An Exploration of the Applications of Increased Information Availability in Smart Buildings

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Mum and Dad,

My TC and Fiancée,

My sisters,

This work represents the everlasting support and love you have all given me.

I am eternally grateful.

“The world as we have created it is a process of our thinking.

It cannot be changed without changing our thinking”

Albert Einstein

Abstract

Modern buildings have the capability to capture vast quantities of information about the building itself, its purpose, the people that use it and its wider environment. With the development of fields such as the Internet of Things and Big Data, the future of buildings will involve more data around all aspects of their operation and the people using them. Within the context of these changes, this research hypothesises that the availability of increasing information within buildings can enable new ways of operation to step change their performance.

Initially the thesis combines an extensive literature review of modern building developments and the current landscape that buildings operate within to develop clarity around the term "Smart Building". Two case studies are then presented to demonstrate the potential of Smart Building concepts: The first case study involves a pilot study within an existing university library building using occupancy, energy, occupant satisfaction and building functionality data to investigate the potential of the buildings ability to vary physical space with occupancy. The second study uses computational fluid dynamics to model the thermal comfort variations throughout a large underfloor heated naturally ventilated atrium. The results are then used to investigate potential energy savings and comfort improvements through correlating individual comfort preferences with environmental variations.

The work forms a clear definition of a Smart Building to create a framework for researchers and designers to focus future Smart Building developments. The first case study then demonstrates that by varying physically occupied space with occupancy, energy consumption of the building can be reduced by approximately 33%. The second study demonstrates that a step change in both comfort and energy efficiency can be achieved in flexible working spaces by aligning individual preferences with environmental conditions. These finding are discussed in detail, addressing limitations and future expansions of the novel approaches developed.

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List of Key Acronyms and Notations

Acronym	
ATC	Adaptive thermal comfort
BCC	Berkeley Civic Center Database
CFD	Computational Fluid Dynamics
FDM	Finite Differenc Method
FEM	Finite Element Method
FVM	Finite Volume Method
HVAC	Heating Ventilation and Air Conditioning
LES	Large Eddy Simulation4
NV	Naturally Ventillated
PMV	Predicted Mean Vote
PNC	People no change
PPD	Percentage people dissatisfied
PPNC	Percentage people no change
RANS	Reynolds averaged Navier Stokes
RNG	Re-normalisation Group
SCATs	Smart Controls and Thermal Comfort Projepct Database
Symbol	
α	solar altitude
Δ	time-step
ε	turbulent dissipation
k	kinetic energy
λ	Conductivity of air
ρ	density
ρ_g	solar reflectance of the ground
v_{ar}	Relative air velocity
ω	Specific rate of dissipation
c_p	specific heat capacity
F	Fourier Number
h_c	heat transfer coefficient
I_{sdiff}	diffuse sky solar flux
I_{gdiff}	diffuse ground solar flux
I_{hglob}	total solar flux that falls on the ground
I_{beam}	Solar flux measured perpendicular to the beam
I_{cl}	Clothing Insulation
m	mass
M	Metabolic rate
p_a	Water vapour partial pressure (or humidity)
Q	heat flux
t_a	Air temperature
t_r	Mean radiant air temperature
T	Temperature
T_s	Surface Temperature
V	Volume

1 Introduction

Our world is facing an increasing number of conflicting pressures; whilst our population is increasing, the demand for lower environmental impact is increasing; whilst our greenhouse gas emissions are reaching levels widely reported to be a tipping point for climate change cycles, the amount of energy required to sustain a larger population in increasing. The energy trilemma of equity, efficiency and security as defined by the World Energy Council defines the three dominating factors that encourage all levels of government and industry to reduce their energy consumption as much as possible; to ensure reliable and affordable energy supply.

Buildings and the activities of their occupants account for between 20% and 40% of a country's end use energy demand with the average approximately 30% (this does not account for construction and embodied energy consumption). They account for approximately a third of global energy related carbon emissions. In Europe, North America and Japan, commercial buildings account for between a third and a half of the total building energy demand in these respective countries. The end use consumption within these commercial buildings varies significantly by country, but thermal comfort provision and illumination are frequently the most significant factors of energy demand: in the US, they contribute a combined total of 59% of primary energy end use within commercial buildings [1], and in the UK, they contribute up to 85% office building and 78% domestic building end use [2].

The challenge that the building industry faces is how to reduce energy consumption in their building stock without impacting upon the services that they provide to their users. Although operating costs are significantly higher than construction costs, the cost of staff over a commercial building's lifetime is significantly more costly than operating costs. Therefore, it is important to building users to maintain the services provided to their staff and occupants to ensure maximum output, both in terms of minimising absent days and maximising productivity. The methods to achieve these energy savings are either encouraged through legislation and standards, or through higher standards set by a client. The Global Energy Assessment recommended that a 46% reduction in heating and cooling use across all buildings can be achieved by 2050 through proliferation of best practice building design [1], construction and operation and retrofit using advanced technologies. The growth of Building Information Modelling in the construction sector is expected to aid in energy efficient design by providing evidence for correctly sized equipment and reducing errors in the construction phase of a build, as is the development of advanced building materials and more efficient building service systems.

