.2%	1.36
Model 5 (*p* = 29%)	44.8%	47.5%	1.06	8.2%	10.9%	1.33
Model 5 (*p* = 29%)	46.2%	49.4%	1.07	9.6%	12.8%	1.33
Model 6 (*p* = 57%)	65.1%	66.5%	1.02	28.5%	29.9%	1.05

As previously with the model without the glass surface, Model 1 with the addition of glass has all surfaces completely black and model 6 has all surfaces completely white and hence the DF remains constant on inverting the model. But for models 2, 3, 4 and 5 with bands, it was found that by inverting the models (from black band on top to white band on top), there was a change in the DF at the base of the atrium (Figure 4:8). The DF values for models 2b, 3b, 4b and 5b were higher by about 1.4% to 6.2% *(relatively higher by 3% to 13%)* than models 2a, 3a, 4a and 5a for the centre position at the base of the atrium.

DF values increased with the addition of a specular surface for all the models but followed the curve for the diffused matt surface models without glass as seen in Figure 4:8. The DF in the centre position of the atrium floor increased by 4.3% for model 1, by between 2.7% to 3.7% *(relative increase of 25% to 36%)* for models 2a, 3a, 4a and 5a; and by 1.4% *(relative increase of 5%)* for model 6. DFs increased by 2.3% to 4.3% *(relative increase of 15% to 20%)* for models 2b, 3b, 4b and 5b, with the addition of glass. Figure 4:8 shows that the effect of the different distribution patterns in the banded models was reduced for the specular surfaces in comparison with the diffuse atrium wall surfaces for the atrium centre position.

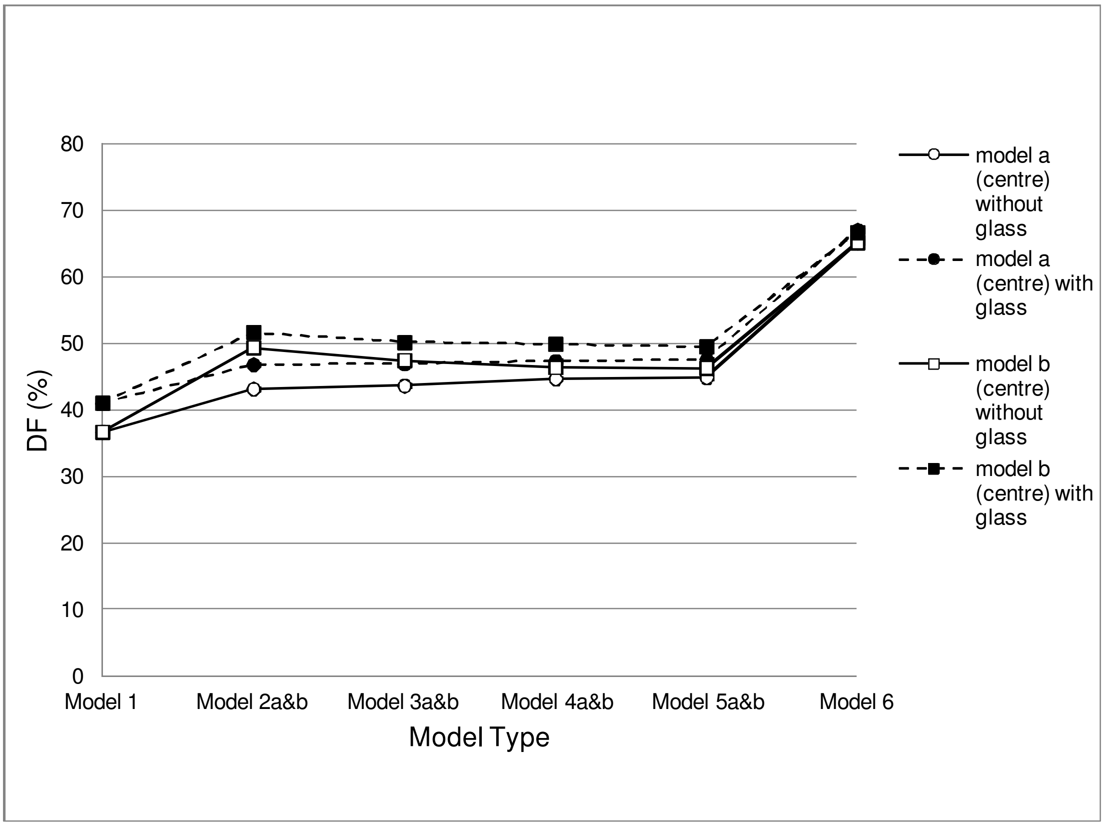


Figure 4:8 DF in the centre of the atrium floor with and without glass surfaces

As seen in Figure 4:9, DF values for all the ‘b’ type banded models were higher than those for the ‘a’ type models with the glass. The DFs reduced by 4.8% *(relative decrease 32%)* from the model 2b to the model 2a, by 3.2% *(relative decrease 23%)* from the model 3b to the model 3a, by 2.6% *(relative decrease 20%)* from the model 4b to the model 4a, and by 1.9% *(relative decrease 15%)* from the model 5b to the model 5a. Similar to the models with the diffuse painted surfaces, as the width of the bands decreased, the difference between the DFs for the ‘a’ and ‘b’ type models reduced.

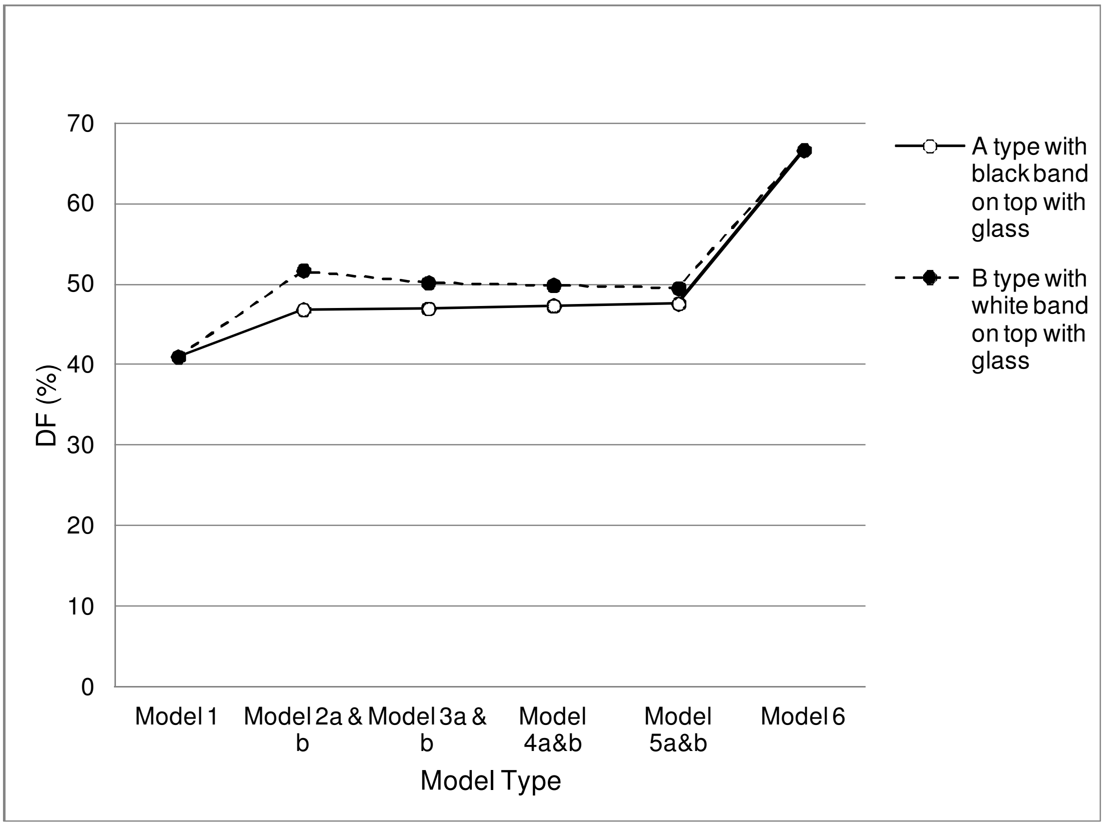


Figure 4:9 Influence of reflectance distributions with specular surfaces (a/b type models) on DF

The ARC_g values showed a relatively similar proportional increase from the ARC values as a result of the addition of specular glass surfaces as shown in Table 4:5. Not surprisingly, the biggest increase occurred for the all-black model and the smallest increase was observed in the all-white model.

Figure 4:10 compares the effect of the specular glass surfaces on the ARC values for the four models with the banded wall surfaces. Again, there appears in general to be a relatively consistent relationship between the glazed and the non glazed ARC values.

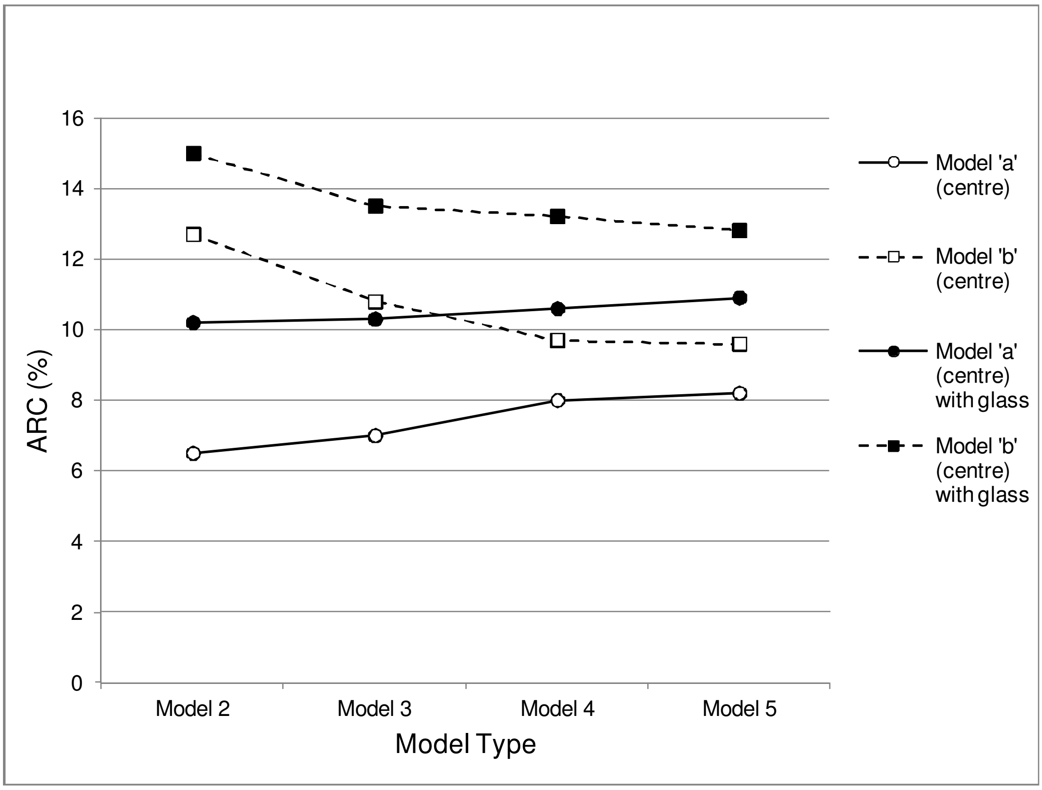


Figure 4:10 ARC in the centre of the atrium floor with and without glass surfaces

4.4.4 Comparison of the results with other studies

In order to confirm the reliability of the measurement procedure used in this study, some of the results were compared with the findings from previous studies.

The findings from the scale model study were compared with those presented by Liu et al. (1991), Baker et al. (1993), Boubekri (1995), Aizlewood et al. (1996) and Aizlewood et al. (1997) as shown in Table 4:5.

Although the parameters were very similar with Liu et al.'s (1991) study, DF results for both the banded and the white models were higher by 10-28% despite the lower area weighted average reflectance of the models.

Results from this study compared very well with the findings of Baker et al. (1993) with a maximum difference of 7% DF and 9% ARC. Difference in the ARCs and the DFs from the two studies for the banded models demonstrates the impact of the surface reflectance distributions on the daylight availability at the base of an atrium.

Although Boubekri (1995) gave DFs at the atrium floor for a rectangular atrium with a glazed roof, when an approximate correction factor of 50% as suggested by Fontoynont (1999a) and Calcagni and Paroncini (2004) is applied, the DFs for the model are slightly higher than those presented by Boubekri (1995). However, as suggested by the previous studies (Liu et al., 1991, Matusiak et al., 1999; Calcagni and Paroncini, 2004; Lau and Duan, 2008; and Du and Sharples, 2009a), the DFs for the square atrium model should have been lower than the rectangular atrium. Therefore, the findings are in agreement with those presented by Oretskin, 1982; Willbold-Lohr, 1989; and Baker et al. 1993 who show that the wells of square plans receive better illumination than the rectangular/linear plans at a given level and that the elongated plans have a steeper drop in illumination.

Despite the slight differences in the surface reflectances of the two studies, DFs from the model study for the atrium centre position compared well with the findings of Aizlewood et al. (1996) and Aizlewood et al. (1997). There is, as would be expected for the similar reflectances and identical WI values used in the two studies, good agreement.

Finally, findings from the experiment are also in agreement with the subsequent study undertaken by Sharples and Lash (2004) which used the models (1 to 6) of this Chapter to examine the effect of different reflectance distributions on the vertical daylight factors and the ARCs. They demonstrated that the different reflectance distributions had little effect on both, the vertical daylight factors and the ARC low down in the atrium well. However, large differences were noted higher up in the atrium. In agreement with the findings of this study, as the number of bands increased and they became narrower, the vertical DFs produced were similar to those predicted by the standard formulae (Aizlewood et al., 1997) which uses the area-weighted reflectance of the atrium.

Table 4:5 Comparison of model study results with data presented by Liu et al. (1991); Baker et al. (1993); Boubekri (1995), Aizlewood et al. (1996) and Aizlewood et al. (1997)

Other Studies	Model Study WI 1 open, four sided square atrium		
	Wall reflectance 0.42 and area weighted reflectance 0.29 (banded models)	Wall reflectance 0.83 and area weighted reflectance 0.57 (white)	Wall reflectance and area weighted reflectance 0.02 (black)
Liu et al. (1991) DF% 4 sided open square atrium WI 1 atrium centre	Atrium centre DF%	Atrium centre DF%	
Wall Reflectance 0.45 = 33%	43 to 49%	65%	
Wall Reflectance 0.60 = 37%			
Baker et al. (1993) DF% and ARC% on the floor of a square atrium WI 1	Atrium centre DF% & ARC%	Atrium centre DF% & ARC%	
Wall Reflectance white (0.7) = 58% DF and 32% ARC		65% DF 28.5% ARC	
Wall Reflectance 50% glazed & 50% white (0.4)= 43% DF and 16% ARC	43 to 49% DF & 7 to 13% ARC		
Boubekri (1995) four sided, rectangular atrium WI 1.05, PAR 1.5 and SAR 0.5 with glazed roof: DFs% along the walls	DFs% at the edge of the atrium	DFs% at the edge of the atrium	
weighted average wall reflectance 0.56 = 23.5%		56%	
weighted average wall reflectance 0.42 = 18.5%	37 to 40%		
Aizlewood et al. (1996) WI 1, centre of atrium floor (DF %)	Atrium centre DF%	Atrium centre DF%	
Wall reflectance 0.74 = 70%		65%	
Wall reflectance 0.47 = 47%	43 to 49%		
Wall reflectance 0.06 =33%			37%
Aizlewood et al. (1997) WI 1 (atrium centre DF %)		Wall reflectance 0.83 (atrium centre DF %)	Wall reflectance 0.02(atrium centre DF %)
Wall reflectance 0.845 = 70%		65%	
Wall reflectance 0.039 = 35%			37%

4.5 CONCLUSIONS

This study has investigated the effect of reflectance distributions for diffuse and specular atrium wall surfaces on the DFs and ARCs at the atrium floor. Findings from the study are:

- For diffuse surfaces with identical area-weighted surface reflectances (R = 29%) distribution of the reflectances did affect the measured DF and ARC values. As expected, higher wall reflectances result in higher DFs.
- DFs at the centre of the atrium floor are higher than other positions because at this position more of Sky Component (SC) is received than the edge and corner positions. On the other hand, the edge and corner positions see progressively less of the overhead CIE sky and more of the less bright lower altitude skylight. This is in agreement with the findings of Kim and Boyer (1986) who demonstrated that the illumination levels will be highest at the centre of the atrium well, with longer walls receiving higher values than the shorter walls, followed by the corners receiving the least illumination.
- A large white surface (83% reflectance) near the top of the atrium reflected light towards the atrium base while a black surface absorbed the light as also evidenced by Lau and Duan (2008).
- The impact of different reflectance distributions on DFs reduced as the number of bands with different reflectances increased. This converge took place quite rapidly, suggesting that DFs were not very sensitive to the different reflectance distributions once four or more bands of each of the high and low surfaces had been created for an atrium of WI 1. These findings are in agreement with the subsequent study undertaken by Sharples and Lash (2004).
- Measured data from this study, for the all-white surfaces and the converged value for the banded models where the number of bands increased and the bands became narrower with the effective reflectance verging to the average value, gave a good agreement with the approximate analytical expression for ARC developed by Aizlewood

et al. (1997) which uses the area-weighted reflectance of the atrium. The expression could not be used to find the ARC for an atrium with a small number of large bands of different reflectances. This is also found in agreement with the findings of Sharples and Lash (2004) that based their study on the models used in this chapter.

- Atrium design should avoid putting too narrow a band of high reflectance wall surface adjacent to the atrium floor, particularly if there are darker surfaces immediately above this band.
- The introduction of specular glass surfaces into the atrium produced a consistent increase in the ARCs which in turn increased the DFs, but did not alter the general conclusions drawn from the measurements with just the diffuse surfaces. Obviously, the SC remained unaltered. However, the effect of the different distribution patterns in the banded models was slightly reduced for the atrium with the specular surfaces in comparison with the atrium with the diffuse atrium wall surfaces.

When findings from the scale model study were compared with previous studies, it was found that the results compared very well with those presented by Baker et al. (1993), Aizlewood et al. (1996), Aizlewood et al. (1997) and Sharples and Lash (2004).The difference in the ARCs and the DFs between the model study and Baker et al.'s (1993) study demonstrates the impact of surface reflectance distributions on the daylight availability at the base of an atrium.

The findings from this experiment are in agreement with those presented by Oretskin, 1982; Willbold-Lohr, 1989; and Baker et al. 1993 who show that wells of square plans receive better illumination than rectangular/linear plans at a given level.

The experiments undertaken in this Chapter demonstrate the importance of the reflective properties of the atrium surfaces, their distribution pattern and the surface type (diffuse, specular) on the DF and the ARC on the atrium floor. This is vital considering that the atrium floor will usually reflect this daylight back up onto the ceilings of the adjoining spaces on the lower floors and therefore contribute to the penetration of daylight into them. In the next Chapter, this physical scale model experiment is repeated using RADIANCE and the DF results from the two methods are compared. Whilst the influence of atrium surface reflectance distributions on the DF at individual measurement points is established in this Chapter, it is also important to know whether they affect ADF at the atrium floor. Therefore, Chapter Five also compares ADF obtained from the physical scale model experiments undertaken in this Chapter with those obtained from RADIANCE and Littlefair's (2002) ADF expression.

5 COMPARISON OF DAYLIGHT ASSESSMENT TOOLS: PHYSICAL SCALE MODELS, ALGORITHM AND RADIANCE SIMULATION

5.1 INTRODUCTION

Detailed investigation of the use of physical scale models in daylighting studies was described in Chapter Four. The influence of different distribution patterns of atrium well reflectances on DF at the floor of a square, four-sided, top-lit atrium model under overcast sky conditions was examined. However, to justify the use of RADIANCE for the further experiments to be undertaken in Chapter Six and Seven, it was vital to repeat the physical scale model study of Chapter Four using RADIANCE and compare the findings from the two methods. Therefore, the aim of this Chapter is to compare the accuracies of different methods used to obtain the DF and the ADF in an atrium. This is undertaken to establish reliability of the alternative technique to develop the research work further. ADF is calculated from the DF results obtained from the physical scale model and the RADIANCE experiment and these are compared with the ADF results obtained using the standard formula calculation for ADF proposed by Littlefair (2002).

The first part of this Chapter examines issues related to the analysis of daylighting in buildings. It includes a brief overview of the computer simulation programmes available particularly focussing on RADIANCE and ECOTECT (only used for modelling) used in this study. Finally, a literature review highlights research investigations undertaken to assess the reliability and to compare the performance of the research tools.

This is followed by the second part of the Chapter which includes a comparative investigation of DF values from the physical scale model study of Chapter Four with the RADIANCE study. For this, methodology for the RADIANCE study is presented followed by the results and the discussion, from which conclusions that inform the final component of this chapter are drawn.

In the third part of the Chapter, after the introduction of the ADF formula proposed by Littlefair (2002), a comparison of ADF values obtained by the three different methods is undertaken: physical scale model, algorithm (Littlefair, 2002), and the RADIANCE study. Finally, the results have been discussed and the conclusions are drawn.

5.2 METHODS OF DAYLIGHTING ANALYSIS

Interior daylight illumination can be predicted by monitoring of real buildings, physical scale models, graphic techniques and calculations and computer simulations. Monitoring real buildings can be difficult as it is affected by climatic changes (Ubbelohde, 1998) and can be very time consuming. Fontoynont (1999a) and Sharples and Lash (2007) noted that undertaking daylight measurements in real buildings is often difficult and not very common due to the problems of access, working at height and security.

Calculations can be categorized into simplified procedures and computer programs, both of which provide a quick and precise evaluation of the illumination levels that might be obtained for typical rooms and glazings. However, whilst simplified procedures often make certain assumptions reducing their flexibility and accuracy, computer programs require detailed input in terms of the data and offer more flexibility and accuracy (Bryan and Autif, 2002).

Tregenza and Loe (1998) very clearly summarise the available tools and their limitations, and draw attention to the significance of making appropriate choices when examining and estimating the daylight availability in buildings. They highlight that whilst calculations are important, they are only tools to enable the development of suitable solutions and form a small part of the lighting design process. Furthermore, while there are many methods to estimate each of the quantities of light, none of them are ideal for all circumstances (depending on the nature and the design stage of the project) and vary in accuracy and costs (in terms of time and resources).

Tregenza and Loe (1998) classified tools in three categories; those used at the initial design stage, detailed design stage and those that are used for presentations. The initial design stage requires procedures that can be used to generate forms, basic dimensions, orientation, choice of key materials and a quick assessment of the different design options and their implications for sunlight and daylight in relation to site planning and developing strategies for energy use. Specific performance predictions are not required at this stage but what is more useful is an indication of the general overall performance. At the detailed design stage, the key parameters have been decided but there is a requirement to find specific dimensions and calculations to confirm that specific criterion. The third category of calculations is those that are used for presentations in the form of visual, rendered images or numerical data demonstrating the performance of the solution.

Accuracy of the data obtained is based on the exact assumptions made in the calculations and results should take into consideration factors such as actual furnishing and finishes, exterior obstructions and maintenance factors (this is also used to represent surface dirt). Unless data are interpreted taking into account these factors, the daylight factor expressed to several decimal places is of no real value or precision. Furthermore, small changes in the illuminances are of no significance in comparison to the natural daylight variation and because they do not affect visual performance, they are often imperceptible. The precise calculated numbers are only useful when comparing with established standards. Therefore care needs to be taken when interpreting data, whether it is undertaken using manual procedures or computer simulations as they both are derived from some uncertainty in the input data (Tregenza and Loe, 1998). Tregenza and Loe (1998) highlighted that “lighting within a room is a complex, varying quantity, and most calculations are based on very simplified models of reality, with input data that are mere estimates”.

Tregenza and Loe (1998) recommended key references for lighting design that include the *Code for Interior Lighting* published by the Chartered Institution of Building Services Engineers (CIBSE) in the UK and the *Lighting Handbook* of the IES of North America. They refer to the national standards and the legislation for the different building types. When undertaking daylighting and energy use studies, it is important to use up to date manufacturers’ data for the materials and equipment, and local climate wherever possible.

5.3 COMPUTER PROGRAMMES

Benefits of the use of computer programmes are that they allow for a quick and easy modification of models, and the resultant rapid exploration and comparison of the performance of different design parameters including spatial variations, geometrical dimensions, fenestration, site orientations and climatic conditions.

Although physical scale models provide accurate results, they can take a significant amount of time to build and to make changes. Close (1996) suggests that a lengthy computation time associated with computer simulations would still be faster than building physical scale models. Mabb (2008) highlights one of the key advantages of the computer simulations as the opportunity they present to simultaneously assess performance for different climatic conditions, i.e. worst, best and long term. The alternative, monitoring under real conditions, can be very time consuming and can take at least six months or even longer as mentioned before.

While the computer programs offer several benefits, “the simulation of any physical process will include some approximations or assumptions. The key is to make sure that they do not make a large difference in the overall result and that they are clearly stated. Simulations cannot give absolute values; the best they can do is consistently provide realistic values within an acceptable range” (Mabb, 2008). This study suggests that while the simulation programs may provide absolute data that is applicable to the real world, they are useful for providing meaningful data when comparing similar systems and testing different options to establish the best relative design option or the better of the systems.

Over the last few decades computer simulation of building performance has developed significantly. Mid 1980s saw the emergence of a powerful daylight simulation tool, Superlite, while RADIANCE (discussed in detail in the next section) developed in the late 1980s. Superlite is based on the CIE standard overcast and the clear sky. It predicts the spatial distribution of illuminance in a building based on the sun and the sky conditions, the site obstructions, the fenestration and the shading devices, and the interior room properties.

For the purpose of the experiments undertaken in this thesis, RADIANCE and ECOTECT have been used and are described below:

5.3.1 RADIANCE

RADIANCE was developed by Greg Ward Larson during his employment (1985 - 1997) at the Lawrence Berkeley National Laboratory in collaboration with the Pacific Gas and Electric and the California Institute of Energy Efficiency. Version 2.4, its 9th official release, is rigorously tested and debugged.

RADIANCE is a lighting design and architectural specific rendering system, which can analyse both complex and simple internal environments and determine the effect of both natural and artificial lighting (Ward, 1994). The distinctiveness of RADIANCE is that it successfully combines features that are characteristic of the accepted computer graphics rendering programs with the physical accuracy of an advanced lighting simulation. This unique combination of accurately predicting lighting conditions and simulating advanced daylighting systems and materials, and presenting high quality and realistic images makes it attractive for use by a range of built environment professionals including architects, engineers and lighting designers (Chadwell, 1997; Mabb, 2008).

Notably, Chadwell (1997) highlighted that “RADIANCE has been compared to other lighting calculations, scale model measurements and real spaces to validate its capabilities. No other lighting calculation has undergone a more rigorous validation”.

Modelling and Input

As most daylighting programs do not have geometric modelling capabilities, CAD data modelled in another program is usually imported. However, this is often not very straightforward due to the "incompatibility with peculiar model geometries (like 3d-solids, meshes etc.), surface normal orientation problems, and problems with layers and object groupings (blocks)" (Bryan and Autif, 2002). As Desktop RADIANCE works inside AutoCAD, the modelling process is built-in and does not create problems usually associated with importing the CAD data. Commands for Desktop RADIANCE are under a drop down menu within the host AutoCAD's interface.

Furthermore, RADIANCE can take unmodified input from the CAD systems; it does not impose any restrictions on the number of shapes or surfaces in a scene and supports the analysis of complicated geometries. It also evaluates a scene simply focussing on the important elements of the scene and ignores any unnecessary factors resulting in very efficient and quick calculations (Ward, 1994).

Surface Properties

Surfaces are infinitely thin in Desktop RADIANCE and cannot have different materials on the front and back of a surface. "This makes the surface normal orientation of materials irrelevant, except for transparent surfaces, which should have their normals aligned properly. The program has a good feature for checking and reversing normal orientations" (Bryan and Autif, 2002). RADIANCE materials library includes an extensive collection of materials such as plastic, brick, metal, glass etc, which can be modified if required, and with the option of defining customized materials using its materials editor function. "Reflectance and transmittance properties are general in the sense that an arbitrary bidirectional reflectance or transmittance distribution function may be given, but only the predefined types will include the specular indirect component" (Chadwell, 1997).

Daylighting Set Up

A correct sky model is a fundamental component for the accurate simulation of daylight. While the sky condition is a dynamic entity that depends on time and location, standard sky models that are based on estimates are typically used by daylighting simulation programs, most common being the CIE clear and overcast skies.

In addition to the clear, intermediate, overcast and uniform sky conditions that may be chosen, Desktop RADIANCE includes data for several locations and allows the users to customise the skies based on weather and location data of new locations. Simulations can be set up to obtain luminance, illuminance or DFs.

Simulation and Rendering

For simulation of light levels and rendered images, input in terms of a description of the geometry, surface materials and light sources is required with further information in relation to the view point, direction and angles that are required for rendering images. “Once a scene's geometry has been described, it is compiled into an "octree" that acts as an efficient data structure for the ray tracing process (i.e. determining which surface a ray intersects)” (Chadwell, 1997).

Daylighting is challenging to model due to its complex and dynamic nature. There are numerous CAD systems that model the solar position and determine the shadows for a given building model. However, RADIANCE also models the diffuse skylight and its inter-reflected component and in this sense atria offer one of the more complicated and challenging lighting modelling tasks (Ward, 1994). The use of diffuse inter-reflection modelling algorithms enables the accurate simulation of daylight in the internal and external spaces.

Radiosity and Raytracing

Radiosity and Raytracing are the two most common rendering techniques that are used by most simulation programs. RADIANCE uses zonal/radiosity for the direct component and backward ray tracing for the indirect component (Mabb, 2008). Letherman and Wright (1998) stated that “Ray tracing allows the designer to simulate building features with a good degree of accuracy under a range of sky luminance distributions”.

Tregenza (1994) set out the use of a geometrical framework to determine the intersection point of the internal surface reflections to find light levels within buildings. He developed the forward radiosity computer program; this process traces patches of light rays from the source to the working plane and the accuracy is based upon the size of the patches (Mabb, 2008). Radiosity technique, best suited for the diffuse reflections and shadows, and simple geometric forms, is more accurate than raytracing. It involves the division of a surface into a mesh of smaller surfaces, where light distributed from one mesh element to the other is calculated and the radiosity values for each element of the mesh are stored and retained. This allows several views to be rendered from the initial radiosity calculation, even when the view point is changed (Bryan and Autif, 2002). However, when dealing with vast amounts of individual surfaces and modelling non-diffuse environments, it greatly increases processing time and memory usage (Ward, 1994).

Raytracing, best used for specular reflections and refractions, tracks the path of a ray of light as it bounces off or is refracted through the surface. This backward ray tracing method traces rays from the measuring point (usually a viewpoint) on the work surface back to the source (i.e. emitters). The calculation takes into account the direct component, and the specular and the diffuse indirect component.

Output

A view can be set up by defining a camera within the space and simulating for its viewpoint; this can be done in an interactive mode, batch mode or no-image mode. The interactive mode is useful as the user can see a draft rendered image and change settings if required (Bryan and Autif, 2002). The time required for rendering depends on several factors, some more influential than others. The key factors that affect rendering time include “output image resolution, the number of light sources, scene complexity, the importance of indirect illumination, and the desired accuracy" (Chadwell, 1997). Rendering times are also somewhat affected by the "materials used, emitting surface dimensions and output distributions, and the number of images rendered under the same lighting conditions ..." (Chadwell, 1997).

Depending on the focus of a program, its output of simulation and rendering processes will vary. The outputs may be image or data intensive; output from Desktop RADIANCE can be viewed and saved as rendered images, tables, isolumen contours and false colour images (Bryan and Autif, 2002). The image can be analysed, displayed and manipulated within RADIANCE or indeed converted to other formats for exporting to different programs to create a hard copy (Chadwell, 1997).

5.3.2 ECOTECT

ECOTECT is a 3D building performance analysis program developed by Dr Andrew Marsh, who describes it as "a software package with a unique approach to conceptual building design. It couples an intuitive 3-D design interface with a comprehensive set of performance analysis functions and interactive information displays" (Marsh, 2003). In particular, it enables the assessment of solar exposure, thermal performance, acoustics, lighting and shading. ECOTECT is a tool that can be used by architects as it allows for the quantitative assessment of the projects during its early design phases and for its design development.

Models can be created in ECOTECT; however, as it is compatible with other 3D CAD formats, models can be built in programs such as SketchUp or ArchiCAD and imported into ECOTECT. Even the most complex geometries can be modelled and visualised very quickly using ECOTECT. The models can be easily manipulated and changed which is of particular benefit for assessing preliminary design ideas and testing different design strategies.

"Each material in ECOTECT can store a wide range of information including basic thermal and surface properties, detailed layer descriptions, acoustic response and even cost and environmental impact data if it is available to you. Similarly, you can generate and assign complex annual operational schedules and hourly profiles for controlling occupancy, appliances or internal conditions" (Marsh, 2003).

In addition to using its own built in routines, ECOTECT has very useful import and export capabilities which means the building models can be exported to analysis and validation programmes such as EnergyPlus and RADIANCE enabling the use of a large range of conceptual design tools and advanced modelling and visualisation interface. This allows for all the design and building data to be stored in one file which can be used for different focused analysis such as lighting or thermal. On completion of the analysis, the model can be imported back into ECOTECT for the information to be read and visualized within the original model.

Although ECOTECT has its own daylight analysis tool, it is based on the split flux method and so it does not handle inter-reflection in a sufficiently accurate manner. Therefore for the purpose of the comparative studies of this Chapter and the experiments undertaken in Chapter Six and Seven of this thesis, ECOTECT has been used only as an intermediate tool to generate the atrium models. It was used for defining the atrium geometry, its finishes, light sources etc and exporting the data to RADIANCE for the daylight analysis. Finally, the output from RADIANCE was imported back into ECOTECT for the data to be read.

5.4 LITERATURE REVIEW OF DAYLIGHTING RESEARCH METHODS – COMPUTER SIMULATION AND PHYSICAL SCALE MODEL STUDIES

The previous section discussed the available tools, in particular RADIANCE and ECOTECT, that can be employed to undertake daylighting research and included key considerations in relation to their use as highlighted by Tregenza and Loe (1998).

A parametric study, such as the one included in this thesis, is a time-tested and effective method within the realm of daylight research. It enables the examination of the influence of the key design parameters on daylighting in buildings and can be undertaken through a physical scale model or computer simulations.

As discussed in Chapter Four, physical scale models have long been recognised as a useful and reliable means of accurately predicting interior daylight illumination within specific limits of scale, detail and metering protocols (Hopkinson et al. 1963; Evans, 1981; Moore, 1991; Baker et al.1993; Ubbelohde, 1998).

While, physical models have been used in architectural practices for a long time but they are being rapidly replaced by CAD programs over the last 20 years. Similarly, physical model as a design tool is being replaced by advanced computer simulations in daylighting research (Ubbelohde, 1998). Reinhart and Fitz's (2006) confirmed that RADIANCE is now widely used to accurately predict light levels in buildings and obtain photo realistic visualization of spaces. Sharples and Lash (2007) concluded that daylighting research in the next 15 years will rely heavily on computer modelling. Nonetheless, physical scale model studies tested in calibrated artificial skies have long been used as a universal reference for validating the daylight levels predicted by computer simulations (Aizelwood et al.1998; Jongewaard 1993; Love & Navvab 1991; Spitzglas et al. 1985; Ward 1990).

RADIANCE has been validated by several researchers (Mardaljevic, 1995; Fontoynont et al., 1999; Calcagni and Paroncini, 2004) as it has shown high accuracies when compared with model studies and theoretical analysis, in addition to its ability to simulate complex architectural scenes.

Aizlewood et al. (1997) compared physical scale model measurements with those obtained from RADIANCE. There was complete agreement for the sky component (SC) at the base of the atrium. However, RADIANCE underestimated the reflected light in deep, high reflectance atria in comparison with the physical model. The study points out the possible sources of simulation errors to be geometry errors; sky definition errors; limitations and bugs in the algorithm; inappropriate ambient parameters; and errors in the definitions of surface properties

In agreement with Aizlewood et al. (1997), Fontoynont et al. (1999b) also highlighted the importance of setting modeling parameters accurately to obtain accurate simulated data in RADIANCE.

Using a contemporary building, Ubbelohde (1998) presented a comparative evaluation of results from field measurements, software predictions ,and physical modelling. Both RADIANCE and physical scale model data closely matched the measured data obtained from the building confirming their reliability for daylighting analysis under overcast sky conditions as shown in Figure 5:1. Importantly, Ubbelohde (1998) suggested that it is unlikely for a real sky to match the CIE overcast distribution. Therefore for overcast sky conditions, the use of physical models tested in an artificial sky provides a better base case than real buildings for comparing findings from simulation programs.

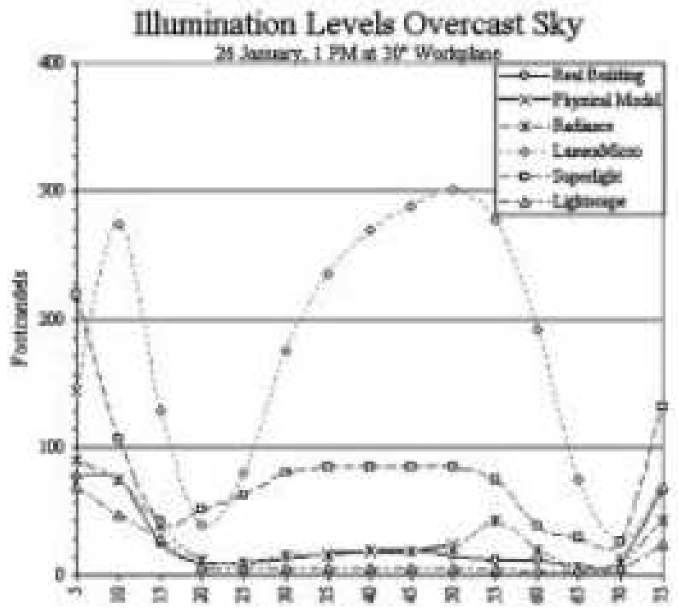


Figure 5:1Comparison of illumination levels for overcast sky obtained from real building, physical scale models, RADIANCE, LumenMicro, Superlight and Lightscape

Mabb (2008) compared computer programmes (RADIANCE, Radiosity, 2D Raytrace, 3D Raytrace) with both, field measured and scale model illuminance data in an adjoining room of an atrium building under overcast and clear skies.

The results generally showed a good correlation between simulations and field data but RADIANCE generally underestimated the illuminance levels under the overcast sky as shown in Figure 5:2.

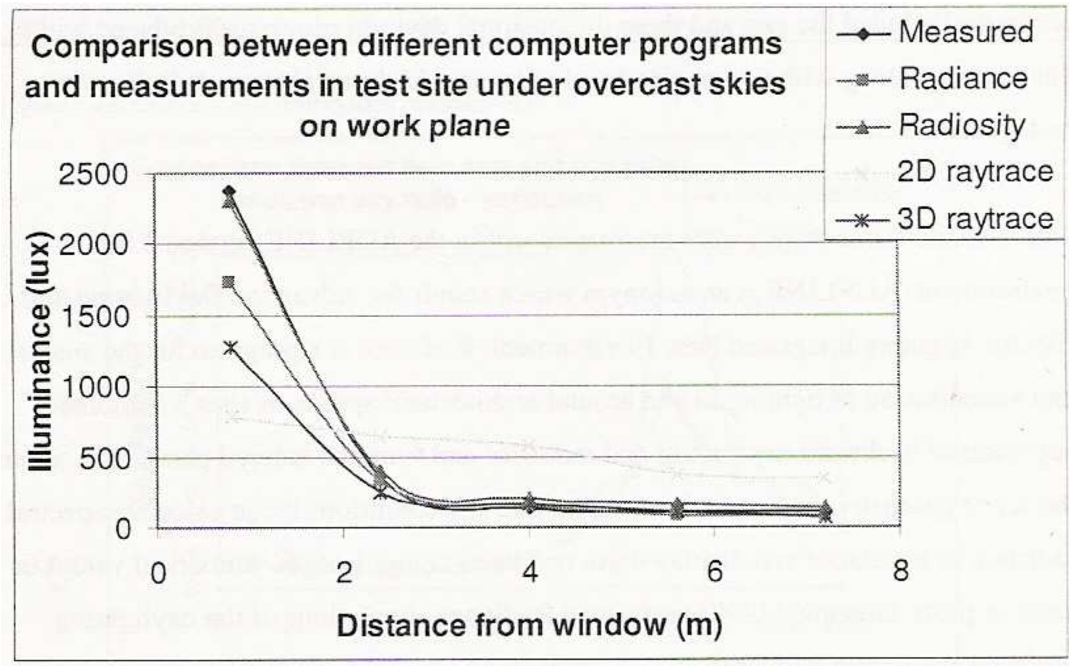


Figure 5:2 Correlations between the computer simulations and field measured data (Mabb, 2008)

Illuminance results from 3D computer simulations when compared with scale model measurements under overcast sky conditions in the adjoining room of an atrium building of well index 2 also showed good agreement as seen in Figure 5:3.

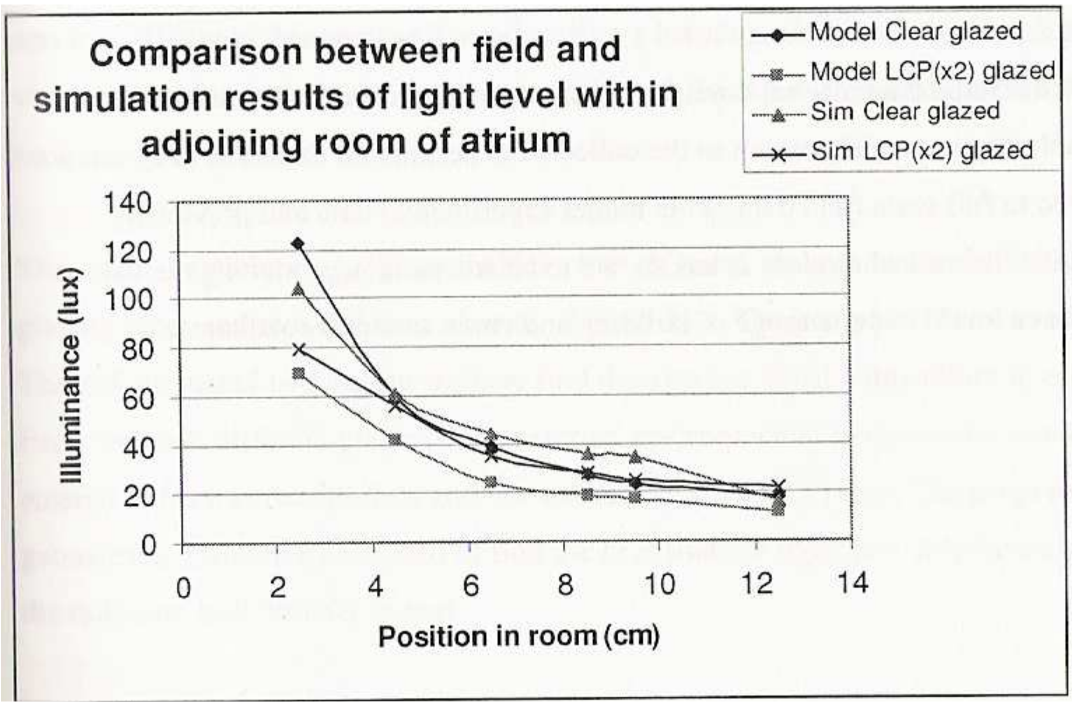


Figure 5:3 Comparison between field and computer simulated results for atrium's adjoining room under overcast sky (Mabb, 2008)

Du and Sharples (2009a and 2009b) also concluded that RADIANCE was accurate in predicting the vertical sky components (2009a) and the vertical DFs (2009b) in comparison with the outputs from the scale model measurements and the analytical theory (2009a).

Galasiu and Atif (1998) compared Superlite, Superlink and RADIANCE computed interior daylight level outputs against data collected in a real building's atrium space. Comparison between measured and RADIANCE computed data showed that, for any particular sky condition, the computer model had the potential to accurately model the daylighting performance of a space if relevant input data, such as the precise space geometry, construction materials properties and actual sky description are available. Indoor illuminance was very well predicted by RADIANCE for an overcast skyand diffuse daylight was simulated more accurately than the direct component.

Bryan and Autif (2002) examined the advantages and disadvantages of several daylighting simulation programs and in agreement with Ubbelohde (1998) and Galasiu and Atif (1998), Bryan and Autif (2002) concluded that Desktop RADIANCE was most accurate for daylight simulation amongst the programs they examined.

Most studies suggest RADIANCE to be a reliable tool for daylighting studies in atrium buildings. Importantly, for overcast skies, Ubbelohde (1998) suggests the use of physical models as a better base case than even a real building for comparing results from RADIANCE. Considering these findings and the common use of physical scale models to validate daylight predictions from the computer simulations, the next section compares results from RADIANCE (DF) with those obtained from the physical scale model studies undertaken in Chapter Four.

5.5 COMPARISON BETWEEN DF OBTAINED BY ECOTECT/RADIANCE, AND PHYSICAL SCALE MODEL STUDY

5.5.1 Methodology for ECOTECT AND RADIANCE Study

All six models developed for the physical scale model study were created in ECOTECT. These include atria with area weighted average reflectance of 2% for model 1 with all wall surfaces completely black, 57% for model 6 with all white wall surfaces and 29% for the models 2, 3, 4 and 5 that comprised of various, systematic patterns of alternate horizontal bands (2, 4, 6, 8 bands) of black and white surfaces as shown in Figure 5:4. The floor of the atrium was always black to eliminate its influence on DFs obtained on the atrium floor.

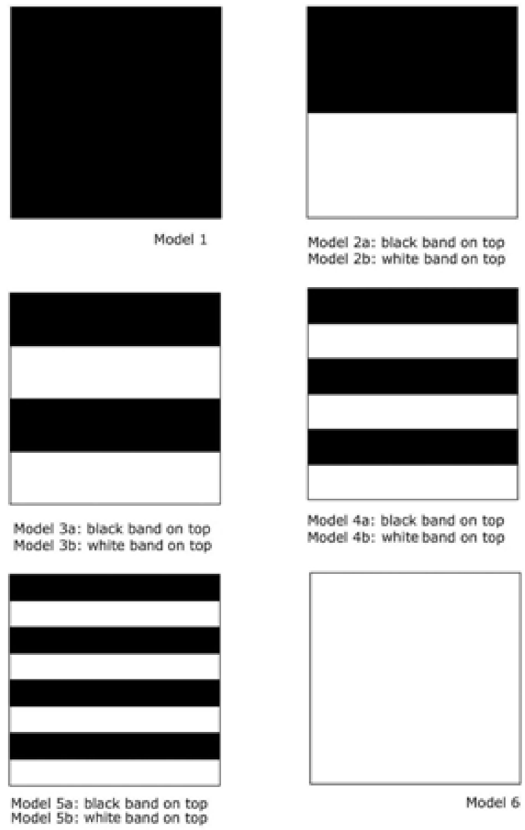


Figure 5:4 Wall surfaces of the atrium WI 1 (black; 2, 4, 6, 8 horizontal bands; and white surfaces)

Zone tool in ECOTECT was used to model the atria and create the bands. Each of the zones was assigned material properties including internal reflectances in ECOTECT. The roof of the atrium was set as void. Except for the bottom zone whose floor formed the floor of the atrium, the roof and floor of every horizontal band was also set as void.