These incremental improvements in efficiency are desirable but are subject to lengthy development timescales and are often afforded only to those with the foresight to set higher than required standards for their energy efficiency. Innovative approaches to saving energy over shorter timescales with smaller financial investment would therefore be welcomed in the current economic and political climate.

One area that offers a potential step change in the way that we use energy is the way that information is collected, stored and acted upon. The Information Age in recent years has resulted in concepts such as Big Data, The Internet of Things, Building Information Modelling and a number of other ideas that rely upon the availability of previously unimaginable amounts of data being assimilated. The move to IPV6 has opened the door to mass connectivity of previously unconnected objects, and a plethora of research across the globe is creating ways to access information previously unavailable to us, such as individual metabolism rates, real-time CFD modelling and the use of smart phones as distributed sensor networks for both environmental variables and spatial positioning tools. The questions that building designers need to answer today are ‘How can data be used to ensure that our building stock of the future reduces net energy consumption when compared with today?’ and ‘How can we utilise this data in ways that don’t simply build upon existing principles of energy saving, but fundamentally change the way that we use, interact and engage with our buildings to produce efficiency gains?’.

With environmental control accounting for such a big proportion of end use energy consumption, it is useful and timely to investigate novel methods of utilising increasing information availability within buildings to increase the effectiveness of energy in providing a suitable internal environment. Research into the supply side of information generation and assimilation is thriving, but there is potential to research innovative concepts in the demand-side role of this information.

Similarly it is pertinent to recognise recent areas of research that challenge established thinking and methods of comfort provision; an example is adaptive comfort, which is quickly being recognised as an important move away from increasingly uniform building design guidelines. Although currently only included in some standards at a high level, the concept of adaptive comfort can be applied to many different facets of the occupant's role within the built environment. Another area of research that is developing quickly is the methods through which integration of building systems can be achieved. Open protocols and middleware are creating opportunities through which information can be leveraged to make a building work harder without increasing energy consumption.

Central to the development of these new approaches to the way the buildings and occupants make use of information available to them is innovation. In order to encourage innovation, clarity is needed to define the purpose of it. Therefore, it is important within this field to clarify the end product of innovation; what is the purpose? The use of the terms "Smart Building", "Intelligent Building" and "Automated Building" are sometimes seen as synonymous, yet over time their use and meaning has changed and diverged. With a "Smart Building" being the latest term to be developed, it is an interesting question to ask "What are Smart Buildings?" and once that question is answered, innovations can be developed within the defined purpose of Smart Buildings in the modern built environment.

1.1 *Research Aims*

Within the context of the field, this research looks to achieve the following aims:

- Understand the drivers behind modern building design and the key areas that future buildings will use data within to create improvements.
- Demonstrate examples of applications of increased data availability within buildings, quantify the potential benefits and identify applicability to wider building types.

1.2 *Thesis Structure*

In order to provide a basis upon which the demonstrations can be developed, a literature review has been carried out into modern building design and a definition of the term “Smart Building” developed. Two demonstrations of Smart Building concepts are then be developed: one on an existing building using practical experiments, and another on a designed (but at the time unbuilt) building using computational fluid dynamics. As sections of the research use different techniques, an appropriate literature review is presented for each study before the relevant section, rather than at the beginning of the research, for clarity when reading.

2 Literature Review

This chapter presents a thorough literature review of existing research in the fields of intelligent and smart buildings, forms of building control, energy performance metrics, thermal comfort within buildings and relevant building physics literature.

2.1 ***Intelligent and Smart Building research***

2.1.1 Intelligent Building research

Evolving definitions of Intelligent Buildings have been developed since the 1980's [3] and these are continuing to be suggested using the latest knowledge and experience [4, 5]. In 1990, Powell defined an Intelligent Building as being:

"'A building which totally controls its own environment'[6]. This seems to imply that it is the technical control of heating and air conditioning, lighting, security, fire protection, telecommunication and data services, lifts and other similar building operations that is important – a control typically given to a management computer system. Such a definition for a conventionally Intelligent Building does not suggest user interaction at all" [7]