Using the grid management tool in ECOTECT, an analysis grid was formed, which emulated the horizontal and vertical positions of the photocell used in the physical model i.e. the atrium centre, four positions halfway along the atrium's edge (22.5 mm from the atrium's wall edge) and the four corner positions (22.5 mm from the corner of the atrium) on the atrium floor as shown in Figure 6:5. Therefore, the physical scale model grid determined by the photocell was used in the RADIANCE study. Measurements were taken for the horizontal DF at a working plane height of 0.85 metres above the atrium floor.

Measurements were taken by the following processes. Using the lighting analysis tool within ECOTECT, under the “sky illumination model” option, the “CIE overcast sky” was chosen. The data of “design sky illuminance” (lux) was set according to the figures of external illuminance obtained from the previous physical scale model experiment outlined in Chapter Four (Table 4:4) and as shown in Figure 5:5. This was done to maintain consistency and enable comparison of the data obtained by the two methods.

After completing the data input, models were exported to RADIANCE using the export manager tool for the daylight analysis. Parameters defined to carry out the calculations are also shown in Figure 5:5.

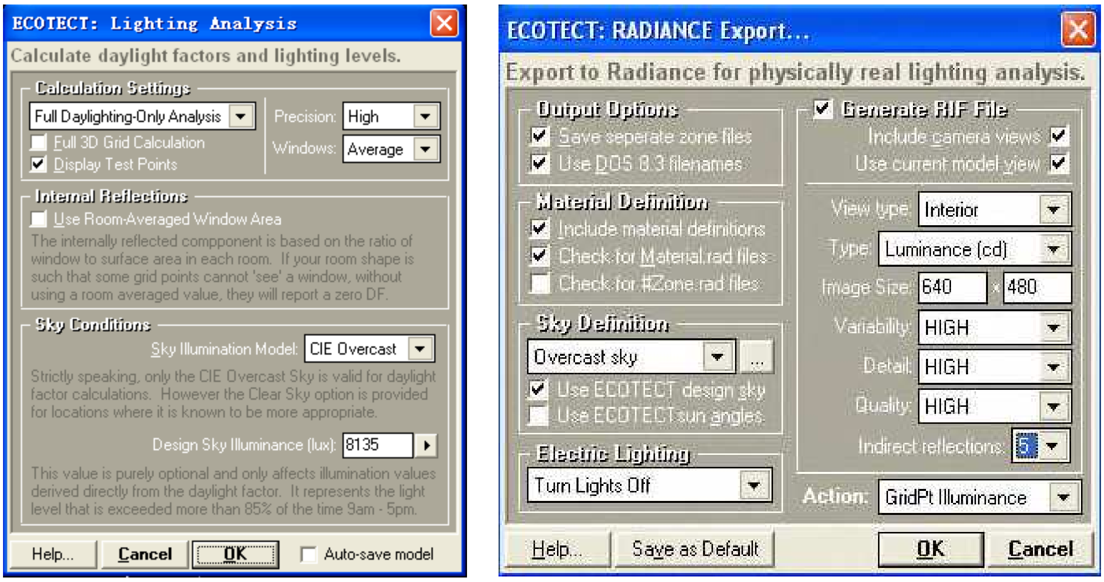


Figure 5:5 Parameters defined in ECOTECT and RADIANCE

Once the calculations were carried out in RADIANCE, data were brought back into ECOTECT using the import/merge and overwrite tool under grid management and was saved as a DAT file produced by RADIANCE. Illuminance data for the different positions on the atrium floor were obtained. DF values for all the measurement points on the atrium floor for all the models were systematically calculated by the following expression:

$$DF_c = \text{Indoor Illuminance} \times 100\% / \text{Outdoor Illuminance} \qquad (1)$$

Arithmetic averages of DFs obtained for the four sides were calculated to provide DFs for the edge and corner positions.

5.5.2 Results and Discussion

As outlined in the methodology and shown in Table 5:2, external illuminance values from the physical scale model study described in Chapter Four were input into the RADIANCE simulated study to calculate the DFs. Table 5:2 shows DFs obtained from the physical scale model study (Chapter Four) and RADIANCE for the three measurement points across the atrium floor, and the six wall reflectance distribution configurations. It also shows the difference between the physical model DF values (P) and the Radiance DF values (R) defined as (P-R) %.

DFs predicted by RADIANCE were lower by between 4.6% and 9.7% *(relatively lower by 13% to 23%)* in comparison with those obtained from the physical scale model study (Chapter Four) as shown in Table 5:1. This shows a consistent difference between the results from physical and Radiance models. As expected, due to the influence of atrium surface reflectances, DFs were highest for model 6 (40.8%-55.4%), lowest for model 1 (19.7%-31.8%) with DFs values in between the two ranging between 24.7% and 40.2% for the models 2, 3, 4 and 5 for the three measurement positions on the atrium floor. Table 5:1 and Figure 5:6 show that for model 1 with all black atrium walls, difference in DFs obtained by the two methods was also lowest and was less than 5% *(relative difference of 13% to 20%)* for all the three measured positions. Difference between DFs obtained by the two methods was highest for model 6 and was between 9% and 10% *(relative difference of 15% to 18%)* for all the three positions. While difference in the DFs obtained by the two methods for all the banded models, 2, 3, 4 and 5 was between 5.2% and 9.1% *(relative difference of 13% to 23%)*. The lowest difference of 5.2% DF was observed for model 5a in the corner position while the highest difference of 9.1% DF was noted for model 2b in the atrium centre position.

Table 5:1 DFs from Physical Model Study and RADIANCE, and the Difference between DFs from the two methods

Model Type and reflectance (*p*)	Position	External Illuminance (lux)	DF (%) Physical Scale models (P)	DF (%) RADIANCE (R)	Absolute Difference P-R %	Relative Difference P-R/P %
Model 1 (black) (*p* = 2%)	Centre Edge Corner	7885 8065 8080	36.6% 29.6% 24.5%	31.8% 25.0% 19.7%	4.8% 4.6% 4.8%	13.1% 15.5% 19.5%
Model 2a (Halves) (*p* = 29%)	Centre Edge Corner	7790 8172 8170	43.1% 39.8% 36.2%	36.9% 33.6% 29.3%	6.2% 6.2% 6.9%	14.3% 15.5% 19.0%
Model 2b (Halves) (*p* = 29%)	Centre Edge Corner	8185 8157 8175	49.3% 38.8% 31.6%	40.2% 30.8% 24.3%	9.1% 8.0% 7.3%	18.4% 20.6% 23.1%
Model 3a (Quarters) (*p* = 29%)	Centre Edge Corner	7657 8235 8255	43.6% 38.7% 34.5%	37.1% 31.7% 28.5%	6.5% 7.0% 6.0%	14.9% 18.0% 17.3%
Model 3b (Quarters) (*p* = 29%)	Centre Edge Corner	8245 8250 8245	47.4% 38.7% 32.0%	39.1% 30.5% 25.1%	8.3% 8.2% 6.9%	17.5% 21.1% 21.5%
Model 4a (Sixths) (*p* = 29%)	Centre Edge Corner	8135 7900 7855	44.6% 38.3% 33.4%	36.9% 31.2% 27.1%	7.7% 7.1% 6.3%	17.2% 18.5% 18.8%
Model 4b (Sixths) (*p* = 29%)	Centre Edge Corner	8222 8075 8125	46.3% 38.7% 33.0%	38.8% 30.9% 26.2%	7.5% 7.8% 6.8%	16.1% 20.1% 20.6%
Model 5a (Eighths) (*p* = 29%)	Centre Edge Corner	8185 8240 8235	44.8% 37.1% 31.7%	38.9% 31.0% 26.5%	5.9% 6.1% 5.2%	13.1% 16.4% 16.4%
Model 5b (Eighths) (*p* = 29%)	Centre Edge Corner	8205 8277 8235	46.2% 38.5% 33.2%	38.3% 30.9% 26.7%	7.9% 7.6% 6.5%	17.0% 19.7% 19.5%
Model 6 (white) (*p* = 57%)	Centre Edge Corner	8195 8240 8260	65.1% 56.4% 50.0%	55.4% 47.2% 40.8%	9.7% 9.2% 9.2%	14.9% 16.3% 18.4%

Figure 5:6 shows DFs obtained at the atrium centre position by the physical scale model and the RADIANCE experiments. For atrium model 1 with low wall and floor reflectances, there is a very good agreement between the DF data obtained by the physical scale model and the RADIANCE simulated study. However, with an increase in the surface reflectances in Model 6, the difference in DF values obtained by the two methods also increased.

On comparing DFs for the banded models, it was found that difference in the DFs obtained by the two methods for the 'a' type models was generally slightly lower than the 'b' type models as shown in Figure 5:6.

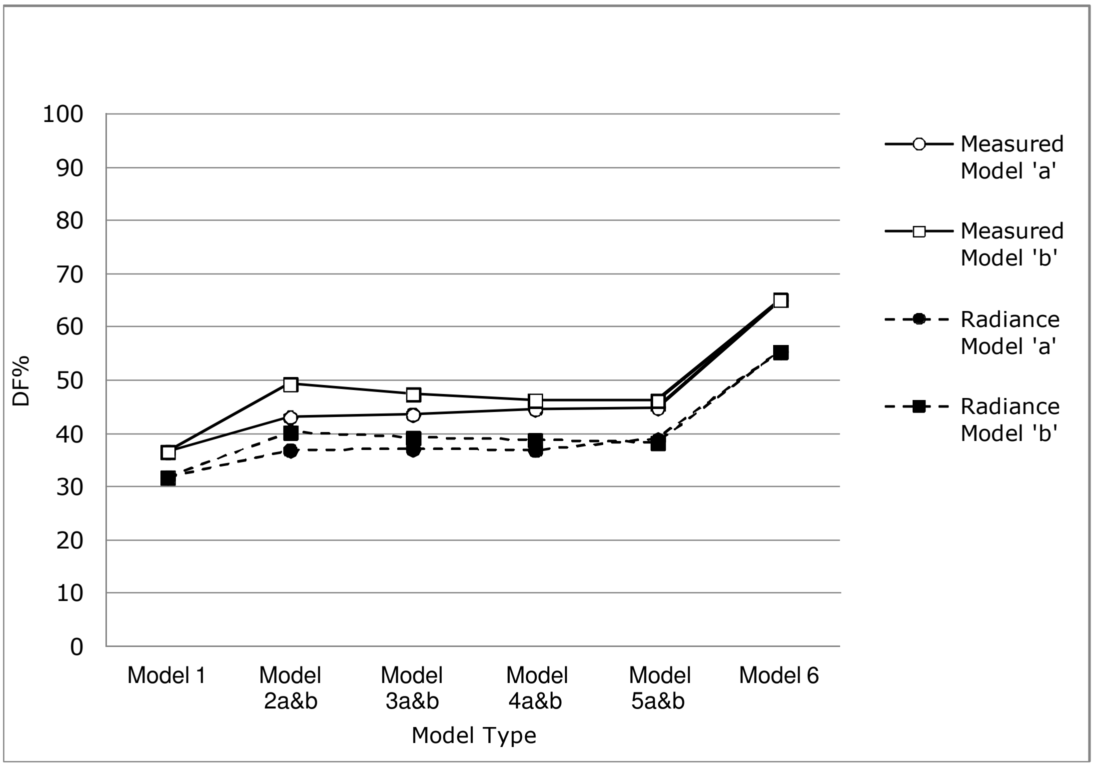


Figure 5:6 Comparisons between Physical Scale Model Measured and RADIANCE Simulated DF values for centre of the Atrium Floor

On comparison of DFs obtained for the three positions on the atrium floor, it was found that the DFs were always highest at the atrium centre, followed by the edge position and they were lowest for the corner position in both methods. While on the whole DF predictions were generally lower in RADIANCE than those obtained from the physical scale model study, the way the DFs were distributed across the atrium floor and the form of decay from one position to the other evidenced through the three measurement points was very similar for both the methods (Table 5:1 and Figure 5:6). For all the models, the drop in DFs from the atrium centre to the edge position and from the edge to the corner position were similar for both the methods and differed marginally in some cases at the most by around 1% only. This demonstrates that there is very good agreement between the two methods in terms of their daylight distribution prediction but RADIANCE generally underestimated DFs in comparison with the physical scale model measurements.

Table 5:2 compares difference in the DFs obtained between the ‘a’ and ‘b’ type banded models 2, 3, 4 and 5 from the physical scale model and the RADIANCE experiments. This is undertaken to examine the influence of reflectance distributions on DFs as identified by the two methodological approaches.

In both the methods, DFs at the atrium centre position for the ‘b’ type models with the white band on top were higher than the ‘a’ type models for most cases except for model 5 of the RADIANCE experiment. The effect of alterations to the distribution of reflectances on the DF was highest in the atrium centre position with a maximum difference of 6.2% *(relative difference of 13%)* noted for model 2. This effect was slightly lower for the corner position with a maximum difference of 5% *(relative difference of 17%)* and lowest for the atrium edge position with a maximum difference of 2.8% *(relative difference of 8%)* noted for model 2. Change in the sequencing of bands mainly affected model 2 which had only two very large bands but as the number of bands increased from Models 2 to 5, the reversing of model from ‘a’ to the ‘b’ type had limited influence on the DFs as shown in Table 5:2 with a slightly higher difference noted for model 5 in the physical scale model study.

Table 5:2 Difference the in DFs obtained between the 'a' and 'b' type banded models 2, 3, 4 and 5 from the physical scale model and RADIANCE experiments

	PHYSICAL SCALE MODEL			RADIANCE		
Models 2-5 (p = 29%)	'a' type DF%	'b' type DF%	'b'-'a' DF% Difference	'a' type DF%	'b' type DF%	'b'-'a' DF% Difference
Model 2						
Centre	43.1	49.3	+6.2	36.9	40.2	+3.3
Edge	39.8	38.3	-1.0	33.6	30.8	-2.8
Corner	36.2	31.6	-4.6	29.3	24.3	-5.0
Model 3						
Centre	43.6	47.4	+3.8	37.1	39.1	+2.0
Edge	38.7	38.7	±0.0	31.7	30.5	-1.2
Corner	34.5	32.0	-2.5	28.5	25.1	-3.4
Model 4						
Centre	44.6	46.3	+1.7	36.9	38.6	+1.7
Edge	38.3	38.7	+0.4	31.2	30.9	-0.3
Corner	33.4	33.0	-0.4	27.1	26.2	-0.9
Model 5						
Centre	44.8	46.2	+1.4	38.9	38.1	-0.8
Edge	37.1	38.5	+1.4	31.0	30.9	-0.1
Corner	31.7	33.2	+1.5	26.5	26.7	+0.2

When the difference in DFs obtained between models 'b' and 'a' defined by 'b'-'a' in Table 5:2 from the physical scale model and RADIANCE were compared as shown in Figure 5:7, a maximum difference of 2.9% (for atrium centre position 6.2% - 3.3% = 2.9%) was noted for model 2 suggesting that there was a good agreement between the DF results obtained for the 'a' and 'b' type models from the two methods.

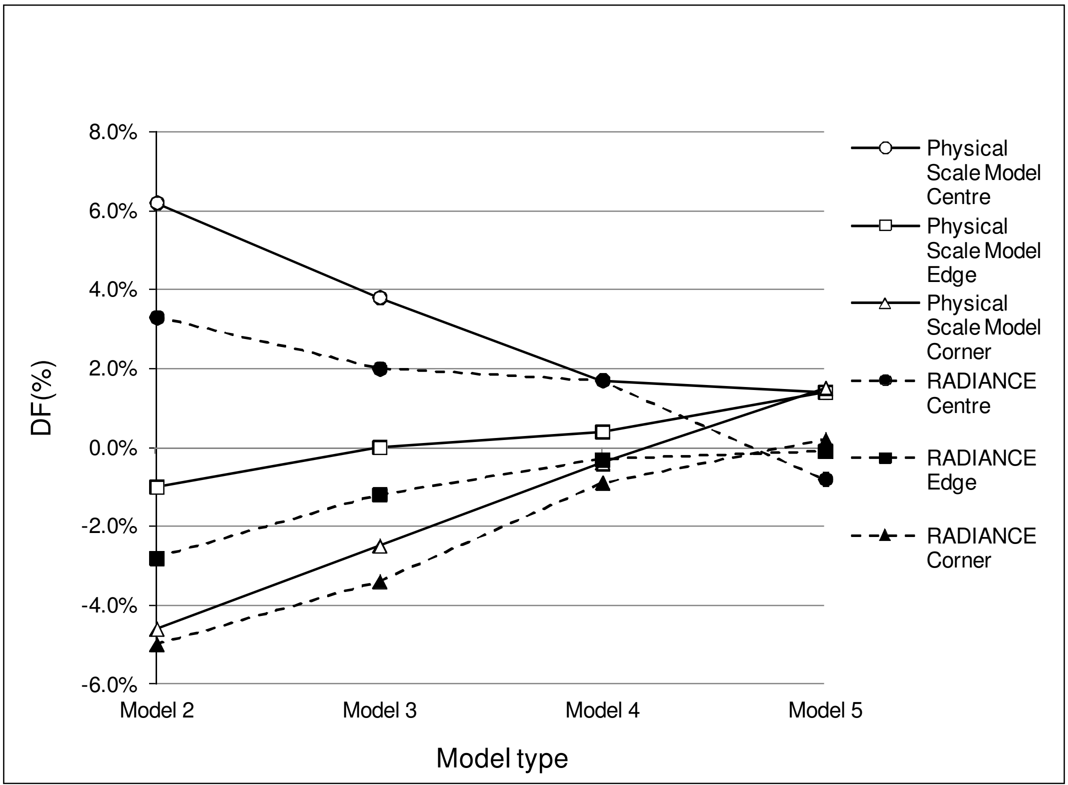


Figure 5:7 Comparisons between Physical Scale Model and RADIANCE (b-a DF% difference) for models 2, 3, 4 and 5 for atrium centre, edge and corner positions

Table 5:3 compares difference in DFs from the physical scale model and RADIANCE experiments between models 2 and 3, 3 and 4, and 4 and 5 for both, the ‘a’ and ‘b’ type banded models. This is undertaken to examine the impact of the change in the reflectance distributions on DFs as identified by the two methods.

For the ‘a’ type models, as the number of bands increased, DFs reduced marginally except for the atrium centre position where DFs increased for both, the physical scale model and the RADIANCE experiment. Maximum difference in the DFs due to the increase in the number of bands was noted between models 2a and 3a; and 4a and 5a, where the DFs for model 3a and 5a were lower by 1.7% *(relatively lower by 5%)* compared to models 2a and 4a respectively at the corner position in the physical scale model experiment. On the other hand, in RADIANCE, DF for model 5a was 2% higher *(relatively higher by 5%)* compared to model 4a at the atrium centre position.

For the ‘b’ type models, in the physical scale model study, increase in the number of bands from 2b to 3b resulted in a maximum difference in DF of 1.9% (centre position) *(relative difference of 4%)* while this difference was 1.1% (centre and corner positions) *(relative difference of 3% to 4%)* for the RADIANCE study. Overall, in comparison with the ‘a’ type models, the ‘b’ type models were less affected by the change in the reflectance distributions.

Table 5:3 Difference in the DFs from the physical scale model and RADIANCE experiments between models 2 and 3, 3 and 4, 4 and 5 for both ‘a’ and ‘b’ type banded models

Models 2 to 5 (*p* = 29%) & Measurement Positions	PHYSICAL SCALE MODEL DF%			RADIANCE DF%		
2a and 3a	2a	3a	3a-2a Difference	2a	3a	3a-2a Difference
Centre	43.1	43.6	+0.5	36.9	37.1	+0.2
Edge	39.8	38.7	-1.1	33.6	31.7	-1.9
Corner	36.2	34.5	-1.7	29.3	28.5	-0.8
3a and 4a	3a	4a	4a-3a Difference	3a	4a	4a-3a Difference
Centre	43.6	44.6	+1.0	37.1	36.9	-0.2
Edge	38.7	38.3	-0.4	31.7	31.2	-0.5
Corner	34.5	33.4	-1.1	28.5	27.1	-1.4
4a and 5a	4a	5a	5a-4a Difference	4a	5a	5a-4a Difference
Centre	44.6	44.8	+0.2	36.9	38.9	+2.0
Edge	38.3	37.1	-1.2	31.2	31.0	-0.2
Corner	33.4	31.7	-1.7	27.1	26.5	-0.6
2b and 3b	2b	3b	3b-2b Difference	2b	3b	3b-2b Difference
Centre	49.3	47.4	-1.9	40.2	39.1	-1.1
Edge	38.8	38.7	-0.1	30.8	30.5	-0.3
Corner	31.6	32.0	+0.4	24.3	25.1	+0.8
3b and 4b	3b	4b	4b-3b Difference	3b	4b	4b-3b Difference
Centre	47.4	46.3	-1.1	39.1	38.6	-0.5
Edge	38.7	38.7	±0.0	30.5	30.9	+0.4
Corner	32.0	33.0	+1.0	25.1	26.2	+1.1
4b and 5b	4b	5b	5b-4b Difference	4b	5b	5b-4b Difference
Centre	46.3	46.2	-0.1	38.6	38.1	-0.5
Edge	38.7	38.5	-0.2	30.9	30.9	±0.0
Corner	33.0	33.2	-0.2	26.2	26.7	+0.5

5.5.3 Conclusions

As expected and similar to the physical scale model study, due to the influence of atrium surface reflectances, DFs in RADIANCE were highest for model 6 (40.8%-55.4%), lowest for model 1 (19.7%-31.8%) with the DFs values for models 2, 3, 4 and 5 ranging between the two (24.7% and 40.2%) for the three measured positions on the atrium floor. Furthermore, DFs were always highest at the atrium centre, followed by the edge position and were lowest for the corner position for both the methods. This is similar to the findings of the scale model study and in agreement with the findings of Kim and Boyer (1986).

While there was generally a very good agreement between the two methods, in congruence with previous research (Aizlewood et. al., 1997), it was found that RADIANCE generally underestimated the atrium floor DFs in comparison with the results obtained from the physical scale model. DFs predicted by RADIANCE were lower by between 5% and 10% *(relatively lower by 13% to 23%)*. Small changes in illuminance levels might be due to the uncertainty in the input data as suggested by (Tregenza and Loe, 1998).

As the reflectances increased, difference in the DFs obtained by the two methods also increased; in RADIANCE, DFs were reduced by 5% *(relative reduction of 13% to 20%)*, 5-9% *(relative reduction of 15% to 18%)* and 9-10% *(relative reduction of 13% to 23%)* for model 1 (R=2%), models 2 to 5 (R=29%), and models 6 (R=57%) respectively. This suggests that there is a better agreement between DF data from the two methods for the low reflectance (2%) atria in comparison with the medium (29%) and the high reflectance (57%) atria. This is in agreement with the findings of Aizlewood et al. (1997) who also showed larger difference in DFs in high reflectance atria.

However, considering the suggestion by Cannon-Brookes (1997) that the physical scale models could potentially overestimate daylight availability in comparison with what might be expected in real buildings, it is possible that DFs from RADIANCE might be even closer to what might be expected in real buildings as demonstrated by Galasiu and Atif (1998) and Ubbelohde (1998).

Whilst on the whole DFs predictions were generally lower in RADIANCE than those obtained from the physical scale model study, the way DFs were distributed across the atrium floor and the form of decay from one position to the other, evidenced through the three measurement points, were very similar for both the methods (Table 5:1). For all the models, the drop in DFs from the atrium centre to the edge position and from the edge to the corner position were similar for both the methods and differed marginally in some cases at the most by around 1% only. This demonstrates that there is very good agreement between the two methods in terms of their daylight distribution prediction.

Differences in the DFs for the ‘a’ and ‘b’ type banded models from the physical model and RADIANCE study was at the most 2.9% suggesting that there was a good agreement in the way in which reflectance distributions were assessed by the two methods.

Finally, for both the experiments, the ‘a’ type models were more affected by the different reflectance distribution patterns than the ‘b’ type models.

Possible reasons for the differences might be because of the way in which the light is distributed in the artificial sky used for the physical scale models and the simulated sky in RADIANCE. The reflective properties used in the physical models may also have an influence, i.e. the degree of diffusion and the dependence on the angle of incident light. In both cases, those used in the physical models are correct, i.e. they are what dictate the measured results. Those used in the simulation may or may not represent the reality accurately. In the results, an error in the sky simulated in RADIANCE might reasonably be observable in the result for model 1 with black walls (where the ARC is small) and an error in the reflectivity might be observable in the results with the white model (where the ARC is high).

5.6 COMPARITIVE STUDY OF THE ADF USING THREE METHODS (PHYSICAL SCALE MODEL, ALGORITHM, AND RADIANCE SIMULATION)

5.6.1 Introduction

In the previous section, physical scale model experiments of Chapter Four were repeated using RADIANCE and DF obtained in individual positions on the atrium floor from the two methodological approaches were compared. This section is an extension of that work, concentrating on ADF values on the floor of the atrium well.

The ADF concept is a popular one at the early stages of a daylight design as it provides a quick way of estimating daylight conditions in a space. ADF is defined as the ratio of the average internal illuminance E_i (a spatial average over the working plane) to the external unobstructed horizontal illuminance E_o. Figure 5:8 shows the concept.

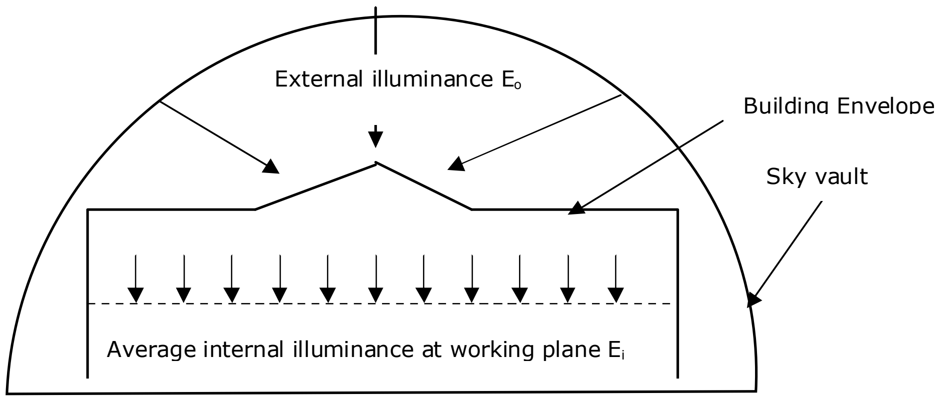


Figure 5:8 Average Daylight Factor Concept

Average daylight factor at the base of an atrium, ADF_b, can be found from the formula presented by Littlefair in 2002:

$$ADF_b = \frac{WT_gT_r\theta}{S\,(1 - R^2)} \qquad (2)$$

In equation (2) W is the area of the atrium roof opening (m^2); T_g is the diffuse visible transmittance of the glazing (corrected for dirt); T_r is an atrium roof structure's blockage factor; S is the total area of all the atrium surfaces (roof, windows, walls and floor) in m^2; R is the average, area-weighted reflectance of all the surfaces used to estimate S and θ is the angle of visible sky in degrees seen from the reference plane (Figure 5:9).

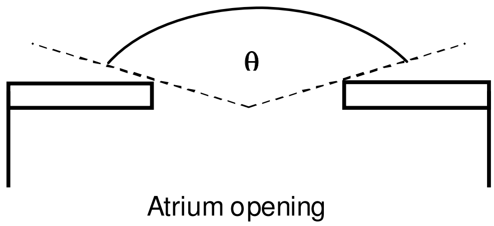


Figure 5:9 Definition of Visible Sky Angle

ADF has the design advantages that:

- ADF uses just one number to describe the daylight levels in a space rather than a grid of daylight factor values. While the DF distributions across the whole floor are useful, the ADF provides a quick and convenient estimate of daylight availability on the floor.
- ADF can be related to the glazing area, by rearranging equation (2) and so allows a designer to estimate what area of glazing will be required to provide a specified ADF level

However, the ADF approach uses in its calculation a simplified average area-weighted reflectance to describe the reflective properties of the entire atrium. Whilst this may simplify calculations, the distribution of luminous flux is condensed to a single number and where there are large areas of contrasting materials this description may be poor. Therefore, it does not take into consideration the impact of the different atrium facade reflectance distributions. In real buildings the well facades will usually comprise of more complicated arrangements and distributions of reflectances.

To understand the impact of different reflectance distributions in the atrium facades on daylight conditions on the atrium floor, the experiments undertaken in Chapter Four and the previous section examined the effects of parametric changes to the atrium wall reflectance distributions on the DF distribution on the atrium floor of a square atrium building with an atrium well index of 1 under simulated overcast sky conditions. While the atrium facade reflectance distributions affected DFs at individual positions on the atrium floor, it is not clear if the ADF is also affected as a result. Hence, ADF values derived from the physical scale model measurements and the RADIANCE simulation are compared with ADF data obtained using Littlefair's (2002) formula which uses the area weighted reflectance concept.

5.6.2 Results and Discussion

As shown in Chapter Four, 0.83 and 0.02 reflectance was assigned for the white and the black wall areas respectively. The floor reflectance was 0.02. Since the roof was not included, in calculating the area-weighted average reflectance the non-existent roof was allocated a surface area equal to the floor area and a reflectance value of zero.

Area weighted average reflectance, R, of all the atrium surfaces for the three atrium configurations (white walls, black and white walls, and black walls) was calculated as follows:

(3)

$$\text{Area weighted reflectance R} = \frac{4 \text{ x wall area x reflectance} + 1 \text{ x floor area x reflectance} + 1 \text{ x roof area x reflectance}}{6 \text{ x area of all the surfaces}}$$

Reflectance of black walls-model 1 = 2%

Reflectance of half black and half white walls-model 2, 3, 4 and 5 = 29%

Reflectance of white walls-model 6 = 57%

ADF across the atrium base was calculated from DF values measured at the centre, edge and corner locations in the physical scale model experiments as well as those studied in the RADIANCE simulations. For this, several analysis grids were tested on the floor of the atrium of WI 1 to assess their impact on ADF values obtained. It was found that the selection of a grid affected the resultant ADF values and that for a grid ranging between 4 and 1.7 metres, there was a difference of less than 1% in the ADF values (Figure 5:10).

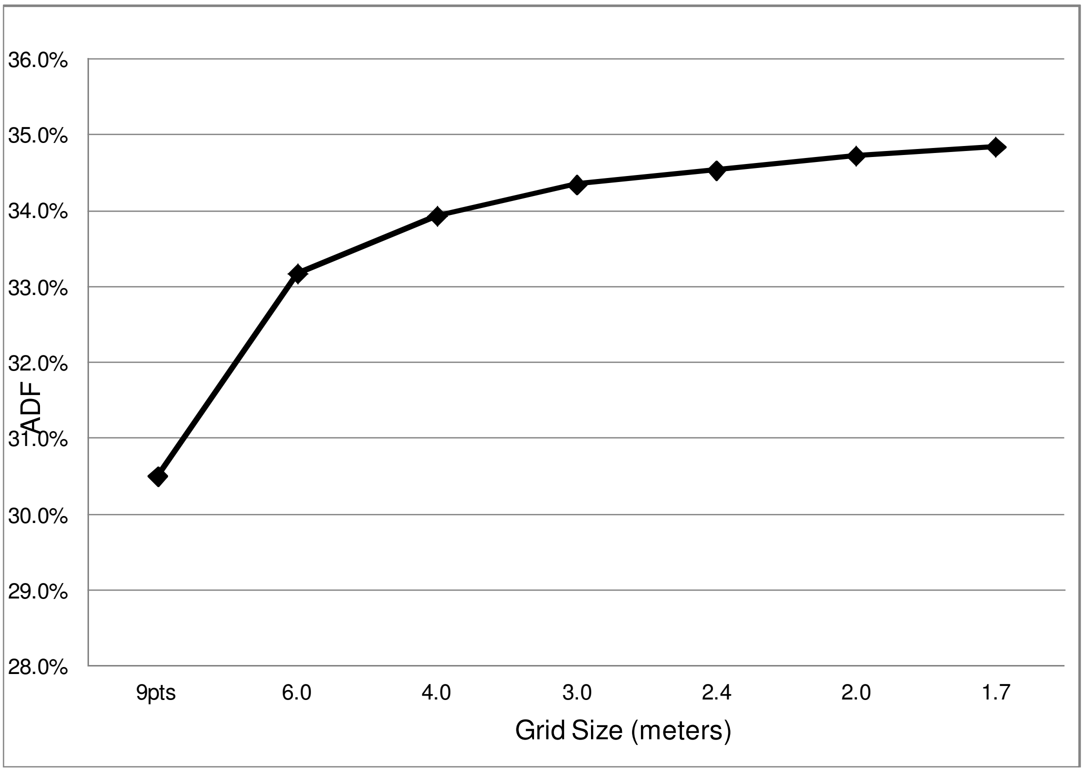


Figure 5:10 ADF values obtained for different grids at the atrium floor

Based on this, a 1.7 metre square grid was used to assess the distribution of DF values for all the models and to establish an appropriate weighting that could be applied to the DF values previously obtained for the nine positions (four corners, four edges and one atrium centre position) as shown in Figure 5:11. An approximate weighting of 33% for the atrium centre, 49% for the atrium edge and 18% for the atrium corner DF values was applied for both, the physical scale model and RADIANCE experiments, to provide ADF values as shown in Table 5:4.

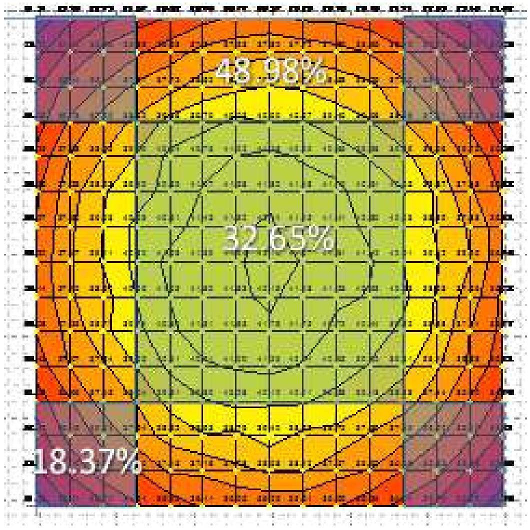


Figure 5:11 DF distribution used to establish their weighting to calculate ADF on the atrium floor

Table 5:4 Average Daylight Factor Values for the Different Model Configurations

Model No	Atrium configuration and area-weighted average reflectance (*p*)	(P) Physical Model ADF (%)	(R) RADIANCE Model ADF (%)	Relative difference in ADF (P-R/P) %
1	All black; *p* =2%	30.9	26.2	15.2%
2a	1/2 black on top; *p* = 29%	40.2	33.9	15.6%
2b	1/2 white on top; *p* = 29%	40.9	32.7	20.0%
3a	1/4 black on top; *p* = 29%	39.5	32.9	16.7%
3b	1/4 white on top; *p* = 29%	40.3	32.3	19.8%
4a	1/6 black on top; *p* = 29%	39.4	32.3	18.0%
4b	1/6 white on top; *p* = 29%	40.1	32.6	18.7%
5a	1/8 black on top; *p* = 29%	38.6	32.7	15.2%
5b	1/8 white on top; *p* = 29%	40.0	32.5	18.7%
6	All white; *p* = 57%	58.1	48.7	16.1%

For the three different area-weighted reflectances used in the models (black, white and black bands, and white) the predicted ADF values from equation (2) are given in Table 5:5. In calculating these values it was assumed that W had a value of 0.0576 m^2 (i.e. floor plan area), T_g and T_r had values of 1 (because there was no glazing and no roof obstructions in the models), S had a value of 0.3456 m^2 (i.e. area of all surfaces, including the area of roof) and θ had a value of 180^o.

Table 5:5 ADF Values Calculated Using Equation (4) (Littlefair, 2002)

Model No.	Atrium Configuration and area-weighted average reflectance (*p*)	(C) Calculation predicted ADF value (%)
1	All surfaces painted black; *p* = 2%	30.0
2 to 5	black and white bands; *p* = 29%	32.8
6	All walls painted white; *p* = 57%	44.4

It can be seen from Table 5:4 and Figure 5:12 that the ADF values for models 2 to 5 are affected by the different reflectance distributions in the atrium walls. However, only the 'a' type models were nominally affected where a maximum difference of 1.6% *(relative difference up to a maximum of 4 to 5%)* was noted between model 2a and 5a for the physical scale model study and between 2a and 4a in RADIANCE. ADFs for the 'b' type models were very similar.

On comparison of ADF values obtained from Littlefair's algorithm (Table 5:5) with those obtained from the physical models and RADIANCE (Table 5:4) it was found that: the calculated algorithm ADF for the black model 1 was similar to that obtained from the physical model; for the banded models, it was very similar to the RADIANCE predicted ADFs and for the white model, it was lower than that obtained for both, physical model and RADIANCE (Figure 5:12).

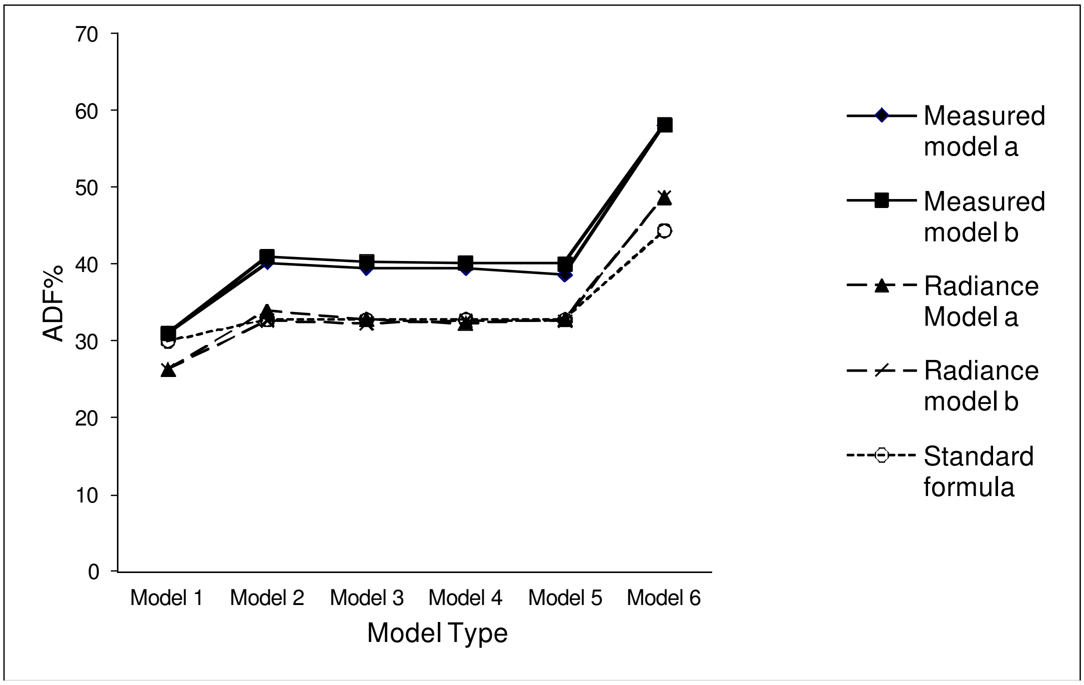


Figure 5:12 Comparison between Physical Model Study, Standard Formula Calculation (Littlefair, 2002), and RADIANCE Simulated ADF Values

Table 5:6 shows the difference between the ADFs obtained by the three methods:

1. Difference between the physical scale model ADF values (P) and those obtained using RADIANCE (R) (P-R)
2. Difference between the physical scale model ADF values (P) and those obtained using equation (2) by Littlefair (2002)(C) (P-C)
3. Difference between the equation (1) ADF values (C) and those obtained using RADIANCE(R) (C-R)

Table 5:6 Difference between ADF Values from the Different Methods

Model No.	Atrium configuration	P-R%	P-C%	C-R %
1 (*p* = 2%)	All surfaces painted black	4.7	1.0	3.7
2a (*p* = 29%)	1/2 black at the top	6.3	7.4	-1.1
2b (*p* = 29%)	1/2 white at the top	8.2	8.1	0.1
3a (*p* = 29%)	1/4 black on top	6.7	6.8	-0.1
3b (*p* = 29%)	1/4 white on top	8.0	7.6	0.5
4a (*p* = 29%)	1/6 black on top	7.2	6.7	0.5
4b (*p* = 29%)	1/6 white on top	7.5	7.4	0.2
5a (*p* = 29%)	1/8 black on top	5.9	5.9	0.0
5b (*p* = 29%)	1/8 white on top	7.5	7.9	0.2
6 (*p* = 57%)	All walls painted white	9.4	13.7	-4.3

For all the models, there was a large difference between the physical scale model and the RADIANCE ADF values ranging between 4.7% *(relative difference of 15%)* and 9.4% *(relative difference of 16%)*. The lowest difference of 4.7% ADF was noted in Model 1 while the highest difference of 9.4% was noted for model 6. It was observed that for the 'a' and 'b' type models, ADF values obtained through physical scale models and RADIANCE follow the same pattern. However, ADF values were underestimated by RADIANCE by comparison with the physical scale model study. As expected, this mirrors the results from the previous section where DFs for RADIANCE were lower than those obtained from the physical scale models. Difference between RADIANCE and physical model ADF remained practically constant for the 'a' and 'b' type models. Difference between RADIANCE and physical scale model ADF for the 'a' type models was lower than the 'b' type models. Relative difference between the ADF values obtained from the physical scale model experiment and RADIANCE was consistent and ranged between 15% and 20%.

For all the models, generally there was a large difference also between the physical scale model and equation predicted ADF values ranging between 1% *(relative difference of 3%)* and 13.7% *(relative difference of 24%)*. For the black model 1, agreement between the physical scale model and the equation predicted ADF was reasonably good with only 1%

difference. This is reassuring as this model represents the simplest lighting configuration. For the 'a' type models (black band at the top of the well and white band at the bottom) there was a large difference of 7.4% *(relative difference of 18%)* for the half-black, half-white arrangement in model 2. This difference steadily decreased as the number of bands increased, but even for the 1/8th bands (model 5a) the difference was nearly 5.9% *(relative difference of 15%)*. The pattern of change was different for the 'b' type models (white band at the top of the well and black band at the bottom). For these models, difference between the physical scale model and equation predicted ADF values was reasonably large, between 8.1% *(relative difference of 20%)* and 7.4% *(relative difference of 18%).* A maximum difference of 8.1% for model 2b suggests that black horizontal bands immediately adjacent to the atrium floor were having an impact on the ADF value.

For model 6 (white walls) ADFs for both, RADIANCE and Littlefair's equation were lower than those for the physical scale model by 9.4% and 13.7% *(relatively low by 16% and 24%)* respectively. This suggests that the accuracy of RADIANCE and equation (2) is more limited when used to assess ADFs in very light coloured atria in comparison with their use in dark or medium reflectance atria. This is of some concern as many atria are deliberately finished in light colours to enhance reflected light into the adjoining spaces.

Although maximum difference between Littlefair's (2002) formula and RADIANCE ADF was 3.7% *(relative difference of 12%)* for the black model 1 and was 4.3% *(relative difference of 10%)* for the white model 6 generally there was a better agreement between ADFs predicted by Littlefair's (2002) formula and RADIANCE. For the banded models there was a maximum difference of 1.1% for the 'a' type models (black band at the top of the well and white band at the bottom) *(relative difference of 3%)* and 0.5% for the 'b' type models *(relative difference of 2%)*. This difference steadily increased as the number of bands increased. The pattern of change was different for the 'b' type models (white band at the top of the well and black band at the bottom). For these models difference between the predicted and RADIANCE values did not change markedly with the change in the number of bands.

5.6.3 Conclusions

This section examined the effect on ADF of various reflectance distributions for diffuse atrium wall surfaces and concluded that:

For diffuse surfaces with identical area-weighted surface reflectances (R= 29%) the distribution of the reflectances have a very small effect on ADF values. A maximum difference of 1.6% *(relative difference up to a maximum of 4 to 5%)* ADF was noted between models 2a and 5a (in physical model study) and 2a and 4a (in RADIANCE); however the different reflectance distributions did not affect the DFs for the 'b' type models. Generally, Littlefair's (2002) expression generally had a better agreement with the ADF data obtained from RADIANCE than the physical scale model experiment. Although, for the model with all-black surfaces (R=2%), Littlefair's (2002) equation ADF value was only 1% higher *(relatively higher by 3%)* than that obtained for the physical scale model while RADIANCE ADF was 3.7% lower *(relatively lower by 12%)* than the physical scale model value. In comparison with physical model data for the banded models (R=29%), Littlefair's (2002) expression and RADIANCE underestimated ADF on the atrium floor by 5.9% to 8.2% *(relatively by 15% to 20%)* and 5.9% to 8.1% *(relatively by 18% to 25%)* respectively.

In comparison with the physical model, and RADIANCE and Littlefair's (2002) expression both underestimated, by 9.4% and 13.7% (relatively low by 16% and 24%) the atrium floor ADF for the white walled atrium (R=57%) respectively. Therefore, Littlefair's expression and RADIANCE ADF had a better agreement with the physical scale model ADF in low (2%) reflectance atria than in the medium (29%) and high reflectance (57%) atria.

It is difficult to establish accuracies of the different methods without comparing the results with real building data. While the banded models emulate horizontal banding evident in buildings, they are not representative in terms of either their sizes or proportions what might be realistically expected. Furthermore, it is possible that daylight availability was overestimated in physical scale models (Cannon-Brookes, 1997), in which case values predicted by RADIANCE or Littlefair's equation might be closer to those found in real buildings.

5.7 CONCLUSIONS

While monitoring of real buildings is vital in terms of assessing daylight availability in buildings, very few studies undertake this approach due to the several limitations of access to buildings and the need to take measurements over extended periods of time to account for differing climatic conditions. There are several tools available for daylight prediction. These include physical scale models, graphic methods, including nomographs, equations and tables, and a range of computer simulation programs. Physical scale models have long been recognised as a useful and reliable means of accurately predicting interior daylight; however they are being replaced by advanced computer simulations for daylighting research (Aizelwood et al.1998; Jongewaard 1993; Love & Navvab 1991; Spitzglas et al. 1985; Ward 1990). Although physical models are easy to build and understand, they might not be so suitable for parametric studies that require making several changes to the chosen parameters. On the other hand, computer programs allow for a quick and easy modification of the models and comparison of the performance of different design parameters. However, as these programs are based on some underlying assumptions and uncertainty in the input data, Mabb (2008) suggests that absolute values are rarely obtained from computer simulations and that they are usually used to make comparisons and find the relative best design solution.

Cannon-Brookes (1997) highlighted the physical model's tendency to overestimate illuminance levels in buildings; however several studies show that they are used as a common reference for validating the daylight levels predicted by computer simulations. Indeed, Ubbelohde (1998) suggested the use of physical models as a better base case than a real building for comparing results from RADIANCE.

RADIANCE has been validated by several researchers as it has shown high accuracies when compared with model studies and theoretical analysis, in addition to simulating complex architectural scenes. In comparison with the physical models, Aizlewood et al. (1997) showed that RADIANCE underestimated illuminance levels for high reflectance surfaces and in deeper atria while Mabb (2008) showed that RADIANCE overestimated results slightly.

Therefore, the physical scale model study of Chapter Four was repeated using RADIANCE and DF and ADF results from the two studies were compared. ADF values obtained by the physical scale model and RADIANCE were also compared with the ADFs obtained using Littlefair's (2002) expression.

DFs at the atrium floor from RADIANCE were lower by 5% to 10% *(relatively lower by 13% to 23%)* in comparison with the physical scale model study. It was found that there is a better agreement between DF data from the two methods for the low reflectance (2%) atrium in comparison with the medium (29%) and the high reflectance (57%) atria. This is in agreement with the previous research undertaken by Aizlewood et al. (1997).

Possible reasons for the disagreement in the results might be due to the fact that the reflective properties of the physical models and light distribution predictions in the artificial sky may not have been represented accurately in the simulation. It can be argued that an error in the sky simulated in RADIANCE might reasonably be observable in the result for model 1 with black walls (where ARC is small) and an error in the reflectivity might be observable in the results with the white model (where the ARC is high).