Wong et al. (2005) [3] show in their review of Intelligent Building research that most of the early definitions revolved around minimising the human interaction with the building. The early definitions of Intelligent Buildings are what would be expected, since at that time architects and building engineers were progressing from what can now be seen to be automated buildings, as demonstrated in Figure 3-1. Generally, definitions of intelligence within buildings refer to the integration of numerous systems which revolve around building operation [8-11]; a basic example of which would be the integrating of the building management system with the lighting systems. However, since their initial conceptualisation, definitions of Intelligent Buildings have expanded the number of features involved in order to accommodate the latest understanding of building requirements; especially regarding the ways in which occupants interact with a building, and the effect of this on building performance. Smith (2002) suggests that many of the earlier buildings described as *intelligent* do not fulfil the majority of currently accepted definitions [12]; indeed many modern buildings are likely to push the traditional definitions to their very limits of acceptance. In 1995 the Conseil International du Bâtiment Working Groups defined an Intelligent Building as:

"A dynamic and responsive architecture that provides every occupant with productive, cost effective and environmentally approved conditions through continuous interaction among its four basic elements: places (fabric; structure; facilities); processes (automation; control; systems) people (services; users) and management (maintenance; performance) and the interrelation between them." [CIB, 1995 as quoted by 13]

Furthermore in 2009 Clements-Croome developed the following definition:

> "An Intelligent Building is one that is responsive to the requirements of occupants, organisations and society. It is sustainable in terms of energy and water consumptions besides being lowly polluting in terms of emissions and waste: healthy in terms of well-being for the people living and working within it; and functional according to the user needs" [Clements-Croome, 2009 as quoted by 14]

As the definitions expand, the term *intelligence* loses both meaning and focus; which is contrary to what the updated definitions were trying to achieve. In order to try and make some correlation between the two and provide direction upon which the research is based, Everett [13], for example, offers different definitions for Intelligent Buildings. Brooks [5] later suggested that Intelligent Buildings are equivalent to the Building Management Systems (BMS) within them. The BMS is usually seen to be just one of the integrated tools within a building and not the entire system. This significant difference to other previously mentioned definitions is possibly due to the loss of meaning in the term. Other research recognises the lack of focus and is conducted with regard to trends in definitions [15, 16], whilst Yang and Peng [17] suggest that the implementation of Intelligent Building concepts is being hindered due to a lack of understanding by owners and developers. A focus on progression in the building industry and research sectors cannot be achieved if the aims upon which the research is being conducted are constantly changing.

There is an academic view that smart systems are a subdivision of Intelligent Buildings [14, 18], although there is sparse literature that justifies this relationship. By recognising intelligence as the ability for a building to gather information and respond to it, as described throughout the literature, there is now an opportunity that can limit the addition of further ambiguity to definitions of intelligence and allow progressive research into future building design. It can be recognised that intelligence will play a significant part in future building designs, but can be built upon using a term which has been increasingly used in recent literature; *Smart Building*. Smart Buildings are Intelligent Buildings but with additional, *integrated* aspects of *adaptable* control, enterprise and materials and construction. In Smart Buildings, building systems and structure are developed alongside each other, utilising information from one in the operation of another. This is in contrast to Intelligent Buildings, which have largely developed intelligence independently of the other methods.

The defining of the term Smart Building will address the need for focus and progression and will also prevent the further fragmentation of terminology in the building sector where Intelligent and Smart Buildings are often classed as synonymous to each other [19, 20].

2.1.2 Current research into Smart Buildings

Although there is an increasing amount of academic, popular, and industrial literature addressing Smart Buildings as a concept, there are few justified definitions as to what they are, and, at the time of writing, the author can find no literature addressing how this emerging concept can be achieved or assessed. In creating an appropriate definition for a Smart Building, the current literature addressing the subject shall be used in order to gauge an indication of the new aspects and advantages that academics and industry feel Smart Buildings can provide.

An academic view is given by Wang et al. [21], agreeing that Smart Buildings are part of the next generation building industry, suggesting that they:

"Address both intelligence and sustainability issues by utilising computer and *intelligent* technologies to achieve the optimal combinations of overall comfort level and energy consumption."

Kiliccote et al. [22] propose that Smart Buildings are self-aware and grid-aware, interacting with a *smart* grid whilst focussing on the real-time demand side response and an increased granularity of controls. The theme of responsiveness, adaptability and flexibility recurs in further descriptions of Smart Buildings and is a key area in which Smart Buildings can differentiate from previous generations [21, 23].

The use of increasing knowledge, or information to achieve the drivers for building progression is highlighted in many publications; McGlinn et al. [19] define Smart Buildings as "A subset of *smart environments*" where *smart* environments are "able to acquire and apply knowledge about the environment and its inhabitants in order to improve their experience in that environment" [23]. The author acknowledges the need for information on both environment and occupants but suggests that the Smart Building should itself be an entire system rather than a collection of smaller *smart* environments, in order to encourage the interaction between all spaces in the building. Sinopoli [24] suggests that a Smart Building revolves predominantly around integration, both of the systems within the building, and the method through which the building is designed and implemented. Sinopoli also highlights the need for technology systems to be integrated horizontally, as well as vertically in order to "allow information and data about the building's operation to be used by multiple individuals occupying and managing the building". The author believes that this approach may resemble a Smart Building, although Sinopoli does not make a distinction between Smart and Intelligent Buildings.

In contrast to the sparse academic research in the area, there have been numerous definitions of the Smart Building which have been developed by organisations and companies such as the GSA (General Services Administration), the Climate Group and CABA (Continental Automated Buildings Association). The last defines the meaning of Smart Buildings to be the ability to "figure out behaviour and behave according to impacts of parameters around it" [25]. The significance of this definition is that it implies that the ability of the building is to adapt to different situations using external context related data surrounding the behaviour of the occupants. The Climate Group suggest that the term Smart Building describes "a suite of technologies used to make the design, construction and operation of buildings more efficient, applicable to both existing and new-build properties" [26]. In a similar way to Sinopoli, they highlight the holistic nature of a Smart Building; in suggesting a more integrated design, construction and operation.

An additional recurring feature within current definitions of Smart Buildings is the focus on the occupancy and the higher level interaction with the occupants of a building [22, 27-29]. It is a widely debated area as to how much control should be given to the occupant of a building in order to meet both comfort and energy performance criteria, but the latest concepts of advanced building research emphasise the need to create a convergence between building technology and the behaviour and objectives of occupants.

2.2 *What forms of control are used in buildings*

2.2.1 Control Methods

One of the most debated aspects around modern building design is control. When designed, implemented and used correctly, buildings with predominantly human control can perform very well, as can buildings which are fully automated. Both, however, have intrinsic risks which can result in poorly performing buildings if any of the three factors mentioned above change. An example is given by Masoso and Grobler [30] of behaviour causing poor performance in numerous buildings and Menezes et al. [31]explain that occupants are one of five reasons for a difference in the design and actual performance in non-domestic buildings [31] due to their ability to influence internal conditions. Examples can range from using electric heaters to opening windows and blocking air inlets. Demanuele et al.[32] identify that occupant behaviour patterns create high amount of uncertainty when creating energy predictions and cite occupant behaviour as the cause of higher than predicted energy use in many buildings due to the inability to use the building systems properly [32]. Buildings relying upon human control assume that the occupants will use the building in the way it was designed for; automated buildings tend to be designed to the theoretical climatic conditions, occupancy and use. Both types are subject to changes during construction and commissioning that differ from the design intent, as well as deteriating performance over time. Therefore both categories are susceptible to decreases in performance during change of occupancy, use or climatic conditions.

Modern buildings are recognising the importance to re-engage the occupants with the building in order to allow them to have control over their own environment. There have been numerous studies showing that there cannot be a single set of conditions that will be suitable for all occupants [33, 34], and many studies showing that a degree of control in a workplace results in benefits such as increased comfort, lighting quality [35] and occupant satisfaction [36].

As Dounis and Caraiscos [37] indicate, comfort in a building is not one dimensional but has multiple variables. In Figure 2-2, Leaman [38] highlights a number of points that occupants of a building like and dislike. Within these points they highlight that occupants of a building like normal states which they can “utilise habitually” and, in traditionally controlled buildings, the multidimensional nature of comfort opposes this ability. For example, in winter, a room may be much colder than expected, which encourages the use of inefficient electric heaters, but the air quality may deteriorate, resulting in windows being opened which will obviously negate the effect of electric heaters and may even have a cooling effect on surrounding rooms.

Users like

1. Situations where they need to intervene to change things only occasionally, with predictable `normal' or `default' states which they can utilize habitually, and, for most situations, forget about

2. Opportunities to act quickly to make corrections or interventions if conditions alter

3. The ability to carry out interventions quickly and effectively

Users' frustrations

For building users, greatest frustration arises when they are:

1. Prevented from intervening to change physical settings from an undesirable existing state to a preferred new one

2. Subjected to arbitrary changes in conditions which they perceive and are affected by but cannot themselves over-ride

3. Working in an unfamiliar setting which may require intervention to make things habitable or comfortable

4. Required to act quickly and or in stressful circumstances, e.g. in an emergency

FIGURE 2-1 - USER LIKES AND FRUSTRATIONS

The Probe studies used post-occupancy evaluations to conclude that more technically complex buildings were more likely to be energy inefficient, especially if these had little building management input. Thus less complex buildings with a large building management input are expected to perform most efficiently[39]. It could be inferred that the more control that a building requires from its managers, or occupants, in order to run efficiently, the harder and less likely, it is to achieve its design energy performance.

There is a need to strike a balance between allowing users to have control of their environment, and creating stable, reliable and comfortable conditions which allow the building systems to manage the energy consumption efficiently.