There was also a very good agreement (maximum difference 1% DF) between the two methods in terms of the daylight distribution predictions across the atrium floor and the form of decay from one position on the atrium floor to the other.

For the diffuse surfaces with identical area-weighted surface reflectances (R= 29%) the distribution of the reflectances had a very small influence on ADF at the atrium floor. This suggests that the use of area-weighted surface reflectances to estimate ADF might not be very problematic.

Generally, Littlefair's (2002) expression had a better agreement with ADF data obtained from RADIANCE than that from the physical scale model experiment.

Mirroring the findings of the DFs at the atrium floor earlier, as expected, RADIANCE ADF as well as Littlefair's (2002) expression ADF had a better agreement with the physical scale model ADF in low (2%) reflectance atria than in the medium (29%) reflectance and high (57%) reflectance atria.

Differences in the absolute DFs and the ADF obtained by physical scale models and RADIANCE (lower by only up to 10%) demonstrate an acceptable difference in the data thereby confirming its use for undertaking further experiments presented in Chapter Six and Chapter Seven. As highlighted by Tregenza and Loe (1998), changes in the illuminance levels might be due to an uncertainty in the input data. Furthermore, Tregenza and Loe (1998) also highlight the relevance of relative changes in levels rather than the absolute values and in this study the form of decay from one position to the other on the atrium floor from RADIANCE was similar to that noted in physical scale models.

The findings are obviously limited to the specific geometries and reflectances used in this experiment. However, it is recognised that the DF, ADF and their sensitivity to reflectance distributions may be more critical for a wider range of reflectance values than was used in the physical scale model experiment or for atria with different well indices. Therefore, the next Chapter examines the influence of the chosen reflectance distributions on DF values in atria of three different well indices.

6 PARAMETRIC STUDY OF THE INFLUENCE OF ATRIUM GEOMETRY AND SURFACE REFLECTANCES ON THE DAYLIGHT IN ATRIUM BUILDINGS

6.1 INTRODUCTION

As evidenced in the previous experiments, wall reflectance has a direct and significant impact on the inter-reflectance occurring inside an atrium and determines the distribution of light within it. Several researchers including Szerman (1992); Willbold-Lohr (1989); Baker et al. (1993), Boubekri (1995); Boubekri and Anninos (1996); Aizlewood et al. (1996); CIBSE (1999); Calcagni and Paroncini (2004); Mabb (2008); and Du and Sharples (2009b) have examined the influence of both, the atrium geometry and its enclosing surface reflectances, on the daylight conditions in atrium buildings. The review of these investigations outlined in Chapter Three demonstrated differences in their findings in relation to the atrium well indices and geometries in which DFs are affected due to the atrium wall surface reflectances. Moreover, these studies do not examine the effects of varying reflectance distributions on DFs in atria of different well indices.

This Chapter uses RADIANCE to examine the effects of varying distributions of atrium wall reflectances on DF and ADF values at the base of atria of three different well indices. The atrium well indices chosen in the study are based on those recommended by previous studies and fall within the plausible range of 0.1-1 PAR and 0.5-4 SAR as suggested by Liu et al. (1991) who undertook a survey of built atria. The objective is to establish the range of well indices over which reflectance distributions affect daylight levels. Results obtained from the model study are compared with those obtained in built atria to establish the similarities and differences.

6.2 PARAMETRIC STUDY OF ATRIUM SURFACE REFLECTANCES AND GEOMETRY

6.2.1 Methodology for ECOTECT - RADIANCE Study

All the models were created using ECOTECT. The models represent four-sided, top lit atria with a square plan of 24 x 24 metres creating a PAR of 1 for all the models. The height of the atrium was increased from 12 meters to 24 meters and then to 48 meters, making the atrium well indices and SARs 0.5, 1 and 2, and their aspect ratio (AR) 4, 1 and 0.25 respectively as shown in Figure 6:1.

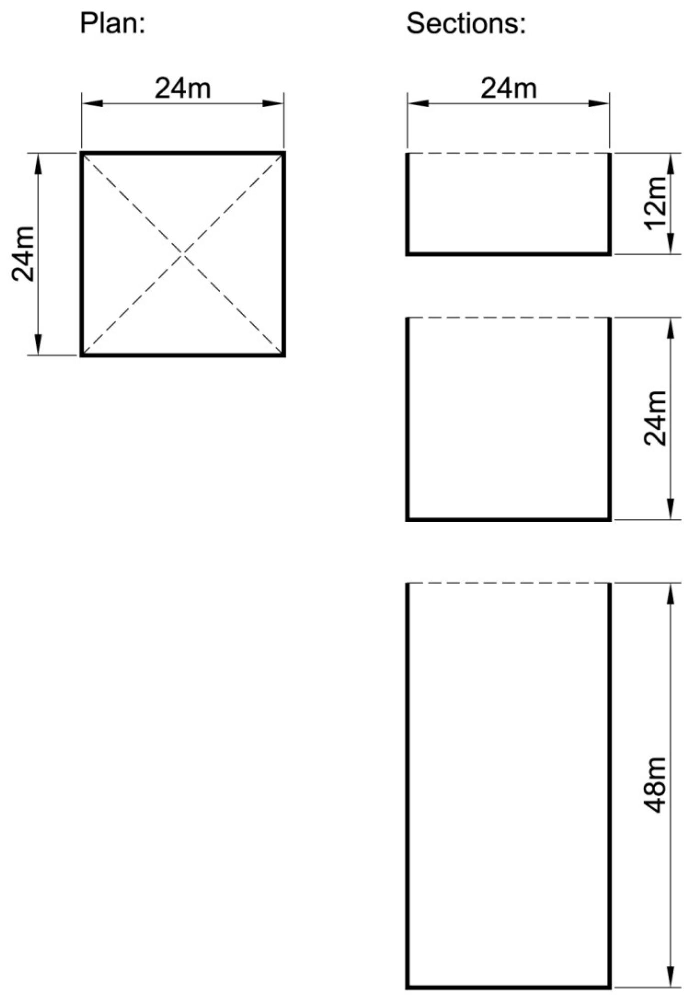


Figure 6:1 Plan and sections for atria of WI 0.5, 1 and 2

Models were created in the same way as that described in the methodology section of the previous Chapter Five (Section 5.5.1). Models comprised atria of WI 0.5, 1 and 2 with all black wall surfaces (2% reflectance), 50% black (2% reflectance) and 50% white wall surfaces (83% reflectance) and all white wall surfaces (83% reflectance) as shown in Figures 6:2, 6:3, and 6:4 respectively. The floor of the atrium was kept black (2% reflectance) to minimize its influence on the DFs. An area-weighted reflectance for each of the model was calculated manually as shown in Table 6:1.

Table 6:1 Area weighted average reflectances for models 1 to 6 for WI 0.5, 1 and 2

Model Type	Area Weighted Average Reflectance of the atrium, *p*		
	WI = 0.5	WI = 1.0	WI = 2.0
Model 1- All black walls (reflectance *p* = 0.02)	*p* = 0.02	*p* = 0.02	*p* = 0.02
Banded Models 2, 3, 4 and 5 (reflectance *p*, 50% black [0.02] and 50% white [0.83])	*p* = 0.22	*p* = 0.29	*p* = 0.34
Model 6 – All white walls(reflectance *p* = 0.83)	*p* = 0.42	*p* = 0.57	*p* = 0.67

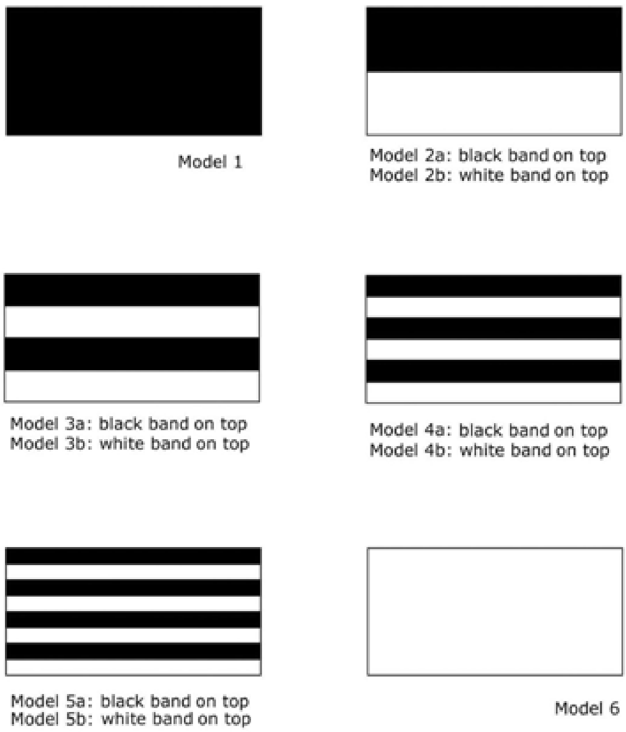


Figure 6:2 Wall surfaces of the atrium WI 0.5 (black; 2, 4, 6, 8 horizontal bands; and white surfaces)

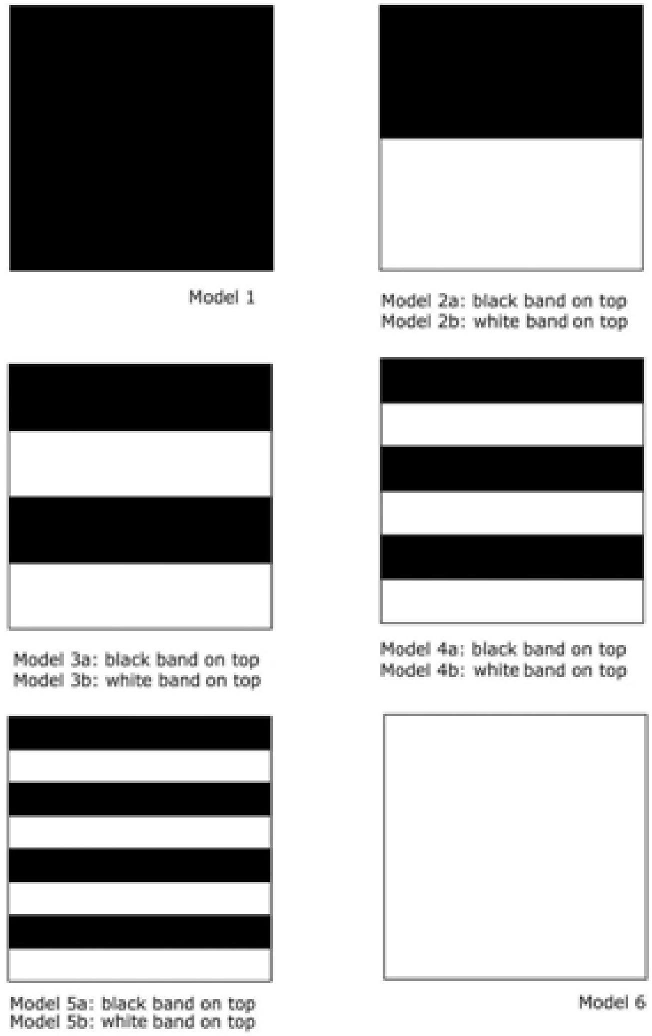


Figure 6:3 Wall surfaces of the atrium WI 1 (black; 2, 4, 6, 8 horizontal bands; and white surfaces)

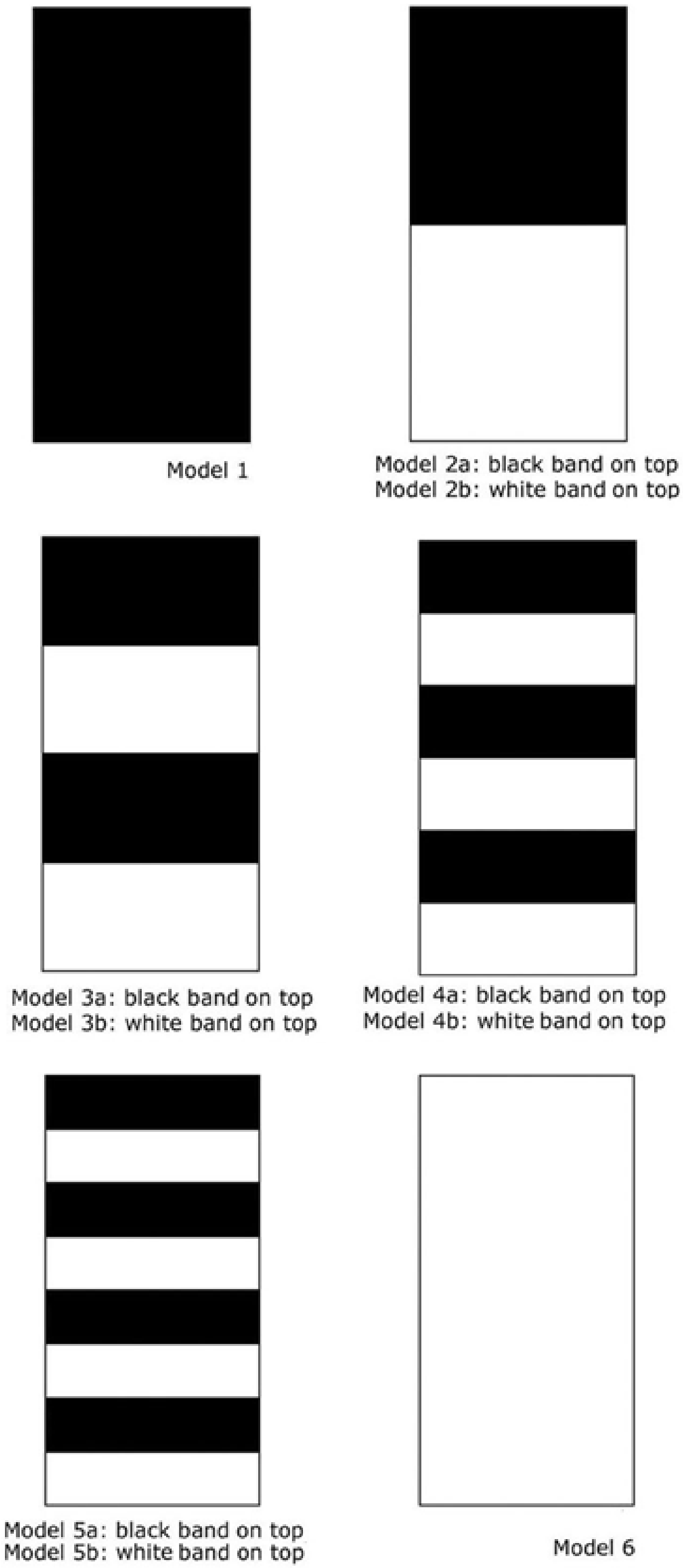


Figure 6:4 Wall surfaces of the atrium WI 2 (black; 2, 4, 6, 8 horizontal bands; and white surfaces)

Using the grid management tool, an analysis grid was formed that emulated the horizontal and vertical positions of the photocell used in the physical models, i.e. centre, corner, edge of the atrium floor (for corner and edge positions, measurements were taken at a distance of 22.5mm from the atrium's walls), and at a vertical position of 850mm above the atrium floor as shown in Figure 6:5.

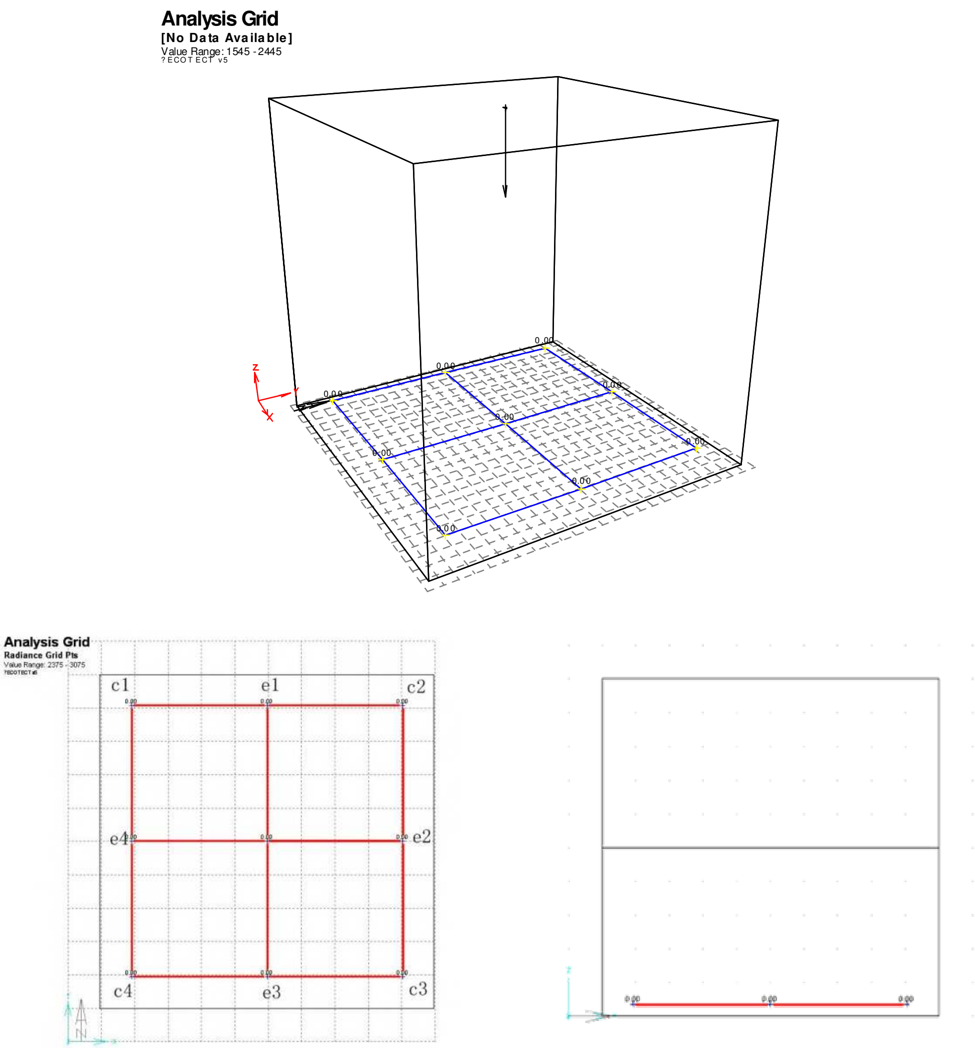


Figure 6:5 Atrium model, plan and section showing centre, edge, and corner testing positions at 850mm above the atrium floor

The parameters set in ECOTECT and RADIANCE and the procedures undertaken for the daylight analysis as described in the methodology section of Chapter Five (5.5.1) were repeated. As shown in Figure 6:6, data of the "design sky illuminance" was set according to the figures of outdoor illuminance obtained from the previous physical scale model experiments described in Chapter Four and repeated in Chapter Five. This was done to maintain consistency across the different sets of experiments and to allow for a comparison of the results.

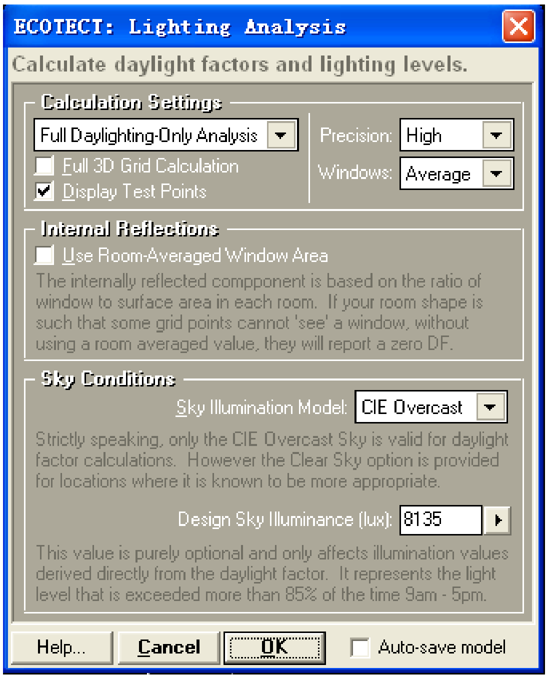


Figure 6:6 CIE Overcast Sky Design Sky Illuminance in ECOTECT

Models with uniform reflectance, for the area weighted average reflectances calculated for the banded models shown in Table 6:1, were also created. DF and the ADF results at the atrium floor for the banded and the un-banded atria of WI 0.5, 1 and 2 were compared examine the influence of the reflectance distribution patterns.

6.2.2 Results and Discussion

Tables 6:2, 6:3 and 6:4 show DFs obtained at the centre, corner and edge positions, and ADFs on the floor of the atria of WI 0.5, 1 and 2 respectively. They include data for the six model cases (1, 2a/2b, 3a/3b, 4a/4b, 5a/5b and 6) and the model with uniform reflectance equivalent to the reflectance of the banded models. DF data and the differences in DFs are always discussed in terms of their absolute values, and where appropriate relative data is presented in brackets in italics.

As done in Chapter Four, to calculate ARC for the banded and white models, ARC for the black models is assumed to be zero. Therefore, and subtracting Model 1 DF values from DFs for the other models gave ARC values for the remaining models shown in the Tables 6:2, 6:3 and 6:4. This allowed an analysis of how the change in surface reflectance distributions affected individual ARC values on the atrium floor. While tables show more specific values, the graphs are generally used to provide an overall impression of the daylight availability at the atrium floor.

Table 6:2 DFs at centre, corner and edge positions, and ADF on the floor of Atrium of WI 0.5

WI = 0.5 Model Type and reflectance *p*	Position	Outdoor Illuminance (lux)	Indoor Illuminance (lux)	DF (%)	ARC (%)	ARC contribution to DF (%)	ADF (%)
Model 1	Centre	7885	5300	67.2	0	0	
(All Black) *p* =	Edge	8065	3857	47.8	0	0	51.8
2%	Corner	8080	2840	35.1	0	0	
Model 2a	Centre	7790	5341	68.5	1.3	1.9	
（Halves)	Edge	8172	4639	56.7	8.9	15.6	58.7
p = 22%	Corner	8170	3804	46.5	11.4	24.5	
Model 2b	Centre	8185	6316	77.1	9.9	12.8	
(Halves)	Edge	8157	4560	55.9	8.1	14.4	60.2
p = 22%	Corner	8175	3357	41.0	5.9	14.3	
Model 3a	Centre	7657	5509	71.9	4.7	6.5	
(Quarters)	Edge	8235	4597	55.8	8.0	14.3	58.9
R=22%	Corner	8255	3597	43.5	8.4	19.3	
Model 3b	Centre	8245	6218	75.4	8.2	10.8	
(Quarters)	Edge	8250	4754	57.6	9.8	17.0	60.9
p = 22%	Corner	8245	3597	43.6	8.5	19.4	
Model 4a	Centre	8135	5933	72.9	5.7	7.8	
(Sixths)	Edge	7900	4398	55.6	7.8	14.0	58.9
p = 22%	Corner	7855	3337	42.4	7.3	17.2	
Model 4b	Centre	8222	6135	74.6	7.4	9.9	
(Sixths)	Edge	8075	4542	56.2	8.4	14.9	60.1
p = 22%	Corner	8125	3629	44.6	9.5	21.3	
Model 5a	Centre	8185	5751	70.2	3.0	4.2	
(Eighths)	Edge	8240	4546	55.1	7.3	13.2	57.8
p = 22%	Corner	8235	3504	42.5	7.4	17.4	
Model 5b	Centre	8205	5892	71.8	4.6	6.4	
(Eighths)	Edge	8277	4624	55.8	8.0	14.3	58.9
p = 22%	Corner	8235	3641	44.2	9.1	20.5	
Model 6	Centre	8195	6765	82.5	15.3	18.5	
(All white)	Edge	8240	5545	67.2	19.4	28.8	70.3
p = 42%	Corner	8260	4662	56.4	21.3	37.7	
Uniform	Centre	8078	5939	73.5	6.3	8.5	
reflectance *p* =	Edge	8163	4603	56.3	8.5	15.0	59.5
22% for 2a-5b	Corner	8161	3510	43.0	7.9	18.3	

Table 6:3 DFs at centre, corner and edge Positions, and ADF on the floor of Atrium of WI 1

WI=1 Model Type and reflectance *p*	Position	Outdoor Illuminance (lux)	Indoor Illuminance (lux)	DF (%)	ARC (%)	ARC contribution to DF (%)	ADF (%)
Model 1 (All Black) *p* = 2%	Centre	7885	2468	31.2	0	0	26.1
	Edge	8065	2017	25.0	0	0	
	Corner	8080	1602	19.8	0	0	
Model 2a (Halves) *p* = 29%	Centre	7790	2970	38.1	6.9	18.1	34.2
	Edge	8172	2730	33.4	8.4	25.1	
	corner	8170	2409	29.4	9.6	32.6	
Model 2b (Halves) *p* = 29%	Centre	8185	3480	42.5	11.3	26.5	34.2
	Edge	8157	2640	32.3	7.3	22.6	
	Corner	8175	1992	24.3	4.5	18.5	
Model 3a (Quarters) *p* = 29%	Centre	7657	2958	38.6	7.4	19.1	33.6
	Edge	8235	2665	32.3	7.3	22.6	
	Corner	8255	2332	28.2	8.4	29.7	
Model 3b (Quarters) *p* = 29%	Centre	8245	3418	41.4	10.2	24.6	33.9
	Edge	8250	2661	32.2	7.2	22.3	
	Corner	8245	2069	25.0	5.2	20.8	
Model 4a (Sixths) *p* = 29%	Centre	8135	3162	38.8	7.6	19.5	33.5
	Edge	7900	2561	32.4	7.4	22.8	
	Corner	7855	2123	27.0	7.2	26.6	
Model 4b (Sixths) *p* = 29%	Centre	8222	3338	40.5	9.3	22.9	34.0
	Edge	8075	2637	32.6	7.6	23.3	
	Corner	8125	2119	26.0	6.2	23.8	
Model 5a (Eighths) *p* = 29%	Centre	8185	3211	39.2	8.0	20.4	33.3
	Edge	8240	2638	32.0	7.0	21.8	
	Corner	8235	2149	26.0	6.2	23.8	
Model 5b (Eighths) *p* = 29%	Centre	8205	3340	40.7	9.5	23.3	34.0
	Edge	8277	2688	32.4	7.4	22.8	
	Corner	8235	2176	26.4	6.6	25.0	
Model 6 (All white) *p* = 57%	Centre	8195	4466	54.4	23.2	42.6	47.9
	Edge	8240	3842	46.6	21.6	46.3	
	Corner	8260	3297	39.9	20.1	50.3	
Uniform reflectance *p* 29% for 2a-5b	Centre	8078	3188	39.4	8.2	20.8	33.3
	Edge	8163	2613	32.0	7.0	21.8	
	Corner	8161	2118	25.9	6.1	23.5	

Table 6:4 DFs at centre, corner and edge positions, and ADF on the floor of Atrium of WI 2

WI=2 Model Type and reflectance *p*	Position	Outdoor Illuminance (lux)	Indoor Illuminance (lux)	DF (%)	ARC (%)	ARC contribution to DF (%)	ADF (%)
Model 1	Centre	7885	779	9.8	0	0	
(All Black)	Edge	8065	720	8.9	0	0	9.0
p = 2%	Corner	8080	641	7.9	0	0	
Model 2a	Centre	7790	1142	14.6	4.8	32.8	
（Halves)	Edge	8172	1094	13.3	4.4	33.0	13.5
p = 34%	Corner	8170	985	12.0	4.1	34.1	
Model 2b	Centre	8185	1212	14.8	5.0	33.7	
(Halves)	Edge	8157	1032	12.6	3.7	29.3	13.0
p = 34%	Corner	8175	899	10.9	3.0	27.5	
Model 3a	Centre	7657	1046	13.6	3.8	27.9	
(Quarters)	Edge	8235	1052	12.7	3.8	29.9	12. 8
p = 34%	Corner	8255	983	11.9	4.0	33.6	
Model 3b	Centre	8245	1228	14.8	5.0	33.7	
(Quarters)	Edge	8250	1024	12.4	3.5	28.2	12.8
p = 34%	Corner	8245	871	10.5	2.6	24.7	
Model 4a	Centre	8135	1118	13.7	3.9	28.4	
(Sixths)	Edge	7900	971	12.2	3.3	27.0	12.5
p = 34%	Corner	7855	914	11.6	3.7	31.8	
Model 4b	Centre	8222	1180	14.3	4.5	31.4	
(Sixths)	Edge	8075	999	12.3	3.4	27.6	12.6
p = 34%	Corner	8125	847	10.4	2.5	24.0	
Model 5a	Centre	8185	1120	13.6	3.8	27.9	
(Eighths)	Edge	8240	1031	12.5	3.6	28.8	12.6
p = 34%	Corner	8235	950	11.5	3.6	31.3	
Model 5b	Centre	8205	1188	14.4	4.6	31.9	
(Eighths)	Edge	8277	1013	12.2	3.3	27.0	12.6
p = 34%	Corner	8235	879	10.6	2.7	25.0	
Model 6	Centre	8195	2217	27.0	17.2	63.7	
(All white)	Edge	8240	1965	23.8	14.9	62.6	24.3
p = 67%	Corner	8260	1756	21.2	13.3	62.7	
Uniform	Centre	8078	1097	13.5	3.7	27.4	
reflectance *p*	Edge	8163	989	12.1	3.2	26.4	12.3
34% for 2a-5b	Corner	8161	886	10.8	2.9	26.8	

DF and ADF data for WI 1 shown in Table 6:3 from this experiment was compared with that obtained from the experiments undertaken in Chapter Five (Table 5:1 and 5:4) respectively. As shown in Figure 6:7, there was a good agreement between the two experiments with a maximum difference in DFs of up to 3%, 2% and 1% in the atrium centre, edge and positions respectively. ADF values were also comparable for the two experiments, with a maximum difference of less than 2% observed between the two studies. As highlighted by Tregenza and Loe's (1998) study, small changes in the DFs might have been due to the minor differences in data input in the simulation set up.

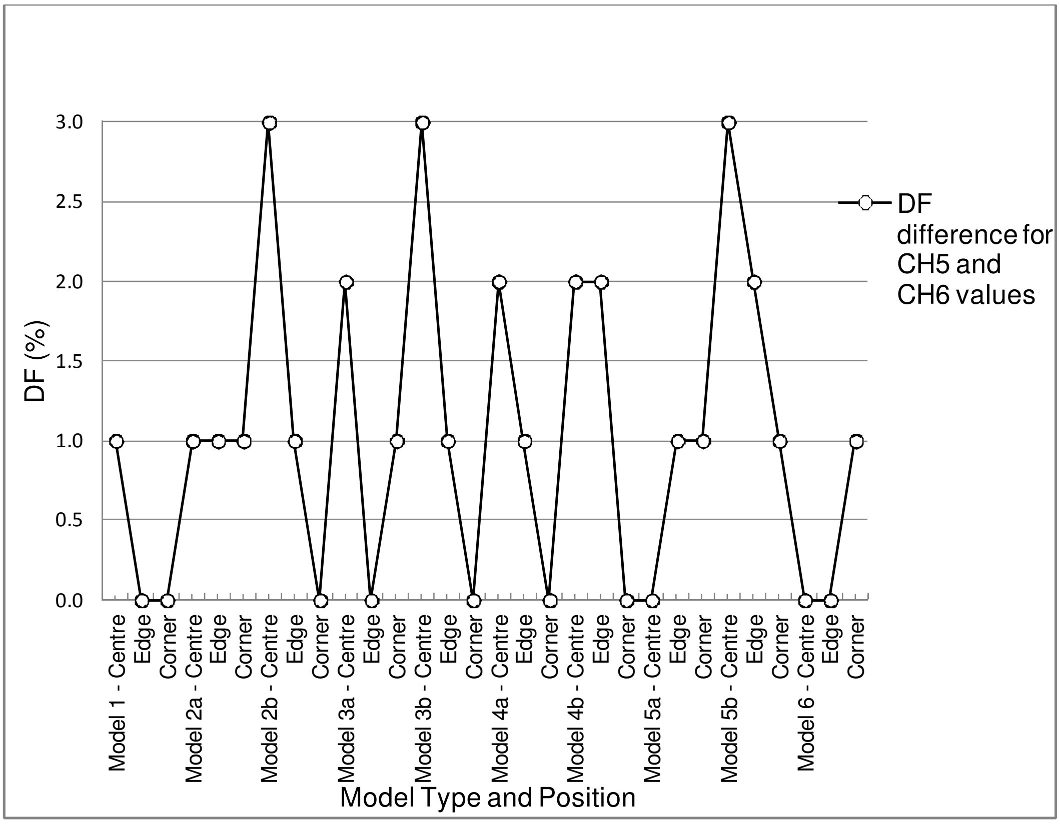


Figure 6:7 Difference in DFs obtained for RADIANCE experiments of Chapter Five and Six

Daylight Factors obtained for atria of WI 0.5, 1 and 2

Readings from Tables 6:2, 6:3 and 6:4 were plotted on a series of graphs to discuss findings from the experiments. DFs for all the measured positions on the atrium floor of the three atria are shown in Figure 6:8 (models 1, 2a to 5a and 6) and Figure 6:9 (models 1, 2b to 5b and

6). As the WI increased, DFs reduced as expected. For all the three atria (WI 0.5, 1 and 2) as reflectances increased from Model 1 to Model 6, DFs increased in all the measured positions on the atrium floor demonstrating the effect of surface reflectances in these atria as also shown by previous studies (Baker et al, 1993; Boubekri, 1995; Aizlewood et al., 1996; and Du and Sharples, 2009a).

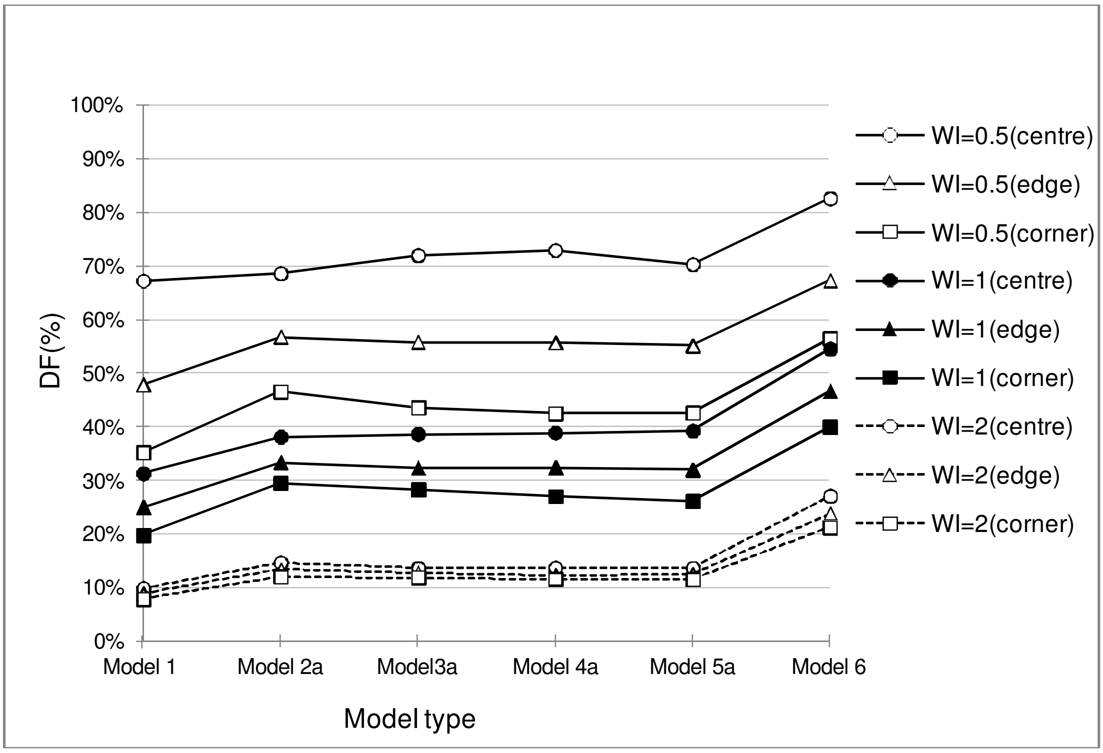


Figure 6:8 Comparison of DF values obtained for WI - 0.5, 1, and 2 at the centre, edge, and corner positions on the atrium floor for Models 1, 2a, 3a, 4a, 5a (black bands on top), and 6

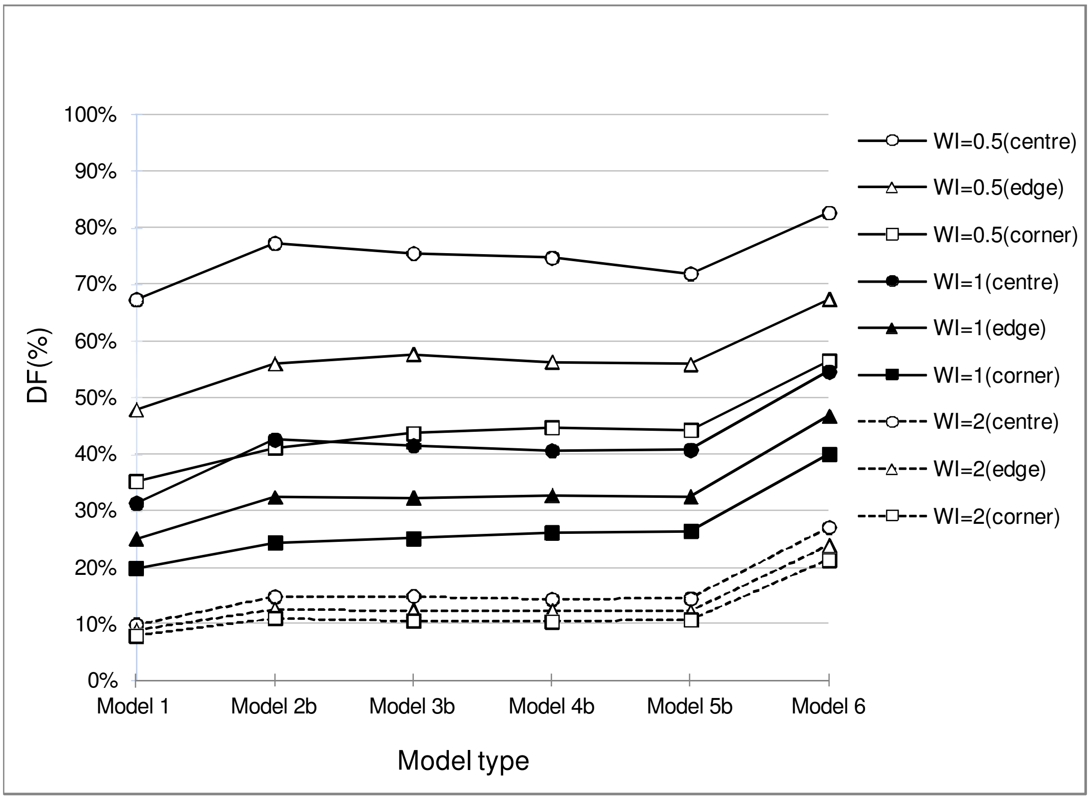


Figure 6:9 Comparison of DF values obtained for WI - 0.5, 1, and 2 at the centre, edge, and corner positions on the atrium floor for Models 1, 2b, 3b, 4b, 5b (black bands on top), and 6

Table 6:2, and Figures 6:8 and 6:9 show an increase in DFs of 16-21% *(relative increase 19 to 38%)*, 20-23% *(relative increase 43 to 50%)* and 13-17% *(relative increase 62 to 63%)* for model 6 (white walls) in comparison with model 1 for the atria of WI 0.5, 1 and 2 respectively. This shows that the pattern of change in the DFs does not mirror the systematic change in the atrium well indices and consequent wall areas. Due to the larger proportion of wall surfaces in comparison with the floor, the area weighted average reflectance of the models increases with the increase in the atrium WI. Therefore, DF increases of 20-23% for WI 1 were higher than those found in WI 0.5 (16-21%). However DFs in the atrium of WI 2 due to the increase in reflectances from model 1 to 6 ranged only between 13-17%, which is lower than that seen in atria of WI 0.5 and 1. This suggests that due to the increase in WI to 2 the wall luminance is reduced, consequently reducing daylight availability on its floor. Furthermore, although the relative increases in the DFs due to the increase in wall reflectances might be higher for WI 2 (as shown in Table 6:5), it is due to the lower DFs found in this atrium which makes even small increases proportionally greater than those found in atria of WI 0.5 and 1.

Table 6:5 DFs and difference in DFs for models 1 to 6 for WI 0.5,1 and 2

Position	Model 1 DF%	Model 2a-5a		Model 2b-5b		Model 6 DF%	Absolute difference DF% between Model 1 & 6	Relative % increase from model 1 to 6
		DF%	Diff in DF%	DF%	Diff in DF%			
WI = 0.5								
centre	67%	69-73%	4%	72-77%	5%	83%	16%	19.2%
edge	48%	55-57%	2%	56-58%	2%	67%	19%	28.3%
corner	35%	42-47%	5%	41-45%	4%	56%	21%	37.5%
WI = 1								
centre	31%	38-39%	1%	41-43%	2%	54%	23%	42.5%
edge	25%	32-33%	1%	32-33%	1%	47%	22%	46.8%
corner	20%	26-30%	4%	24-26%	2%	40%	20%	50.0%
WI = 2								
centre	10%	14-15%	1%	14-15%	1%	27%	17%	62.9%
edge	9%	12-13%	1%	12-13%	1%	24%	15%	62.5%
corner	8%	12%	0%	10-11%	1%	21%	13%	61.9%

Comparing the DFs for models 1 to 6 with an increase in the WI

For model 1 with all black surfaces (Figures 6:8 and 6:9), when the atrium WI increased from 0.5 to 1, DFs at the centre, edge and corner positions on the atrium floor were lower by 36%, 23% and 15% *(relatively lower by 54%, 48% and 44%)* respectively. When the atrium WI increased from 1 to 2 for the same model, DFs at the atrium centre, edge and corner positions were lower by 21%, 16% and 12% *(relatively lower by 69%, 64% and 60%)* respectively.

For model 6 with all white surfaces (Figures 6:8 and 6:9), when the atrium WI increased from 0.5 to 1, DFs at the centre, edge and corner positions on the atrium floor dropped by 28%, 21% and 17% *(relatively lower by 34%, 31% and 29%)* respectively. When the atrium WI increased from 1 to 2 for model 1, DFs at the atrium centre, edge and corner positions dropped by 27%, 23% and 19% *(relatively lower by 50%, 49% and 47%)* respectively.

Therefore there is a much steeper drop (15-36%) in the DFs at the atrium floor for the black model 1 when the atrium WI increases from 0.5 to 1 than when the WI increases from 1 to 2 (12-21%). However, for the white model 6, the drop in DFs is steadier for WI increases from 0.5 to 1 (17-28%) and from 1 to 2 (19-27%). This suggests that atria with darker or low reflectances (area weighted average reflectance 2%) will see a higher drop in DFs at the atrium floor when the atrium WI increases from 0.5 to 1 than when the WI increases from 1 to 2. On the other hand, the light or high reflectance atria (area weighted average reflectance 42-67%) will see a steady drop in the DFs with the atrium WI increases from 0.5 to 1 and from 1 to 2.

Compared with the high reflectance atrium, a low reflectance atrium will see a higher drop in DFs with a WI increase from 0.5 to 1. On the other hand, a high reflectance atrium will see a higher drop in the DFs with a WI increase from 1 to 2 than a low reflectance atrium. This is possibly due to the fact that as the atrium WI increases, DFs on the floor of the atria with low reflectances is reduced significantly consequently the drop in DFs is also reduced.

Drop in the DFs for the mixed reflectance, banded ‘a’ and ‘b’ type models at the atrium centre, edge and corner positions for WI increases from 0.5 to 1 and 1 to 2 is shown in Table 6:6. For both ‘a’ and ‘b’ type models, there was a higher drop in the DFs from atrium WI increase from 0.5 to 1 (15-35%, *relative 35-47%*) than from 1 to 2 (13-28%, *relative 55-68%*). Therefore in mixed reflectance atria (average weighted reflectance of 0.22 to 0.34), a higher drop in the DFs can be expected with an increase in the atrium WI from 0.5 to 1 than for a WI increase from 1 to 2.

Table 6:6 Drop in DFs for the banded 'a' and 'b' type models for the atrium centre, edge and corner positions for WI increases from 0.5 to 1 and 1 to 2

WI increases	Centre Position		Edge Position		Corner Position	
	Model 'a'	Model 'b'	Model 'a'	Model 'b'	Model 'a'	Model 'b'
from 0.5 to 1	30% to 34% Relative drop 44-47%	31% to 35% Relative drop 43-44%	23% to 24% Relative drop 41-42%	23% to 25% Relative drop 42-44%	15% to 17% Relative drop 35-37%	17% to 19% Relative drop 41-43%
from 1 to 2	24% to 26% Relative drop 62-65%	26% to 28% Relative drop 64-65%	20% Relative drop 60-62%	20% Relative drop 61-63%	15% to 17% Relative drop 56-59%	13% to 16% Relative drop 55-60%

Boubekri (1995) showed that in a four sided rectangular atrium of WI 1.05 under overcast skies, quadrupling of reflectance values (0.56, 0.42, 0.28 and 0.14) led to a doubling of DFs on the atrium floor. In the atrium of WI 1 of this study, atrium centre DF and ADF for the uniform reflectance model (reflectance 0.29) were compared with the white model 6 which had nearly double the reflectance of 0.57. When the reflectance doubled, relative increase in DF (atrium centre) and ADF of 28% and 32% respectively was noted. This suggests that the impact of ARC might be higher in a square atrium in comparison with a rectangular atrium as suggested by Oretskin (1982); Willbold-Lohr (1989); and Baker et al. (1993).

For an atrium of WI 0.5, when the area weighted average reflectance increased from 0.22 for the uniform reflectance model to 0.42 for the white model, relative increase in DF at the atrium centre and ADF on the floor was 11% and 18% respectively. For the atrium with WI 2, when the area weighted average reflectance increased from 0.34 for the uniform reflectance model to 0.67 for the white model, a relative increase in DF at the atrium centre and ADF on the floor was both 50%. This demonstrates that relative increases in the DF and the ADF due to the increase in the surface reflectances is higher in the atrium of WI 2; when the reflectances approximately doubled, DF and ADF also doubled. This is due to the lower DFs in the atrium of WI 2 making even small increases proportionally greater than those found in atria of WI 0.5 and 1.

Aizlewood et al. (1996) concluded that for an atrium with lower reflectances, fall in DFs at the atrium floor is rapid as the WI increases. This was also found for the black models with 0.02 reflectance; ADFs on the floor saw a relative reduction of 15%, 23% and 27% for WI 0.5, 1 and 2 respectively.

The effect of surface reflectances on ARC in atria of WI of 0.5, 1 and 2

Figure 6:10 shows ARCs on the atrium floor for models 1, 6 and the banded models 2'a' to 5'a' while Figure 6:11 shows ARCs on the atrium floor for models 1, 6 and the banded models 2'b' to 5'b'. ARCs for models 1 to 6 ranged between 1-21%, 7-23%, and 3-17% for the atria of WI 0.5, 1 and 2 respectively (Tables 6:2, 6:3 and 6:4). Figures 6:10 and 6:11 show a sharp increase in ARCs for model 6 in comparison with the banded and black models for all the three well indices demonstrating the impact of surface reflectances.