2.2.2 Occupancy led building control and energy management

There are two categories of energy consumption related to occupancy in a non-domestic building:

1. The energy load corresponding to the density and activity of occupancy within a given space – including process loads.
2. The base load energy requirement to make a space habitable for occupation.

Furthermore, there are three types of actuator within buildings that are used to implement strategies to adapt energy use to occupancy:

1. Occupants themselves
2. Facilities managers
3. Automation systems

Themes within recent literature relate to behavioural aspects of occupants in order to control their individual energy impact and the ability for intelligent automation systems to modify HVAC, light and plug loads in a given space in response to varying occupancy levels [40]. In both scenarios, the occupants are interacting with the building, but through either active (their behaviour and actions) or passive methods (whereby the building reacts to their unaltered actions).

In respect to active methods, Azar et al. [41] used agent based modelling to predict the energy reductions that can be achieved by raising awareness, converting high energy consumers into medium and low energy consumers, demonstrating a possible 23% reduction in total building electricity consumption and 5% drop in gas. Tetlow et al.[36] applied the concept of post-completion errors to lighting in office meeting rooms and showed that by incorporating simple prompts to turn off light switches upon leaving was more effective at saving energy than PIR sensors. Nguyen and Aiello [40] refer to an experiment carried out regularly by 3M in which their office workers in the HQ in Minnesota turn off unused devices and lights, reducing 26% of the building's power consumption after 2 hours. Further literature corroborates that energy aware occupants do have the ability to align energy consumption with occupancy [42, 43].

Looking beyond energy and towards thermal comfort, a significant amount of research around active engagement with the building is based around adaptive comfort, which will be discussed in §2.4.2.2. However, there is a small amount of research involving a more subtle form of active occupant interaction with the building, whereby occupant feedback and input can influence its operation [44, 45] and furthermore how the exchange of information from the building to an occupant can influence occupant behaviour in a manageable way [46, 47]. An interesting recent example of the former is the Green 2.0 project at The University of Toronto which is looking to create a 'public-building' middleware platform that interacts with future BIM models which feed into the control of the building itself [48].

In respect to passive methods of interaction, intelligent automation systems are at the forefront of literature; especially the sensing of occupants [27] or the prediction of occupancy trends through model predictive controllers [49]. Goyal et al. have shown that although using any form of passive occupancy based controller a large amount of energy can be saved, the comfort levels of these occupants are only maintained, if not reduced by a small margin [50]. Nguyen and Aiello [40] give a thorough review of extensive studies into occupancy influenced Building Energy and Comfort Management (BECM) systems. Examples include: using badges, wireless networks and cameras to track occupants, accounting for occupant preferences and predicting unoccupied periods to adjust building services [51-53]. Nguyen and Aiello conclude that the effective implementation of occupancy based control techniques can allow for up to 40% reduction in HVAC and lighting consumption. Goldstein et al. [54] recognise the importance of occupant schedules on building performance whilst Dong and Lam [55] demonstrate an 18.5% potential energy saving through monitoring the number of occupants in a space.

2.3 *Metrics used to assess building performance*

Evaluating and communicating the energy performance of non-domestic buildings is recognised as fundamental to both enforce and encourage the reduction of energy use in buildings during both design and operation [56, 57]. There are numerous energy performance metrics utilised worldwide, including Display Energy Certificates (DECs) in the UK and the Building Energy Quotient developed by ASHRAE in the US. These ratings generally account for variations in building type, with CIBSE TM46 suggesting 196 building types that can be sorted into 29 categories [58]. The use of categories in order to compare different building use characteristics recognises that different buildings have, for example, different functions and occupancy hours, and therefore inherent energy costs. However, the basis of these metrics is the Energy Use Intensity, which uses rigid data defined at the design stages of building development, in which the energy use of the building is divided by a defined space – usually the total useful floor area (TUFA) or the gross internal area (GIA) [56] and occasionally by volume, such as in hospitals. Inherently, by removing occupants from the calculation it is difficult to account for occupancy patterns using these metrics.

The methods through which energy consumption is tailored to occupancy generally focusses upon the acquisition and response to more granular data on occupancy through advanced sensors and control algorithms utilised within the building itself [40, 51] or through human mounted reporting devices [59]. The ability for the building to become more aware of the distribution of occupants within it [60] enables potential improvements of the distribution of lighting, HVAC and plug loads within buildings. However, these improvements are dependent upon the actuator technology being available within the building to control local climates around varying numbers of people, and with many building types moving towards open plan structures [61], the ability to implement this local control is reduced.

Further information can be gathered on building occupation through trends and informed data from the integration of time tabling enterprise systems into the building control systems. These trends could be slight variations in occupancy dependent upon time of year, or they could be significant diurnal swings in occupancy during a 24 hour access building. The potential of this further occupancy data can increase the extent to which a building can adapt in innovative ways.

The recognition that conventional energy efficiency metrics are often not suitable is concluded by Bordass et al. within their final review of the Probe Studies [39]. Furthermore, within this report it is suggested that:

> “Ideally, energy benchmarks would be separated into area-, occupancy- and production-related parts, and FMs would keep records of say person-hours occupancy to some agreed industry standard.” [39]

2.4 *Comfort in buildings*

2.4.1 Introduction

Thermal comfort is one contributor to occupant comfort and impacts upon a number of building performance evaluation criteria; for example, the impact on satisfaction [62], health [63], productivity [59] and energy consumption through heating and cooling demand [2] are all ongoing research areas. Alongside these metrics, thermal comfort is a source of value for a building, whether domestic or non-domestic. It has been researched since the 1930’s [64] and has been at the centre of a wealth of research since the 1960s. However, this value is balanced with economic cost, as thermal comfort within non domestic buildings accounts for up to 57% of primary energy use in the US [2, 65]. Pe´rez-Lombard et al. suggest that this figure is lower but expected to increase within EU countries [2]. This energy consumption is primarily caused by heating, ventilation and cooling methods used within buildings, in order to provide thermally comfortable conditions for the building occupants.

Since the 1960s, there has been a thriving field of research in thermal comfort. There are a number of thorough review papers and books on the development of different methods for the prediction and measurement of thermal comfort such as Djongyang et al. [56], de Dear et al. [66] and others [39, 63, 67-69]. The basis of the majority of research, however, revolves around the two most notable developments in the understanding of thermal comfort in the past half century. The first is through the static heat balance model, which was proposed by Fanger in 1970 and built upon his climate chamber studies [70] whilst the second is the adaptive comfort approach which is based upon field work and has been gaining an increasing amount of attention and credibility in the past two decades. The former's primary metric, the Predicted Mean Vote (PMV), has become the basis of thermal comfort standards, whilst the latter Adaptive Thermal Comfort (ATC) approach has some recent recognition in standards for naturally ventilated buildings. These comfort metrics are discussed in more detail later in this chapter.

IS0 7730:2005 states that:

"Thermal comfort is that condition of mind which expresses satisfaction with the thermal environment"

This statement is rarely questioned, but interpretations of it vary. Research surrounding the heat balance model suggests that this state of mind can be adequately defined by physical and physiological variables, whereas the adaptive comfort approach creates higher resolution in comfort indication by recognising demographics, context and cognition as variables that need to be considered in order to gain an accurate prediction of thermal comfort [71]; for example, de Dear et al. have shown empirically that thermal neutrality and relative preference varies with external temperature [71], which has not been taken into account within Fanger's heat balance model; nor has evidence for behavioural adaptations such as clothing changes or changes to the physical environment around occupants [72] [73].

The following section of the literature review is not intended to supply a history of thermal comfort since this has been successfully addressed by a number of researchers, as previously stated. This literature review focuses upon the methodology behind the two predominant approaches, current legislations for large non-domestic buildings, and the sociology of thermal comfort. The literature review will address:

I. Current methods and international standards

II. Evidence for variations in comfort perception

III. Compromises within building thermal comfort

2.4.2 Approaches to Thermal Comfort

2.4.2.1 The heat balance model

Fanger's comfort model, also referred to as the Predicted Mean Vote (PMV) model, is a heat balance approach to comfort, forming an index that predicts the mean thermal sensation vote on a standard scale for a large group of persons for any given combination of the thermal environmental variables, activity and clothing [70]. It is a tool that has been used in both design and analysis of built environments for over four decades.

Heat balance models assume that the magnitude of physical response by human's thermoregulatory system in order to maintain a constant body temperature is proportional to the thermal sensation that they feel. This can be measured through skin temperature and latent heat loss. [74]

The PMV model was developed from Fanger's comfort equation (Fanger 1967). The comfort equation aims to predict a condition where occupants will feel thermally neutral. In order to achieve this, Fanger carried out two investigations to develop two linear relationships between activity level and: (i) sweat rate (ii) skin temperature [75]. These studies were then built upon using climate chamber studies in which 1296 Danish college-aged and elderly people were subjected to a range of conditions and asked to record the thermal sensation that they felt. In order to have more useful implications, Fanger asked the students to vote using the ASHRAE 7-point thermal sensation scale [39, 74]:

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

A thorough calculation method for PMV is given in ISO 7730-2005 [76]. Although fundamentally taking into account a wide range of variables, such as skin temperature and wettedness, the PMV calculation is made through the use of two personal and four physical, measurable variables shown in Table 2.1:

TABLE 2.1 - VARIABLES USED WITHIN FANGER'S PMV CALCULATION

Personal Variable	M	Metabolic rate	W/m^2
	I_{cl}	Clothing Insulation	clo
Physical Space Variables	t_a	Air temperature	^{o}C
	$\overline{t_r}$	Mean radiant air temperature	^{o}C
	v_{ar}	Relative air velocity	m/s
	p_a	Water vapour partial pressure (or humidity)	kPa

So for a given set of variables, the PMV method will produce a value which intends to predict the mean vote of a large group of people. The personal variables are usually kept at constant values suggested by standards and legislations such as ISO 7300:2005 [76] or ASHRAE [77].