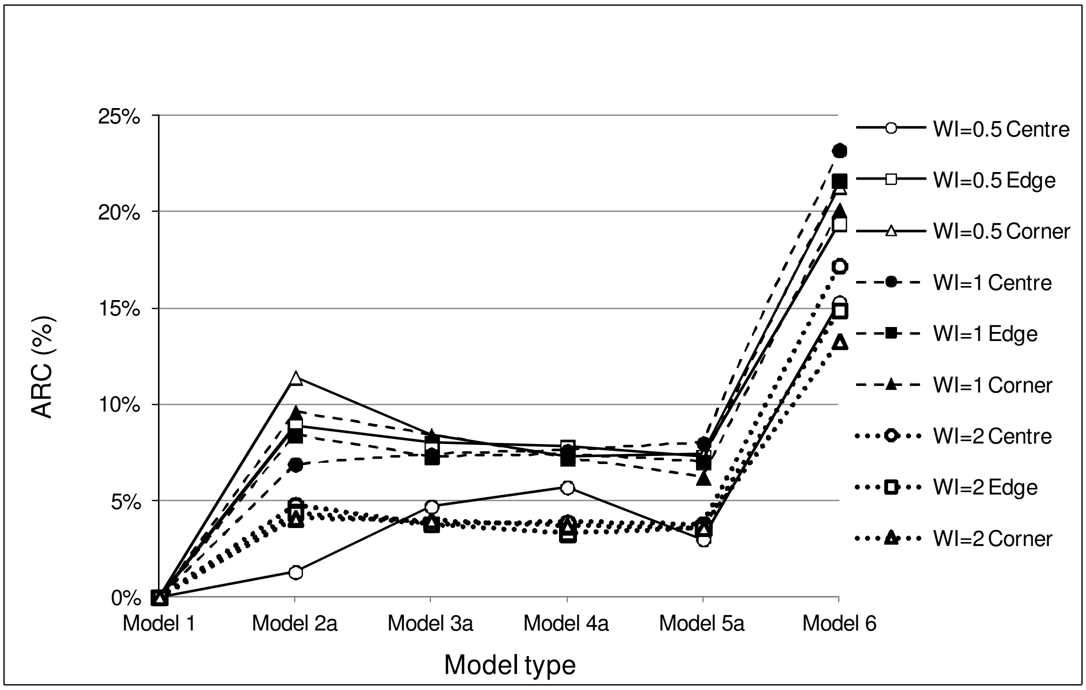


Figure 6:10 Comparison of ARC for model 1, 'a' type banded models and model 6 for atrium WI 0.5, 1 and 2

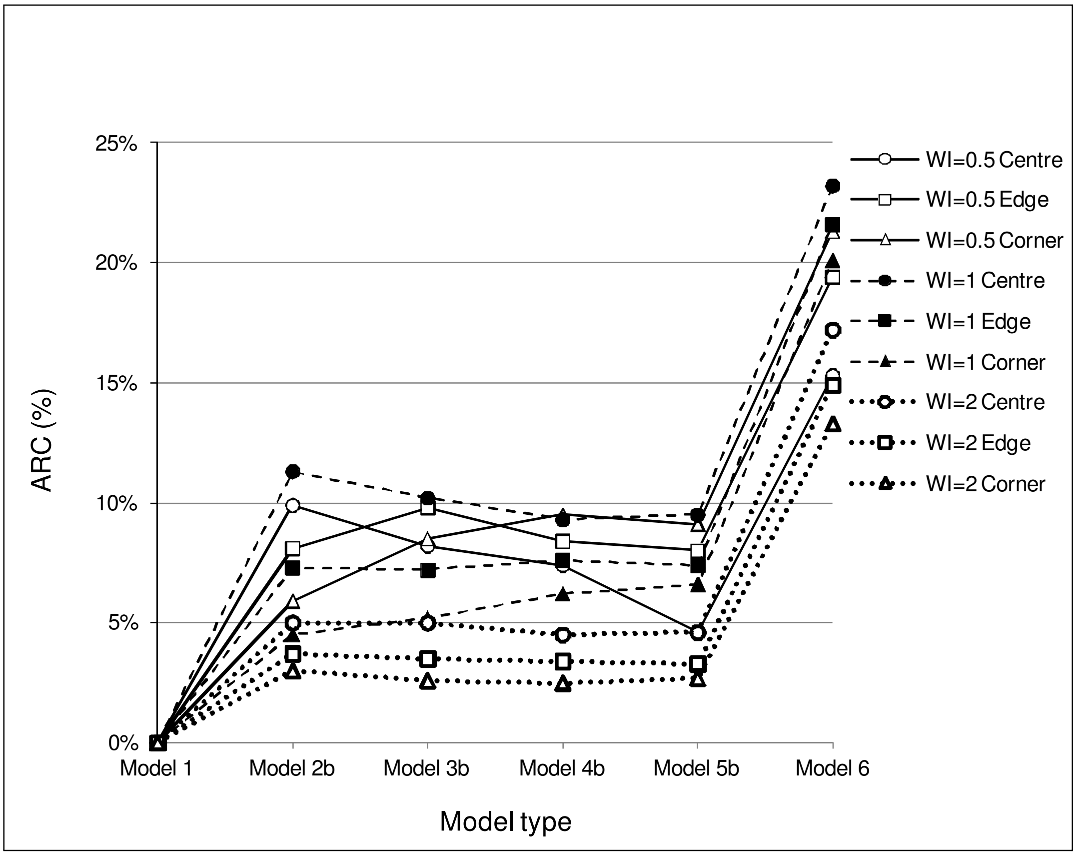


Figure 6:11 Comparison of ARC for model 1, 'b' type banded models and model 6 for atrium WI 0.5, 1 and 2

As mentioned earlier, in model 1 (black surfaces) the ARC contribution to DFs was assumed to be 0%, making the DFs essentially SCs in these cases. Therefore SCs for atria of WI 0.5, 1 and 2 are as shown below:

Atrium (WI 0.5) SC = 67.2% atrium centre; 47.8% atrium edge; 35.1% atrium corner

Atrium (WI 1) SC = 31.2% atrium centre; 25.0% atrium edge; 19.8% atrium corner

Atrium (WI 2) SC = 9.8% atrium centre; 8.9% atrium edge; 7.9% atrium corner

On comparing SCs with the DFs for the models 2 to 6 and the uniform reflectance model in Table 6:7, it is evident that the contribution of SC to the DF values in the three atria is highest for the atrium of WI 0.5, followed by the atrium of WI 1 and it is lowest for the atrium of WI 2. This shows that SC is highest for the atrium with the lowest well index. Conversely, although DFs were highest for the atrium of WI 0.5, contribution of ARCs to the DF values (Table 6:7) are lowest for the atrium of WI 0.5, are higher for the atrium of WI 1 in comparison with the atrium of WI 0.5 and are highest for the atrium of WI 2. Therefore, it is suggested that surface reflectances have an increasing impact in the atria of WI 1 and 2 in comparison with the shallow/wide atrium of WI 0.5.

Although absolute DF (Tables 6:2, 6:3 and 6:4) and ARC (Figures 6:10 and 6:11) values were lower for the atria of WI 1 or 2 in comparison with that of WI 0.5, the proportion of contribution the ARC made to the DFs on the atrium floor was much higher in the atria of WI 1 and 2. Moreover, if relative differences in DFs due to the increase in surface reflectances between model 1(black) and 6(white) are compared, DFs in the atrium of WI 2 saw higher increases (62-63%) compared to the atria of WI 0.5 (19-38%) and 1(43-50%) (Table 6:5). This is due to lower DFs in the atrium WI of 2 where even small increases are proportionally greater than those found in the atria of WI 0.5 and 1. However, if actual DF values are considered, these increases are very small.

Table 6:7 DFs, SCs and the contribution of ARCs to the DFs in the atria of WI 0.5, 1 and 2

Model Type	WI = 0.5 DF (%)	WI = 0.5 ARC% contribution to the DFs	WI = 1 DF (%)	WI = 1 ARC% contribution to the DFs	WI = 2 DF (%)	WI = 2 ARCs % contribution to the DFs
Model 1 (All Black)	67.2% 47.8% 35.1%	0% 0% 0%	31.2% 25.0% 19.8%	0% 0% 0%	9.8% 8.9% 7.9%	0% 0% 0%
Model 2a （Halves)	68.5% 56.7% 46.5%	1.9% 15.6% 24.5%	38.1% 33.4% 29.4%	18.1% 25.1% 32.6%	14.6% 13.3% 12.0%	32.8% 33.0% 34.1%
Model 2b (Halves)	77.1% 55.9% 41.0%	12.8% 14.4% 14.3%	42.5% 32.3% 24.3%	26.5% 22.6% 18.5%	14.8% 12.6% 10.9%	33.7% 29.3% 27.5%
Model 3a (Quarters)	71.9% 55.8% 43.5%	6.5% 14.3% 19.3%	38.6% 32.3% 28.2%	19.1% 22.6% 29.7%	13.6% 12.7% 11.9%	27.9% 29.9% 33.6%
Model 3b (Quarters)	75.4% 57.6% 43.6%	10.8% 17.0% 19.4%	41.4% 32.2% 25.0%	24.62% 22.3% 20.8%	14.8% 12.4% 10.5%	33.7% 28.2% 24.7%
Model 4a (Sixths)	72.9% 55.6% 42.4%	7.8% 14.0% 17.2%	38.8% 32.4% 27.0%	19.5% 22.8% 26.6%	13.7% 12.2% 11.6%	28.4% 27.0% 31.8%
Model 4b (Sixths)	74.6% 56.2% 44.6%	9.9% 14.9% 21.3%	40.5% 32.6% 26.0%	22.9% 23.3% 23.8%	14.3% 12.3% 10.4%	31.4% 27.6% 24.0%
Model 5a (Eighths)	70.2% 55.1% 42.5%	4.2% 13.2% 17.4%	39.2% 32.0% 26.0%	20.4% 21.8% 23.8%	13.6% 12.5% 11.5%	27.9% 28.8% 31.3%
Model 5b (Eighths)	71.8% 55.8% 44.2%	6.4% 14.3% 20.5%	40.7% 32.4% 26.4%	23.3% 22.8% 25.0%	14.4% 12.2% 10.6%	31.9% 27.0% 25.0%
Model 6 (All white)	82.5% 67.2% 56.4%	18.5% 28.8% 37.7%	54.4% 46.6% 39.9%	42.6% 46.3% 50.3%	27.0% 23.8% 21.2%	63.7% 62.6% 62.7%
Uniform reflectance for 2a-5b	73.5% 56.3% 43.0%	8.5% 15.0% 18.3%	39.4% 32.0% 25.9%	20.8% 21.8% 23.5%	13.5% 12.1 % 10.8%	27.4% 26.4% 26.8%

In agreement with the findings of Letherman and Wright (1998) it is found that in the atrium of WI 2, view factor between the atrium's walls and the sky vault is small resulting in lower wall luminance and lower DFs. However, the relative surface area of the atrium's walls is high resulting in higher potential for a larger ARC. As the WI decreases to 1 and further to 0.5, the contribution of SC increases with an increase in the view factor with the sky vault resulting in higher DFs but the contribution of ARC is reduced, particularly for the atrium of WI 0.5. The findings are also in agreement with those presented by Willbold-Lohr (1989) who showed that the impact of ARC was mainly in square atria of WI higher than 0.75 and Liu et al. (1991) who suggest that they only affect in atria of well indices ranging between 1 and 2 suggesting that ARC in lower well indices might be weaker.

Comparing the effect of reflectance distributions on the ARCs and the DFs in the banded models 2a-5a and 2b-5b

As shown in Tables 6:2, 6:3 and 6:4, in the atrium of WI 0.5, it is found that the contribution of ARC is lowest at the atrium centre; it increases at the edge and is highest in the corner. This is expected considering that the atrium centre will mostly receive the SC in a shallow atrium.

In the atrium of WI 1, it is also found that in most cases the contribution of the ARC is lowest at the atrium centre position, it increases at the edge and is highest in the corner position except for the models 2b, 3b and 5b where the contribution of the ARC is highest for the centre position, followed by the edge and is least for the corner position. This is also found in the atrium of WI 2 and it's because in the 'b' type models white band close to the top of the atrium results in more light being reflected down towards the centre of the atrium floor. This is in agreement with the findings of Lau and Duan (2008) who showed that increasing reflectances at the top of the atrium resulted in a 25% increase in DFs on the atrium floor.

In the atrium of WI 2, it is found that for models 2a, 3a and 5a, the contribution of the ARC is highest in the corner position because of the enhanced reflectance from the white band adjacent to measurement point on the atrium floor.

As shown in Tables 6:2, 6:3 and 6:4, although the contribution of ARC to the DFs achieved increases with an increase in the atrium WI for the banded models (2-25% for WI 0.5; 18-33% for WI 1 and 24-34% for WI 2), DF values are dominated by the SC. Moreover, DFs reduce significantly with an increase in the atrium WI, consequently difference in the DFs due to the banding also reduces as shown in Figures 6:12 (WI 0.5), 6:13 (WI 1.0) and 6:14 (WI 2.0). Therefore, when DFs obtained for the banded models 2a to 5a were compared and 2b to 5b were compared with each other, a maximum difference in DFs of 5%, 4% and 1% was found in the atria of WI 0.5, 1 and 2 respectively. This shows that the impact of reflectance distributions on DFs is reduced in the atrium of WI 2 despite an increase in the ARC contribution to DFs in this atrium.

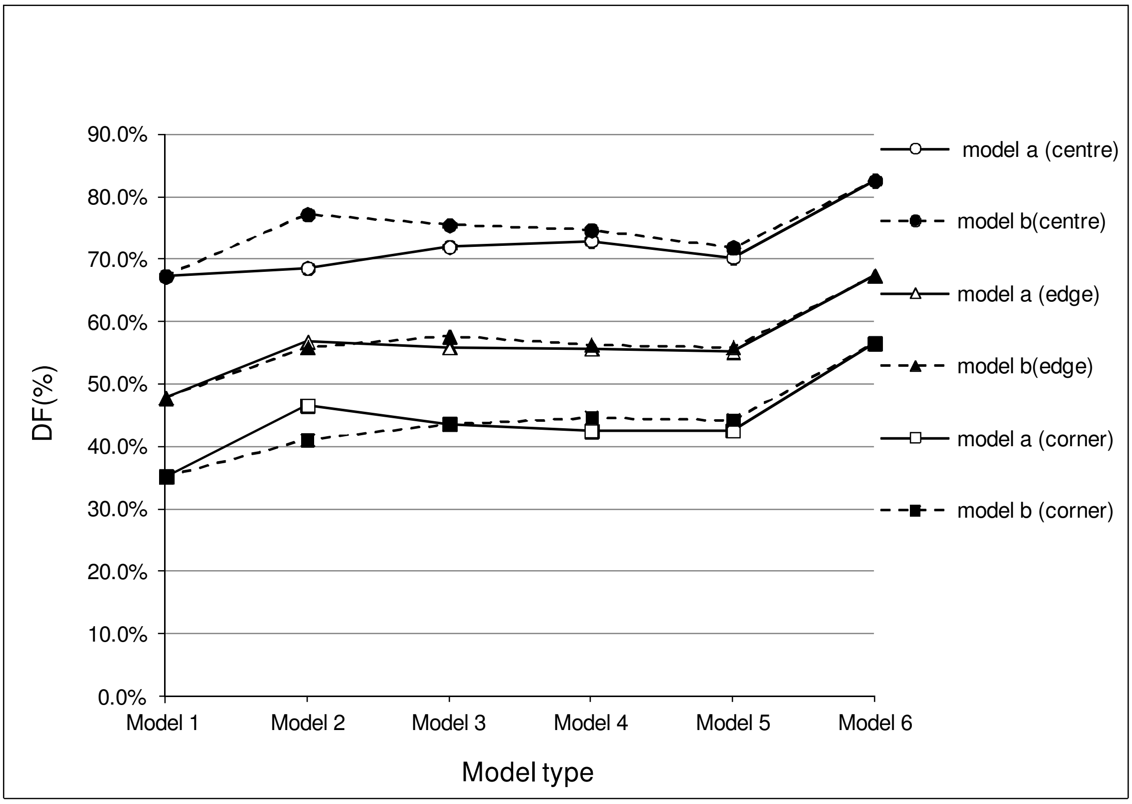


Figure 6:12 Comparison between ‘a’ and ‘b’ type models for WI 0.5

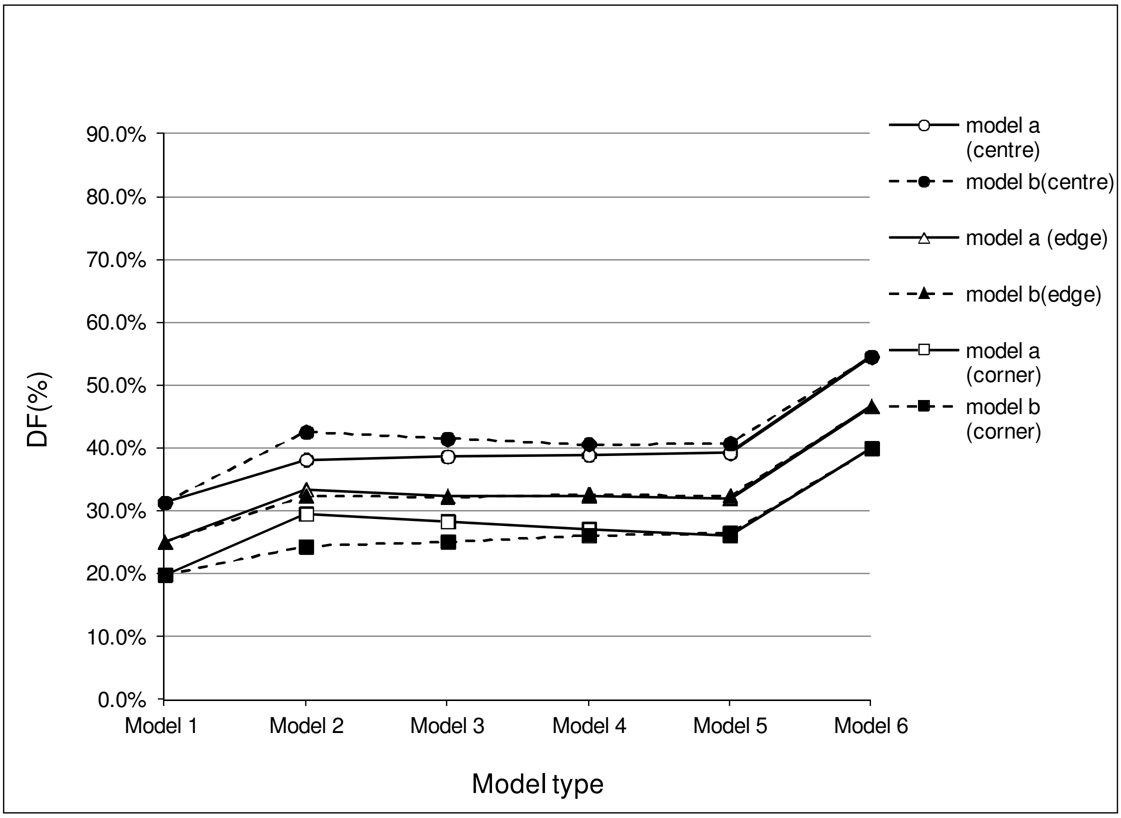


Figure 6:13 Comparison between ‘a’ and ‘b’ type models for WI 1

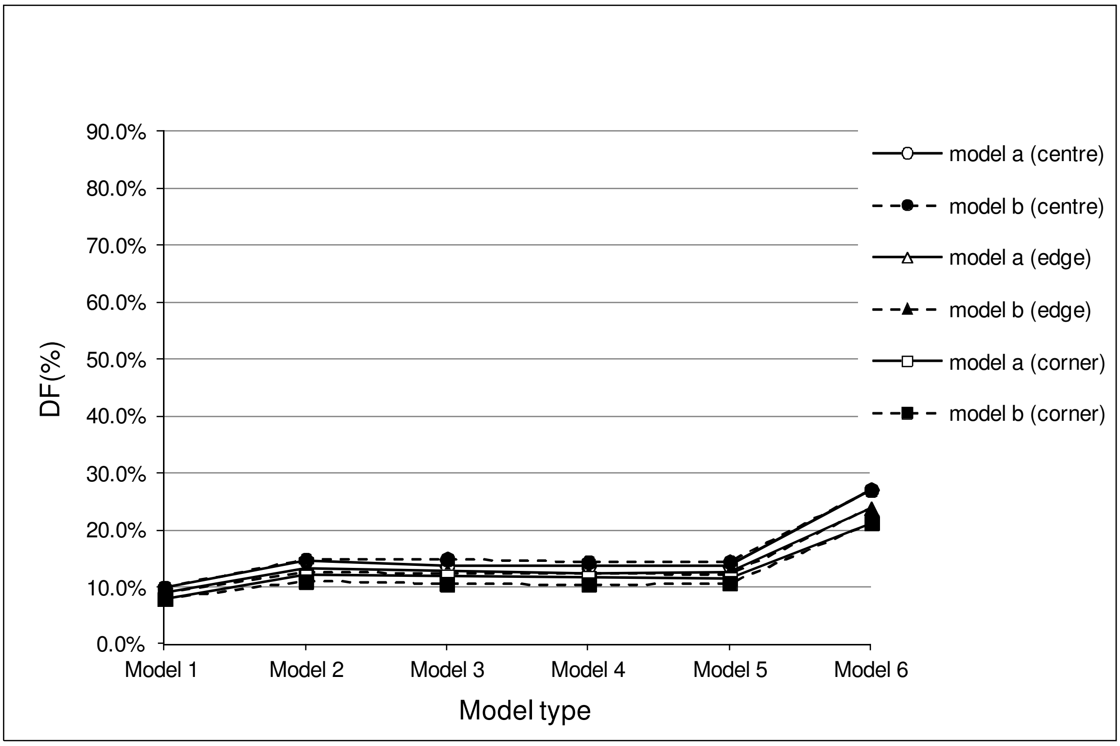


Figure 6:14 Comparison between ‘a’ and ‘b’ type models for WI 2

At the edge position, DFs for the 'a' type and 'b' type models were very similar and a maximum differences in DF values of 2%, 1% and 1% for atria of WI 0.5, 1, and 2 respectively were noted despite the higher ARC contribution in this position compared to the atrium corner position. It might be due to the fact that the SC dominated the DFs and had a balancing effect on the final DF value obtained in this position.

Comparisons between DFs for the 'a' and 'b' type models shown in Figure 6:12 and 6:13 respectively demonstrate that the different sequencing of the bandings influenced DFs significantly at the atrium centre (up to 9%) and corner (up to 6%) positions in the atria of WI 0.5 and 1(up to 5%). However, this was mainly noted in model 2 which had only two bands. As the number of bands increased and the width of the bands reduced from models 2 to 5, difference between the DFs for the 'a' and 'b' type models also reduced. For WI 2, when the 'a' and 'b' type models were compared, a maximum difference in DFs of 1% was noted for the atrium centre and corner positions (Figure 6:14).

Given the low DFs in WI 2, even a small change in DFs due to the banding might be proportionately large. Therefore it is suggested that although the contribution of the ARC is higher in the atrium of WI 2, due to the reduced SC and consequently DFs, the distribution of atrium wall reflectances had a small influence on DFs at the atrium floor. In comparison with WI 2, in atria of WI 0.5 and 1, DFs were influenced more by the distribution of the atrium wall reflectances, the extent of which was determined by the configuration of the reflectances. Therefore, the effect of the different reflectance distributions on DF reduces as the WI increases and the number of bands of the different reflectances increase as also found by Sharples and Lash (2004).

Comparison of DFs for the three positions due to well index increases

As shown in Figures 6:8 and 6:9, DFs were always highest at the centre position, lower at the edge position, and lowest at the corner position. For the atrium of WI 0.5, DFs dropped by 12-19% *(relative drop of 17-29%)* from the atrium centre to its edge and dropped by 10-

15% *(relative drop of 16-27%)* from the edge to its corner. For the atrium of WI 1.0, DFs dropped by 5-10% *(relative drop of 12-24%)* from the atrium centre to its edge and dropped by 4-8% *(relative drop of 17-25%)* from the edge to its corner. For the atrium of WI 2.0, DFs dropped by up to 3% *(relative drop of up to 15%)* from the atrium centre to its edge and from the edge to its corner. This demonstrates that as the WI increases, DFs reduce and consequently variation in the DFs across the atrium floor also reduces.

Comparison of DFs for the Banded and Uniform reflectance models

Tables 6:2, 6:3 and 6:4 demonstrate that DFs obtained for the models with a uniform reflectance of 22%, 29% and 34% for atrium WIs of 0.5, 1, and 2 respectively were within the range of the DFs obtained for the banded models. Comparisons between the banded and un-banded models showed a maximum difference of only 1% for WI2, while those for WI 0.5 and 1 ranged between 1 and 5%, and 1 and 4% respectively. This demonstrates that although daylight distribution on the atrium floor is influenced by the atrium surface distribution patterns, average reflectance of these surfaces provide a fairly good estimate of DFs for WI 2 but it may not be very accurate for WI 0.5 and 1. This also indicates that the surface reflectance distribution patterns influence DFs in the atria of WI 0.5 and 1 more than they do in WI of 2.

Table 6:8 shows the drop in DFs in the banded and uniform reflectance models for WI increases from 0.5 to 1 and from 1 to 2. It shows that for a mixed reflectance atrium, a uniform reflectance atrium will provide a good indication of possible DF losses due to WI increase from 1 to 2 but it may not do so for a WI increase from 0.5 to 1. This is suggested because the uniform reflectance model overestimated the drop in DF at the atrium centre position by 4% when the WI increased from 0.5 to 1.

Table 6:8 Drop in DFs for the uniform reflectance model for the atrium centre, edge and corner positions for WI increases from 0.5 to 1 and 1 to 2

Uniform Reflectance						
WI increases	Centre Position		Edge Position		Corner Position	
From 0.5 to 1	34%		24%		17%	
From 1 to 2	26%		20%		15%	
Banded Models						
	Model 'a'	Model 'b'	Model 'a'	Model 'b'	Model 'a'	Model 'b'
From 0.5 to 1	30 to 34%	31 to 35%	23 to 24%	23 to 25%	15 to 17%	17 to 19%
From 1 to 2	24 to 26%	26 to 28%	20%	20%	15 to 17%	13 to 16%

Comparison of ADFs for the Banded and Uniform reflectance models

As done previously in Chapter Five, ADF across the atrium base was calculated from weighted DF values obtained at the centre, edge and corner positions. Figure 6:15 shows that when ADFs for the banded models were compared with each other and with the uniform reflectance ADFs, a maximum difference of 3.1% *(relative difference of 5%)*, 0.9% *(relative difference of 3%)* and 1% *(relative difference of 9%)* was found for the atria of WI 0.5, 1 and 2 respectively. This suggests that the reflectance distributions had a small influence on ADFs; this was noted in the atrium of WI 0.5 more than atria of WI 1 and 2. Furthermore, ADFs predicted by a uniform reflectance atrium representing a mixed reflectance atrium will provide a rough estimate of the ADFs that might be obtained on the atrium floor.

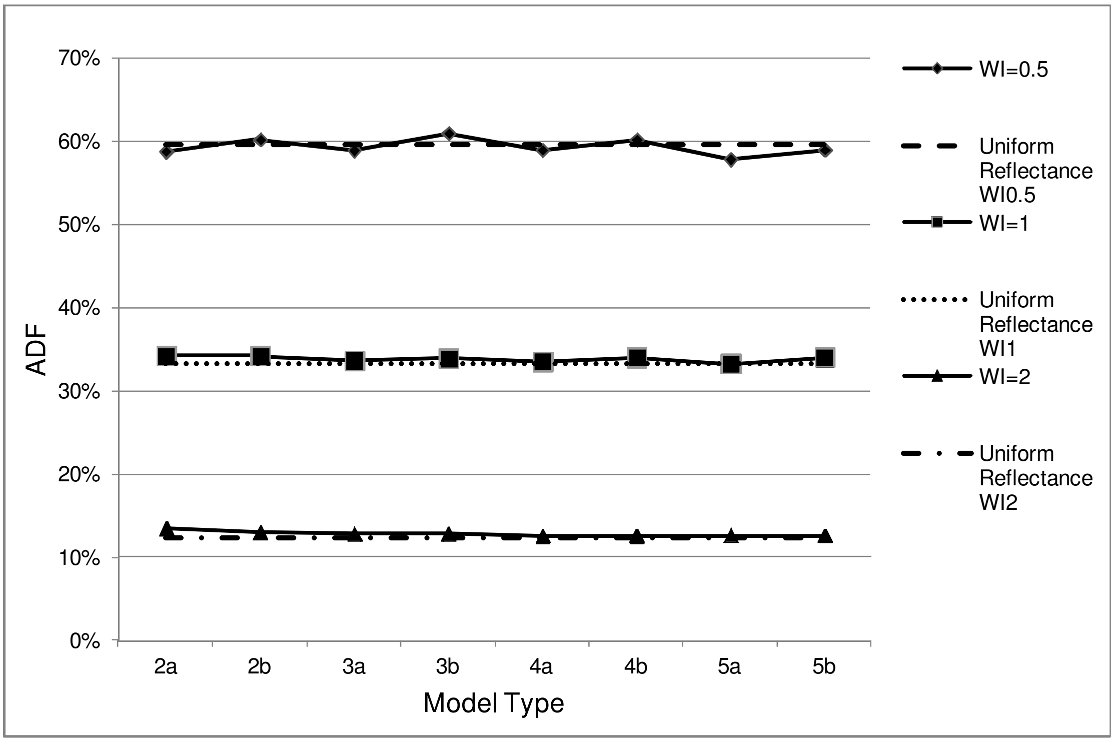


Figure 6:15 ADFs for banded models (2a, 2b, 3a, 3b, 4a, 4b, 5a, 5b) and uniform reflectance models for WI 0.5, 1 and 2

Comparison of ADFs and DFs for the Banded and Uniform reflectance models

Large differences between ADF on the atrium floor of the uniform reflectance model and DFs for atria of WI 0.5 and 1 in Table 6:9 show that the use of ADF to predict daylight availability across an atrium floor can be misleading as the ADF values do not appropriately represent the full range of DFs that might actually be achieved on the atrium floor. It is evident that in comparison with the ADFs, DFs might be much higher in the centre position and much lower in the corner positions. Difference between the ADFs and DFs is much higher for the atria of WI 0.5 and 1 in comparison with that of WI 2 demonstrating that the use of ADF to predict daylight availability in shallow or medium proportioned atria can be problematic.

Table 6:9 Range of DF% difference between ADF and DFs for atrium WI 0.5,1 and 2

In comparison with ADF			
WI	Atrium centre DFs%	Atrium edge DFs%	Atrium corner DFs%
0.5	10-17% higher *(relatively higher by 14- 22%)*	2-4% lower *(relatively lower by 4 -7%)*	12-19% lower*(relatively lower by 26-46%)*
1	4-8% higher *(relatively higher by 10- 20%)*	1-2% higher *(relatively higher by 2-6%)*	5-10% lower *(relatively lower by 16-41%)*
2	1-3% higher *(relatively higher by 8-10%)*	Up to 1% higher *(relatively higher by 1-2%)*	1 to 3% lower *(relatively lower by 14-15%)*

6.2.3 Comparison of data with real buildings

As discussed earlier in Chapter Three, Fontoynont's (1999a) edited book *Daylight Performance of Buildings* includes monitored daylight performance data for several European buildings, many of which include atria and are discussed in the following section. Comparisons of theoretical models, albeit representative, with real buildings are difficult due to the lack of like for like published data and differences between the key parameters and several underlying assumptions. However, an attempt has been made to draw links and contextualise the work undertaken in this thesis, where possible. Due to the fact that the well indices were unknown in some of the cases discussed, SARs of the models that do not take into account the atrium shape were compared with those of the buildings. Therefore, square models were compared with rectangular atria in the case of St Hubert's Galleries and the Sukkertoppen in Valby. Daylight levels in the built examples will be lower due to the atrium roof, windows and dirt factor, which were not included in the RADIANCE models. Therefore for the purpose of making comparisons with data from buildings, DFs obtained in the RADIANCE models were reduced by 50%.

St Hubert Galleries in Brussels

St Hubert Galleries in Brussels comprise of three covered streets between Italian neo-Renaissance style buildings that include shops, offices and apartments (Figure 6:16). The street has a SAR of 2 and is defined by high transmittance (90%) cylindrical glazed roof; white and light grey bright building facades of high reflectance 65%; and a black floor of 16% reflectance. WI for the St Hubert Galleries is unknown therefore SARs for the two studies are compared. Table 6:10 outlines the atrium parameters and compares data obtained from the real building and model 6 with an SAR/WI of 2.

Figure 6:16 St Hubert Galleries in Brussels
(http://www.flickr.com/photos/jaapwillem/4181690970/)

High SAR (approximately 2) of the St Hubert Galleries results in a reduced view factor between the atrium's walls and the sky vault resulting in lower wall luminance (Letherman and Wright, 1998) and reduces DFs on the atrium floor despite the increased wall reflectances. This is in agreement with the findings of the RADIANCE experiment, which also shows reduced DFs in WI 2.

DF on the atrium floor of the building is 12% while ADF on the atrium floor of the white model is 24% (Table 6:10). With 50% reduction, ADF on the model floor will be 12% or lower indicating that the RADIANCE model compared well the real building.

Table 6:10 Comparison of daylight availability on the atrium floor between St Hubert Galleries in Brussels and Model 6 with white walls

St Hubert Galleries SAR = 2 Glazed street – 90% roof transmittance	Model 6, SAR/WI = 2 Square Atrium with no roof
Atrium wall reflectance = 65%	Atrium wall reflectance, white walls = 83% ; Area weighted average reflectance of the atrium = 67%
Atrium floor reflectance = 16%	Atrium floor reflectance = 2%
DF at atrium floor centre 12%	ADF at atrium floor 24% (50% reduction = 12%)

Berthold Brecht School in Dresden

In the Berthold Brecht School, converting the two courtyards into covered atria reduced daylight availability in the atria to one third, reducing DFs from 50% to 15% on the atrium floor (Figure 6:17) (Fontoynont, 1999a). DF on the atrium floor of the building (SAR = 0.66) compared reasonably well with ADF on the atrium floor of model 6 with a WI and SAR of 0.5 (Table 6:11).

Although DFs for the model should be lower than the monitored building due to the lower floor reflectance and area weighted average reflectance of the model, DFs are possibly higher due to the lower WI and higher wall reflectance of the model.

Figure 6:17 Berthold Brecht School in Dresden
(http://www.annex36.com/eca/uk/03viewer/case_studies/de_2_user.html)

Table 6:11 Comparison of daylight availability on the atrium floor between Berthold Brecht School and Model 6 with white walls

Berthold Brecht School with even facade 3 storeys , WI unknown, SAR = 0.66	Model 6 – All white walls, WI = 0.5, SAR = 0.5 No adjoining spaces monitored
Glazing: Outside facade, atrium facade, atrium roof = 67% transmission	No roof included
Atrium wall reflectance= 59% Atrium floor reflectance = 17%	Atrium wall reflectance= 83% Atrium floor reflectance =2% Area Weighted Average Reflectance of the atrium = 42%
Atrium floor DF = 15%	Atrium floor ADF = 70% If roof was added, this would reduce to 21% approximately

Sukkertoppen in Valby

Sukkertoppen in Valby, a suburb of Copenhagen, is an old sugar refinery whose two to three storey brick building (21% reflectance) was retrofitted and included an addition of a new white (86% reflectance), four storey, 84m long and 13 m deep office building to its south (Figure 6:18). The two buildings were connected by a glazed atrium to reduce the heating load and maintain daylight penetration in both the buildings. The new white building increased reflected daylight penetration in the old building, while the older brick building reduced DFs across the atrium by 2% to 3% near its facade in comparison with the white facade (Fontoynont, 1999a). Therefore this building demonstrates the impact of reflectances on DFs and in congruence with the model study it shows that the low reflectance/darker surfaces immediately adjacent to the atrium floor will affect DFs locally.

Table 6:12 compares the atrium parameters and daylight availability on the atrium floor between the building and Model 6 with white walls. Considering 50% reduction in DFs, there is a good agreement between the DFs obtained on the atrium floor of the building and the square, all white walled model 6 of SAR 2 (Table 6:12). While the SARs are similar, WI of the square model is nearly double that of the rectangular building. While some researchers show that the wells of square plans receive better illumination than rectangular/linear plans at a given level, others suggest that keeping the height the same and increasing the length of the atrium increases the light-admitting area (or reduces WI) and increases the DFs. In this study, perhaps as comparison between the model and the building relies on several assumptions, DFs for the square (WI=2) and the rectangular atrium (WI=1.1) with similar SAR were fairly comparable. This might also be due to the lower wall reflectances found in the old building. However, when the much lower floor reflectance (2%) used in the model is considered, it might be that DFs on the atrium floor of the square model will be higher than those found in the building with an increase in the floor reflectance to 33% as that of the building. This suggests that the DFs will be higher in a square atrium in comparison with a rectangular atrium as also found when the results for the model study of this Chapter and Chapter Four were compared with the findings of Boubekri (1995) for a rectangular atrium.

Figure 6:18 Atrium of the Sukkertoppen in Valby
(http://www.arkitekturbilleder.dk/bygning_Sukkertoppen_$$516)

Table 6:12 Comparisons of atrium parameters and daylight availability on the atrium floor between Sukkertoppen in Valby atrium and Model 6 with white walls

Sukkertoppen in Valby Rectangular Atrium with roof SAR = 1.9, WI = 1. 1	Model 6 Square Atrium with no roof SAR = 2, WI = 2
Atrium wall reflectance Old building = 21% New building grey columns = 36% New building white walls = 86%	Atrium wall reflectance White walls = 83% Area weighted average reflectance of atrium = 67%
Atrium floor reflectance = 33%	Atrium floor reflectance = 2%
DF at atrium floor centre 13% DF at atrium edge 13% for old building DF at atrium edge 15 to 16% for new building	ADF at atrium floor 24% (12% with 50% reduction) DF at atrium floor centre 27.0%(13.5% with 50% reduction) DF at atrium edge 24%(12% with 50% reduction)

The effect of low wall reflectances is also evidenced in the Brundtland Centre in Denmark which includes a four sided, two storey, top and side lit south west atrium with integrated PV in the south-facing saw tooth roof of the atrium (Figure 6:19). The atrium floor receives adequate daylight from the atrium roof and the full height partially glazed south-west facade of the atrium, increasing DFs from 4% to 19% along the centre line of the floor towards the glazed facade. However, in comparison, the red brick facade to the south east reduces DFs by approximately 2% close to the facade. Therefore, this building like the Sukkertoppen in Valby demonstrates localised effect on the atrium floor DFs due to the altered surface reflectance as shown in model 2a where DF also increased due to the large white band near to the atrium floor.

Figure 6:19 The Brundtland Centre in Denmark
(http://www.ecoarchwiki.net/pmwiki.php?n=Projects.TheBrundtlandCentre)

6.3 CONCLUSIONS

This Chapter investigated the effect of surface reflectances and their distribution patterns on DFs, ADFs and ARCs in atria of different well indices. Outlining key results and applying them to architectural design gave the following practical findings:

- The well index of an atrium has a significant effect on DFs at its base. As WI increases, DFs on the atrium floor drop dramatically despite an increase in the area weighted average reflectances. DFs at the base of all three atria (WI 0.5,1 and 2) are affected by the altered facade reflectances as also shown by the previous studies (Willbold-Lohr, 1989; Liu et al., 1991; Baker et al, 1993; Boubekri, 1995; Aizlewood et al., 1996; Du and Sharples, 2009a).

- The contribution of SC to DFs at the atrium floor is highest for the atrium of WI 0.5, followed by the atrium of WI 1 and it is lowest for the atrium of WI 2. Although absolute DFs and ARC values are lower for WI 1 or 2 compared with WI 0.5, the contribution ARC made to DFs on the atrium floor is much higher in these atria. Therefore, it is concluded that surface reflectances have an increasing impact in higher WI atria of 1 and 2 in comparison with the shallow/wide atrium of WI 0.5. These findings are in agreement with those presented by Willbold-Lohr (1989) who showed that the impact of ARC was mainly in square atria of WI higher than 0.75 and Liu et al. (1991) who suggest that they affect in WIs ranging between 1 and 2.
- Although the contribution of ARC increases in atria of higher WIs, as DFs reduce significantly with the increase in the atrium's WI, difference in the DFs due to the reflectance distributions also reduces. Therefore, the distributions of well reflectances influence daylight levels and their distribution on the floor of the atria of WI 0.5 and 1.0 but their influence is reduced in the atrium of WI 2. However, relative increases in DFs and ADF due to the increase in surface reflectances are higher in WI 2; when the reflectances approximately doubled, DFs and ADF also doubled. This is because with lower DFs in the atrium of WI 2, even small increases in the DFs are proportionally greater than those found in the atria of WI 0.5 and 1.
- The effect of the different reflectance distributions is determined by the configuration of the reflectances; its effect on the DF reduces as the number of bands of different reflectances increase as also shown by Sharples and Lash (2004).
- Atria with darker or low reflectances will see a higher drop in the DFs when the WI increases from 0.5 to 1 than when the WI increases from 1 to 2. While the light/high reflectance atria will see a steady drop in the DFs with WI increases from 0.5 to 1 and 1 to 2. Compared to a high reflectance atrium, a low reflectance atrium will see

a higher drop in DFs with a WI increase from 0.5 to 1. On the other hand, a high reflectance atrium will see a higher drop in DFs with a WI increase from 1 to 2 than a low reflectance atrium. In mixed reflectance atria, a higher drop in DFs can be expected with a WI from 0.5 to 1 than from an increase from 1 to 2.

- The impact of ARC might be higher in a square atrium in comparison with a rectangular atrium as suggested by Oretskin, 1982; Willbold-Lohr, 1989; and Baker et al. 1993.
- In agreement with the findings of Aizlewood et al (1996) for lower reflectances, fall in the DF at the atrium floor is rapid as the WI increases.
- DFs are always highest at the centre, lower at the edge, and lowest at the corner positions on the atrium floor as also shown in Chapter Four and by Kim and Boyer (1986). However as the WI increases difference in DFs at the different positions is reduced. Moreover, different reflectance distributions have a lower impact on DFs at the edge of the atrium floor in comparison with the atrium centre and its corners.
- A large band of high reflectance (83% reflectance) wall surface at the top of the atrium can improve DFs in the centre of the atrium floor but may not necessarily improve DFs across the entire floor particularly if there are darker surfaces (2% reflectance) immediately adjacent to the atrium floor. This is also found by Sharples and Lash (2004) and Lau and Duan (2008).
- A large white band on the walls adjacent to the measurement point at the corner of the atrium floor may increase DFs in this position.
- In the atrium of WI 2, as the impact of the atrium surface reflectance distribution patterns is reduced, a uniform reflectance atrium representing these surfaces can provide a fairly good estimate of DFs achieved within this atrium but may not be very accurate for atria of WI 0.5 and 1. Furthermore, a uniform reflectance atrium will provide a good indication of the possible DF losses due to the WI increases from 1 to 2 in a mixed reflectance atrium.
- Atrium surface reflectance distributions have a small influence on ADF in the atria of WI 0.5, 1 and 2. Therefore, ADFs predicted for a uniform reflectance atrium could be

used to provide a reasonable estimate of the ADFs that might be obtained for a banded atrium of equal reflectance. However, large differences between ADFs and DFs in atria of WI 0.5 and 1 show that the use of ADFs to predict DFs on the atrium floor of a shallow or medium proportioned atrium can be problematic.

To contextualise the work undertaken in this Chapter, findings from the model studies were compared with some built examples. RADIANCE results compared well with built the Berthold Brecht School, St Hubert Galleries and the Sukkertoppen building. In St Hubert's Galleries, high SAR (approximately 2) resulted in reduced DFs on the atrium floor despite the high area weighted wall reflectances as also evidenced by the model study. Moreover, Sukkertoppen in Valby and the Brundtland Centre demonstrate the impact of reflectances on DFs and in congruence with the model study show that low reflectance surfaces immediately adjacent to the atrium floor will reduce DFs locally.

On comparison of the DFs for the square atrium model of WI 2 in RADIANCE with the rectangular atrium of Sukkertoppen in Valby and that studied by Boubekri (1995), it was found that the DF increases due to the increased reflectances in the square atrium were higher. Therefore, it is concluded that perhaps the DFs in a square atrium will be higher in comparison with a rectangular atrium as also found in Chapter Four and by the previous studies (Oretskin, 1982; Willbold-Lohr, 1989; and Baker et al. 1993).

Finally, surface reflectances affected DFs in atria of WI 0.5, 1 and 2 and fall within the range of well indices identified by previous studies in which the reflectances were identified to affect the DFs (Willbold-Lohr, 1989 (WI >0.75); Liu et al., 1991 (WI 1 to 2); Baker et al, 1993 (AR 0.5 – 2); Boubekri, 1995 (WI 1.05); Aizlewood et al., 1996 (WI 0.5-2); Du and Sharples, 2009b (WI 0.25 – 1.5). Furthermore the study showed the increasing impact of ARC in atria of higher well indices. However, the influence of the reflectance distribution patterns on DFs on the atrium floor was higher in atria of WI 0.5 and 1 in comparison with the atrium of WI 2.

While daylight levels in an atrium space might be sufficient, they might be inadequate in the adjoining space, particularly lower down the building. Considering the findings from this Chapter and the range of well indices typically found in built atria (Liu et al., 1991), the final set of experiments in Chapter Seven parametrically assess the influence of different fenestration distributions in the atrium facades on DFs in the atrium as well as its adjoining spaces in a medium proportioned, four sided, top-lit, square atrium building.

7 PARAMETRIC STUDY OF THE INFLUENCE OF ATRIUM FACADE FENESTRATION ON THE DAYLIGHT IN AN ATRIUM AND ITS ADJOINING SPACES

7.1 INTRODUCTION

The previous chapter established the impact of atrium surface reflectance distributions on daylight availability on the floor of the atria of different well indices. Developing an understanding of the daylight availability on the atrium floor was important due to its potential to reflect light in the lower adjoining spaces. It demonstrated that whilst ADFs might not be particularly affected, DFs on the floor of the atria of WI 0.5,1 and 2 are affected by the atrium surface reflectances. Although it was found that the contribution of ARC to the DFs was high in higher atria, because of the lower wall luminance, DFs on the floor of this atrium were low, consequently reducing the impact of the surface reflectance distributions. Therefore, it was concluded that surface reflectance distributions affect DFs at the floor of the atria of WI 0.5 and 1 but their effect is significantly reduced with an increase in the atrium's well index to 2.

Whilst daylight levels within the atrium space are generally sufficiently high, this may not be the case for spaces adjoining the atria, where daylight availability varies significantly with every floor level. Rooms on the top floors can be over-lit and suffer from glare while daylight levels on the lower floors can be low, particularly in the tall/deep atria. Altering the facade in this way would inevitably result in different wall reflectances and reflectance distributions.

Previous studies (Willbold-Lohr, 1989; Cole, 1990; Aschehoug, 1992; Szerman, 1992, Iyer, 1994; Boubekri 1995; Matusiak et al., 1999) suggest that the proportion of window area in the atrium facades should vary on the different floors. Since most daylight is available at the top of the atrium, adjoining spaces need the smallest windows to achieve the desired daylight levels. A progressive increase in the amount of fenestration in an atrium's facade from its roof to its floor can lead to higher daylight availability in an atrium and its adjoining spaces lower down. Whilst there is general consensus in terms of the positive influence of this facade strategy, an area of continued uncertainty is whether a particular incremental approach to fenestration in an atrium's facade might be advantageous.

For example, Cole (1990) examined a square, five storey, four sided atrium but only compared one option of variable fenestration facade (100% opening on the first floor, 80% on the second, 60% on the third, 40% on the fourth and 20% on the top floor) with 100% glazed, and 50% glazed and 50% opaque facade. The study concluded that the variable opening facade option was the most effective in terms of bringing daylight on the lower floors. Aschehoug (1992) on the other hand presented an "optimum" glazing ratio for a glazed street of 50% on the fourth floor, 60% on the third floor, 70% on the second floor and 100% on the first floor to give quite similar daylighting conditions in the adjoining spaces on all of the floors. This shows a lack of consensus, due to the different geometries, with respect to the appropriate approach to facade design (fenestration and opaque atrium surface area ratios) and the improvements in DFs that might be achieved.

Therefore this Chapter explores the influence of different atrium facades on daylight availability in atrium buildings. The experiments are undertaken in RADIANCE, and the findings are discussed and compared with monitored data from real buildings to contextualise the experimental work. Finally, conclusions are drawn with reference to the atrium facade design and presented at the end of the Chapter.

7.2 PARAMETRIC STUDY OF ATRIUM SURFACE REFLECTANCES AND GLAZING RATIOS

7.2.1 Aims and Objectives

The aim of the experiments is to undertake a systematic parametric study of the effects of atrium facades characterised by different ratios of fenestration and opaque surface areas on DFs in the atrium and the adjoining spaces of a four sided, top-lit, square shaped five storey atrium building under overcast sky conditions. It includes a comparison of the performance of several different facade options, both with variable opening sizes as well as even opening sizes on the different floors.

The objective is to establish whether particular fenestration ratios and incremental approach to fenestration from the atrium roof to its floor improves daylight levels in the adjoining spaces.

7.2.2 Methodology

The experiments were undertaken in RADIANCE and used the same methodology as that outlined in Chapter Six (Section 6.2.1). ECOTECT was mainly used as a platform for modelling and adding properties to the atrium models. After completing the data input, models were exported to RADIANCE using the export manager tool for daylighting analysis. Once the calculations were carried out in RADIANCE, data were brought back into ECOTECT using the import/merge and overwrite tool under grid management and was saved as a DAT file produced by RADIANCE.

The proportions of the atrium (16m x 16m x 20m) in relation to its adjoining spaces (depth of 12 m) (Figure 7:1) chosen in this study are representative of the building stock as previously highlighted by Liu et al. (1991), making the study useful in terms of understanding the impact of facades on daylight behaviour in a typical atrium building. The atrium has a WI of 1.25, an AR of 0.64, a PAR of 1 and a SAR of 1.25. No roof elements were used over the atrium well in order to reduce the number of variables under consideration. Cut outs in the atrium facades were made to represent glazing positions, however, no glazing was included. The adjoining spaces had a floor to floor height of four metres and included a one metre zone between the floors to represent the floor structure and the service void leaving a floor to ceiling height of three metres (Figure 7:1). The adjoining spaces were unilaterally lit from the atrium with no windows incorporated in the building's external facades to understand the impact of the atrium and its envelope on the adjoining spaces. Reflectances of all the surfaces were chosen to represent real buildings; the atrium walls and floor were assigned 85% and 40% reflectance respectively. However, when the glazed areas were considered, overall reflectance of the walls was reduced and consequently the area weighted average reflectance of the atria was also reduced. The adjoining space walls, floor and ceiling were assigned 60%, 40% and 95% reflectances respectively.

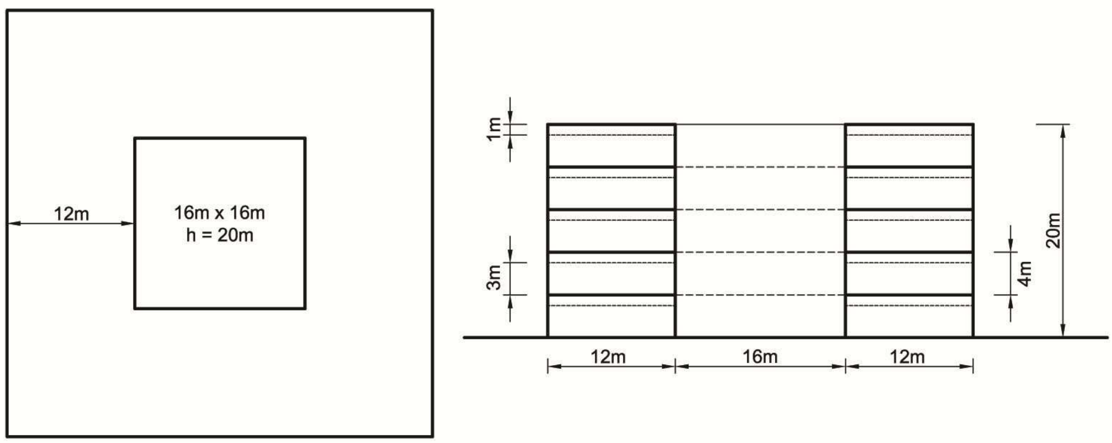


Figure7:1 Atrium building configuration (plan and sectional elevation)

Options with different fenestration ratios were developed for the atrium facade strategy of an incremental increase in fenestration from the top of the atrium to its floor. Performance of the different options of variable facades is compared with each other as well as with the facades comprising even openings. This was done to assess the impact of the strategy of variable fenestration in atrium facades over facades with even openings on all floors typically found in buildings.

Curves 1, 2 and 3 as shown in Tables 7:1, 7:3 and 7:5 were developed; each curve includes five options with 20%, 30%, 40%, 50% and 60% opening on the top floor, followed by a progressive increase in the openings on the intermediate floors and 100% opening on the ground floor. The three curves were developed on the following basis:

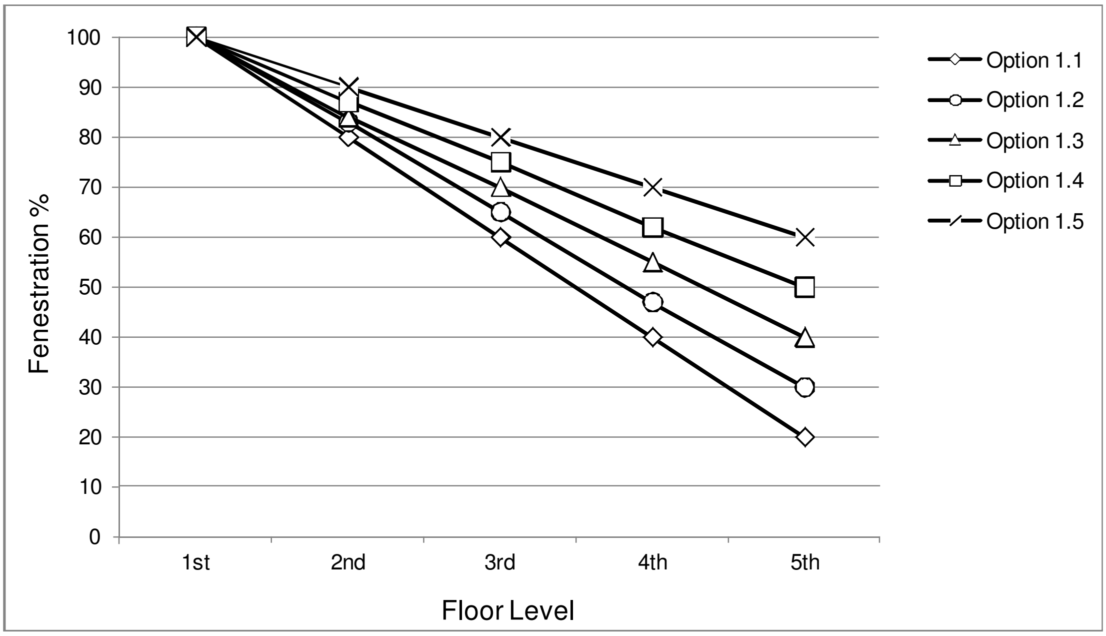
Curve 1 - A consistent and gradual increase in openings from the fifth to the first floor

Curve 2 - A shallow/slow increase in openings on the higher floors followed by a steep increase in openings on the lower floors

Curve 3 - A steep increase in openings on the higher floors followed by a shallow/slow increase in openings on the lower floors

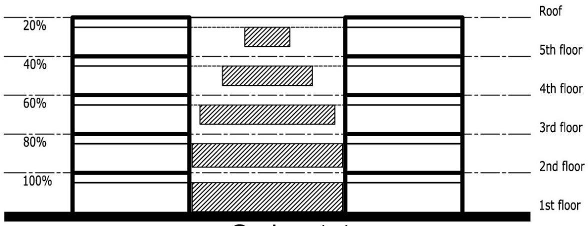
Tables 7:1 and 7:2 (Curve 1); 7:3 and 7:4(Curve 2); and 7:5 and 7:6 (Curve 3) show the different atrium facade elevations and the window size calculations respectively. Windows were always positioned with the top reveal in line with the underside of the service void centred in the plan; keeping a minimum of 0.3 metres from the end walls and a sill of one metre from the floor. Higher window head height above the floor was chosen as it allows deeper penetration of direct daylight into the adjoining room and light the ceiling from which light can be reflected, increasing DF at the rear of the room (Michel, 1996; and Bell and Burt, 1995). The window sill dropped below 1 metre to accommodate an increase in the window size when the maximum window width of 15.4 metres was reached as shown in the window size calculations described in Tables 7:2, 7:4 and 7:6. These tables also show the wall reflectance and area weighted average reflectance of the atria as a result of the different facade options tested.

Table 7:1 Curve 1 with five facade compositions of window distributions

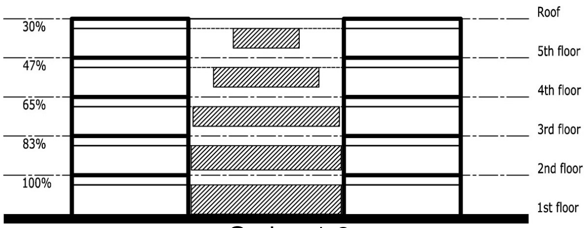


Option	1st floor	2nd floor	3rd floor	4th floor	5th floor
1.1	100	80	60	40	20
1.2	100	83	65	47	30
1.3	100	84	70	55	40
1.4	100	87	75	62	50
1.5	100	90	80	70	60

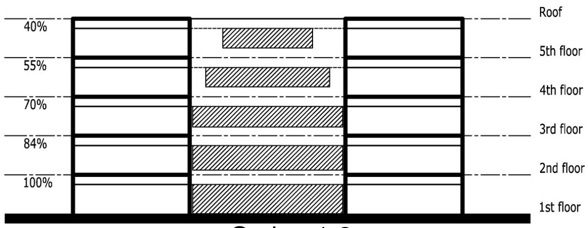
Glazing Ratios



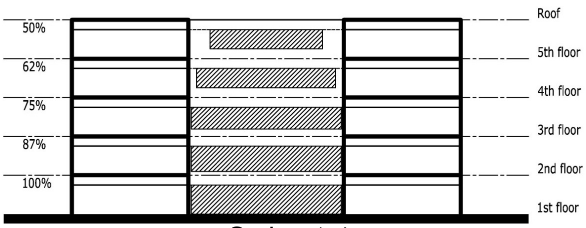
Option 1.1



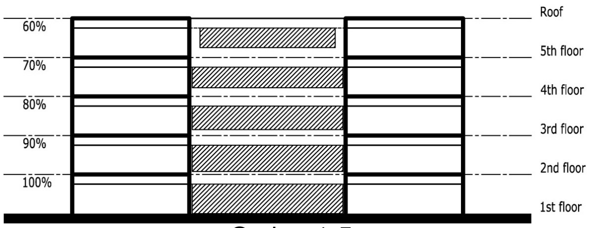
Option 1.2



Option 1.3



Option 1.4

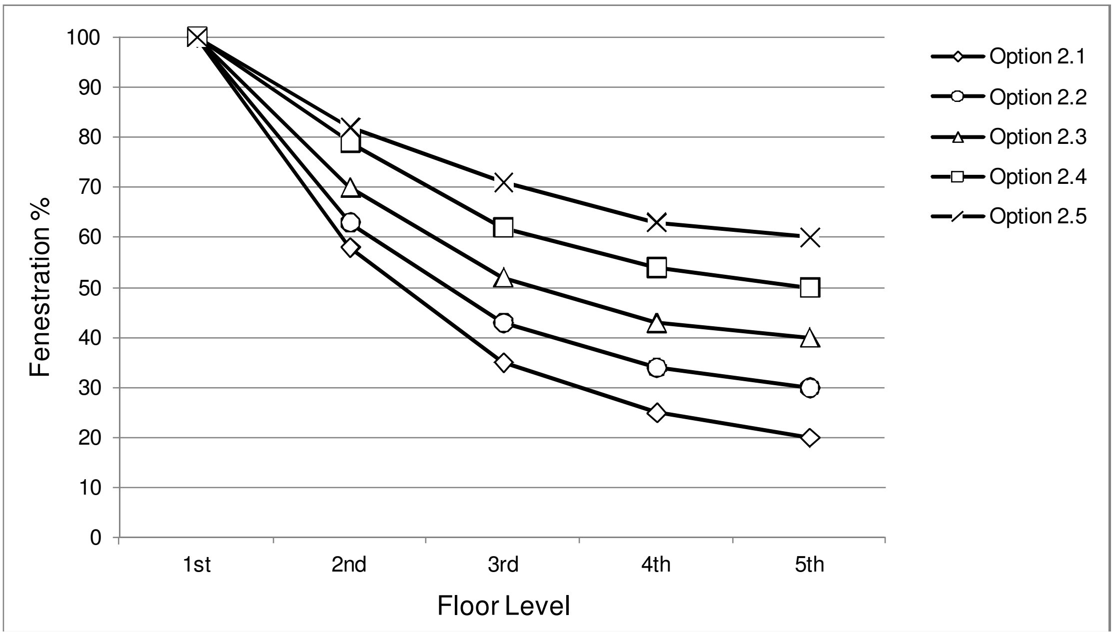


Option 1.5

Table 7:2 Window dimensions for Curve 1

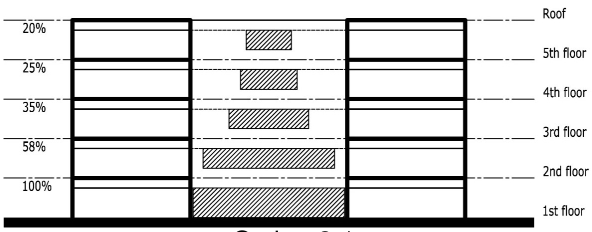
SIZE OF OPENINGS				
OPTION 1	% OF OPENING	OPENING AREA	DIMENSIONS	SILL
1.1	20	9.24	4.62 x 2.00	1.00
Area weighted average	40	18.48	9.24 x 2.00	1.00
Reflectance = 0.39	60	27.72	13.86 x 2.00	1.00
Wall reflectance = 0.47	80	36.96	15.40 x 2.40	0.60
	100	46.20	15.40 x 3.00	0.00
1.2	30	13.86	6.80 x 2.00	1.00
Area weighted average	47	21.71	10.85 x 2.00	1.00
Reflectance = 0.37	65	30.03	15.01 x 2.00	1.00
Wall reflectance = 0.44	83	38.34	15.40 x 2.49	0.51
	100	46.20	15.40 x 3.00	0.00
1.3	40	18.48	9.24 x 2.00	1.00
Area weighted average	55	25.41	12.70 x 2.00	1.00
Reflectance = 0.33	70	32.34	15.40 x 2.10	0.90
Wall reflectance = 0.41	84	38.80	15.40 x 2.52	0.48
	100	46.20	15.40 x 3.00	0.00
1.4	50	23.10	11.55 x 2.00	1.00
Area weighted average	62	28.64	14.32 x 2.00	1.00
Reflectance = 0.33	75	34.65	15.40 x 2.25	0.75
Wall reflectance = 0.38	87	40.19	15.40 x 2.61	0.39
	100	46.20	15.40 x 3.00	0.00
1.5	60	27.72	13.86 x 2.00	1.00
Area weighted average	70	32.34	15.40 x 2.10	0.90
Reflectance = 0.31	80	36.96	15.40 x 2.40	0.60
Wall reflectance = 0.35	90	41.58	15.40 x 2.70	0.30
	100	46.20	15.40 x 3.00	0.00

Table 7:3 Curve 2 with five facade compositions of window distributions

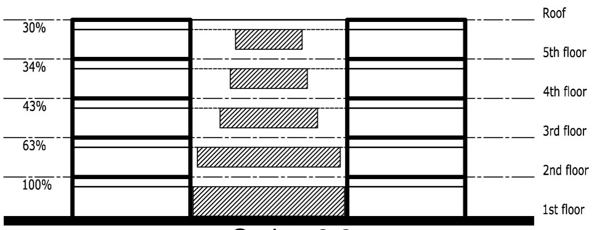


Option	1st floor	2nd floor	3rd floor	4th floor	5th floor
2.1	100	58	35	25	20
2.2	100	63	43	34	30
2.3	100	70	52	43	40
2.4	100	79	62	54	50
2.5	100	82	71	63	60

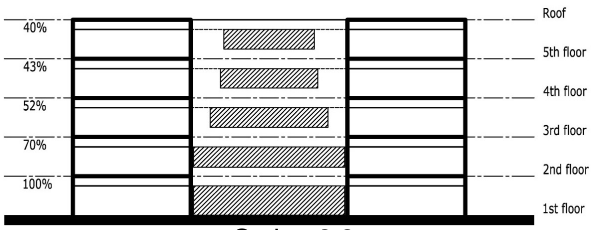
Glazing Ratios



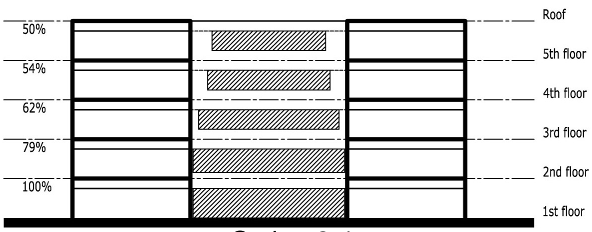
Option 2.1



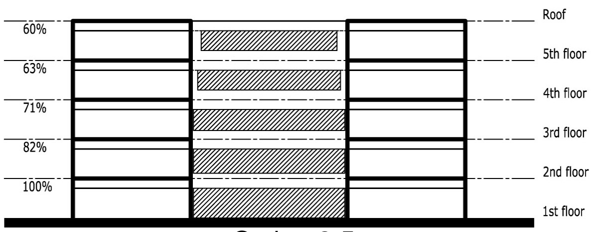
Option 2.2



Option 2.3



Option 2.4

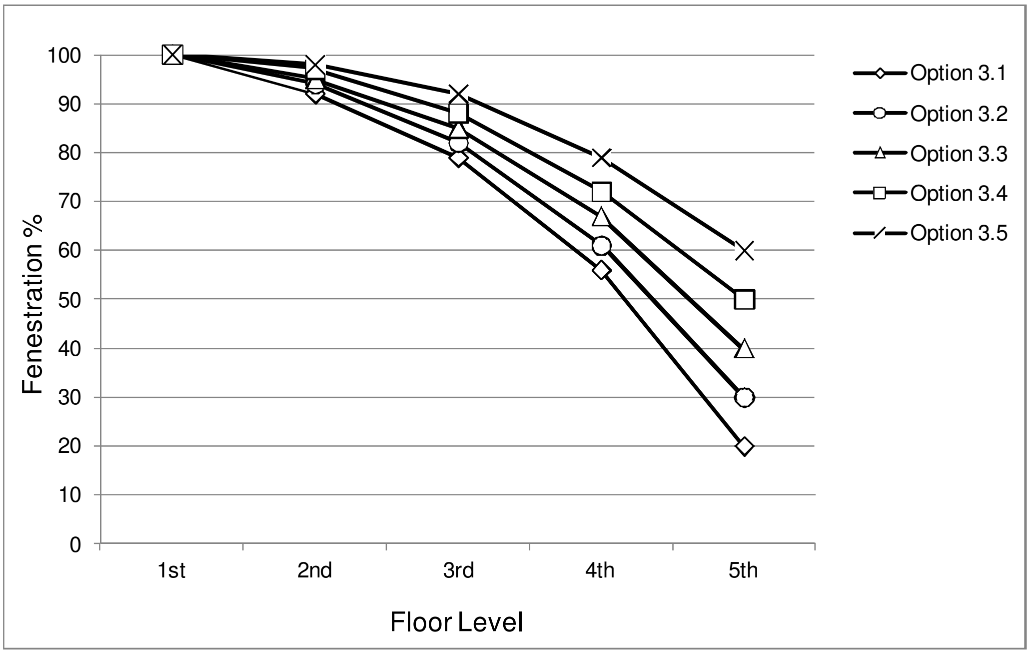


Option 2.5

Table 7:4 Window dimensions for Curve 2

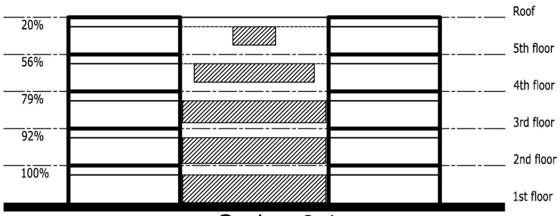
SIZE OF OPENINGS				
OPTION 2	% OF OPENING	OPENING AREA	DIMENSIONS	SILL
2.1	20	9.240	4.62 x 2.00	1.00
Area weighted average	25	11.550	5.77 x 2.00	1.00
Reflectance = 0.45	35	16.170	8.08 x 2.00	1.00
Wall reflectance = 0.55	58	26.796	13.39 x 2.00	1.00
	100	46.200	15.40 x 3.00	0.00
2.2	30	13.860	6.80 x 2.00	1.00
Area weighted average	34	15.708	7.85 x 2.00	1.00
Reflectance = 0.42	43	19.866	9.93 x 2.00	1.00
Wall reflectance = 0.51	63	29.106	14.55 x 2.00	1.00
	100	46.200	15.40 x 3.00	0.00
2.3	40	18.480	9.24 x 2.00	1.00
Area weighted average	43	19.866	9.93 x 2.00	1.00
Reflectance = 0.39	52	24.024	12.01 x 2.00	1.00
Wall reflectance = 0.47	70	32.340	15.40 x 2.10	0.90
	100	46.200	15.40 x 3.00	0.00
2.4	50	23.100	11.55 x 2.00	1.00
Area weighted average	54	24.948	12.47 x 2.00	1.00
Reflectance = 0.35	62	28.644	14.32 x 2.00	1.00
Wall reflectance = 0.42	79	36.489	15.40 x 2.37	0.63
	100	46.200	15.40 x 3.00	0.00
2.5	60	27.720	13.86 x 2.00	1.00
Area weighted average	63	29.106	14.55 x 2.00	1.00
Reflectance = 0.33	71	32.802	15.40 x 2.13	0.87
Wall reflectance = 0.38	82	37.884	15.40 x 2.46	0.54
	100	46.200	15.40 x 3.00	0.00

Table 7:5 Curve 3 with five facade compositions of window distributions

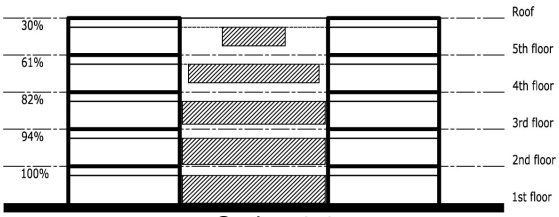


Option	1st floor	2nd floor	3rd floor	4th floor	5th floor
3.1	100	92	79	56	20
3.2	100	94	82	61	30
3.3	100	95	85	67	40
3.4	100	97	88	72	50
3.5	100	98	92	79	60

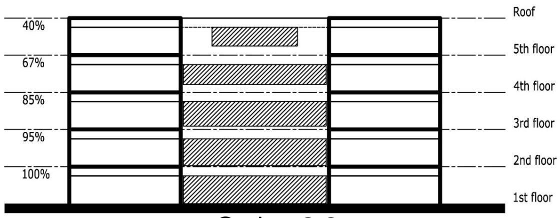
Glazing Ratios



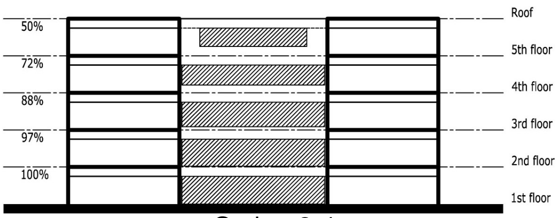
Option 3.1



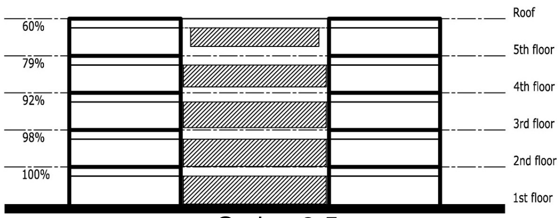
Option 3.2



Option 3.3



Option 3.4



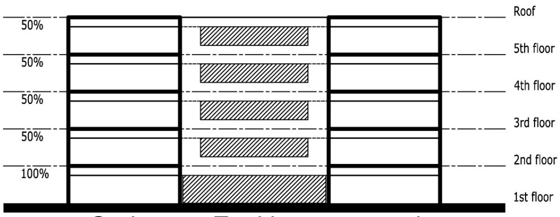
Option 3.5

Table 7:6 Window dimensions for Curve 3

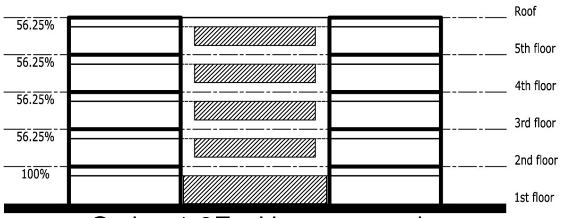
SIZE OF OPENINGS				
OPTION 3	% OF OPENING	OPENING AREA	DIMENSIONS	SILL
3.1	20	9.24	4.62 x 2.00	1.00
Area weighted average	56	25.87	12.93 x 2.00	1.00
Reflectance = 0.35	79	36.49	15.40 x 2.37	0.63
Wall reflectance = 0.41	92	42.50	15.40 x 2.76	0.24
	100	46.20	15.40 x 3.00	0.00
3.2	30	13.86	6.80 x 2.00	1.00
Area weighted average	61	28.18	14.09 x 2.00	1.00
Reflectance = 0.33	82	37.88	15.40 x 2.46	0.54
Wall reflectance = 0.39	94	43.42	15.40 x 2.82	0.18
	100	46.20	15.40 x 3.00	0.00
3.3	40	18.48	9.24 x 2.00	1.00
Area weighted average	67	30.95	15.4 x 2.01	0.99
Reflectance = 0.32	85	39.27	15.4 x 2.55	0.45
Wall reflectance = 0.37	95	43.89	15.4 x 2.85	0.15
	100	46.20	15.4 x 3.00	0.00
3.4	50	23.10	11.55 x 2.00	1.00
Area weighted average	72	33.26	15.40 x 2.16	0.84
Reflectance = 0.30	88	40.65	15.40 x 2.64	0.36
Wall reflectance = 0.34	97	44.81	15.40 x 2.91	0.09
	100	46.20	15.40 x 3.00	0.00
3.5	60	27.72	13.86 x 2.00	1.00
Area weighted average	79	36.49	15.40 x 2.37	0.63
Reflectance = 0.28	92	42.50	15.40 x 2.76	0.24
Wall reflectance = 0.31	98	45.27	15.40 x 2.94	0.06
	100	46.20	15.40 x 3.00	0.00

Atrium facades with even openings on the second to the fifth floor with 100% openings on the first floor were also developed (Table 7:7). Window sizes for the even opening facades were derived from the average of the window sizes used in the facades with variable openings on the second to the fifth floor as shown in Table 7:8. The total area of fenestration for the facades with the even openings was the same as that of the different options developed for the facades with variable openings.

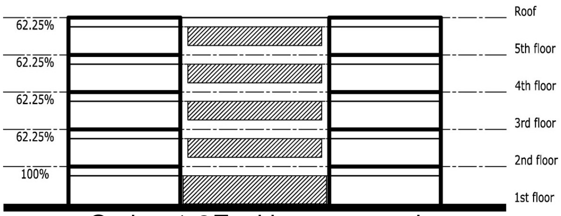
Table 7:7 Elevations of atrium facades with 100% opening on the first floor and even openings on second to the fifth floor for curves 1, 2 and 3



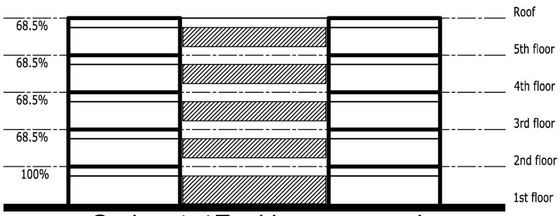
Option 1.1E with even openings



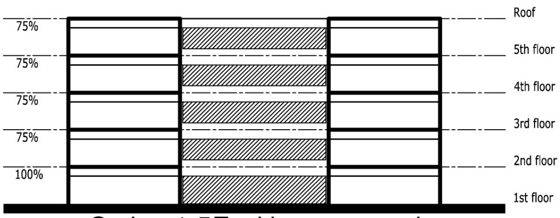
Option 1.2E with even openings



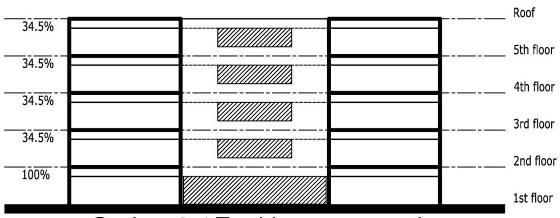
Option 1.3E with even openings



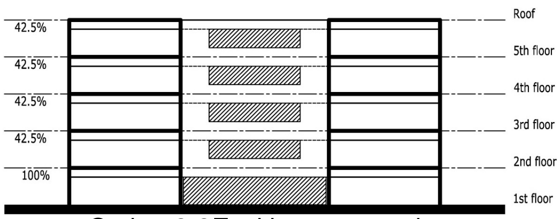
Option 1.4E with even openings



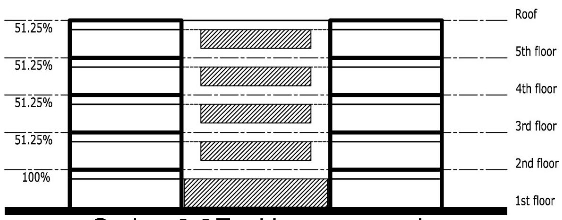
Option 1.5E with even openings



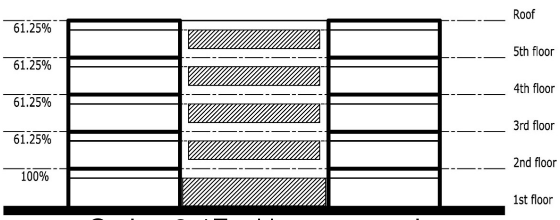
Option 2.1E with even openings



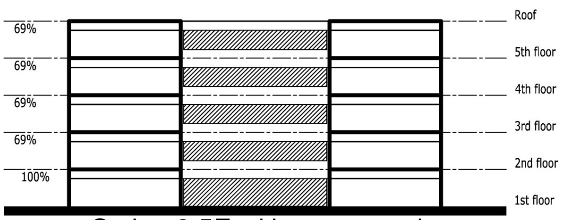
Option 2.2E with even openings



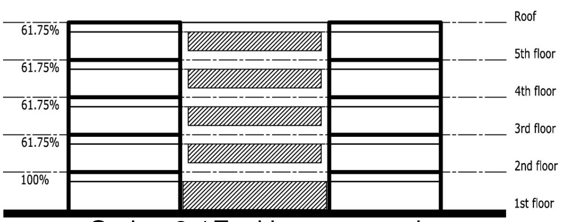
Option 2.3E with even openings



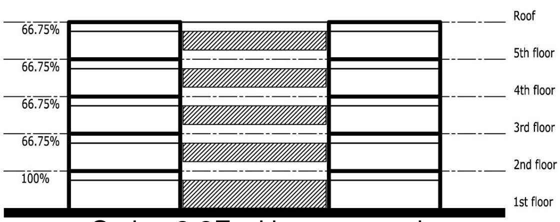
Option 2.4E with even openings



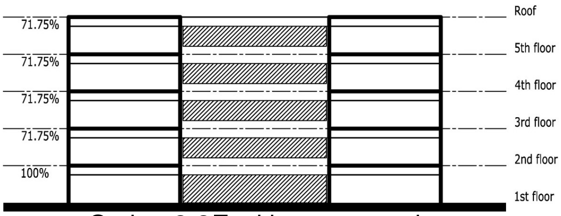
Option 2.5E with even openings



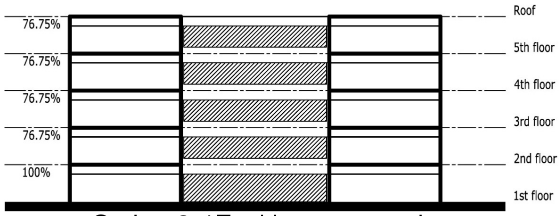
Option 3.1E with even openings



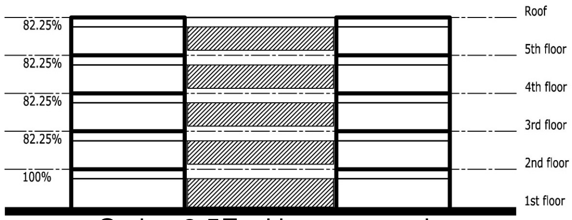
Option 3.2E with even openings



Option 3.3E with even openings



Option 3.4E with even openings



Option 3.5E with even openings

Table 7:8 Window Dimensions for Even Openings for Curves 1, 2, 3

SIZE OF OPENINGS				
EVEN OPTION	% OF OPENING	OPENING AREA	DIMENSIONS	SILL
1.1E	50.00	23.10	11.22 x 2.00	1.00
2.1E	34.50	15.93	7.97 x 2.00	1.00
3.1E	61.75	28.52	14.26 x 2.00	1.00
1.2E	56.25	25.98	12.99 x 2.00	1.00
2.2E	42.50	19.63	9.82 x 2.00	1.00
3.2E	66.75	30.83	15.40 x 2.00	0.99
1.3E	62.25	28.75	14.38 x 2.00	1.00
2.3E	51.25	23.67	11.84 x 2.00	1.00
3.3E	71.75	33.14	15.40 x 2.15	0.84
1.4E	68.50	31.64	15.40 x 2.05	0.94
2.4E	61.25	28.30	14.14 x 2.00	1.00
3.4E	76.75	35.45	15.40 x 2.30	0.69
1.5E	75.00	34.65	15.40 x 2.25	0.75
2.5E	69.00	31.87	15.40 x 2.07	0.93
3.5E	82.25	37.99	15.40 x 2.46	0.53

Cartwright (1985), Cole (1990), Szerman (1992), Baker et al. (1993) and Mabb (2008) showed that the DFs in the adjoining spaces can be established by directly measuring light levels at several positions within the space. Measurement points represented a working plane height of 0.85 metres above the floor level on each of the five floors, including for the atrium centre and wall positions. The depth of the adjoining space is 12 metres and no fenestration was included in the external wall of the adjoining space and therefore no daylight was admitted from here. Horizontal DF measurements were taken for the atrium centre and on the atrium wall positions, and at five positions (at 0.5m, 1m, 2m, 3m, 4m, 5m) in the adjoining space on each floor along its centre line as indicated below.

Position 1: At the centre of the atrium at 0.85 metres

Position 2: On the atrium wall on its centre line and at the centre of the glazed area

Position 3: At 0.5 metre inside the adjoining space along its centre line

Position 4: At 1 metre inside the adjoining space along its centre line

Position 5: At 2 metres inside the adjoining space along its centre line

Position 6: At 3 metres inside the adjoining space along its centre line

Position 7: At 4 metres inside the adjoining space along its centre line

Position 8: At 5 metres inside the adjoining space along its centre line

7.2.3 Results and Discussion

Unless otherwise stated, data presented and its analysis focuses on absolute figures of DFs obtained and where appropriate, relative data is presented in brackets in italics. Table 7:9 shows tabulated DF data obtained for Curve 1 (options 1.1-1.5), Curve 2 (options 2.1-2.5) and Curve 3 (options 3.1-3.5) for atrium facade with progressive increase in openings. It also includes the difference and relative difference from minimum DF observed for the different options for eight measured positions on each of the five floors.

Table 7:9 DF results, difference (diff) and relative difference (diff) from minimum (min) DF for Curves 1, 2 and 3 - (Options 1.1-1.5), (Options 2.1-2.5), (Options 3.1-3.5) for atrium facade with progressive increase in openings

Option	atrium centre 5th floor DF%	Diff from min DF%	Relative diff % from min DF	atrium centre 4th floor DF%	Diff from min DF%	Relative diff % from min DF	atrium centre 3rd floor DF%	Diff from min DF%	Relative diff % from min DF	atrium centre 2nd floor DF%	Diff from min DF%	Relative diff % from min DF	atrium centre 1st floor DF%	Diff from min DF%	Relative diff % from min DF
1.1	96.42	0.90	**0.94**	78.31	1.65	**2.15**	58.99	1.61	**2.81**	43.85	1.52	**3.59**	30.82	0.66	**2.19**
1.2	95.87	0.35	**0.37**	78.37	1.71	**2.23**	59.26	1.88	**3.28**	43.59	1.26	**2.98**	32.11	1.95	**6.47**
1.3	95.52	0.00	**0.00**	78.07	1.41	**1.84**	58.72	1.34	**2.34**	42.39	0.06	**0.14**	30.16	0.00	**0.00**
1.4	95.76	0.24	**0.25**	76.66	0.00	**0.00**	57.38	0.00	**0.00**	42.36	0.03	**0.07**	31.65	1.49	**4.94**
1.5	95.96	0.44	**0.46**	78.01	1.35	**1.76**	57.54	0.16	**0.28**	42.33	0.00	**0.00**	31.53	1.37	**4.54**
2.1	96.00	0.28	**0.29**	77.50	0.15	**0.19**	57.99	0.57	**0.99**	43.18	0.80	**1.89**	32.38	1.02	**3.25**
2.2	96.03	0.31	**0.32**	77.52	0.17	**0.22**	58.16	0.74	**1.29**	43.17	0.79	**1.86**	31.92	0.56	**1.79**
2.3	95.72	0.00	**0.00**	77.82	0.47	**0.61**	57.76	0.34	**0.59**	42.61	0.23	**0.54**	32.30	0.94	**3.00**
2.4	95.98	0.26	**0.27**	77.35	0.00	**0.00**	58.07	0.65	**1.13**	42.39	0.01	**0.02**	32.00	0.64	**2.04**
2.5	96.26	0.54	**0.56**	78.09	0.74	**0.96**	57.42	0.00	**0.00**	42.38	0.00	**0.00**	31.36	0.00	**0.00**
3.1	96.20	0.74	**0.78**	77.95	0.61	**0.79**	58.01	1.11	**1.95**	42.61	0.40	**0.95**	31.46	0.06	**0.19**
3.2	95.95	0.49	**0.51**	78.30	0.96	**1.24**	57.67	0.77	**1.35**	43.24	1.03	**2.44**	31.84	0.44	**1.40**
3.3	95.74	0.28	**0.29**	78.03	0.69	**0.89**	57.52	0.62	**1.09**	42.92	0.71	**1.68**	32.05	0.65	**2.07**
3.4	95.91	0.45	**0.47**	77.34	0.00	**0.00**	57.20	0.30	**0.53**	42.37	0.16	**0.38**	31.65	0.25	**0.80**
3.5	95.46	0.00	**0.00**	77.76	0.42	**0.54**	56.90	0.00	**0.00**	42.21	0.00	**0.00**	31.40	0.00	**0.00**

Option	atrium wall 5th floor DF%	Diff from min DF%	Relative diff % from min DF	atrium wall 4th floor DF%	Diff from min DF%	Relative diff % from min DF	atrium wall 3rd floor DF%	Diff from min DF%	Relative diff % from min DF	atrium wall 2nd floor DF%	Diff from min DF%	Relative diff % from min DF	atrium wall 1st floor DF%	Diff from min DF%	Relative diff % from min DF
1.1	50.36	0.26	**0.52**	43.97	0.63	**1.45**	35.94	0.71	**2.02**	28.41	0.53	**1.90**	22.12	0.13	**0.59**
1.2	50.12	0.02	**0.04**	43.43	0.09	**0.21**	35.37	0.14	**0.40**	27.97	0.09	**0.32**	22.10	0.11	**0.50**
1.3	50.15	0.05	**0.10**	43.34	0.00	**0.00**	35.59	0.36	**1.02**	28.10	0.22	**0.79**	22.14	0.15	**0.68**
1.4	50.10	0.00	**0.00**	43.51	0.17	**0.39**	35.23	0.00	**0.00**	27.88	0.00	**0.00**	22.13	0.14	**0.64**
1.5	50.32	0.22	**0.44**	43.47	0.13	**0.30**	35.32	0.09	**0.26**	28.09	0.21	**0.75**	21.99	0.00	**0.00**
2.1	49.95	0.02	**0.04**	43.39	0.42	**0.98**	35.43	0.49	**1.40**	28.01	0.26	**0.94**	22.14	0.10	**0.45**
2.2	49.93	0.00	**0.00**	43.22	0.25	**0.58**	35.25	0.31	**0.89**	28.02	0.27	**0.97**	22.22	0.18	**0.82**
2.3	50.08	0.15	**0.30**	43.36	0.39	**0.91**	35.27	0.33	**0.94**	27.92	0.17	**0.61**	22.13	0.09	**0.41**
2.4	50.06	0.13	**0.26**	43.55	0.58	**1.35**	35.19	0.25	**0.72**	27.75	0.00	**0.00**	22.04	0.00	**0.00**
2.5	50.28	0.35	**0.70**	42.97	0.00	**0.00**	34.94	0.00	**0.00**	27.83	0.08	**0.29**	22.09	0.05	**0.23**
3.1	49.92	0.00	**0.00**	43.52	0.36	**0.83**	35.26	0.03	**0.09**	28.14	0.39	**1.41**	22.17	0.23	**1.05**
3.2	50.07	0.15	**0.30**	43.34	0.18	**0.42**	35.24	0.01	**0.03**	28.57	0.82	**2.95**	21.97	0.03	**0.14**
3.3	50.15	0.23	**0.46**	43.16	0.00	**0.00**	35.33	0.10	**0.28**	27.75	0.00	**0.00**	22.18	0.24	**1.09**
3.4	50.20	0.28	**0.56**	43.47	0.31	**0.72**	35.36	0.13	**0.37**	27.89	0.14	**0.50**	21.99	0.05	**0.23**
3.5	50.22	0.30	**0.60**	43.36	0.20	**0.46**	35.23	0.00	**0.00**	27.82	0.07	**0.25**	21.94	0.00	**0.00**

Option	0.5m 5th floor DF%	Diff from min DF%	Relative diff % from min DF	0.5m 4th floor DF%	Diff from min DF%	Relative diff % from min DF	0.5m 3rd floor DF%	Diff from min DF%	Relative diff % from min DF	0.5m 2nd floor DF%	Diff from min DF%	Relative diff % from min DF	0.5m 1st floor DF%	Diff from min DF%	Relative diff % from min DF
1.1	30.25	0.00	**0.00**	30.68	0.80	**2.68**	24.03	0.00	**0.00**	19.43	0.56	**2.97**	14.52	0.06	**0.41**
1.2	35.00	4.75	**15.70**	30.22	0.34	**1.14**	24.18	0.15	**0.62**	19.15	0.28	**1.48**	14.67	0.21	**1.45**
1.3	34.89	4.64	**15.34**	29.88	0.00	**0.00**	24.99	0.96	**4.00**	18.93	0.06	**0.32**	14.84	0.38	**2.63**
1.4	35.04	4.79	**15.83**	30.22	0.34	**1.14**	24.54	0.51	**2.12**	18.87	0.00	**0.00**	14.46	0.00	**0.00**
1.5	34.82	4.57	**15.11**	31.14	1.26	**4.22**	24.55	0.52	**2.16**	18.98	0.11	**0.58**	14.47	0.01	**0.07**
2.1	33.59	0.00	**0.00**	30.28	0.30	**1.00**	24.32	0.27	**1.12**	18.70	0.22	**1.19**	14.90	0.40	**2.76**
2.2	34.63	1.04	**3.10**	30.04	0.06	**0.20**	24.11	0.06	**0.25**	18.48	0.00	**0.00**	14.63	0.13	**0.90**
2.3	34.81	1.22	**3.63**	29.98	0.00	**0.00**	24.27	0.22	**0.91**	18.93	0.45	**2.44**	14.50	0.00	**0.00**
2.4	34.84	1.25	**3.72**	29.99	0.01	**0.03**	24.05	0.00	**0.00**	19.06	0.58	**3.14**	14.60	0.10	**0.69**
2.5	35.29	1.70	**5.06**	30.05	0.07	**0.23**	24.46	0.41	**1.70**	18.89	0.41	**2.22**	14.64	0.14	**0.97**
3.1	33.61	0.00	**0.00**	30.37	0.06	**0.20**	24.87	0.42	**1.72**	18.82	0.00	**0.00**	14.65	0.24	**1.67**
3.2	35.12	1.51	**4.49**	30.60	0.29	**0.96**	24.60	0.15	**0.61**	18.95	0.13	**0.69**	14.41	0.00	**0.00**
3.3	35.06	1.45	**4.31**	30.31	0.00	**0.00**	24.45	0.00	**0.00**	18.91	0.09	**0.48**	14.45	0.04	**0.28**
3.4	35.04	1.43	**4.25**	30.85	0.54	**1.78**	24.81	0.36	**1.47**	18.96	0.14	**0.74**	14.74	0.33	**2.29**
3.5	35.19	1.58	**4.70**	30.49	0.18	**0.59**	24.83	0.38	**1.55**	18.90	0.08	**0.43**	14.60	0.19	**1.32**

Option	1m 5th floor DF%	Diff from min DF%	Relative diff % from min DF	1m 4th floor DF%	Diff from min DF%	Relative diff % from min DF	1m 3rd floor DF%	Diff from min DF%	Relative diff % from min DF	1m 2nd floor DF%	Diff from min DF%	Relative diff % from min DF	1m 1st floor DF%	Diff from min DF%	Relative diff % from min DF
1.1	20.92	0.00	**0.00**	21.41	0.44	**2.10**	16.04	0.00	**0.00**	12.51	0.64	**5.39**	8.78	0.31	**3.66**
1.2	25.24	4.32	**20.65**	21.36	0.39	**1.86**	16.26	0.22	**1.37**	12.00	0.13	**1.10**	8.56	0.09	**1.06**
1.3	25.76	4.84	**23.14**	20.97	0.00	**0.00**	16.72	0.68	**4.24**	12.13	0.26	**2.19**	8.48	0.01	**0.12**
1.4	26.02	5.10	**24.38**	21.52	0.55	**2.62**	16.48	0.44	**2.74**	12.11	0.24	**2.02**	8.71	0.24	**2.83**
1.5	25.70	4.78	**22.85**	21.45	0.48	**2.29**	16.43	0.39	**2.43**	11.87	0.00	**0.00**	8.47	0.00	**0.00**
2.1	24.20	0.00	**0.00**	20.62	0.00	**0.00**	16.06	0.00	**0.00**	12.23	0.50	**4.26**	8.65	0.08	**0.93**
2.2	25.33	1.13	**4.67**	20.85	0.23	**1.12**	16.17	0.11	**0.68**	11.73	0.00	**0.00**	8.61	0.04	**0.47**
2.3	25.86	1.66	**6.86**	20.86	0.24	**1.16**	16.31	0.25	**1.56**	12.07	0.34	**2.90**	8.71	0.14	**1.63**
2.4	25.73	1.53	**6.32**	20.95	0.33	**1.60**	16.16	0.10	**0.62**	11.90	0.17	**1.45**	8.67	0.10	**1.17**
2.5	25.94	1.74	**7.19**	20.94	0.32	**1.55**	16.34	0.28	**1.74**	12.26	0.53	**4.52**	8.57	0.00	**0.00**
3.1	24.18	0.00	**0.00**	21.32	0.39	**1.86**	16.32	0.10	**0.62**	12.10	0.37	**3.15**	8.49	0.00	**0.00**
3.2	25.56	1.38	**5.71**	21.57	0.64	**3.06**	16.47	0.25	**1.54**	11.73	0.00	**0.00**	8.71	0.22	**2.59**
3.3	25.54	1.36	**5.62**	20.98	0.05	**0.24**	16.23	0.01	**0.06**	11.86	0.13	**1.11**	8.56	0.07	**0.82**
3.4	25.96	1.78	**7.36**	21.55	0.62	**2.96**	16.49	0.27	**1.66**	12.03	0.30	**2.56**	8.52	0.03	**0.35**
3.5	25.72	1.54	**6.37**	20.93	0.00	**0.00**	16.22	0.00	**0.00**	11.96	0.23	**1.96**	8.65	0.16	**1.88**