Fanger then derived the PPD (Percentage People Dissatisfied) equation which uses the PMV value to calculate the percentage of the people who are likely to be uncomfortable in the given conditions[70]. Fanger defines uncomfortable as being values beyond ±1. Although this is largely accepted in current practice [78, 79], some recent research suggests that in some conditions this range is shifted and will be discussed in §2.4.2.2.

2.4.2.1.1 Using the Heat Balance Model to design and evaluate

Although still utilised within all common standards for comfort provision within buildings, it is widely acknowledged that Fanger's PMV model is not accurate for all conditions for all people. An extensive summary of these have been carried out by van Hoof [80] with the following key outcomes relevant to this research:

- Fanger's PPD equation generally results in an optimistic amount of satisfied occupants at a given condition compared to field studies.
- Field studies have found optimum conditions to be both cooler and warmer than Fanger's model.
- None of the proposed improvements have found widespread practice in environmental engineering practice.

The final point here is crucial, as Fanger's model remains one of the most applicable models to implement. It can be used to design in conjunction with modelling software in order to assess conditions resulting from design choices and it can be used to evaluate performance as seen in the RP-884 database of post-occupancy evaluations [81]. It is interesting to recognise this capability since Fanger originally did not intend for the model to be used as a design tool to create homogenous conditions within a building, intending for it to be a “servant, not a master” [80].

The recognised weaknesses of the PMV model include the apparent reliance upon unknown variables such as ‘clo’ value (representing the level of clothing on a person) and individual metabolic rates and this has led to the development of a new approach the thermal comfort modelling named the adaptive comfort approach.

2.4.2.2 The adaptive comfort approach

The adaptive comfort approach recognises that occupants are not passive recipients of a buildings environment but are actively engaged in it.

An adaptive comfort hypothesis was initially proposed by Humphreys in the 1970’s [82] and its wide recognition can largely be attributed to the ASHRAE commissioned report by de Dear et al. [83] in the 1990’s which investigated the idea that factors beyond the physical and physiological effect the perception of comfort within real buildings. It is suggested that demographics, context and cognition all play a part when defining an individual’s comfort perceptions in a building.

There has been a growing volume of research looking to show how adaptations may affect the traditional views on comfort, specifically those suggested within the heat balance model. Baker and Standeven [84] identified three distinct levels at which occupants adapt, shown in Table 2.2.

TABLE 2.2 - LEVELS OF OCCUPANT INTERVENTION – PARTIALLY ADAPTED FROM [84]

Level of Interaction	Example
Building and climate level	Operating building controls, including windows Internal adaptations based on external conditions
Room level	Seeking the most comfortable part of the room Adjusting time spent in the environment
Local conditions	Adjusting local environment (e.g. blocking drafts) Personal adaptation Posture, Activity level Clothing

De Dear and Brager's report for ASHRAE however hypothesised another perspective by splitting adaptation components into those listed in Table 2.3. Although the heat balance model does account for some behavioural aspects such as clothing level and activity rate, the adaptive comfort model theorises that a number of other factors play a part.

TABLE 2.3 – COMPONENTS OF ADAPTATION HYPOTHESISED BY DE DEAR AND BRAGER [83]

Adaptation to Indoor Climate – de Dear and Brager	
Adjustment	• Behavioural changes such as adjusting clothing, moving to a different location, or changing activity. • Technical changes such as turning on fans or heating or operating controls
Habituation	• Psychological adaptations such as changes in expected conditions based upon previous experiences
Acclimatization	• Genetic adaptations of a group of people extends across generations • Adaption to a change in climate over a period of time

The most conclusive adaptive comfort research has been around the relationship between external climate and internal expectations. Humphreys has both established this research [82] and provided a summary of and updated model [69]. The inclusion of this relationship in newer standards will be discussed in §2.4.2.2.2.

Chappell and Shove summarise academic literature evidence for adaptive comfort up until 2003 [68] alongside the potential negative impacts of standardising comfort within buildings. This research, along with Shove's individual work [85] take a broader approach to evidence for the effectiveness and necessity of the adaptive comfort approach, highlighting existing cultural adaptations (such as siestas) to climate among others. It is suggested that conditioning buildings needlessly will have a direct contribution towards climate change which agrees with a more recent study by Yang et al. [74] . Shove goes as far as saying that highly homogenous environments are causing sensory deprivation among the occupants [85] and recent research by Parkinson and de Dear into thermal alliesthesia demonstrates a more complex requirement from the thermal environment than simply homogenous neutrality [86].