Option	2m 5th floor DF%	Diff from min DF%	Relative diff % from min DF	2m 4th floor DF%	Diff from min DF%	Relative diff % from min DF	2m 3rd floor DF%	Diff from min DF%	Relative diff % from min DF	2m 2nd floor DF%	Diff from min DF%	Relative diff % from min DF	2m 1st floor DF%	Diff from min DF%	Relative diff % from min DF
1.1	9.72	0.00	**0.00**	9.90	0.15	**1.54**	6.77	0.09	**1.35**	4.44	0.32	**7.77**	2.06	0.10	**5.10**
1.2	11.87	2.15	**22.12**	9.87	0.12	**1.23**	6.73	0.05	**0.75**	4.12	0.00	**0.00**	2.04	0.08	**4.08**
1.3	12.48	2.76	**28.40**	9.75	0.00	**0.00**	6.98	0.30	**4.49**	4.19	0.07	**1.70**	2.03	0.07	**3.57**
1.4	12.81	3.09	**31.79**	9.88	0.13	**1.33**	6.71	0.03	**0.45**	4.12	0.00	**0.00**	2.01	0.05	**2.55**
1.5	12.72	3.00	**30.86**	9.89	0.14	**1.44**	6.68	0.00	**0.00**	4.18	0.06	**1.46**	1.96	0.00	**0.00**
2.1	10.74	0.00	**0.00**	8.98	0.00	**0.00**	6.61	0.21	**3.28**	4.20	0.05	**1.20**	2.06	0.08	**4.04**
2.2	12.07	1.33	**12.38**	9.85	0.87	**9.69**	6.40	0.00	**0.00**	4.19	0.04	**0.96**	2.04	0.06	**3.03**
2.3	12.52	1.78	**16.57**	9.69	0.71	**7.91**	6.63	0.23	**3.59**	4.29	0.14	**3.37**	2.05	0.07	**3.54**
2.4	12.65	1.91	**17.78**	9.53	0.55	**6.12**	6.60	0.20	**3.12**	4.15	0.00	**0.00**	2.01	0.03	**1.52**
2.5	12.82	2.08	**19.37**	9.51	0.53	**5.90**	6.71	0.31	**4.84**	4.17	0.02	**0.48**	1.98	0.00	**0.00**
3.1	10.76	0.00	**0.00**	9.46	0.00	**0.00**	6.77	0.10	**1.50**	4.40	0.50	**12.82**	2.06	0.09	**4.57**
3.2	12.31	1.55	**14.41**	9.89	0.43	**4.55**	6.76	0.09	**1.35**	4.22	0.32	**8.21**	2.01	0.04	**2.03**
3.3	12.42	1.66	**15.43**	9.55	0.09	**0.95**	6.85	0.18	**2.70**	4.16	0.26	**6.67**	2.02	0.05	**2.54**
3.4	12.57	1.81	**16.82**	9.63	0.17	**1.80**	6.77	0.10	**1.50**	4.14	0.24	**6.15**	1.97	0.00	**0.00**
3.5	12.90	2.14	**19.89**	9.59	0.13	**1.37**	6.67	0.00	**0.00**	3.90	0.00	**0.00**	2.00	0.03	**1.52**

Option	3m 5th floor DF%	Diff from min DF%	Relative diff % from min DF	3m 4th floor DF%	Diff from min DF%	Relative diff % from min DF	3m 3rd floor DF%	Diff from min DF%	Relative diff % from min DF	3m 2nd floor DF%	Diff from min DF%	Relative diff % from min DF	3m 1st floor DF%	Diff from min DF%	Relative diff % from min DF
1.1	4.77	0.00	**0.00**	4.63	0.06	**1.31**	2.90	0.11	**3.94**	1.75	0.17	**10.76**	1.03	0.05	**5.10**
1.2	6.03	1.26	**26.42**	4.58	0.01	**0.22**	2.79	0.00	**0.00**	1.60	0.02	**1.27**	0.98	0.00	**0.00**
1.3	6.35	1.58	**33.12**	4.57	0.00	**0.00**	3.10	0.31	**11.11**	1.58	0.00	**0.00**	1.34	0.36	**36.73**
1.4	6.65	1.88	**39.41**	4.82	0.25	**5.47**	2.91	0.12	**4.30**	1.58	0.00	**0.00**	0.98	0.00	**0.00**
1.5	6.88	2.11	**44.23**	4.88	0.31	**6.78**	2.88	0.09	**3.23**	1.59	0.01	**0.63**	0.98	0.00	**0.00**
2.1	4.97	0.00	**0.00**	3.99	0.00	**0.00**	2.67	0.00	**0.00**	1.61	0.04	**2.55**	1.04	0.06	**6.12**
2.2	6.02	1.05	**21.13**	4.21	0.22	**5.51**	2.71	0.04	**1.50**	1.60	0.03	**1.91**	1.01	0.03	**3.06**
2.3	6.67	1.70	**34.21**	4.55	0.56	**14.04**	2.86	0.19	**7.12**	1.60	0.03	**1.91**	0.98	0.00	**0.00**
2.4	6.65	1.68	**33.80**	4.48	0.49	**12.28**	2.78	0.11	**4.12**	1.57	0.00	**0.00**	1.00	0.02	**2.04**
2.5	6.71	1.74	**35.01**	4.71	0.72	**18.05**	2.87	0.20	**7.49**	1.58	0.01	**0.64**	0.98	0.00	**0.00**
3.1	5.05	0.00	**0.00**	4.70	0.14	**3.07**	2.93	0.10	**3.53**	1.61	0.06	**3.87**	1.01	0.04	**4.12**
3.2	6.08	1.03	**20.40**	4.89	0.33	**7.24**	2.83	0.00	**0.00**	1.55	0.00	**0.00**	0.97	0.00	**0.00**
3.3	6.84	1.79	**35.45**	4.56	0.00	**0.00**	2.85	0.02	**0.71**	1.56	0.01	**0.65**	0.98	0.01	**1.03**
3.4	6.61	1.56	**30.89**	4.68	0.12	**2.63**	3.12	0.29	**10.25**	1.59	0.04	**2.58**	0.99	0.02	**2.06**
3.5	6.69	1.64	**32.48**	4.71	0.15	**3.29**	2.84	0.01	**0.35**	1.58	0.03	**1.94**	0.98	0.01	**1.03**

Option	4m 5th floor DF%	Diff from min DF%	Relative diff % from min DF	4m 4th floor DF%	Diff from min DF%	Relative diff % from min DF	4m 3rd floor DF%	Diff from min DF%	Relative diff % from min DF	4m 2nd floor DF%	Diff from min DF%	Relative diff % from min DF	4m 1st floor DF%	Diff from min DF%	Relative diff % from min DF
1.1	2.57	0.00	**0.00**	2.59	0.07	**2.78**	1.39	0.00	**0.00**	1.10	0.12	**12.24**	0.60	0.01	**1.69**
1.2	3.40	0.83	**32.30**	2.55	0.03	**1.19**	1.41	0.02	**1.44**	0.99	0.01	**1.02**	0.60	0.01	**1.69**
1.3	3.68	1.11	**43.19**	2.52	0.00	**0.00**	1.56	0.17	**12.23**	0.98	0.00	**0.00**	0.75	0.16	**27.12**
1.4	3.88	1.31	**50.97**	2.75	0.23	**9.13**	1.47	0.08	**5.76**	1.01	0.03	**3.06**	0.59	0.00	**0.00**
1.5	4.00	1.43	**55.64**	2.80	0.28	**11.11**	1.42	0.03	**2.16**	1.00	0.02	**2.04**	0.60	0.01	**1.69**
2.1	2.66	0.00	**0.00**	2.07	0.00	**0.00**	1.25	0.00	**0.00**	0.97	0.00	**0.00**	0.61	0.03	**5.17**
2.2	3.35	0.69	**25.94**	2.26	0.19	**9.18**	1.31	0.06	**4.80**	0.98	0.01	**1.03**	0.62	0.04	**6.90**
2.3	3.78	1.12	**42.11**	2.52	0.45	**21.74**	1.36	0.11	**8.80**	0.98	0.01	**1.03**	0.62	0.04	**6.90**
2.4	3.89	1.23	**46.24**	2.52	0.45	**21.74**	1.38	0.13	**10.40**	1.02	0.05	**5.15**	0.60	0.02	**3.45**
2.5	3.92	1.26	**47.37**	2.58	0.51	**24.64**	1.44	0.19	**15.20**	1.00	0.03	**3.09**	0.58	0.00	**0.00**
3.1	2.74	0.00	**0.00**	2.61	0.00	**0.00**	1.44	0.00	**0.00**	1.01	0.02	**2.02**	0.59	0.00	**0.00**
3.2	3.46	0.72	**26.28**	2.75	0.14	**5.36**	1.46	0.02	**1.39**	0.99	0.00	**0.00**	0.59	0.00	**0.00**
3.3	3.08	0.34	**12.41**	2.64	0.03	**1.15**	1.47	0.03	**2.08**	1.01	0.02	**2.02**	0.61	0.02	**3.39**
3.4	3.89	1.15	**41.97**	2.78	0.17	**6.51**	1.65	0.21	**14.58**	1.01	0.02	**2.02**	0.59	0.00	**0.00**
3.5	3.97	1.23	**44.89**	2.64	0.03	**1.15**	1.48	0.04	**2.78**	1.00	0.01	**1.01**	0.59	0.00	**0.00**

Option	5m 5th floor DF%	Diff from min DF%	Relative diff % from min DF	5m 4th floor DF%	Diff from min DF%	Relative diff % from min DF	5m 3rd floor DF%	Diff from min DF%	Relative diff % from min DF	5m 2nd floor DF%	Diff from min DF%	Relative diff % from min DF	5m 1st floor DF%	Diff from min DF%	Relative diff % from min DF
1.1	1.51	0.00	**0.00**	1.42	0.01	**0.71**	0.97	0.03	**3.19**	0.76	0.07	**10.14**	0.42	0.05	**13.51**
1.2	1.99	0.48	**31.79**	1.41	0.00	**0.00**	0.94	0.00	**0.00**	0.71	0.02	**2.90**	0.42	0.05	**13.51**
1.3	2.25	0.74	**49.01**	1.50	0.09	**6.38**	1.04	0.10	**10.64**	0.69	0.00	**0.00**	0.47	0.10	**27.03**
1.4	2.39	0.88	**58.28**	1.64	0.23	**16.31**	1.00	0.06	**6.38**	0.69	0.00	**0.00**	0.37	0.00	**0.00**
1.5	2.51	1.00	**66.23**	1.68	0.27	**19.15**	0.99	0.05	**5.32**	0.69	0.00	**0.00**	0.41	0.04	**10.81**
2.1	1.59	0.00	**0.00**	1.12	0.00	**0.00**	0.77	0.00	**0.00**	0.65	0.00	**0.00**	0.42	0.02	**5.00**
2.2	2.07	0.48	**30.19**	1.24	0.12	**10.71**	0.85	0.08	**10.39**	0.66	0.01	**1.54**	0.40	0.00	**0.00**
2.3	2.19	0.60	**37.74**	1.39	0.27	**24.11**	0.90	0.13	**16.88**	0.68	0.03	**4.62**	0.42	0.02	**5.00**
2.4	2.36	0.77	**48.43**	1.44	0.32	**28.57**	0.94	0.17	**22.08**	0.68	0.03	**4.62**	0.42	0.02	**5.00**
2.5	2.57	0.98	**61.64**	1.47	0.35	**31.25**	0.95	0.18	**23.38**	0.69	0.04	**6.15**	0.40	0.00	**0.00**
3.1	1.52	0.00	**0.00**	1.46	0.00	**0.00**	1.01	0.00	**0.00**	0.71	0.02	**2.90**	0.41	0.01	**2.50**
3.2	2.01	0.49	**32.24**	1.63	0.17	**11.64**	1.01	0.00	**0.00**	0.70	0.01	**1.45**	0.40	0.00	**0.00**
3.3	2.21	0.69	**45.39**	1.57	0.11	**7.53**	1.01	0.00	**0.00**	0.70	0.01	**1.45**	0.41	0.01	**2.50**
3.4	2.40	0.88	**57.89**	1.51	0.05	**3.42**	1.15	0.14	**13.86**	0.69	0.00	**0.00**	0.40	0.00	**0.00**
3.5	2.38	0.86	**56.58**	1.60	0.14	**9.59**	1.01	0.00	**0.00**	0.70	0.01	**1.45**	0.41	0.01	**2.50**

DFs obtained from the three curves are also presented in Figures 7:2 to 7:7; Figures 7:2 and 7:3 present DFs for Curve 1, Figures 7:4 and 7:5 present results for Curve 2 while Figures 7:6 and 7:7 give DFs for Curve 3. Data for each curve and its options has been split into two figures to show the results clearly; one includes DF data for atrium centre, atrium wall, and 0.5m, 1m and 2m positions inside the adjoining spaces while the other includes DF data for 2m, 3m, 4m and 5m positions inside the adjoining spaces.

While the tables show more specific values, graphs are used to discuss and compare results, plot DF distributions and interpret the trends. DFs will reduce significantly when the atrium roof, windows and the correction factors are considered as discussed previously. Therefore an approximate 50% reduction is applied to the DF data obtained for both the variable and the even opening atrium facade options to assess daylight availability in the chosen atrium configuration, as well as to make comparisons of data from the RADIANCE atrium models with that obtained in real atrium buildings.

Variable Fenestration in atrium facades: DFs for Curves 1, 2 and 3

It is noted that DFs in the adjoining spaces are sufficiently high and in most cases above the recommended minimum of 2% (BS Daylight Code, 1992) for up to 1m position on all floors; up to 2m position on the second, third, fourth and fifth floor; up to 3m position on the fourth and fifth floor; and up to 4m into the adjoining space on the fifth floor. For offices, Kwok and Grondzik (2007) suggest a minimum DF of 0.6% for corridors, therefore corridors can be incorporated at 5 metres in the adjoining space on the fourth and the fifth floor, at 4metre position on the second and third floor and at 3 metre position on the first floor. Beyond these points supplementary artificial lighting will be required. Although adjoining spaces in this study were only unilaterally lit, in reality, these spaces will usually be bilaterally lit and will have higher DFs and improved daylight distribution than that presented in this study.

Figures 7:2 to 7:7 showed that there is a marked difference in the daylight levels in the top floor adjoining space due to changes in the atrium facade fenestration. For Curve 1 (Figure

7:2 and 7:3), maximum differences in the DFs between the five facade options (1.1, 1.2, 1.3, 1.4 and 1.5) at 0.5m, 1m, 2m, 3m, 4m and 5m positions in the adjoining space were 4.8%, 5.1%, 3%, 2.1%, 1.4% and 1% *(relative difference of 14%, 24%, 24%, 30%, 36% and 40%)* respectively.

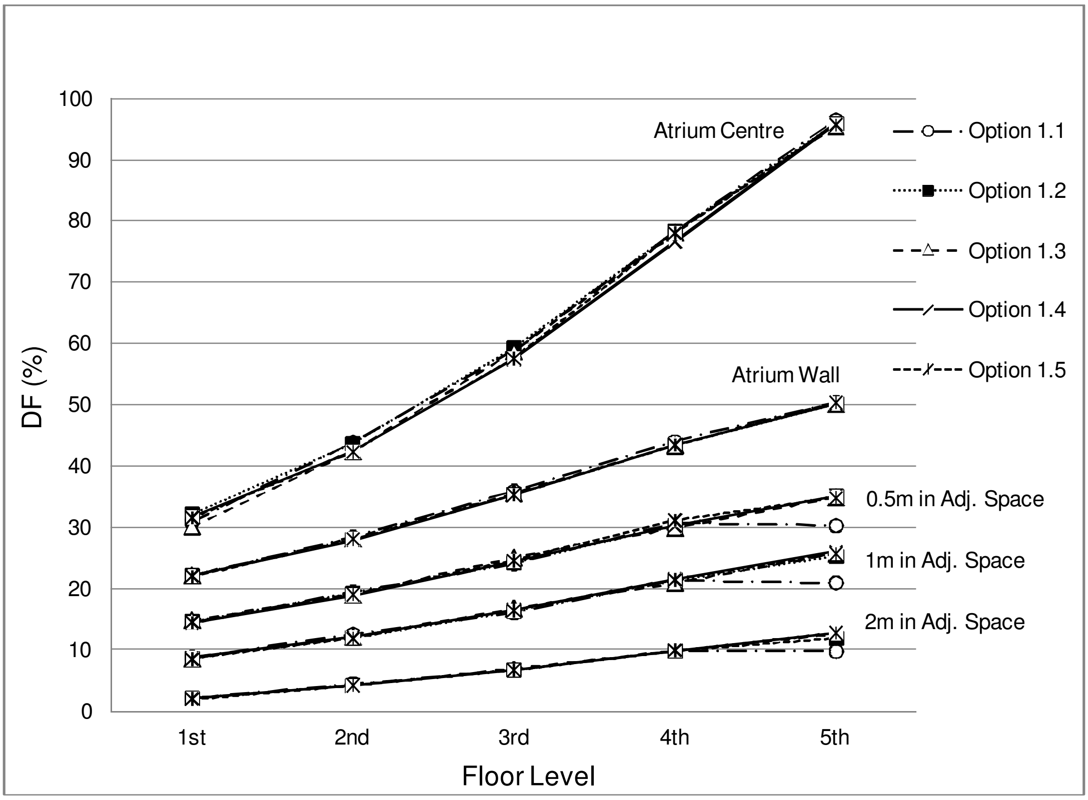


Figure 7:2 DFs for curve 1 (options 1.1 to 1.5) at atrium centre, atrium wall, 0.5m, 1m, and 2m into the adjoining space

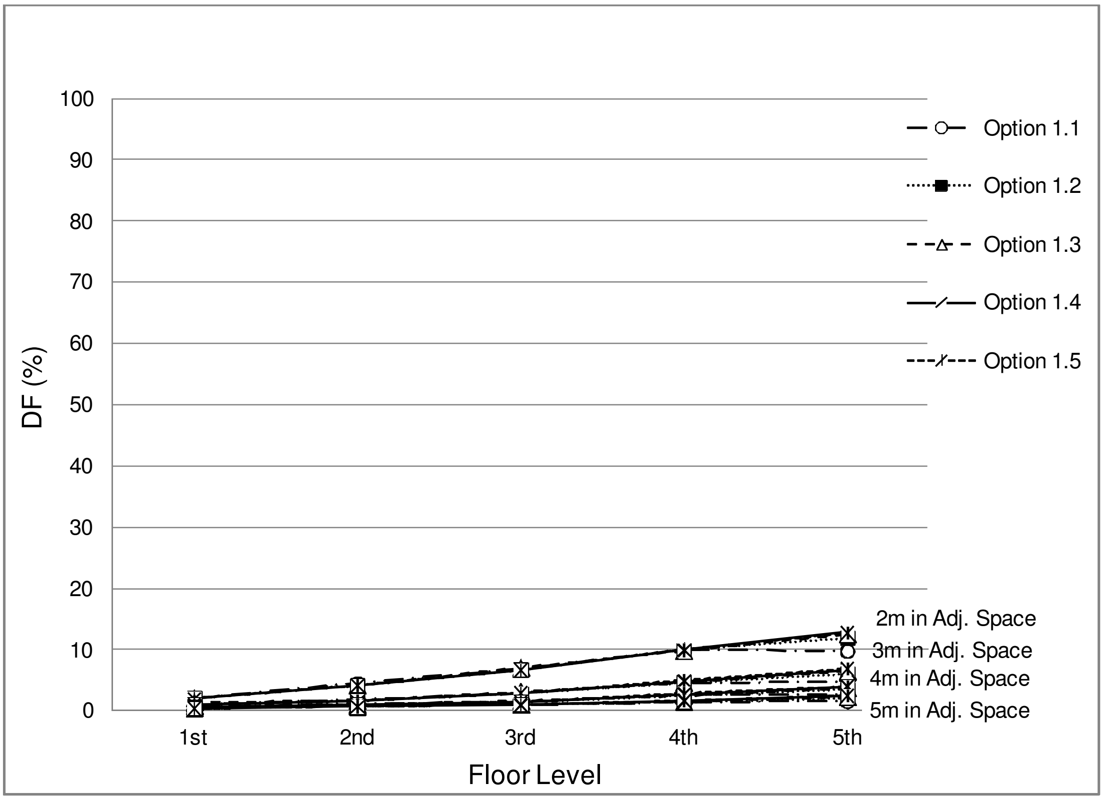


Figure 7:3 DFs for curve 1 (options 1.1 to 1.5) at 2m, 3m, 4m and 5m into the adjoining space

For Curve 2, Figures 7:4 and 7:5 show that in comparison with Curve 1, impact of the different fenestration options (2.1, 2.2, 2.3, 2.4 and 2.5) was reduced. The maximum differences in DFs for the five facade options at 0.5m, 1m, 2m, 3m, 4m and 5m positions in the adjoining space were 1.7%, 1.7%, 2.1%, 1.7%, 1.3%, and 1% *(relative difference of 5%, 7%, 16%, 26%, 32% and 38%)* respectively.

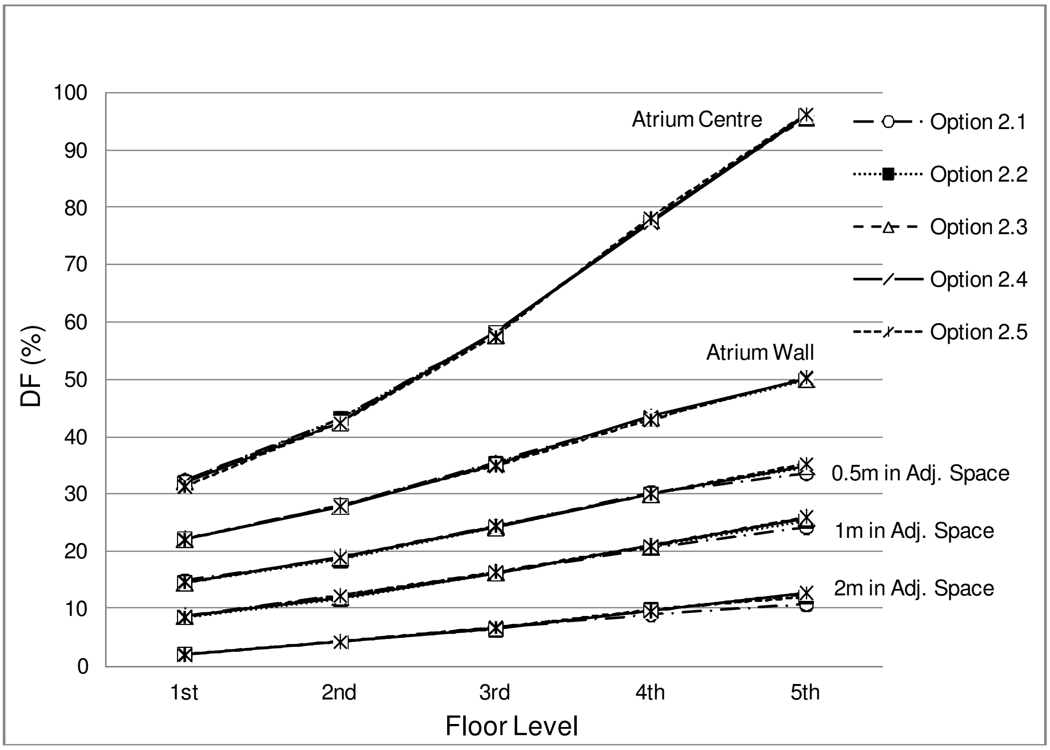


Figure 7:4 DFs for curve 2 (options 2.1 to 2.5) at atrium centre, atrium wall, 0.5m, 1m, and 2m into the adjoining space

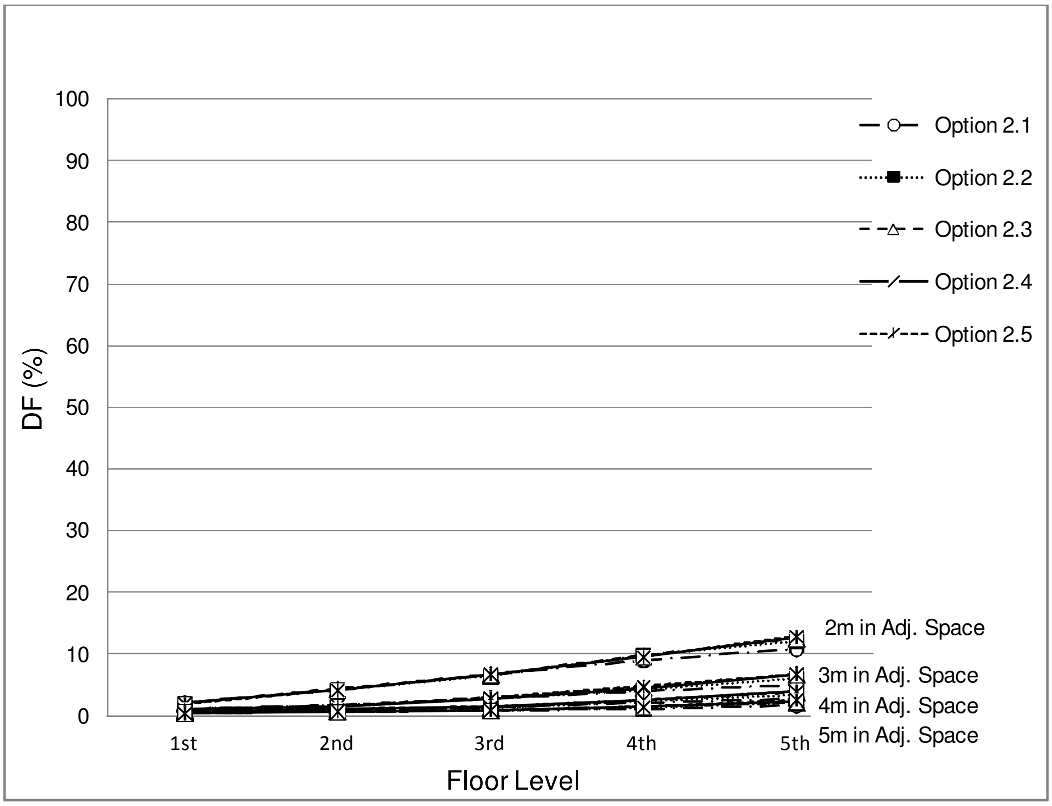


Figure 7:5 DFs for curve 2 (options 2.1 to 2.5) at 2m, 3m, 4m and 5m into the adjoining space

For curve 3, Figures 7:6 and 7:7 show that in comparison with Curves 1 and 2, difference in DFs due to the different facade options (3.1, 3.2, 3.3, 3.4 and 3.5) were even lower for most positions in the top floor adjoining space. Maximum differences in the DFs at 0.5m, 1m, 2m, 3m, 4m and 5m positions in the adjoining space were 1.6%, 1.8%, 2.1%, 1.8%, 1.2% and 0.9% *(relative difference of 4%, 7%, 17%, 26%, 31% and 37%)* respectively.

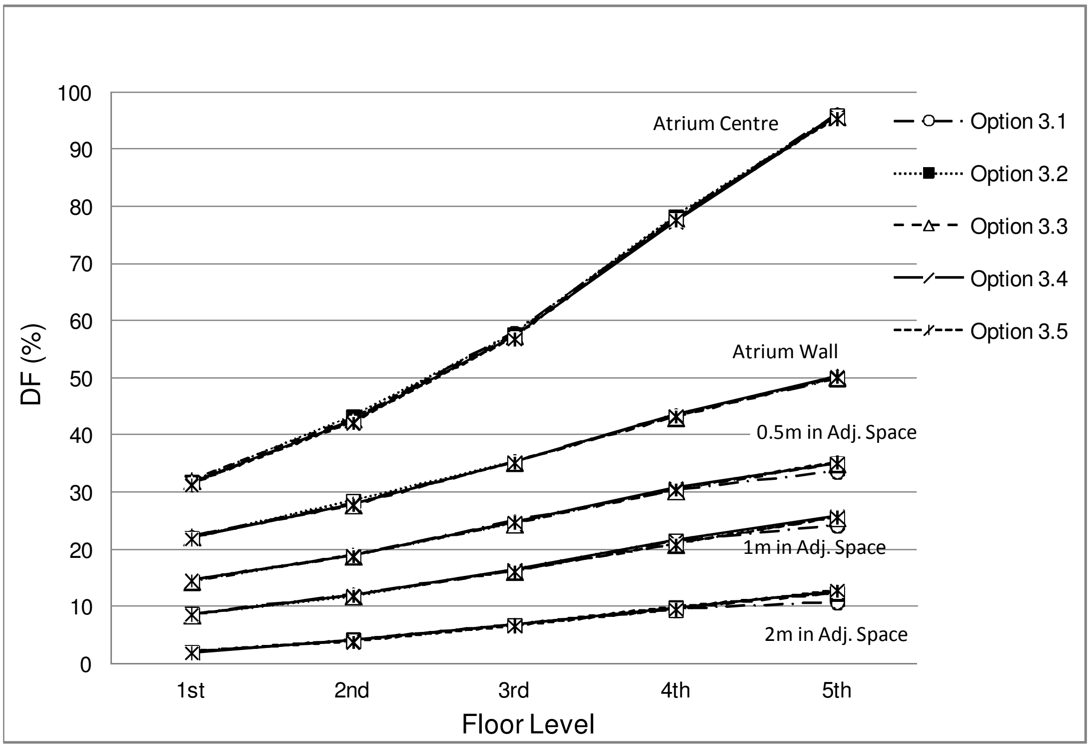


Figure 7:6 DFs for curve 3 (options 3.1 to 3.5) at atrium centre, atrium wall, 0.5m, 1m, and 2m into the adjoining space

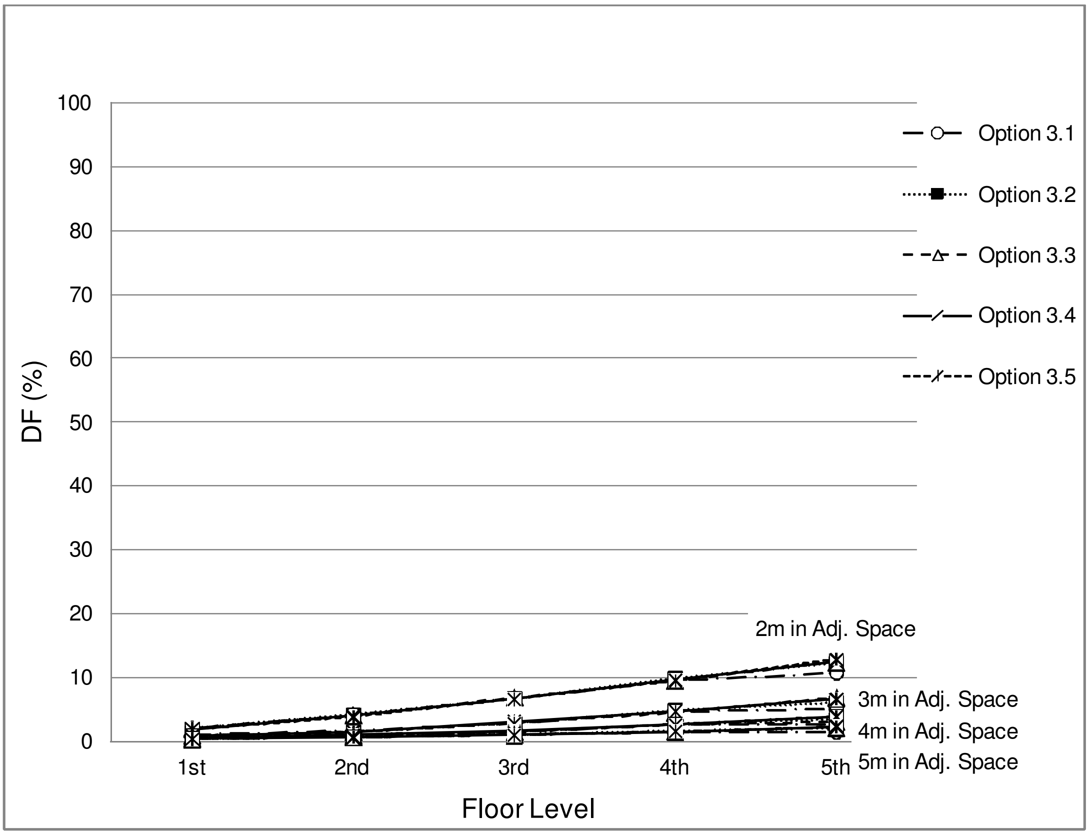


Figure 7:7 DFs for curve 3 (options 3.1 to 3.5) at 2m, 3m, 4m and 5m into the adjoining space

Figures 7:2 to 7:7 suggest that for the facades studied, the fenestration distribution has a minimal effect (maximum difference of 5% DF) on daylight levels in the adjoining spaces. The impact of different facade options was most noticeable on the top floor and was highest for Curve 1 in comparison with Curves 2 and 3. This suggests that DFs in the top floor adjoining spaces are more likely to be affected when an atrium facade adopts a consistent and gradual increase in the openings from the top to bottom floor (Curve1). However, it is difficult to make an assumption of this nature considering that DFs on the top floor are mainly dependent on the SC and the amount of fenestration included in the atrium's facade on this floor.

Difference in the DFs at the measured positions for Curves 1, 2 and 3

DF data for the three curves including their five options (1.1-1.5, 2.1-2.5, 3.1-3.5) for each of the measured positions on the five floors are compared and maximum difference in the DFs obtained as a result of the change in the fenestration are presented in Table 7:9 and Figure 7:8.

Looking more closely, only at the differences in DFs, it is obvious that the impact of the fenestration was highest on the fifth floor and reduced gradually lower down the atrium.

As shown in Figure 7:8, difference in the DFs ranged between 1.0-2.4% *(relative difference of 1-7%)* for the atrium centre position; 0.3-1.0% *(relative difference of 1-3%)* for atrium wall position; 0.5–5.0% *(relative difference of 3-14%)* at 0.5m; 0.3-5.1% *(relative difference of 4-20%)* at 1m; 0.1-3.2% *(relative difference of 4-25%)* at 2m; 0.2-2.1% *(relative difference of 11-30%)* at 3m; 0.1-1.4% *(relative difference of 12-35%)* at 4m; and 0.1-1.0% *(relative difference of 12-41%)* at 5m in the adjoining spaces. Difference in the DFs due to the various facade options was most marked at 0.5m and 1m positions with smaller changes in the DFs noticed at the atrium centre, atrium wall, 2m, 3m, 4m and 5m positions in the adjoining space. As daylight availability reduced away from the atrium, effect of the atrium facades also reduced. Lower impact in the atrium in comparison with the adjoining spaces might be due to the fact that DFs in the atrium receive more of the SC while the adjoining spaces rely more on the ARC.

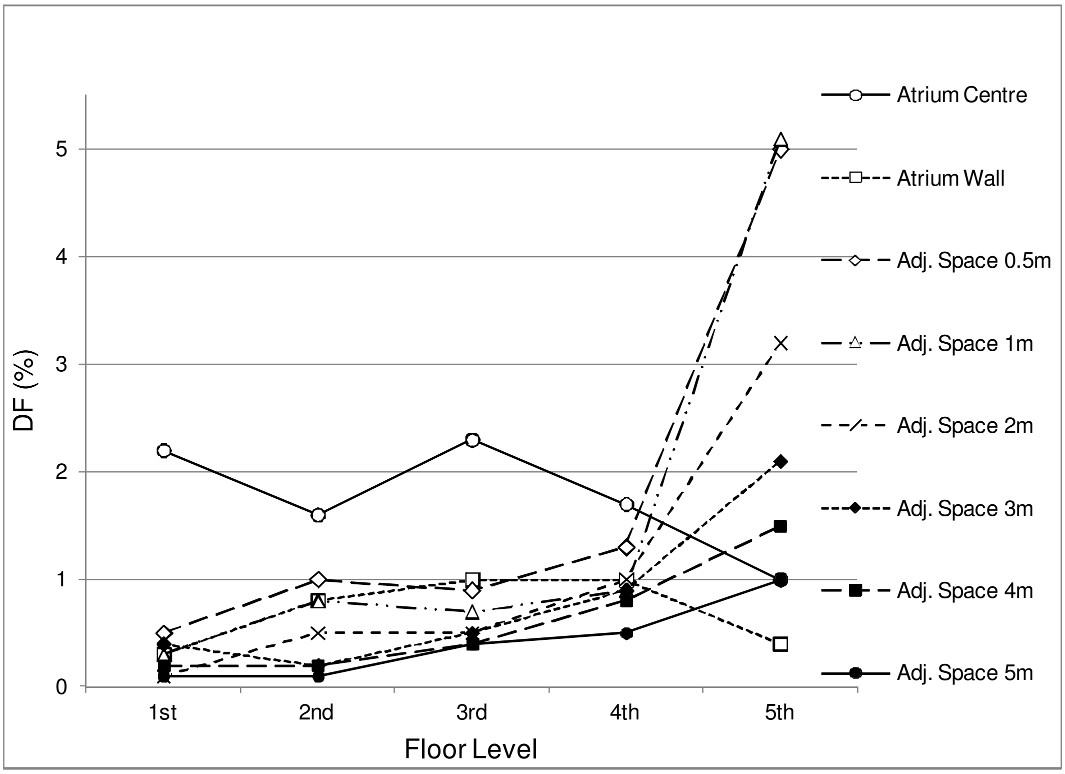


Figure 7:8 Maximum differences in DF% for the different options (1.1-1.5, 2.1-2.5 and 3.1-3.5) for the measurement points on each floor

On comparison of the three curves, it was found that the options 1.1, 2.1 and 3.1 with 20% fenestration on the top floor increasing to 100% openings on the first floor gave lowest DFs on the top floor whilst not improving DFs on the lower floors. On the other hand, options 1.5, 2.5 and 3.5 gave highest DFs in the adjoining spaces indicating that the facade ratios with 60% openings on the fifth floor with an incremental increase up to 100% on the first floor have the potential to improve DFs in the adjoining spaces. However, the DF increases due to the different approaches to facades were only noted on the top floor (maximum difference of around 5%) and this effect is reduced lower down the atrium and its adjoining spaces providing very similar values (maximum difference of around 1% only) and not improving the daylight levels where it is typically needed. Moreover, the nature of the increase in the fenestration from the fifth to the first floor by which the options 1.5, 2.5, 3.5 were defined and differed from one and another was not found to be important. Contribution of SC on the top floor is high and larger fenestration for options 1.5, 2.5 and 3.5 (60%) obviously resulted in higher DFs.

This demonstrates that the different fenestration versus opaque area ratios by which progressive increases in atrium facade openings from the top to the bottom floor might be defined have a minimal influence on the DFs in the atrium and its adjoining spaces of an open square, top-lit atrium of WI 1.25. This suggests that the difference in the reflectance distributions in the atrium facades on the DFs in the adjoining spaces is also low. This is in agreement with the findings of Chapter Four which showed that DFs were not very sensitive to the different reflectance distributions once four or more bands of each of the high and low surfaces were created in the atrium of WI 1. These findings are also in congruence with those of Sharples and Lash (2004) who concluded that the effect of the different reflectance distributions on the vertical DFs and ARCs in a square, open atrium of WI 1 (based on the banded models of Chapter Four) is much less in the lower half of the atrium well but affects vertical DFs in higher locations in the upper half of the atrium.

The highest DF values obtained for the facade with 60% openings on the fifth floor with an incremental increase up to a 100% on the first floor is similar to Aschehoug's (1992) recommended optimum glazing ratio, for a four storied glazed street of infinite length, of 50% on the fourth floor, 60% on the third floor, 70% on the second floor and 100% on the first floor. The similarity with Aschehoug's (1992) findings is interesting considering difference in the geometries used in the two studies.

Difference in the DF values from the fifth (top) to the first (ground) floor

Table 7:10 and Figure 7:9 show the range and average drop in DFs from the fifth to the first floor for all of the facade options. There is a very steep drop of about 63 to 66% *(relative drop of 66-68%)* (average drop 64.2%) in DFs obtained from the fifth to the first floor at the atrium centre position. In comparison with the atrium centre position, at the atrium wall position the drop in DFs from the fifth to the first floor is shallower and is about 27 to 28% *(relative drop of 55-56%)* (average drop 28%). Difference in DFs from the fifth to the first floor adjoining space ranged between 15 to 21% *(relative drop of 52-59%)* (average drop

19.8%) at 0.5 metres, 12 to 17% *(relative drop of 58-67%)* (average drop 16.5%) at 1 metre, 8 to 11% *(relative drop of 78-84%)* (average drop 10%) at 2 metres, 4 to 6% *(relative drop of 78-86%)* (average drop 5.1%) at 3 metres, 2 to 4% *(relative drop of 77-85%)* (average drop 2.8%) at 4 metres, and 1 to 2% *(relative drop of 72-84%)* (average drop 1.7%) at 5 metres in the adjoining space.

Table 7:10 Difference in DF% values from top to the bottom floor

Option	Atrium centre	Atrium wall	0.5m adj sp	1.0m adj sp	2.0m adj sp	3.0m adj sp	4.0m adj sp	5.0m adj sp
1.1	65.6	28.2	15.7	12.1	7.6	3.7	1.9	1.1
2.1	63.6	27.8	18.6	15.5	8.6	3.9	2.0	1.1
3.1	64.7	27.7	18.9	15.6	8.7	4.0	2.2	1.1
1.2	63.7	28.0	20.3	16.6	9.8	5.0	2.8	1.5
2.2	64.8	27.7	20.0	16.7	10.0	5.0	2.7	1.6
3.2	64.1	28.1	20.7	16.8	10.3	5.1	2.8	1.6
1.3	65.3	28.0	20.0	17.2	10.4	5.0	2.9	1.7
2.3	63.4	27.9	20.3	17.1	10.4	5.6	3.1	1.7
3.3	63.6	27.9	20.6	16.9	10.4	5.8	2.4	1.8
1.4	64.1	27.9	20.5	17.3	10.8	5.6	3.2	2.0
2.4	63.9	28.0	20.2	17.0	10.6	5.6	3.2	1.9
3.4	64.3	28.2	20.3	17.0	10.6	5.6	3.3	2.0
1.5	64.1	28.3	20.3	17.2	10.7	5.9	3.4	2.1
2.5	64.9	28.1	20.6	17.3	10.8	5.7	3.3	2.2
3.5	64.0	28.2	20.5	17.0	10.9	5.7	3.3	1.9
% drop from top to bottom	63-66%	27-28%	15-21%	12-17%	7.5-11%	3.5-6%	2-3.5%	1-2%
Average DF% drop from 1st to 5th floor	95.90-31.64= 64.2%	50.13-22.09= 28.0%	34.48-14.61= 19.8%	25.18-8.61= 16.5%	12.09-2.02= 10.0%	6.20-1.02= 5.1%	3.48-0.61= 2.8%	2.13-0.41= 1.7%

As DFs reduce further away from the atrium, drop in the DFs from the fifth to the first floor also reduces in most cases; this is particularly noted beyond 3 metres into the adjoining space. However, there was a larger drop in the DFs from the fifth to the first floor for 1 metre position in comparison with the 2 metre position in the adjoining space (Figure 7:9).

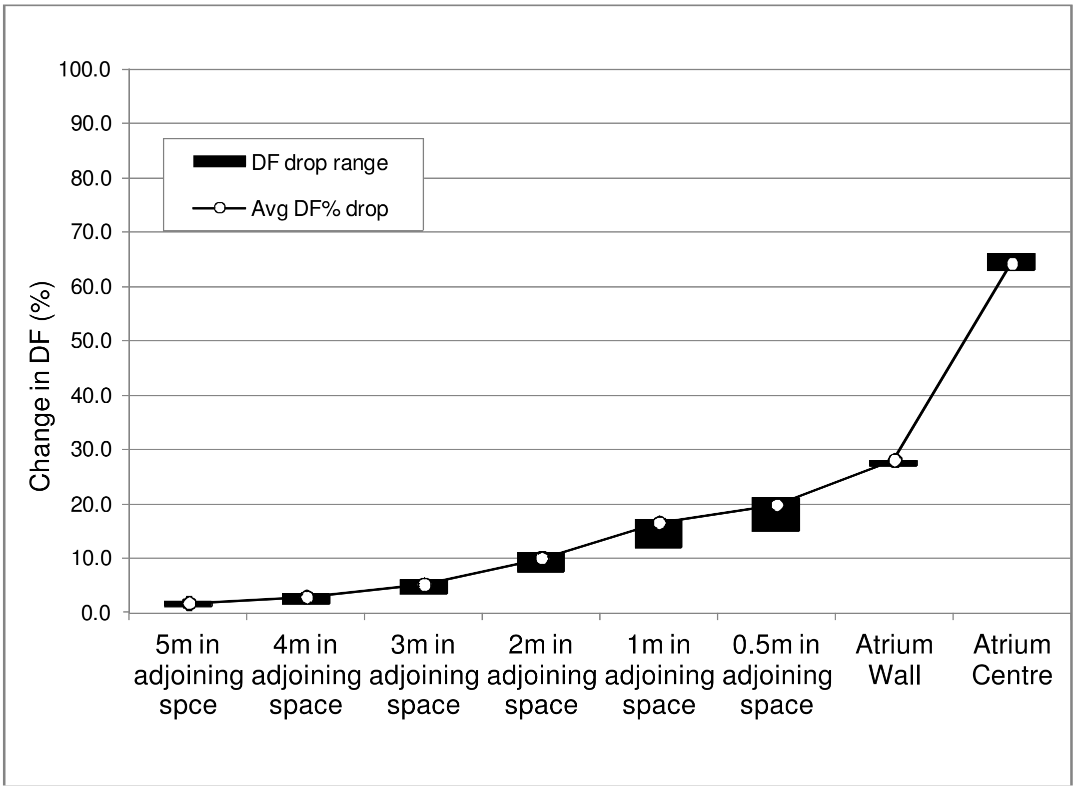


Figure 7:9 Average values of the DFs obtained from the different options and DF drops from fifth to the first floor for each of the eight measurement positions

Difference in DFs from the atrium centre to 5 metres in the adjoining space

DFs are highest at the atrium centre position and reduce in the adjoining spaces further away from the atrium, as expected. Tables 7:11 to 7:15 show difference in the DFs between the eight measured points on each of the floors including the range and average change in the DFs (obtained from the 15 options developed) from one position to the other.

Table 7:11 Difference in DF for different points on 5th floor

Option	Centre to wall	Wall to 0.5m	0.5m to 1m	1m to 2m	2m to 3m	3m to 4m	4m To 5m
1.1	46.1	20.1	9.3	11.2	5	2.2	1
2.1	46.1	16.4	9.3	13.5	5.8	2.3	1.1
3.1	46.3	16.3	9.5	13.4	5.7	2.3	1.2
1.2	45.7	15.1	9.8	13.4	5.8	2.6	1.5
2.2	46.1	15.3	9.3	13.3	6	2.7	1.3
3.2	45.9	14.9	9.6	13.2	6.3	2.6	1.4
1.3	45.5	15.3	9.1	13.3	6.1	2.7	1.4
2.3	45.7	15.2	9.0	13.3	5.9	2.9	1.6
3.3	45.7	14.9	9.5	13.1	5.6	3.8	0.8
1.4	45.7	14.9	9.0	13.8	6.2	2.8	1.5
2.4	45.9	15.2	9.1	13.1	6	2.8	1.5
3.4	45.7	15.2	9.1	13.4	5.9	2.8	1.4
1.5	45.3	15.5	9.1	13.0	5.9	2.8	1.5
2.5	46.0	15.0	9.3	13.1	6.1	2.8	1.4
3.5	45.2	15.1	9.4	12.8	6.3	2.7	1.6
% drop between points	45 - 46.5%	15-20%	9%	11-13.5%	5-6.5%	2-4%	1-1.5%
Average DF% drop between points	95.9-50.1= 45.8%	50.1-34.4= 15.7%	34.4-25.1= 9.3%	25.1-12.0= 13.1%	12.0-6.2= 5.8%	6.2-3.4= 2.8%	3.4-2.1= 1.3%

Table 7:12 Difference in DF for different points on 4th floor

Option	Centre to wall	Wall to 0.5m	0.5m to 1m	1m to 2m	2m to 3m	3m to 4m	4m To 5m
1.1	34.4	13.3	9.2	11.5	5.3	2.1	1.1
2.1	34.2	13.1	9.6	11.7	5	1.9	.9
3.1	34.4	13.2	9	11.9	4.7	2.1	1.2
1.2	34.9	13.2	8.9	11.5	5.3	2	1.1
2.2	34.3	13.2	9.2	12	5.6	2	1
3.2	35	12.7	9.1	11.7	5	2.1	1.1
1.3	34.7	13.5	8.9	11.2	5.2	2	1
2.3	34.5	13.4	9.1	11.2	5.1	2	1.2
3.3	34.9	12.7	9.4	11.4	5	1.9	1.1
1.4	33.1	13.3	8.7	11.7	5	2.1	1.1
2.4	33.8	13.4	9	11.4	5.1	1.9	1.1
3.4	33.9	12.6	9.3	11.9	5	1.9	1.2
1.5	34.6	12.3	9.7	11.6	5	2	1.2
2.5	35.1	12.9	9.1	11.4	4.8	2.2	1.1
3.5	34.4	12.9	9.5	11.4	4.8	2.1	1
% drop between points	33-35%	12.5-13.5%	8.5-9.5%	11-12%	4.5-5.5%	2%	1%
Average DF% drop between points	77.8-43.4=34.4%	43.4-28.3=15.1%	28.3-21.1=7.2%	21.1-9.6=11.5%	9.6-4.6=5.0%	4.6-2.5=2.1%	2.5-1.4=1.1%

Table 7:13 Difference in DF for different points on 3rd floor

Option	Centre to wall	Wall to 0.5m	0.5m to 1m	1m to 2m	2m to 3m	3m to 4m	4m To 5m
1.1	23	11.9	8	9.3	3.8	1.6	.4
2.1	22.5	11.1	8.3	9.4	4	1.4	.5
3.1	22.8	10.4	8.5	9.6	3.8	1.5	.4
1.2	23.9	11.2	7.9	9.5	4	1.3	.5
2.2	22.9	11.1	8	9.7	3.7	1.4	.5
3.2	22.4	10.6	8.2	9.7	3.9	1.4	.4
1.3	23.2	10.6	8.2	9.8	3.8	1.6	.5
2.3	22.5	11	7.9	9.7	3.8	1.5	.4
3.3	22.2	10.9	8.2	9.4	4	1.4	.4
1.4	22.1	10.7	8.1	9.7	3.8	1.5	.4
2.4	22.9	11.1	7.9	9.5	3.9	1.4	.4
3.4	21.9	10.5	8.4	9.7	3.6	1.5	.5
1.5	22.2	10.8	8.1	9.8	3.8	1.4	.5
2.5	22.5	10.5	8.1	9.6	3.9	1.4	.5
3.5	21.7	10.4	8.6	9.6	3.8	1.4	.4
% drop between points	21.5 - 24%	10.5 - 12%	8-8.5%	9-10%	3.5-4%	1.5%	0.5%
Average DF% drop between points	57.9-35.3= 22.6%	35.3-24.4= 10.9%	24.4-16.3= 8.1%	16.3-6.7= 9.6%	6.7-2.8= 3.9%	2.8-1.4= 1.4%	1.4-0.9= 0.5%

Table 7:14 Difference in DF for different points on 2nd floor

Option	Centre to wall	Wall to 0.5m	0.5m to 1m	1m to 2m	2m to 3m	3m to 4m	4m To 5m
1.1	15.4	9	6.9	8.1	2.7	.6	.4
2.1	15.1	9.3	6.5	8	2.6	.7	.3
3.1	14.5	9.3	6.7	7.9	2.6	.6	.3
1.2	15.6	8.8	7.1	7.9	2.5	.7	.2
2.2	15.1	9.6	6.7	7.6	2.5	.7	.2
3.2	14.7	9.6	7.2	7.5	2.7	.6	.3
1.3	14.2	8.9	6.8	8	2.6	.6	.2
2.3	14.7	9	6.9	7.8	2.6	.7	.3
3.3	15.2	8.8	7.1	7.7	2.6	.5	.3
1.4	14.5	9	6.7	8	2.6	.5	.4
2.4	14.6	8.7	6.9	7.8	2.6	.5	.4
3.4	14.5	8.9	6.9	7.9	2.6	.5	.4
1.5	14.3	9.1	7.1	7.7	2.6	.5	.4
2.5	14.5	9	6.6	8.1	2.6	.5	.4
3.5	14.4	8.9	7	8	2.4	.5	.3
% drop between points	14-15.5%	8.5-9.5%	6.5-7%	7.5-8%	2.5%	0.5%	0.3%
Average DF% drop between points	42.7-28.0= 14.7%	28.0-18.9= 9.1%	18.9-12.0= 6.9%	12.0-4.1= 7.9%	4.1-1.6= 2.5%	1.6-1.0= 0.6%	1.0-0.6= 0.4%

Table 7:15 Difference in DF for different points on 1st floor

Option	Centre to wall	Wall to 0.5m	0.5m to 1m	1m to 2m	2m to 3m	3m to 4m	4m To 5m
1.1	8.7	7.6	5.8	6.7	1	0.4	0.2
2.1	10.2	7.2	6.3	6.6	1	0.4	0.2
3.1	9.3	7.5	6.2	6.4	1	0.4	0.1
1.2	10	7.5	6.1	6.5	1.1	0.3	0.2
2.2	9.7	7.6	6	6.6	1	0.4	0.2
3.2	9.9	7.5	5.7	6.7	1.1	0.4	0.1
1.3	8	7.3	6.4	6.4	0.7	0.6	0.3
2.3	10.2	7.6	5.8	6.7	1.1	0.3	0.2
3.3	9.9	7.7	5.9	6.5	1.1	0.3	0.2
1.4	9.5	7.7	5.7	6.7	1.1	0.4	0.2
2.4	10	7.4	6	6.6	1	0.4	0.2
3.4	9.7	7.2	6.2	6.6	1	0.4	0.1
1.5	9.6	7.5	6	6.5	1	0.3	0.2
2.5	9.3	7.4	6.1	6.6	1	0.4	0.1
3.5	9.5	7.3	6	6.6	1.1	0.4	0.1
% drop between points	8-10%	7-8%	5.5-6.5%	6.5%	1%	0.4	0.2
Average DF% drop between points	31.6-22.0= 9.6%	22.0-14.6= 7.4%	14.6-8.6= 6.0%	8.6-2.0= 6.6%	2.0-1.0= 1.0%	1.0-0.6= 0.4%	0.6-0.4= 0.2%

Average decay in DFs from the atrium centre to the adjoining spaces is shown in Figure 7:10. There is a pronounced drop in DFs from the atrium centre to the atrium wall position. DFs drop further from the atrium wall position to 0.5 metres into the adjoining space; this is more noticeable on the higher floors. It is observed that for every floor there is a larger drop in the DF from 1.0 to 2.0 metres into the adjoining space than there is from 0.5 to 1.0 metre into the adjoining space. As expected, with reduced availability of daylight deeper into the adjoining space from 0.5 to 5.0 metres, and from the fifth to the first floor, difference in the DFs between the measured positions is steadily reduced.

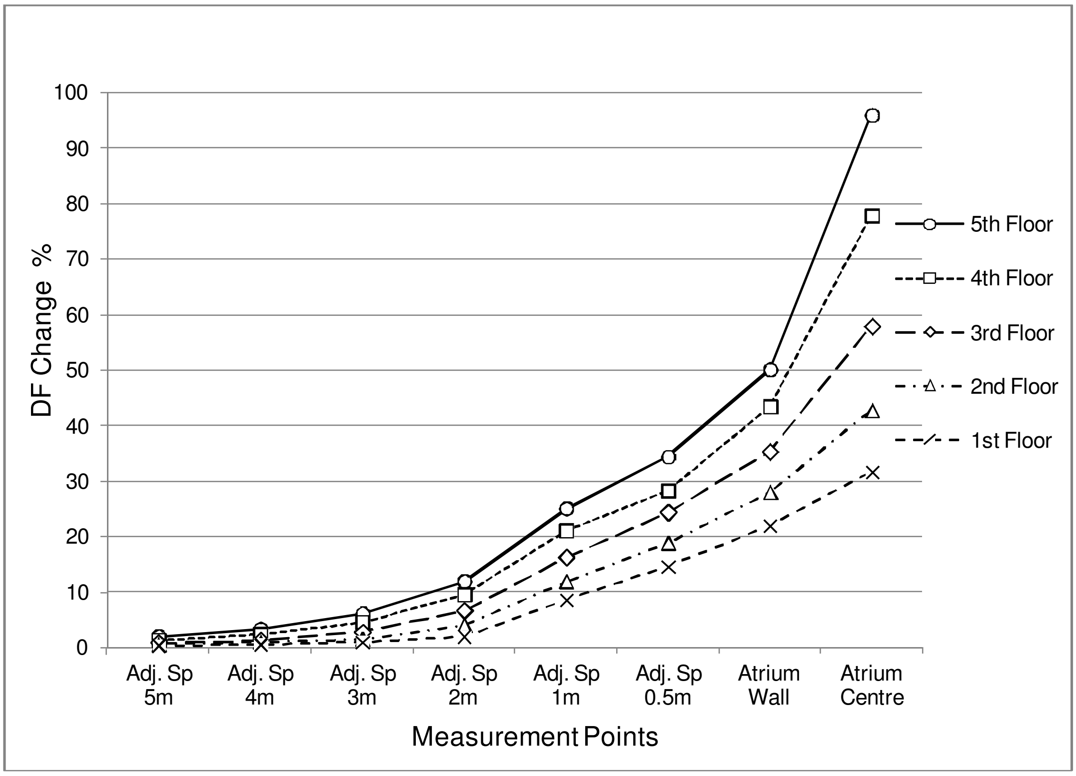


Figure 7:10 Average Change in DFs% for different measurement points on each floor

DF results for Curves 1, 2 and 3 - (1.1E-1.5E), (2.1E-2.5E), (3.1E-3.5E) Even Openings

Although the different facade options with variable openings had a limited influence on DFs when compared with each other, the impact of this strategy can only be ascertained when DFs obtained for the variable facades are compared with the atrium facades with even openings. To make comparisons between the two approaches to facades, even facade options are referred to with an E at the end, for example option 1.1E. Also, differences of only over 1% DFs are discussed.

Data obtained in the adjoining spaces for the atrium facades with variable and even openings (Table 7:16) was compared. When an assessment of the daylight availability in the adjoining spaces was made, the trend for the facades with the even openings was similar to that found for the variable facades discussed previously.

Table 7:16 DF results for the adjoining spaces for Curve 1, 2 and 3 - (Options 1.1E-1.5E), (2.1E-2.5E), (3.1E-3.5E) for atrium facade with even openings (variable opening DF results are also included for comparison)

Option	0.5m 5th floor DF%	0.5m 4th floor DF%	0.5m 3rd floor DF%	0.5m 2nd floor DF%	0.5m 1st floor DF%	1m 5th floor DF%	1m 4th floor DF%	1m 3rd floor DF%	1m 2nd floor DF%	1m 1st floor DF%
1.1	30.25	30.68	24.03	19.43	14.52	20.92	21.41	16.04	12.51	8.78
1.1E	34.92	30.40	24.32	18.52	14.58	25.67	21.15	16.13	11.82	8.62
1.2	35.00	30.22	24.18	19.15	14.67	25.24	21.36	16.26	12.00	8.56
1.2E	35.24	30.11	24.13	18.67	14.36	25.95	21.26	16.31	12.01	8.58
1.3	34.89	29.88	24.99	18.93	14.84	25.76	20.97	16.72	12.13	8.48
1.3E	35.18	30.14	24.17	18.60	14.47	25.66	21.16	16.34	12.13	8.60
1.4	35.04	30.22	24.54	18.87	14.46	26.02	21.52	16.48	12.11	8.71
1.4E	35.68	30.95	24.12	19.13	14.43	26.09	21.57	16.17	12.36	8.60
1.5	34.82	31.14	24.55	18.98	14.47	25.70	21.45	16.43	11.87	8.47
1.5E	36.74	31.28	25.22	19.39	14.81	26.12	21.74	16.59	12.36	9.08
2.1	33.59	30.28	24.32	18.70	14.90	24.20	20.62	16.06	12.23	8.65
2.1E	34.97	30.16	24.07	18.40	14.79	25.49	21.34	16.16	12.00	8.67
2.2	34.63	30.04	24.11	18.48	14.63	25.33	20.85	16.17	11.73	8.61
2.2E	35.17	30.50	24.22	18.69	14.90	25.82	21.45	16.61	12.04	8.93
2.3	34.81	29.98	24.27	18.93	14.50	25.86	20.86	16.31	12.07	8.71
2.3E	35.69	30.73	24.58	19.06	14.65	26.29	21.52	16.50	12.47	8.51
2.4	34.84	29.99	24.05	19.06	14.60	25.73	20.95	16.16	11.90	8.67
2.4E	34.99	30.75	24.32	19.12	14.92	25.60	21.55	16.56	12.38	8.89
2.5	35.29	30.05	24.46	18.89	14.64	25.94	20.94	16.34	12.26	8.57
2.5E	36.19	30.12	24.47	18.86	14.36	26.22	21.67	16.05	11.95	8.54
3.1	33.61	30.37	24.87	18.82	14.65	24.18	21.32	16.32	12.10	8.49
3.1E	35.16	29.81	20.56	18.65	14.38	26.04	21.32	13.62	12.03	8.49
3.2	35.12	30.60	24.60	18.95	14.41	25.56	21.57	16.47	11.73	8.71
3.2E	35.11	26.35	20.53	15.60	11.77	25.68	18.30	13.69	9.92	6.75
3.3	35.06	30.31	24.45	18.91	14.45	25.54	20.98	16.23	11.86	8.56
3.3E	37.17	31.16	20.76	15.72	11.64	26.50	21.81	13.67	9.81	6.78
3.4	35.04	30.85	24.81	18.96	14.74	25.96	21.55	16.49	12.03	8.52
3.4E	36.71	31.34	24.70	18.99	14.95	25.85	21.44	16.32	11.98	8.94
3.5	35.19	30.49	24.83	18.90	14.60	25.72	20.93	16.22	11.96	8.65
3.5E	37.27	31.09	25.05	19.20	14.72	26.85	21.82	16.60	12.34	8.72

Option	2m 5th floor DF%	2m 4th floor DF%	2m 3rd floor DF%	2m 2nd floor DF%	2m 1st floor DF%	3m 5th floor DF%	3m 4th floor DF%	3m 3rd floor DF%	3m 2nd floor DF%	3m 1st floor DF%
1.1	9.72	9.90	6.77	4.44	2.06	4.77	4.63	2.90	1.75	1.03
1.1E	12.68	9.58	6.49	4.18	1.01	6.74	4.48	2.77	1.54	0.63
1.2	11.87	9.87	6.73	4.12	2.04	6.03	4.58	2.79	1.60	0.98
1.2E	13.00	9.64	6.56	3.97	2.03	6.77	4.65	2.87	1.57	0.99
1.3	12.48	9.75	6.98	4.19	2.03	6.35	4.57	3.10	1.58	1.34
1.3E	12.87	9.52	6.71	4.14	1.99	6.83	4.59	2.83	1.56	1.01
1.4	12.81	9.88	6.71	4.12	2.01	6.65	4.82	2.91	1.58	0.98
1.4E	12.80	9.80	6.70	4.40	2.00	6.83	4.93	2.86	1.69	1.00
1.5	12.72	9.89	6.68	4.18	1.96	6.88	4.88	2.88	1.59	0.98
1.5E	13.03	9.97	6.96	4.35	2.11	6.83	5.01	3.17	1.71	1.05
2.1	10.74	8.98	6.61	4.20	2.06	4.97	3.99	2.67	1.61	1.04
2.1E	12.40	9.37	6.62	4.05	2.05	6.83	4.30	2.68	1.45	0.99
2.2	12.07	9.85	6.40	4.19	2.04	6.02	4.21	2.71	1.60	1.01
2.2E	12.52	9.96	6.68	4.21	2.21	6.46	4.79	2.91	1.52	1.09
2.3	12.52	9.69	6.63	4.29	2.05	6.67	4.55	2.86	1.60	0.98
2.3E	13.11	9.89	6.92	4.38	2.06	6.89	4.76	2.95	1.67	1.00
2.4	12.65	9.53	6.60	4.15	2.01	6.65	4.48	2.78	1.57	1.00
2.4E	12.87	10.09	6.88	4.35	2.20	6.64	4.92	2.96	1.69	1.07
2.5	12.82	9.51	6.71	4.17	1.98	6.71	4.71	2.87	1.58	0.98
2.5E	13.10	9.89	6.73	4.17	1.99	6.75	4.85	2.83	1.55	0.99
3.1	10.76	9.46	6.77	4.20	2.06	5.05	4.70	2.93	1.61	1.01
3.1E	12.71	9.64	5.72	4.13	1.97	6.90	4.67	2.56	1.56	1.01
3.2	12.31	9.89	6.76	4.22	2.01	6.08	4.89	2.83	1.55	0.97
3.2E	12.91	8.47	5.69	3.45	1.78	6.76	4.34	2.50	1.48	0.92
3.3	12.42	9.55	6.85	4.16	2.02	6.84	4.56	2.85	1.56	0.98
3.3E	13.19	9.97	5.80	3.36	1.76	7.27	4.98	2.68	1.49	0.92
3.4	12.57	9.63	6.77	4.14	1.97	6.61	4.68	3.12	1.59	0.99
3.4E	12.86	10.01	6.63	4.11	2.13	7.00	4.89	2.82	1.55	1.06
3.5	12.90	9.59	6.67	3.90	2.00	6.69	4.71	2.84	1.58	0.98
3.5E	13.32	10.00	6.92	4.45	2.13	7.17	4.99	3.06	1.69	1.04

Option	4m 5th floor DF%	4m 4th floor DF%	4m 3rd floor DF%	4m 2nd floor DF%	4m 1st floor DF%	5m 5th floor DF%	5m 4th floor DF%	5m 3rd floor DF%	5m 2nd floor DF%	5m 1st floor DF%
1.1	2.57	2.59	1.39	1.10	0.60	1.51	1.42	0.97	0.76	0.42
1.1E	3.94	2.54	1.35	0.94	0.41	2.45	1.45	0.88	0.62	0.30
1.2	3.40	2.55	1.41	0.99	0.60	1.99	1.41	0.94	0.71	0.42
1.2E	4.02	2.67	1.38	0.97	0.61	2.49	1.47	0.91	0.64	0.40
1.3	3.68	2.52	1.56	0.98	0.75	2.25	1.50	1.04	0.69	0.47
1.3E	4.04	2.60	1.39	0.96	0.59	2.57	1.46	0.95	0.66	0.41
1.4	3.88	2.75	1.47	1.01	0.59	2.39	1.64	1.00	0.69	0.37
1.4E	4.14	2.70	1.40	1.06	0.59	2.65	1.64	0.95	0.72	0.41
1.5	4.00	2.80	1.42	1.00	0.60	2.51	1.68	0.99	0.69	0.41
1.5E	4.15	2.77	1.57	1.05	0.62	2.62	1.70	1.06	0.72	0.40
2.1	2.66	2.07	1.25	0.97	0.61	1.59	1.12	0.77	0.65	0.42
2.1E	3.47	2.30	1.23	0.85	0.62	2.10	1.27	0.76	0.57	0.41
2.2	3.35	2.26	1.31	0.98	0.62	2.07	1.24	0.85	0.66	0.40
2.2E	3.82	2.53	1.43	0.90	0.63	2.31	1.49	0.91	0.59	0.41
2.3	3.78	2.52	1.36	0.98	0.62	2.19	1.39	0.90	0.68	0.42
2.3E	4.06	2.76	1.51	1.01	0.61	2.43	1.60	0.97	0.67	0.40
2.4	3.89	2.52	1.38	1.02	0.60	2.36	1.44	0.94	0.68	0.42
2.4E	4.05	2.69	1.52	1.07	0.61	2.60	1.63	1.02	0.70	0.42
2.5	3.92	2.58	1.44	1.00	0.58	2.57	1.47	0.95	0.69	0.40
2.5E	4.08	1.99	1.41	0.96	0.60	2.54	1.18	0.94	0.66	0.42
3.1	2.74	2.61	1.44	1.01	0.59	1.52	1.46	1.01	0.71	0.41
3.1E	3.97	2.59	1.35	0.94	0.61	2.49	1.46	0.92	0.66	0.40
3.2	3.46	2.75	1.46	0.99	0.59	2.01	1.63	1.01	0.70	0.40
3.2E	4.03	2.47	1.36	0.91	0.58	2.58	1.56	0.91	0.65	0.40
3.3	3.08	2.64	1.47	1.01	0.61	2.21	1.57	1.01	0.70	0.41
3.3E	4.31	2.79	1.37	0.95	0.57	2.76	1.72	0.96	0.66	0.40
3.4	3.89	2.78	1.65	1.01	0.59	2.40	1.51	1.15	0.69	0.40
3.4E	4.20	2.78	1.43	0.98	0.62	2.60	1.70	0.99	0.68	0.40
3.5	3.97	2.64	1.48	1.00	0.59	2.38	1.60	1.01	0.70	0.41
3.5E	4.33	2.82	1.59	1.08	0.61	2.81	1.82	1.10	0.71	0.39

In this section, only absolute values are compared as vast differences in relative values were noted with increase in DF drops moving away from the atrium. This somewhat compromises an understanding of the relative contribution and can be misleading as even small changes of less than 1% resulted in very large values of relative contribution. In comparison with the variable openings' facade, for the options with even openings the following observations were made:

At the Atrium Centre: DFs were increased by 1 to 3% for options 1.3E (first floor), 1.4E (second and fourth floor) and 3.4E (fourth floor) or decreased by 1 to 2% for options 1.E (third, fourth and fifth floor), 1.2E and 1.3E (third and fourth floor), 1.4E (second floor), 2.2E (fourth floor) and 3.3E (first floor).

At the Atrium Wall: DFs were not affected by the altered approach to fenestration in the facade.

In the Adjoining Spaces: Even openings and the resultant increase in the opening sizes led to higher SCs and consequently higher DFs of 1-5% on the fifth floor at 0.5, 1m, 2m, 3m and 4m positions for the options 1.1E, 1.2E, 1.5E, 2.1E, 2.5E, 3.1E, 3.3E, 3.4E and 3.5E whilst providing similar DFs as to those obtained by the variable fenestration facade (1.2E, 1.5E, 2.1E, 2.5E, 3.4E and 3.5E) or reducing the DFs by 1-4% (1.1E, 3.1E, 3.2E and 3.3E) at 0.5m, 1m, 2m and 3m positions on the first to the fourth floors. Five metres into the adjoining space DFs were similar indicating that changes to the fenestration did not affect DFs in this position.

For options 1.4E and 3.2E while DFs on the fifth floor were similar to those obtained for the variable openings facade, even openings resulted in a drop in the DFs on the lower floors. For option 1.4E, drop in DF of 1%, was noted at 0.5m position on the fourth floor. For Option 3.2E, drops ranged between 1-4% at up to 2m positions in the adjoining spaces on the second to the fourth floor and up to 1m position on the first floor. Options 1.3E, 2.2E, 2.3E and 2.4E were unaffected by the altered approach to fenestration.

Adequate daylight is generally available in the atrium space; however, daylight availability is more critical in the adjoining spaces. Therefore, it is found that the DFs in atria with even facade openings were improved for the options 1.2E, 1.5E, 2.1E, 2.5E, 3.4E, and 3.5E

(56.3%, 75.0%, 34.5%, 69.0%, 76.8% and 82.3% openings in the facade from the second to the fourth floor respectively).

DFs for options 2.2E, 1.3E, 2.3E and 2.4E (42.5%, 62.2%, 51.2% and 61.3% openings in the facade from the second to the fourth floor respectively) were similar for the two approaches to atrium facades.

For options 1.1E, 1.4E, 3.1E, 3.2E and 3.3E (50.0%, 68.5%, 61.8%, 66.8%, 71.8% openings in the facade from the second to the fourth floor respectively), DFs were reduced for the facade with the even openings.

Comparing the variable and the even opening approaches to the fenestration in the atrium facades and on examining the general trends, it is concluded that depending on the particular percentage of openings adopted in the atrium facades, DFs could be reduced, similar or improved by adopting a facade with even openings. However, it is also noted that for facades with even openings, DF increases ranging between 1 to 5% were limited mainly to the top floor while DF decreases ranging between 1 to 4% were observed on the first to the fourth floor, where more daylight is typically required. Therefore, a facade with a progressive increase in openings from the top to bottom floor can potentially result in an improved balance of daylight availability and result in DF increases of up to 4% up to a distance of 2 metres in the adjoining spaces on the first to the fourth floors. This was achieved for facade options 1.1, 3.1, 3.2 and 3.3 with 20%, 30% and 40% openings on the top floor increasing up to 100% on the lowest floor.

This indicates that for an atrium building with facades characterised by much smaller openings (20, 30, 40%) on the fifth floor increasing up to 100% on the first floor can potentially improve DFs in its adjoining spaces compared to a building with even openings of similar average opening sizes from the fifth to the second floor and 100% opening on the first floor. This is in agreement with the findings of Cole (1990) who demonstrated that the variable opening option (100% opening on the first floor, 80% on the second, 60% on the third, 40% on the fourth and 20% on the top floor) in comparison with 100% and 50% opening is most effective in terms of bringing daylight on the lower floors in a five storey, top-lit, open, square atrium building.

For the facades with a progressive increase in the openings from the top to the atrium floor, options 1.5, 2.5 and 3.5 generally gave the highest DFs (increased by up to 5% on the top floor). For the same options with even openings, DFs were further increased by up to 2% on the top floor whilst providing similar DFs on the other floors as to those obtained by the variable opening facades option. This was probably because in comparison with the variable opening facades with 60% opening on the top floor for options 1.5, 2.5 and 3.5, facades with even openings (1.5E, 2.5E and 3.5E) had larger openings on the top floor of 75%, 69% and 82% respectively and consequently increased the SC. It can be argued that due to the larger openings and a gradual increase in the fenestration from 60% on the top floor to 100% on the first floor, the even opening facade ratios derived from them are characterised by openings that are somewhat similar in size. In other words, difference in the fenestration sizes between these two facades is much lower in comparison with the other facade options tested. Therefore DFs for both these options are high but the benefits associated with the strategy of a progressive increase in openings are not achieved. This suggests that the improvements in daylight availability associated with the variable facade strategy will not be seen in atria that have a high percentage of glazing. Therefore, in such atria, either an even or a variable fenestration facade may be adopted.

7.2.4 Comparison of data with real buildings

Findings of the experiments undertaken in this Chapter were compared with specific buildings from Fontoynont's (1999a) edited book *Daylight Performance of Buildings.* As previously suggested, making comparisons of theoretical representative models with real buildings is difficult due to differences between the key parameters and several underlying assumptions. Nonetheless, an attempt has been made to draw links and contextualise the experimental work undertaken in this Chapter. Due to the fact that the well indices were unknown in some of the case studies discussed, SARs of the models were compared with the building, which do not take into account the atrium shape. Therefore, square models were compared with rectangular atria in the case of Scandinavian Airlines System HQ and the Dragvoll University Centre.

For the purpose of making comparisons with built examples, DFs obtained by RADIANCE were reduced by 50% to take into account external illuminance conditions and obstructions, the atrium roof and windows, and the maintenance factors.

Scandinavian Airlines System HQ

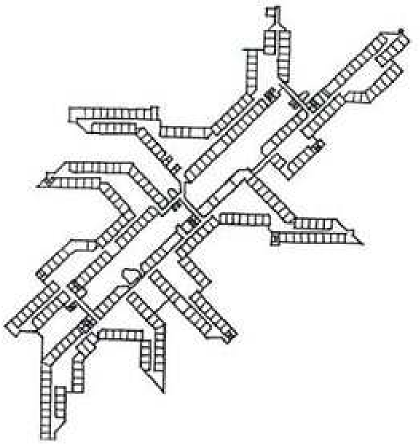
The Scandinavian Airlines System HQ outside Stockholm comprises of five, four to five storey blocks on either side of a covered street/atrium of SAR 1.9 (Figure 7:11). The building facades and the street floor have a reflectance of 75% and 35% respectively and the facades include even openings. The adjoining spaces have a wall reflectance of 76% (Fontoynont, 1999a).

DF comparisons obtained from the building were made with the five storeys, square, four sided, top lit atrium model for Curve 2:1 of WI and SAR of 1.25 and with 35% even openings on the second to the fifth floor and 100% on the first floor. For the model, the atrium wall reflectance is 85%; the area weighted reflectance of the wall including its opaque areas and openings is 55% and the floor reflectance is 40%. The adjoining spaces have a wall reflectance of 60%.

Table 7:17 outlines the atrium parameters and compares DFs obtained from the real building and the RADIANCE model in the top floor adjoining space and on the atrium floor. DFs in the top floor adjoining space of the building were lower at the most by 6% than the model; however DFs obtained on the atrium floor were similar to those obtained in the RADIANCE study. Furthermore, decay in the DFs from one measured position to the other on the top floor is also similar up to 3 metres in the adjoining space. However, beyond 3 metres, DFs in the adjoining space of the model dropped significantly sharply in comparison with the room.

This might be due to the fact that the model adjoining room was much deeper (12m) and was unilaterally lit in comparison with the adjoining space in the building which was only four metres deep and the corridors beyond received light from both the atrium and the external facade of the building. Although data for the lower floor adjoining spaces of the building are not available, it is suggested that white atrium walls of 75% reflectance will contribute significantly to the daylight penetration; “allowing atrium windows to benefit from reflections on atrium walls, particularly for lower floors” (Fontoynont, 1999a).

Despite the fact that high wall reflectances result in high DFs on the atrium floor, the distribution of DF is varied and the DFs are reduced from 16% to about 4% due to local obstructions such as trees and gangways. Furthermore, gaps between the buildings enable side lighting, increasing DFs on the floor from 16% to 25% (Fontoynont, 1999a). The Scandinavian Airlines System HQ building shows that DFs at individual positions on the atrium floor are affected by the reflectance distributions on the atrium walls and floors as suggested in this thesis.



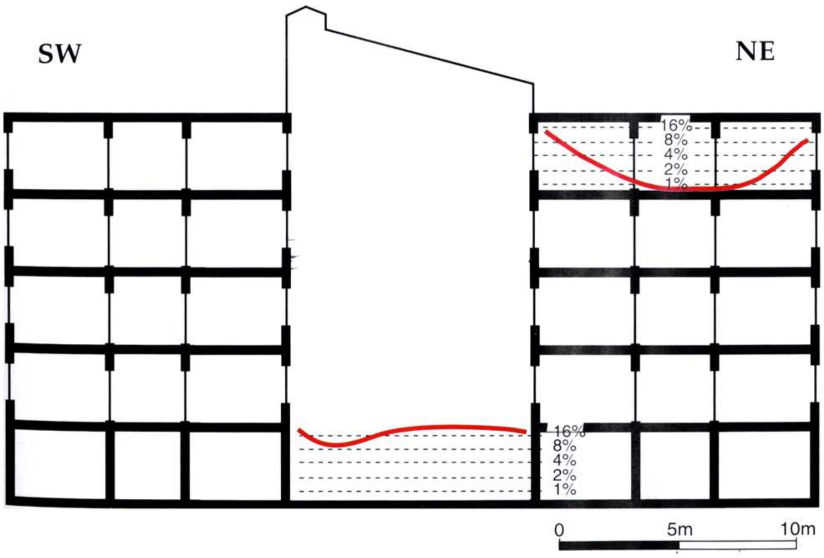


Figure 7:11 Covered street/atrium of the Scandinavian Airlines System HQ (http://www.cityofsound.com/blog/urban_informatics/page/3/) and (South-west/north-east section of the SAR HQ buildings 4 and 5; Fontoynont, 1999a)

Table 7:17 Comparisons of atrium parameters and the daylight availability on the atrium floor between the Scandinavian Airlines System HQ and Model Curve 2:1

Scandinavian Airlines System HQ atrium Long glazed street, even openings in facade, 5 storeys Adjoining space 4metres deep; SAR = 1.9; WI = unknown	Model: Curve 2:1 square four sided top lit atrium with 35% even openings on 2nd to 5th floor and 100% on 1st floor, 5 storeys Adjoining space 12 metres deep; SAR= 1.25 and WI = 1.25	
Transmittance: Atrium facade glazing 73%; Atrium roof glazing 81%; External facade glazing 65%	No glazing included	
Atrium wall reflectance = 75%	Atrium wall opaque area reflectance = 85% area weighted reflectance of wall - Opaque and opening reflectance = 55%	
Atrium floor reflectance = 35%	Atrium floor reflectance = 40%	
Office wall reflectance = 76%	Office wall reflectance = 60%	
Measurement 0.8m above floor on 5th floor (12m deep offices) DFs Approximately: 0.5m = 12% 1m = 8% 2m = 4% 3m = 2.4% 4m = 1.5% between 4 and 7metres =0.5%	Measurement 0.85m above floor on 5th floor (12m deep offices) DFs 0.5m = 34.97% 1m = 25.49% 2m = 12.40% 3m = 6.83% 4m = 3.47% 5m = 2.10%	DFs reduced by 50% due to the atrium roof 0.5m = 17.50% 1m = 12.75 2m = 6.20% 3m = 3.40% 4m = 1.70% 5m = 1.05%
DF at atrium floor 16% With side lighting between buildings: DFs 25% on the floor in parts Local obstructions: Trees and gangways reduce DFs to 4%	Atrium centre = 32.51% Atrium wall = 22.55%	Atrium centre 50% reduced = 16.25%

Domino Haus in Germany

Domino Haus in Germany is a three and four storey, four sided, top and side lit atrium building with a SAR of 1 (Figure 7:12). The atrium facades are varied with 60% opening on other floors and 80% on the first floor and have a wall reflectance of 71%. The adjoining rooms are bilaterally lit and have a depth of 18.5 metres, with the top floor room benefiting from a roof monitor as well (Fontoynont, 1999a). The building was compared with the five storey four sided, top lit atrium RADIANCE model (Curve 2.4) with a WI/SAR of 1.25. The model's atrium facades have even openings (61.25%) on four of its floors and 100% on the first floor and have the opaque area reflectance of 85% and an area weighted average reflectance of 42%. Adjoining rooms of the RADIANCE model are unilaterally lit and have a depth of 12 metres. Table 7:18 outlines the atrium parameters and compares the daylight data obtained from the real building and the RADIANCE model.

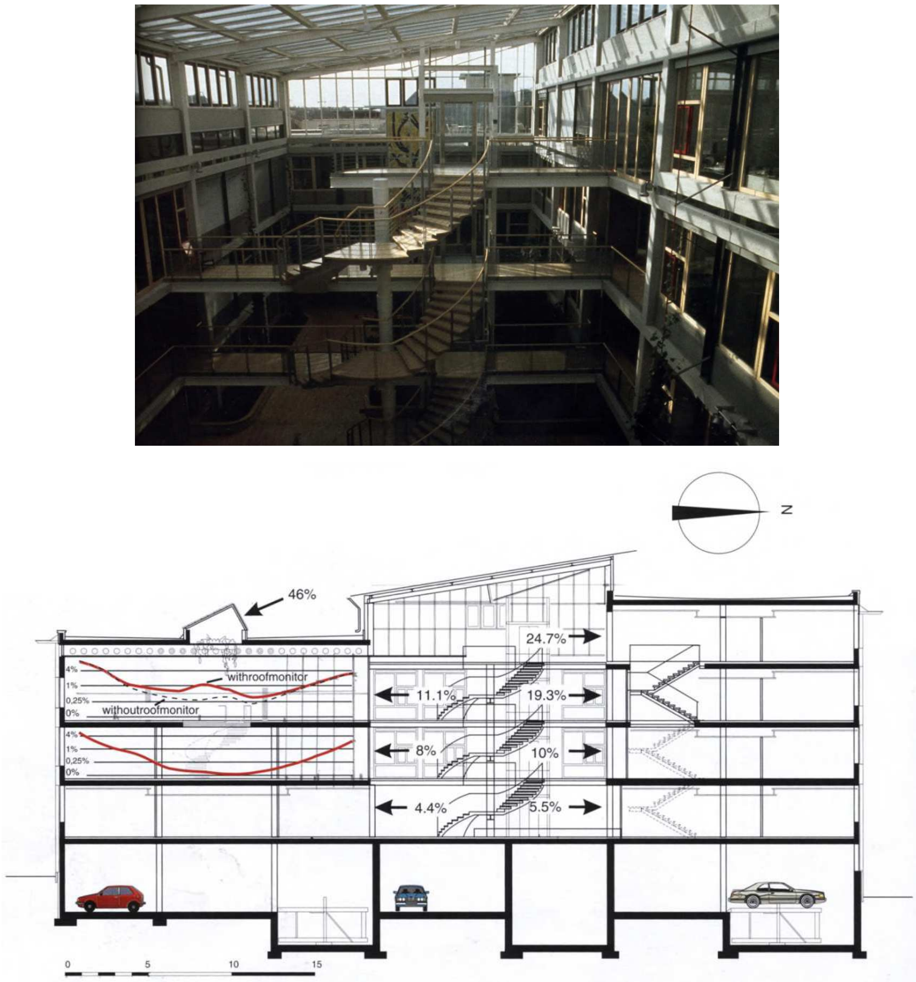


Figure 7:12 Domino Haus atrium, Reutlingen, Germany (Fontoynont, 1999a)

Although the adjoining space in the RADIANCE model is shallower, the model SAR is higher and it does not include a roof or windows. However, with a 50% reduction applied, DFs on the second and third floor compared well except for the 1 metre position; for all the other positions, DFs differed at the most by approximately 1% only.

Usually offices are arranged around a central atrium with the gangway balconies providing access to the adjoining offices. Instead, in this building, stairs, glazed elevator and the gangways are grouped together in the centre of the atrium. This strategy is appropriate to improve DFs in the lower adjoining spaces as also indicated by Iyer (1994), however, it could be that their location in the centre of the atrium present obstruction to daylight availability, consequently giving lower DFs in comparison with the RADIANCE model on the higher floors. This building also uses movable and largely glazed partitions to enable a flexible use of the space and daylight penetration in the adjoining spaces; a strategy that was also adopted in the Scandinavian Airlines System HQ and could be considered in conjunction with the atrium concept.

Table 7:18 Atrium parameters and daylight data obtained from Domino Haus and the RADIANCE model for curve 2.4

Domino Haus, Germany 4 sided, top lit, with atrium with variable facade (60% opening on other floors and 80% on first floor) 3 /4 storeys; SAR = 1.0; WI = Unknown Adjoining space 18.5 metres deep	Curve 2.4 with even openings (61.25% opening on other floors and 100% on first floor) 5 storeys; SAR= 1.25; WI = 1.25 Adjoining space 12 metres deep	
Transmittance: office atrium single glazing 70%; atrium roof 81%; external office double glazing 76%; sheer curtains <50%	No glazing included	
Atrium wall reflectance = 71%	Opaque area reflectance = 85% (area weighted reflectance of wall - Opaque and opening reflectance = 42%)	
Atrium floor reflectance = 47%	Atrium floor reflectance = 40%	
Office : walls = 71% and floor = 47%	Adjoining space : walls = 60% and floor = 40%	
Approximate DFs on second and third floor respectively (18.5m deep offices):	Approximate DFs on second and third floor respectively (12m deep offices) without and with a 50% reduction	
	Without 50% reduction	With 50% reduction
1m = 2.6%; 3.5%; 2m = 1.0%; 2.5% 3m = 0.6%; 2.0% 4m = 0.3%; 1.0% 5m = 0.2%; 0.6%	1m = 12.4%; 16.6% 2m = 4.4%; 6.9% 3m = 1.7%; 2.9% 4m = 1.0%; 1.5% 5m = 0.7%; 1.0%	1m = 6.2%; 8.3% 2m = 2.2%; 3.45% 3m = 0.85%; 1.45% 4m = 0.5%; 0.75% 5m = 0.35%; 0.5%

The Dragvoll University Centre in Trondheim, Norway

The Dragvoll University Centre consists of an 8.4 metres wide and 12 metres tall glazed street with two storey below ground level and three storey of adjoining spaces on either of its sides that comprise offices, classrooms and auditoria buildings with glazed bridges connecting the two sides (Figure 7:13). Adjoining spaces receive daylight from the glazed street on one side and the large, open courtyards on their other side. The building adopts the strategy of progressive increase in openings from the top to the ground floor combined with white opaque wall surfaces to improve DFs on the atrium floor and the lower adjoining spaces. This results in DFs on the working plane height of 4% near the window and 0.5% at about 4 metres distance in the second floor adjoining offices, comparable to those achieved for the offices that are connected to the outdoors (Fontoynont, 1999a). DFs in the adjoining spaces on the second and third floor of the building were similar suggesting that the reflection of daylight due to the opaque walls with variable fenestration may have improved the balance of daylighting on the different floors (Table 7:19).

Figure 7:13 Atrium of the Dragvoll University Centre in Trondheim, Norway (http://www.multinet.no/~paalk/pics1.html) and (http://wn.com/Malm%C3%B6_University)

Data obtained from the building was compared with the RADIANCE model data for curve 2.2 with variable openings (30%, 34%, 43%, 63% and 100% opening on top to the bottom floor) as shown in Table 7:19. DFs obtained from the model study did not compare well with the building; even with the 50% reduction, DFs for the model were higher. This might be due to a number of reasons; difference in the external daylighting conditions, higher SAR, facade glazing and shading devices in the building as seen in Figure 7:13. Reflectances in the adjoining spaces of the building are unknown and were perhaps lower, and the atrium floor reflectanes were lower resulting in lower DFs in comparison with the model. The rate of decay in the DFs from one position to the other also did not compare well (Table 7:19), perhaps due to difference in the characteristics of the adjoining spaces, i.e. different depths, reflectances and unilaterally lit model adjoining spaces in comparison with the bilaterally lit spaces in the building.

Table 7:19 Atrium parameters and daylight data obtained from Dragvoll University Centre and the RADIANCE model for curve 2.2

The Dragvoll University Centre top lit glazed street with variable facade (smallest opening on top floor, medium on middle floor, 100% on first floor- sizes not available) 3 storeys; SAR = 1.42; WI unknown Adjoining spaces bilaterally lit Adjoining space 2nd and 3rd floor = 4m deep Adjoining space 1st floor = 6m deep Double glazed pitched roof	Curve 2.2 with variable openings (30%, 34%, 43%, 63% and 100% opening on top to the bottom floor) 5 storeys; SAR= 1.25 and WI = 1.25 Adjoining space unilaterally lit Adjoining space 12m deep No roof included	
Double and some triple glazing	No window glazing included	
Atrium wall reflectance: Marble tile = 53%; Brick wall tile colour = 20%; Concrete column grey = 36%; Grille on concrete column dark brown/black = 11%; Acoustic panel wall white = 81%	Wall reflectance = 51% Area weighted reflectance of wall - Opaque and opening reflectance = 42%	
Atrium floor reflectance: Brick tile red =14% and Brick tile yellow/brown = 26%	Atrium floor reflectance = 40%	
Adjoining space walls and floor reflectance unknown	Adjoining space walls reflectance = 60% Atrium floor reflectance = 40%	
Approximate DFs on 1st (6m deep), 2nd and 3rd floor (4m deep):	Approximate DFs on 1st, 2nd and 3rd floor (12m deep):	
	Without 50% reduction	With 50% reduction
0.5m = 2%; 6%; 6% 1m = 1.5%; 4%;4% 2m = 1%; 2%; 2% 3m = 0.5%; 1%; 1% 4m =0.25%; 0.5%; 0.5%	0.5m = 14.6%; 18.4%; 24.1% 1m = 8.6%; 11.7%; 16.1% 2m = 2.0%; 4.1%; 6.4% 3m = 1.0%; 1.6%; 2.7% 4m = 0.6%; 0.9%; 1.3%	0.5m =7.3%; 9.2%; 12% 1m = 4.3%; 5.8%; 8.0% 2m = 1.0%; 2.0%; 3.2% 3m = 0.5%; 0.8%; 1.3% 4m = 0.3%; 0.4%; 0.6%

Kristallen Office Building in Sweden and the Beresford Court atrium building in Dublin

The strategy of an incremental increase in the fenestration from the roof to the atrium floor was found to be effective in two other buildings; the Kristallen Office Building in Sweden and the Beresford Court atrium building in Dublin (Fontoynont, 1999a). The Kristallen Office Building includes a large, stepped section, 20m tall atrium space with a central building which also includes its own narrow atrium. The atrium facades are characterised by a 45 degree tilted roof, single glazed windows and a variable fenestration to improve daylight penetration and distribution in the adjoining spaces (Figure 7:14) (Fontoynont, 1999a). The Beresford Court atrium building (Figure 7:15) adopts a strategy of highly reflective atrium walls and floor (57%) and a variable atrium facade of 40% glazing on the top floor increasing up to 80% glazing on the lower floor. This results in an ADF of 2.7%, a maximum DF of 4.3% on the atrium floor and DFs of over 1% up to 6 metres depth in the adjoining offices (Fontoynont, 1999a).

Figure 7:14 Atrium of the Kristallen Office Building in Sweden (http://fjallboskogen.blogspot.com/2009_04_01_archive.html)

Figure 7:15 Atrium of the Beresford Court building in Dublin (Fontoynont, 1999a)

St Hubert Galleries in Brussels

St Hubert Galleries in Brussels, discussed previously in Chapter Six, has a SAR of 2, is covered by a 90% transmittance, cylindrical glazed roof and has a wall and floor reflectance of 65% and 16% respectively. Despite the high wall reflectance and building facades that adopt a progressive increase in the openings from the top to the bottom floor, lower wall luminance due to the opposite building facing the windows reduces vertical DFs rapidly from the top to bottom floor. This causes shallow penetration of the daylight in the adjoining spaces where only 2% DF is achieved barely at one metre distance from the atrium facade indicating that larger windows may be necessary (Figure 7:16) (Fontoynont, 1999a). These findings are in agreement with the conclusions drawn from the previous and the current Chapter which essentially suggest that reduced view factor between the atrium's walls and the sky vault results in lower wall luminance (Letherman and Wright, 1998) and lower DFs despite the improved wall reflectances and their distribution.

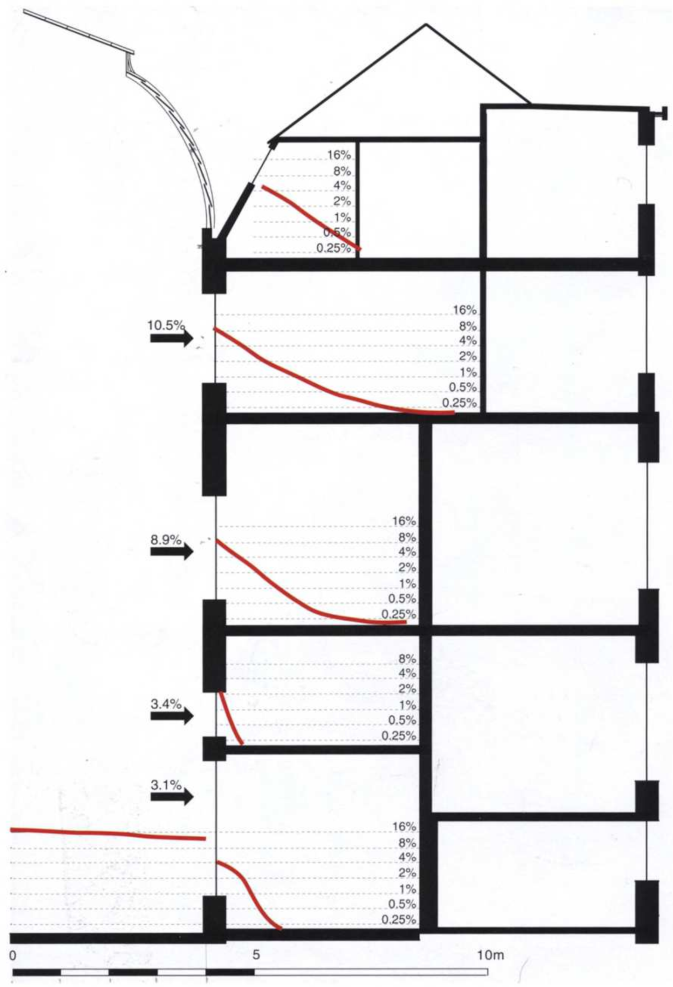


Figure 7:16 Section of the St Hubert Galleries in Brussels, DFs in the adjoining spaces (Fontoynont, 1999a)

The Administration Building in Recanati

The Administration Building in Italy by Mario Cucinella Architects is the headquarters for IGuzzini, the lighting manufacturers. Reflecting the business of the organisation, this four storey, rectangular plan building with a footprint of 40 metres by 19.3 metres is highly glazed and has a central atrium with cellular and open plan offices around it (Figure 7:17). The 100 square metres atrium has a WI and a SAR of 1, a PAR of 1.5 and is designed as a planted courtyard creating an amenity space for the building occupants. The adjoining spaces are 13 metres deep on either side along the length of the building as shown in the section (Figure 7:17), with six metre deep offices and services on its third and fourth side respectively. The atrium is predominantly glazed and characterised by its glass walls and balustrades, white floor fascias and columns, and transparent metal and glass stairs and lifts which it houses, lending transparency to the atrium and enabling daylight distribution within the building (Figure 7:21). Furthermore, the atrium roof incorporates twelve roof lights which have been designed to penetrate daylight deep into the adjoining office spaces (Schittich, 2003).

Although daylight analysis is not available for this building, given the geometry of the atrium, the shallow and bilaterally lit adjoining spaces, the use of light directing elements in the roof, highly reflective surfaces and heavily glazed facades, daylight levels within the building are likely to be high. Moreover, it is argued that the heavily illuminated atrium is possibly created to provide a visual interest to the occupants, looking at the atrium space from the comparatively less well lit adjoining spaces.

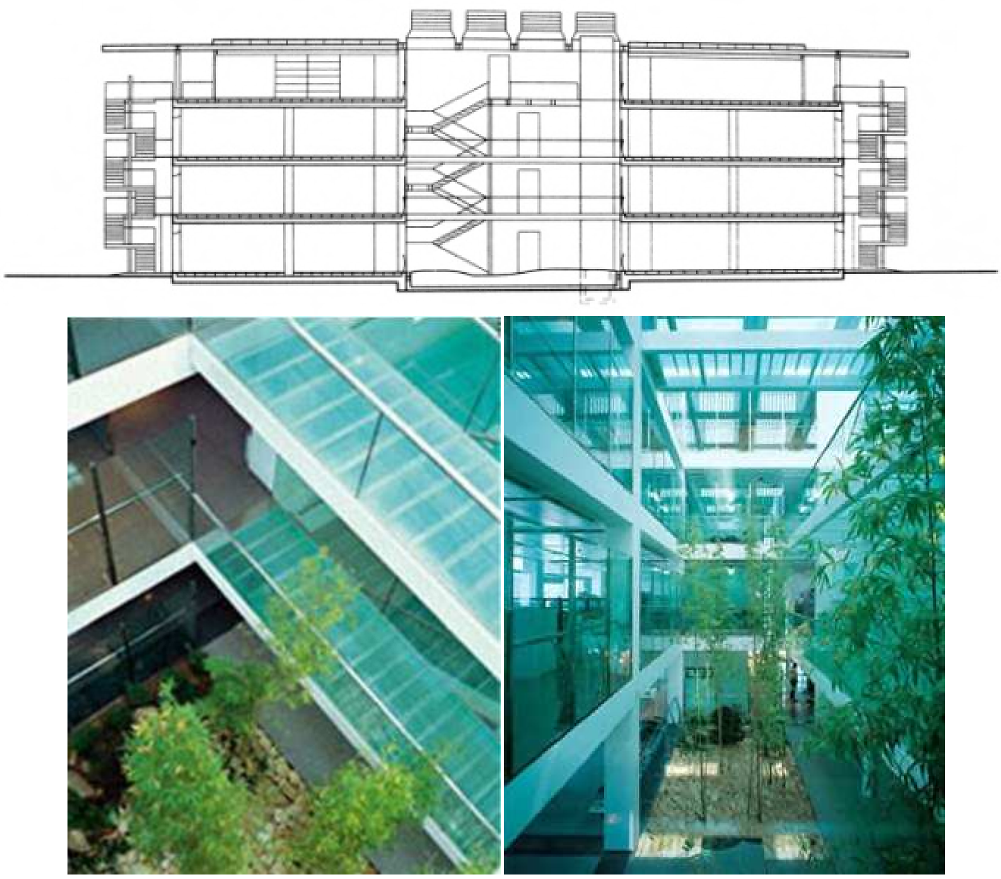


Figure 7:17 Section of Administration Building in Recanati, Italy by Mario Cucinella Architects (Schittich, 2003) and Views of the atrium (http://offtopicdesign.com/tag/cucinella/)

Covent Garden warehouse in Stukeley Street, London

Covent Garden warehouse in Stukeley Street, London was converted into an office building by the architects, Jestico and Whiles, where the original disused courtyard was transformed into an atrium to create a well lit working environment (Figure 7:18). In addition to a south facing reflector which is installed below the glass roof, transparent, reflective or light/white walls and floors are used to reflect light into the adjoining office spaces. Additionally, the workspaces are day-lit as they open onto the atrium through the use of large, folding glass panels (Thomas and Garnham, 2007). Heavily glazed facades in this building may create higher daylight levels as noted in the RADIANCE study earlier in this Chapter.

Figure 7:18 Offices in Stukeley Street, Covent Garden, London by Jestico and Whiles (http://www.jesticowhiles.com/#/projects/1173/)

More generally it is noted that the daylight penetration in the adjoining spaces of an atrium building is aided by shallower floor plans, often dictated by regulations. For example, in France and Germany, maximum distance between an occupant's work space and facade is 6.5 and 7.0 metres respectively. It's the dual aspect, created by the use of a top-lit and a side-lit atrium which when used in conjunction with shallow adjoining spaces, which offers opportunities to admit more light as well as its control than a typical building, which would admit light only from its periphery. Both these strategies are evident in the Commerzbank in Frankfurt where a very shallow plan of 16.5 metre deep office spaces when used in conjunction with a top lit atrium and the side-lit sky gardens, present opportunities for improved daylighting in the lower reaches of this tall building. In some buildings, daylight is further aided by high reflectance surface finishes, both in the atrium and the adjoining spaces and a progressive increase in fenestration from the atrium roof to the floor as evidenced by the experiments. Although well indices of all and SARS of some of the buildings were unavailable, in buildings with medium proportioned atria such as the Domino Haus (SAR 1), the Dragvoll University Centre (SAR 1.42), the Kristallen Office Building and the Beresford Court, in congruence with the findings of the experiments of this Chapter, the strategy of variable fenestration in the atrium facades improved daylight levels in the adjoining spaces.

7.3 CONCLUSIONS

This Chapter examined the influence of atrium facades through different fenestration distributions on DFs in the atrium and its adjoining spaces of a square atrium building with an atrium of WI 1.25 under overcast sky conditions. Atrium facade compositions comprising different ratios of fenestration and opaque surface areas were tested. These were achieved through creating facades with an incremental increase in the fenestration from the top of the atrium to its floor; as well as facades with even fenestration, both with the same overall area of fenestration in the facades. The objective was to establish whether particular fenestration ratios and an incremental approach to fenestration from the atrium roof to its floor improves daylight conditions in the adjoining spaces in the chosen atrium configuration.

On comparison of the performance of the different options of variable facades with increasing opening sizes from the roof to the floor of the atrium, it was found that they had almost no influence on the lower floor adjoining spaces where more daylight is typically required, but increased the daylight factors by up to 5% on the top floor. Therefore it is concluded that for an atrium building of WI 1.25, different options of progressive increase in fenestration from the top to ground floor tested has a small influence on daylight availability in the atrium and its adjoining spaces. These findings are in agreement with those of Sharples and Lash (2004) who showed a reduced influence of different reflectance distributions on vertical DFs and ARCs in the lower half of the atrium in comparison with the upper half of the atrium. This was also found in Chapter Four which showed that DFs were not very sensitive to the different reflectance distributions once four or more bands of each of the high and low surfaces were created in the atrium of WI 1.

Facades with 20% openings on the top floor increasing up to 100% openings on the bottom floor gave the lowest DFs on the top floor as expected whilst not improving DFs on the lower floors. On the other hand, a more gradual increase in the openings with 60% openings on top floor, increasing up to 100% on the lowest floor (options 1.5, 2.5, 3.5) increased the DFs by up to 5% on the top floors without compromising DFs on the lower floors. This suggests that a more gradual progressive increase in openings from top to bottom of the atrium might be more suitable. Therefore, for a five storey, four sided square atrium building with a WI of 1.25, atrium facades with 60% opening on top floor, with a progressive increase in the openings on the intermediate floors and 100% opening on the ground floor give the highest DF values in comparison with the other variable openings facade options. This is in congruence with the facade ratios presented by Aschehoug (1992) despite the difference in the geometries between the two studies.

When different variable opening facades were compared with each other, it was found that the way in which fenestration increased from the fifth to the first floor by which options 1.5, 2.5 and 3.5 were defined and differed from one another was not found to be important. However, when the variable and even fenestration facades were compared, it was found that the fenestration distributions affected DFs in the adjoining spaces.

In comparison with the variable opening facade, it is concluded that depending on the particular percentage of fenestration adopted in the atrium facades, DFs could be reduced, similar or improved with even openings in the atrium's facades. Increased SC on the fifth floor adjoining space due to even openings and resultant increases in the opening sizes led to higher DFs mainly in the top floor while decreasing DFs on the first to the fourth floor. Therefore, it is concluded that the strategy of a progressive increase in openings from the top to the atrium floor in a four-sided, square atrium with a WI of 1.25 can potentially result in an improved balance of daylighting on the different floors and may improve DFs by 1 to 4% up to a distance of two metres in the adjoining spaces on the first to the fourth floors where more daylight is typically needed.

For the open, four sided, top lit square atrium building with an atrium WI of 1.25, it is concluded that DFs in the adjoining spaces will be highest if the facades have a higher proportion of glazed areas (60% on the top floor increasing up to 100% on the bottom floor). However, in these atria, the improvement to the DFs will not be achieved due to the incremental increase in the fenestration from the atrium roof to the floor and that even openings with same average areas of windows would indeed provide similar or better DFs. However, when the percentage of fenestration in comparison with the opaque wall surface area is reduced in the atrium facades to 20%, 30% and 40% openings on the top floor increasing up to 100% on the first floor, the effect of the atrium facades will be evident and will lead to increases in DFs in the adjoining spaces on the lower levels where the daylight availability is typically low.

When the overall environmental performance of a building is considered, the amount of fenestration in the atrium facades will usually be reduced to overcome problems of glare, overheating or heat losses, particularly on the higher floors, in addition perhaps to reduce the costs associated with glazing. Therefore an incremental approach to fenestration with 20, 30 and 40% fenestration on the top floor increasing up to 100% on the bottom floor of an atrium will improve daylight levels in the adjoining spaces without compromising other performance criteria in a medium proportioned atrium building with an atrium of well index 1.25. This is in agreement with the findings of Cole (1990) who demonstrated that the facade with variable openings (100% opening on the first floor, 80% on the second, 60% on the third, 40% on the fourth and 20% on the top floor) in comparison with 100% and 50% opening is most effective in terms of bringing daylight on the lower floors of a five storey open, square atrium building.

DFs reduce significantly from the fifth to the first floor and from the atrium centre to the 5 metre position in the adjoining space. As the daylight levels reduce with increasing distance from the atrium into the adjoining space, difference in the DFs obtained on the fifth and the first floor also reduces considerably in the adjoining spaces, particularly beyond 3 metres.

Due to the higher DFs obtained on the upper floors, decay in the DFs from the atrium centre into the adjoining space is also larger and more noticeable on these floors in comparison with the lower floors.

The parametric RADIANCE study highlighted the influence of atrium facade design, including its glazing ratios and reflectance distributions, on daylight performance of an atrium and its adjoining spaces. A few notable built examples of atria that demonstrate similar traits in terms of their geometries and reflectances, some of which adopt a progressive increase in the openings in their atrium facades from the top to the ground floor, were studied. Where possible, comparisons with the key findings from this Chapter were made.

DF results for the adjoining spaces from the model study did not compare well with the case study buildings in some cases perhaps because the contribution of ARC to the DFs increases in these spaces. The ARC depends on several key characteristics of the atria and their adjoining spaces (i.e. presence of obstructions in the atrium, precise reflectances, geometries of the atrium and its adjoining spaces, and details of fenestration in the atrium's facades etc) which were not fully described in the literature and resulted in a weaker agreement.

The comparisons show that several atrium buildings are characterised by high reflectance surface finishes, both in the atrium and their adjoining spaces, some of which also include progressive increases in fenestration from the atrium roof to its floor. This, when used in combination with medium proportioned atria (SAR of up to 1.5) and shallow adjoining spaces that are bilaterally lit, may result in improved daylighting in the atria and their adjoining spaces as evidenced in the model study and the Domino Haus (SAR 1), the Dragvoll University Centre (SAR 1.42), the Kristallen Office Building and the Beresford Court. St Hubert's galleries adopted both high surface reflectances and variable fenestration in the facades, yet these strategies did not improve DFs in the ground floor adjoining spaces due to the higher SAR of 2.

The RADIANCE model WI and SAR was 1.25 and well indices of the buildings discussed were unavailable; however, built atria with SARs of up to 1.5 demonstrate that the strategy of variable fenestration can improve the daylight levels in the adjoining spaces. This is in congruence with the findings of Du and Sharples (2009b) who also demonstrated higher impact of reflectances on vertical DFs in atrium WIs of 1.25 and 1.5.

Built atria also demonstrate the impact of floor reflectances on DFs in the lower adjoining spaces. Furthermore, the use of glazed partitions in the adjoining spaces enable daylight penetration deeper into these spaces, making small but significant contribution to daylight levels which will reduce artificial lighting in these areas.

Whilst variation in facades may present opportunities to improve daylighting, it is only a small component within the context of the multiple roles that atria play. Indeed practices are adopting innovative design solutions that are aided by technological developments, by perhaps an early engagement with the environmental consultants, and by the use of computer simulations to successfully address daylighting in atrium buildings as shown by the examples described in Chapter One and this Chapter. Thus pointing to the fact that there might be several independent studies of buildings; however much of this information might not be published and is a missed opportunity. Therefore, this draws attention to the gaps that lie between research/academia and practice and that there is a need for more integrated and practice based research so that some of the design solutions can be tested and that the lessons learnt could be developed into early design guidelines for architects.

8 THESIS CONCLUSIONS

8.1 RESEARCH SUMMARY

Atria have the potential to make significant contributions to a range of building types environmentally, socially and economically. Atria provide excellent opportunities for improving the environmental sustainability of buildings (light, heat, shade and ventilate). They provide buildings with an intermediate space/environment between the internal and external that can filter and manipulate environmental factors that permeate through its form to create desired conditions without excessive dependence on automated systems that consume energy and cause harmful emissions.

Atria have a varied impact on buildings but daylighting is one of the key aspects of the atrium form making vital contributions to the buildings' aesthetics, energy efficiency and social needs. Although the covering of courtyards to create atria reduce daylight availability significantly, the creation of a buffer zone with reduced heat losses and gains means larger openings in the atrium facades can be created to admit more daylight. Furthermore, as Fontoynont (1999a) noted, even though the daylight might generally be enough only as ambient lighting, it will be useful in reducing the feeling of being confined and in providing a perception of the outdoor environment through the atrium. In response to this, daylighting in atrium buildings have been investigated in detail over the past three decades using algorithms, physical scale model studies, real building studies and computer simulations with the objective of developing rules of thumb and more specific design guidelines. These studies focus on understanding the influence of key daylight linked atrium parameters (roof, geometry, enclosing surfaces and adjoining spaces) on the daylight quantity and its distribution in the atrium and its adjoining spaces.

After passing through the atrium roof, a portion of the incoming daylight is directed towards the adjoining spaces while the remaining daylight is inter-reflected between the atrium surfaces and reaches the lower floors. Therefore the upper part of the atrium usually receives direct light from the sky while the lower atrium mainly receives reflected light from the atrium walls and floor. Whilst daylight levels in atria are generally high, daylight in the adjoining spaces can vary. Typically, adjoining spaces nearer to the atrium roof tend to be over-lit and suffer from glare while those on the mid and lower floors may not receive adequate daylight, particularly in the atria of higher well indices.

Therefore considering the critical role of an atrium's envelope in the availability and distribution of daylight in the atrium and its adjoining spaces, and having identified certain gaps in the literature review related to this parameter, the following thesis aims were drawn.

The study sought to examine the influence of atrium facades characterised by different surface reflectance distribution patterns, surface types and ratios of fenestration versus opaque areas on the daylight performance of an atrium and its adjoining spaces under overcast sky conditions.

The following paragraphs will outline how these aims were achieved.

Many studies discussed in Chapter Three have examined the impact of surface reflectances on DFs and ARCs using either physical scale models or computer simulation programs. However, the effect of variation in the distribution of reflectances in the atrium facades on the ARC at the atrium floor was not investigated in these studies. Although most atrium facades comprising different materials will consist of bands of different reflectances, both in value and in surface properties, an area-weighted reflectance is often used to calculate the daylight availability. This would not provide a clear picture of how daylight is distributed on the atrium floor due to the arrangement of the various materials and their reflectances typically found in the atrium facades. Therefore the experiments of Chapter Four investigated the effects of different reflectance distributions and surface types (diffuse, specular) in atrium facades on DFs across the atrium floor. It was vital to assess DFs on the atrium floor as tdaylight reaching it can be reflected onto the ceiling of the lower adjoining floors to improve daylight in these spaces.

Letherman and Wright (1998) state that in an atrium of high WI, the relative surface area of the atrium's walls is high resulting in a higher potential for a large ARC. However, the view factor between the atrium's walls and sky vault is small resulting in lower wall luminance and consequently lower DFs on the atrium floor. As the WI decreases, DFs increase with an increase in the view factor with the sky vault with a reasonable contribution from both the SC and the ARC. However, as the WI becomes very low, ARC decreases but the SC increases, increasing the DFs on the atrium floor. The literature review in Chapter Three demonstrated difference in the findings of the previous studies in relation to the atrium well indices and geometries in which DFs are affected due to the atrium wall surfaces. Furthermore, these studies did not examine the effects of varying reflectance distributions on DFs and ARCs in atria of different well indices, which this study examined in Chapter Six. For this, four sided, top lit, square atria of well indices 0.5, 1 and 2 were examined.

Although, the initial experiments focussed on the daylight availability and its distribution on the atrium floor, it was vital also to examine the effect of the surface reflectance distributions on the DFs in the atrium's adjoining spaces. Several authors recommend that daylight potential on the atrium floor and the lower adjoining spaces can be enhanced by gradually increasing the proportion of the opening to the reflective surface areas in the atrium walls from relatively small openings at the top to fully glazed openings at the ground level. However, an area of continued uncertainty is whether a particular incremental approach to fenestration from the roof to the floor of an atrium's facade might be advantageous in terms of improving daylighting in the adjoining spaces. Additionally, there is a lack of consensus, due to the different geometries in the various studies, with respect to the appropriate approach to the facade design (fenestration and opaque atrium surface area ratios) in terms of the improvements in DFs that might be achieved. Therefore, having established the range of well indices in which the reflectances and their distributions affect the DFs in Chapter Six, the experiments of Chapter Seven examined the impact of different facade compositions (even and progressive increase in openings from the atrium roof to its floor) with varied fenestration distributions and ratios in atrium's facades on DFs in the atrium and its adjoining spaces. The objective was to examine whether a particular incremental approach in fenestration from the atrium roof to its floor might be advantageous in terms of improving daylighting levels in the adjoining spaces of a four sided, top lit, square atrium building with a medium proportioned atrium of WI 1.25.

The four-sided atrium was chosen as it provides the least opportunity in terms of admitting daylight in comparison with a two-sided or a three–sided atrium and allows the assessment of the impact of atrium facades on the daylight levels in the atrium and its adjoining spaces in the worst case scenario. The reflectances and well indices chosen in this study are based on those recommended by the previous studies and are representative of the built atria as identified by the survey undertaken by Liu et al. (1991).

While DFs are used in this study to indicate daylight availability at certain measurement points, ADFs are generally used as a broad measure to provide a quick estimation of the daylight availability useful at an early design stage of a project. However, ADFs do not help identify how different distributions of reflectances around an atrium may actually produce different values of DFs or ARC on the atrium floor. Whilst ADF may be high generally, some parts of the floor may have high daylight levels but others may not. Therefore, the impact of surface reflectance distributions on ADF at the atrium floor was also investigated in Chapter Five.

Although physical models were used to undertake the experiments of Chapter Four, to justify the use of RADIANCE for the experimental work undertaken subsequently in Chapters Six and Seven, the experiment of Chapter Four was repeated using RADIANCE in Chapter Five and the data obtained by the two methods were compared. ADF values obtained from the physical model study, the standard ADF formula (Littlefair, 2002) and RADIANCE simulation were also compared in Chapter Five and specific conclusions with respect to their use were drawn.

Finally, to contextualise the work undertaken in this thesis, results obtained from the parametric RADIANCE simulations were also compared with data for the built examples presented in Fontoynont's (1999a) edited book, *Daylight Performance of Building*. The case studies sought to develop a discussion of the work from the parametric modelling. However, the analysis was somewhat approximate due to the lack of information and comparable data in many cases. Therefore, general observations were made in a few notable built examples of atria that demonstrate similar traits in terms of their geometries, reflectances and facade compositions. Further observations were also made in relation to the design of atrium facades and the atrium geometries in buildings to obtain a wider understanding of their role in contemporary buildings.

It is intended that the findings from this study would enable a deeper understanding of the influence of atrium facades on the daylighting in atrium buildings. Furthermore, the information generated in the form of general principles and design strategies could be usefully applied by architects in the preliminary stages of the design process in relation to atrium facade design for an improved daylight performance of atrium buildings under overcast sky conditions without entailing detailed daylight analysis or parametric studies.

The following section includes the results; the general trends are described first, subsequently the key findings are discussed.

8.2 FINDINGS FROM THE EXPERIMENTAL WORK AND THE DESIGN GUIDELINES

8.2.1 The influence of atrium surface reflectances and their distribution on daylight availability on the atrium floor

Atrium surface reflectances affect DFs at the base of atria with well indices ranging between 0.5 and 2. The contribution of the SC to the DF values at the atrium floor will be highest for the atrium of WI 0.5, while the contribution of ARC to the DF will be much higher in the atria of WI 1 and 2. Therefore, surface reflectances have an increasing impact in higher atria of WI 1 and 2 in comparison with the shallow/wide atrium of WI 0.5. The findings are in agreement with those presented by Willbold-Lohr (1989) who showed that the impact of the ARC was mainly in square atria of WI higher than 0.75 and Liu et al. (1991) who suggest that they only affect in the atria of WIs ranging between 1 and 2 suggesting that ARC in atria of lower well indices might be weaker.

DFs on the atrium floor reduce significantly with an increase in the atrium WI, despite the fact that the area weighted average reflectances and the contribution of ARC to the DF values obtained on the atrium floor increase. This is due to the fact that in a high well indexed atrium, because the view factor between the atrium walls and the sky vault is small, the wall luminance is low and this reduces DFs on the atrium floor. This was also evidenced in the St Hubert's Galleries which had a high SAR of approximately 2 where DFs on the atrium floor were reduced despite the increased area weighted wall reflectances.

Although the contribution of ARC increases in atria of higher well indices, as the DFs reduce significantly with the increase in the atrium's WI, difference in the DFs due to the varied reflectance distributions also reduces. For an atrium of WI 1.25, in comparison with an atrium facade with even openings, atrium facade with a progressive increase in the fenestration from the roof to the floor of an atrium improved daylight levels in the adjoining spaces. Altering the proportion and distribution of the fenestration and opaque areas means that the reflectance distributions were also altered. These findings are in congruence with those of Du and Sharples (2009b) who also demonstrated higher impact due the reflectances on vertical DFs in the atrium well indices of 1.25 and 1.5.

Therefore, diffuse surfaces comprising different reflectance distributions with the same area-weighted surface reflectance will affect DFs on the atrium floor of the atria of WI 0.5 to 1.25 more than in an atrium of WI 2; the effect of the reflectance distributions on DFs is reduced as the atrium well index increases. Higher influence of the surface reflectance distributions in atria of WI 0.5 and 1.25 indicates that the use of area-weighted surface reflectances to estimate DFs for these atria might be problematic. However, in an atrium of WI 2, a uniform reflectance atrium representing these surfaces can be used to provide a reasonable estimate of the DFs achieved on the atrium floor.

The atrium surface reflectance distribution patterns in an atrium's facade will have a small influence on ADF on the floor of the atria of WI of 0.5, 1 and 2. Therefore, the ADF predicted by a uniform reflectance atrium could be used to provide a reasonable estimate of ADF which might be achieved in a banded atrium of an equal area weighted reflectance. However, large differences between ADFs and DFs in atria of WI 0.5 and 1 show that the use of ADFs to predict DFs on the atrium floor of a shallow or medium proportioned atrium can be problematic. DFs are expected to be much higher at the atrium centre and much lower in the atrium corner in comparison with ADFs.

On comparing results for the square atrium of WI 1 in Chapter Four and Six with Boubekri's (1995) study of a rectangular atrium of WI 1.05, it is suggested that atrium wells with square plans will receive higher DFs than those with rectangular/linear plans at a given level. These findings are in agreement with those presented by Oretskin, 1982; Willbold-Lohr, 1989 and Baker et al. 1993.

Atria with darker/low (2% reflectance) and mixed/medium reflectance (22 to 34% reflectance) atria will see a higher drop in DFs when the atrium WI increases from 0.5 to 1 than when the WI increases from 1 to 2. On the other hand, the light/high reflectance atria (42 to 67% reflectance) will see a steady drop in the DFs with the well index increases from 0.5 to 1 and 1 to 2. Compared to the high reflectance atrium, a low and a medium reflectance atrium will see a higher drop in the DFs with a WI increase from 0.5 to 1. On the other hand, a high reflectance atrium will see a higher drop in the DFs with a WI increase from 1 to 2 than a low reflectance atrium. A large band of high reflectance wall surface at the top of the atrium can improve DF in the centre position of an atrium but may not necessarily improve DFs across the entire floor particularly if there are darker surfaces immediately adjacent to the atrium floor. Therefore, designers should seek to specify lighter finishes generally to the atrium's enclosing walls, particularly in their top portion. This was also recommended by Sharples and Lash (2004) and Lau and Duan (2008).

DF at the corner position on the atrium floor is affected by the reflectance distribution patterns and can be improved if a large high reflectance surface is used on the walls near the atrium floor. However, this is often not possible as these surfaces are fully glazed doors providing physical access to the adjoining spaces.

Lighter floor finishes are also recommended to improve the DFs but this strategy may not always be possible or advisable due to the difficulties and costs associated with the higher maintenance they may require. Built case studies (for example, the Beresford Court in Dublin) show the use and benefits of high surface reflectances on the atrium floors and walls.

In congruence with the banded model study, Sukkertoppen in Valby and the Brundtland Centre in Denmark showed that low reflectance/darker surfaces immediately adjacent to the atrium floor reduce DFs locally. DF distribution should be taken into account when organising the different activities, including the positioning of planting and furniture on the atrium floor. The use of some dark, low reflectance finishes and landscaping on the atrium floor, walls and balconies that absorb light is also evident in some buildings. This reduces the area of high reflectance surfaces that would otherwise be available to reflect light, therefore potentially reducing daylight availability within the atrium and its adjoining spaces.

A difference in DFs at the centre of the atrium floor where a few large bands of different reflectances are used but as the number of bands increases and the width of these bands reduces, the effect of the reflectance distribution reduces and difference in the DFs is reduced DFs on the atrium floor are not very sensitive to the different reflectance distributions once four or more bands of each of the high and low surfaces had been created.

Although banding used in the models is representative of the horizontal banding evident in most real atrium buildings and relates to the different floors comprising of opaque floor risers or wall surfaces and glazed areas, the bands not representative in terms of scale or proportions. As the bands become very thin and numerous, variation in reflectance becomes un-noticeable and in such cases the effective reflectance verges to the average value. Therefore it is suggested that depending on the WI of the atrium, the effectiveness of this strategy reduces beyond four or more storeys from the top of the atrium in a multi-storey atrium building characterised by several horizontal bands of glazed and opaque areas in its atrium facades.

The use of specular surfaces will generally improve inter-reflection of light and increase DFs within the atrium space as compared with those obtained with the use of diffuse atrium wall surfaces. In particular, specular surfaces might be used to improve the DFs in atria with very dark or low reflectance surfaces.

Daylight at the centre of the atrium floor will be higher than the edge and the corner positions because more of SC is received here. Furthermore, DFs in individual positions across the atrium floor are also affected by the different reflectance distributions; however they have a lower impact on DFs at the edge of the atrium floor in comparison to their impact on DFs at the atrium centre and its corners.

8.2.2 The influence of atrium facades on daylight availability in adjoining spaces

On comparison of DFs obtained for the different facade options with a progressive increase in openings from the top to the ground floor tested, it was found that they had a minimal influence on daylighting in the adjoining spaces. DFs on the lower floor adjoining spaces where more daylight is typically required did not increase but DFs on the top floor increased by up to 5%. These findings are in agreement with those of Sharples and Lash (2004) who showed that the reflectance distributions have a very little effect on the vertical DFs and ARCs in lower half of the atrium well but affect them in higher locations in the upper half of the atrium.

Having only 20% fenestration on the top floor increasing up to 100% on the first floor did not increase DFs in the lower floor adjoining spaces but compromised DFs on the higher floors. On the other hand, 60% openings on top floor increased DFs by 5% at 0.5, 1, and 2 metres in the adjoining space on the top floor without compromising DFs on the lower floors. This is because larger opening sizes led to this floor receiving more of the SC. Therefore, it is suggested that for a five storey, four sided square atrium building with a WI of 1.25, an atrium facade with 60% opening on the top floor, with a progressive increase in the openings on the intermediate floors and 100% opening on the ground floor will give the highest DF values in comparison with the other variable facades tested. These findings are in agreement with Aschehoug's (1992) study of a glazed street, which also proposed a gradual increase in fenestration from top to the bottom floor and presented optimum ratios of 50% glazing on the fourth floor, 60% glazing on the third floor, 70% glazing on the second floor and 100% glazing on the first floor.

When the different variable opening facades were compared with each other, it was found that the nature of the increase in fenestration from the fifth to the first floor by which the different fenestration ratios were defined and differed from one and another, was not found to be important. However, when the variable and even fenestration facades were compared, it was found that the fenestration distributions affected DFs in the adjoining spaces.

When the best performing variable fenestration facade options with 60% openings on the fifth floor increasing up to 100% on the first floor were compared with facades with even openings, DFs were further increased by up to 2% on the top floor whilst providing similar DFs on the other floors. This was due to further increases in window sizes on the higher floors in the atrium facades with even fenestration. Therefore for a five storey, four-sided square atrium building with a WI of 1.25, it is concluded that DFs are highest where the atrium facades have a higher proportion of glazed areas (60% on top floor increasing to 100% on the bottom floor). However, in highly glazed facades, improvement to DFs due to the incremental approach to fenestration is not achieved and even openings with same average areas of windows would indeed provide similar or better DFs. Therefore, either an even or a variable facade can be adopted.

On the other hand, in comparison with the facades with even openings, variable facades characterised by smaller openings and lower overall percentage of fenestration, such as 20%, 30% and 40% openings on the fifth floor increasing up to 100% opening on the first floor improve DFs in its lower floor adjoining spaces where more daylight is typically needed. This is in agreement with the findings of Cole (1990) who proposed a variable opening façade with100% opening on the first floor, 80% on the second, 60% on the third, 40% on the fourth and 20% on the top floorto be most effective.

The study highlights the influence of atrium facade design, ratios of fenestration and opaque areas and reflectance distributions on daylight performance of an atrium and its adjoining spaces. However, in practice it is impossible or indeed recommended not to consider this aspect alone and that the decisions are made taking into consideration several other contrasting factors of solar gain and overheating, glare, ventilation, privacy and views and other aesthetic, functional, economic, socio-cultural and environmental factors. When the overall environmental performance of a building is considered, the amount of fenestration in atrium facades will usually be reduced to overcome problems of glare, overheating and heat losses, particularly on the higher floors, in addition perhaps to reduce costs associated with glazing. In this scenario, an incremental increase in fenestration from the top (20%) to the ground floor (100%) of an atrium will ensure that daylighting is adequate without compromising other performance criteria in a medium proportioned atrium building with an atrium of well index 1.25. This is also evident in some of the real atrium buildings of similar proportions with shallow adjoining spaces that were bilaterally lit. Improved daylighting in atria and their adjoining spaces were noted in the Domino Haus (SAR 1), the Dragvoll University Centre (SAR 1.42), the Kristallen Office Building, and the Beresford Court. While the experiments of this thesis showed the benefits of this strategy in an atrium SAR/WI of up to 1.25, built examples show the impact of this strategy in SARs of up to 1.5 as also shown by Du and Sharples (2009b).

As expected, DFs reduce from the atrium centre to five metres in the adjoining space and from the top to the bottom of an atrium. As one moves away from the atrium, daylight levels drop consequently reducing the difference in the DFs from the top to the bottom floor, particularly beyond 3 metres in the adjoining space.The decay in horizontal DFs from the atrium centre into the adjoining space is more noticeable on the upper floors and is gradually reduced from the fifth to the first floor.

To understand the impact of the atrium and its envelope on daylight availability in the adjoining spaces, these spaces were unilaterally lit with no windows in the building's external facades. In reality though, the adjoining spaces will be bilaterally lit and will have higher DFs and improved daylight distribution than that presented in this study.

8.2.3 Findings related to the daylighting assessment methods

DF and ADF Comparisons

Generally there was a good agreement between data obtained by the physical scale models and RADIANCE; in congruence with the findings of Aizlewood et al., (1997) and Calcagni and Paroncini (2004), DFs and ADFs at the atrium floor from RADIANCE were at the most 10% lower when compared with the physical scale model. This was highlighted to be an acceptable difference by Calcagni and Paroncini (2004). Besides, Tregenza and Loe (1998) suggest that small changes in the illuminance levels might be due to the uncertainty in the input data in RADIANCE. A maximum difference of only 1% in terms of the decay in the DFs from one position to the other across the atrium floor from the two methods was noted. Therefore, in agreement with the findings of Ubbelohde, (1998), Galasiu and Atif *(*1998) and Bryan and Autif (2002), RADIANCE was found to be generally reliable for assessing daylight conditions in buildings.

The difference in DFs and ADFs obtained from the two methods increased with an increase in the atrium surface reflectances. It might be that perhaps the inter-reflections are not being handled well in RADIANCE.

A similar trend is also observed when ADF values obtained by the physical scale model were compared with the ADF expression by Littlefair (2002). Therefore, the use of RADIANCE and Littlefair's (2002) equation may be more suitable for estimating DFs and ADFs in low reflectance atria in comparison with medium and high reflectance atria.

ARC comparisons

ARC obtained from the physical scale model study was compared with Aizlewood et al.'s (1997) analytical approximation for estimating ARC for an overcast sky. Although this expression is more complex and relies on estimates of the SC, it can be used to estimate ARC for atria with all-white/light coloured high reflectance surfaces and in atria where the number of bands of different reflectances increases and the bands became narrower with the effective reflectance tending to the average value. However, this expression may not be suitable to estimate ARC for an atrium with a small number of large bands of different reflectances.

Comparison of data with real buildings

Results from the RADIANCE study compared well with those found in real buildings on the atrium floor but did not compare well with DFs found in the adjoining spaces. This was possibly because of the fact that the SC is likely to be an important contributor to DFs obtained on the atrium floor. Moving into the adjoining spaces, the ARC starts to grow in importance and will be more heavily related to the presence of obstructions in an atrium, its precise reflectances, geometries of the atrium and its adjoining spaces and fenestration in the atrium facades. Given these are not well described in the literature, perhaps the poorer agreement is to be expected or is at least not surprising.

8.2.4 General Observations

More generally, it is noted that innovative approaches to the use of the atrium concept and the manipulation of atrium geometry and surface treatments to enhance daylighting conditions is evident in contemporary buildings. Atrium facades are generally determined by the building's uses, its layout and orientations, its aesthetics and its need to provide physical and visual links with the atrium and across it, and to improve the building's daylight and thermal performance.

Top and side-lit atria are increasingly used to overcome the problems of poor daylighting in the lower reaches of a typical top-lit atrium building. With side-lit atria, greater SC can potentially reach the lower levels and with the likely obstructions created by neighbouring buildings in urban settings, the two buildings together might create a 'virtually' top-lit atrium but perhaps with a more favourable WI and improve daylight conditions on the lower levels of the building. The Commerz bank in Frankfurt (top and side lit- used in combination with sky-courts/sky-gardens), the Heron Tower in London (vertically stacked side lit), the Century Tower in Tokyo (top and side lit) and the Swiss Re in London (peripheral spiralling) evidence innovative use of the atrium form in combination with highly glazed and high reflectance surfaces, and shallow bilaterally lit adjoining spaces. Furthermore, stepped section atria opening out to the roof are also used to enhance daylighting conditions in buildings as seen in the Kristallen Office Building in Sweden.

Generally, in addition to the strategies already discussed, to improve daylight conditions in the atrium buildings, varied atrium roofs and roof covers including ETFE, polycarbonate and intelligent glazing; window sizes and their positioning and orientation; light directing elements on the atrium's facades; innovative structural systems; light coloured opaque or glazed walls, partitions, parapets and furniture; and metal or glazed lifts and balconies are used.

Atrium manifestations are continuously transforming, reflecting not only the pursuit of form driven architecture but also the emphasis on environmental design and energy efficiency.

Furthermore, technological developments and their application in terms of materials, structures and parametric modelling using computer simulations have resulted in more innovative forms and responsive contemporary architecture. Roofing and glazing technology including its support systems has developed enormously influencing atrium envelope design, presenting opportunities for more innovative roofs and facades to be exploited that would otherwise have not been possible.

Innovative daylighting strategies adopted in practice may or may not have been investigated in depth or tested as part of the design process or indeed undergone post occupancy evaluations depending on the time, access to the buildings and costs. Few recent buildings such as the Deutsche Bank Place - 126 Philip Street, Sydney and the Greater London Authority building discussed in Chapter One adopted a performance based approach to design and undertook extensive modelling to improve the buildings' environmental performance while creating visual and spatial interest. During the course of the undertaking of this research, wider uptake of the computer simulations and their increasing role in the iterative design process is evident. To optimise environmental performance, the need for early collaborations with building services engineers is now increasingly recognised.

8.3 RESEARCH CONTRIBUTION

Engagement with environmental issues during the early stages of the design process can influence building form, orientation and ultimately performance. Whilst several available computer simulation programs can be used to assess design solutions, this process can be time consuming. Involving environmental consultants can be expensive and therefore, they are often brought on board towards the end of the design phase. However this would mean lost opportunities in terms of using environmental considerations to shape the design and can lead to remedial strategies that may compromise the original design intents. While designers can't rely on an intuitive design approach solely, it may be used to derive the initial designs that may then be tested using more sophisticated approaches to deliver energy efficiencies in buildings. These typically rely on the interaction between the different and complex performance variables, processes and advanced technologies. However, the specific conclusions drawn within this research could serve as valuable information that would enable architects to make informed early design decisions that may not be time consuming, would beneficially impact on daylight performance of the building and lead to more holistic approaches to energy efficient building design.

The extensive literature review outlined current knowledge on the influence of atrium geometry, and atrium surfaces (atrium walls and floor) and their reflectance properties on daylight in atria and their adjoining spaces. Following this, and although in certain parts it is limited in scope, this research on daylighting in atrium buildings under overcast sky conditions contributed to the understanding of the following:

- the effects of the different reflectance distributions in the atrium walls including the effects of the diffuse and the specular surfaces enclosing an atrium on daylight availability in atrium buildings
- the influence of the surface reflectance distributions in different atrium well indices on DFs at the base of the atrium
- the impact of atrium facades with varied fenestration and opaque area distributions on daylight availability in an atrium building. In particular, it examined whether a particular incremental increase in the fenestration from the top to the bottom floor and the ratio of fenestration versus opaque areas might be adopted in an atrium's facade to improve DFs in its adjoining spaces

8.4 RESEARCH LIMITATIONS

This study demonstrates the influence of atrium facade design on the availability of daylight in atrium buildings. Although the impact of atrium surfaces on the more poetic qualities of architecture and its experience are vital and acknowledged, the study is limited to the quantitative assessment of daylight availability. The study examined the effects of reflective properties and their distribution patterns, diffuse and specular surface types, and distribution of opaque and fenestration areas in the atrium facades. The findings are obviously limited to the specific geometries and reflectances used in this study. However, it is recognised that DFs, ARCs and their sensitivity to reflectance distributions may be more critical for a wider range of reflectance values, geometries and well indices than those used in this study. Furthermore, this research is limited to the overcast sky condition therefore care should be taken when integrating design guidance for other climates and skies. Indeed, dynamic daylight performance metrics, which considers building orientations, different seasons, time in the day, direct solar ingress and variable sky conditions, is suitable for both, overcast and non-overcast skies is recommended for future research.

Due to the focus on atrium facades, this study did not consider the improvements to daylight that might be brought in the lower adjoining spaces by higher atrium floor reflectances or if the adjoining spaces are bilaterally lit. In reality, these spaces will usually be bilaterally lit and daylight levels will be higher with improved daylight distribution than that presented in this study.

It is also vital to consider further DF reductions that would be expected when an atrium roof, windows and maintenance factors are considered. All these aspects, together with the artificial lighting strategy adopted, will affect the overall lighting performance of the atrium buildings.

Comparison of data from the parametric studies with monitored data in real buildings was undertaken to contextualise the work undertaken in this thesis. However due to the lack of available comparable data and several parameters not well described in the literature, the comparisons were limited in their depth and overall extent.

Whilst atrium facades may improve the daylighting conditions in atria and their adjoining spaces, they only form a small component of the overall daylighting and indeed the wider environmental strategy of a building. Furthermore, considering the diverse and complex roles of contemporary atria, there will inevitably be compromises in the design strategies that might be adopted for the atrium facades.

Specific observations made in relation to the atrium design will be valuable to the intuitive design processes adopted by designers at the early stages of a project and important in terms of informing the detailed analysis that would be undertaken subsequently. Furthermore, despite the fact that the design teams now have access to sophisticated modelling software, there is still a need for a base level understanding of the system to develop early design strategies, which this research contributes to.

8.5 SUGGESTIONS FOR FURTHER RESEARCH

Several areas for further research have been identified as a result of undertaking this study.

This study of the atrium surface reflectances and the chosen fenestration options was limited to a top-lit atrium and could be extended to a range of atrium types (three sided, linear and stepped atria) and atrium geometries (rectangular, circular and triangular floor plans) to assess their likely impact relative to the top-lit atrium.

Further studies could explore the influence of atrium floor in conjunction with the proposed facade strategies considering their ability to boost daylight levels in the lower adjoining spaces. Additionally, experiments could be extended to include fenestration in the building's external facades to assess improvements to DFs in the adjoining spaces that might be achieved.

Although this thesis focussed on the horizontal DFs, further experiments could be undertaken to examine vertical DFs at the atrium wall, as they are vital indicators of daylight availability in the adjoining spaces and to date very few studies have examined them.. Furthermore, this research only examined DFs along the centre line of the adjoining spaces; however it is vital to examine both DFs across the entire floor and ADF in the adjoining spaces.

Emulating real buildings, further experiments could be conducted to include different types of wall fenestration, glazing and roof systems to assess their impact on available daylight in an atrium and its adjoining spaces. Atria are often characterised by balconies projecting into or surrounding the atrium spaces, which may reduce daylight availability on the edges of the atrium and their adjoining spaces. The atrium facades in these cases may be defined by the geometry and reflectances of the balconies, and whether or not they act as light directing and/or shading devices. Furthermore, atrium facades may also include other elements including parapets, railings, daylighting systems - lightshelves, light scoops, and blinds. Therefore, there is a need for a much more systematic investigation of the strategies used in real buildings to understand their likely effects over the simple atrium facades and geometries studied in this research.

Largely, previous research on daylighting in atria is limited to overcast skies, having little relevance to other climates. The likelihood of glare problems, for example, will be more evident under sunny skies and would consequently require carefully thought lighting control strategies. Therefore, further research for different sky types using the dynamic daylight performance metrics is also necessary.

Due to the usual difficulties of access to buildings and lengthy time that is essentially required to monitor real buildings, except for a few studies, availability of published investigations of real buildings is very limited and patchy. Undertaking comparative analysis of measured data from real buildings and that predicted by computer simulations would be very useful in terms of assessing the impacts on daylight of furniture, partitions and other measures that might be implemented when buildings are occupied. Furthermore, an integrated research of daylighting in atrium buildings with other contrasting performance variables is also essential, where consideration for the acoustic, thermal and ventilation performance is made and trade-offs between them are established.

Since Saxon's (1983, 1986 and 1994) and Bednar's (1986) books on atrium buildings, extensive research has been undertaken both in academia and practice, and atria have been widely incorporated in a variety of contemporary buildings with the objective of creating 'environmentally sustainable' architecture. Real atrium buildings discussed in this thesis show that international practices are undertaking building simulations to improve daylight and indeed the overall environmental performance of buildings. This indicates that several independent studies probably have been undertaken; however there is a lack of published post occupancy studies evidencing performance of the daylighting strategies used in these buildings. Therefore, this vitally points to the gaps that lie between research, academia and practice and that there is a need for more integrated and practice based research so that some of the design solutions can be tested and the lessons learnt could be developed into early design guidelines for architects. Finally, it demonstrates the need for an up-to-date comprehensive reference guide for design professionals which includes a systematic and detailed survey of contemporary atrium buildings that are designed to deliver sustainable architecture.

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