2.4.2.2.1 *Using the adaptive comfort approach to design and evaluate*

Within this research, the benefits of using the ATC method need to be compared to the ease of application with a design context. Van de Linden et al. agree with the majority of research in showing that the changes in internal environment in a moderate climate, when using the ATC model in place of the PMV model, are not significant [87]. Furthermore, the flexibility of the ATC model to different building types is questioned.

Although widely believed to be a better predictor for occupant comfort temperatures to be used within buildings, the ATC model has a significant weakness in that it is based heavily upon statistical work, which has thus far only correlated internal comfort temperature with external temperature, [76] usually monthly mean temperature. There have been attempts to account for variations in air velocity [75] in specific environments but as yet there is not an ATC model which can be applied within an internal environment to gain an insight into variations in conditions within a space. Adaptive comfort suggests that, where there is ability to adapt, these variations can be normalised through occupant interventions. It would be reasonable therefore to assume that for a given thermal condition, there would be more satisfied occupants than Fanger predicts in the heat balance model, by Langevin et al. demonstrate that the opposite is the case when analysing the RP-884 database [88].

That lack of applicability and granularity of the ATC method makes it difficult to use alongside more detailed modelling of the internal conditions of a building. However, the author expects that in the future, adaptive thermal comfort models will be utilised more within specific modelling projects.

2.4.2.2.2 *Standards for Inclusion of the Adaptive Model when Designing for Internal Conditions*

The adaptive comfort model has recently been included in the latest standards and guides, including Ashrae 55, CIBSE TM52, BS EN 15251:2007 and ISO EN 7730 [77, 78, 89, 90]. Although the adaptive comfort hypothesis in itself is very broad, the inclusions in these publications revolve around the variation of indoor comfort criteria with running mean external temperatures in naturally ventilated buildings. It is pertinent to note that all are optional additions and that they specify restrictions to varying extents, shown in Table 2.4.

TABLE 2.4 - STANDARDS AND GUIDES THAT INCLUDE THE ADAPTIVE COMFORT METHOD

Code/Guide	Form of adaptation addressed	Type of building to be applied	Optional or required?
ISO 7730:2005	Modified comfort ranges in relation of prevailing external environment	• Naturally ventilated, occupant controlled buildings • Only within warm periods or in warm climates.	Optional
ASHRAE Standard 55-2010	Modified comfort ranges in relation of prevailing external environment	• Naturally ventilated building with main form of regulating thermal conditions in the space being through manual operation of windows. • Adaptive option only permissible when heating system is not operational. • Occupants are engaged in near sedentary activity • Affects all climates with prevailing temperatures between 10°C and 33°C.	Optional
BS EN 15251:2007	Modified comfort ranges in relation of prevailing external environment	• Offices and other buildings of similar type • Used primarily for the purpose of human occupancy • Sedentary activities only • Easy access to operable windows and occupants feel free to adapt their clothing • Modified lower ranges are available between 15°C and 30°C outdoor mean running temperature • Modified upper ranges are available between 10°C and 30°C outdoor mean running temperature	Optional

All guides specify that the only buildings that can use these optional design criteria are those with freely accessible windows, natural ventilation and no heating in use. It can therefore be acknowledged that the inclusion of the adaptive comfort method in modern buildings is limited.

2.4.3 Thermal sensation and acceptability

Comfort studies refer to any of three common terms; thermal sensation, thermal acceptability and thermal preference. Thermal sensation is typically measured against the ASHRAE sensation scale, with both PMV and ATC methods using this scale in the development of their respective comfort standards. Indeed, Fanger imposed his PMV model onto the ASHRAE scale and assumed that the thermally neutral zone of each person correlated directly with neutral sensations. The PMV model itself aims to predict thermal sensation.

Thermal acceptability is generally used synonymously with thermal satisfaction and is addressed by Fanger's standardised Percentage People Dissatisfied (PPD) metric, which estimates the number of people who will be dissatisfied at a given PMV value. It is upon this metric that most standards are set but these rely heavily upon the assumption that satisfaction corresponds directly to sensation, and that temperatures corresponding to a neutral PMV will provide maximum satisfaction. ASHRAE 55 suggests that spaces should be within ±0.5 PMV, assuming that 10% of people will be dissatisfied due to the overall environmental conditions and a further 10% will be dissatisfied due to local conditions [77]. However this assumption has been challenged numerous times, particularly by researchers looking into adaptive thermal comfort, as reviewed by van Hoof [91]. Adaptive comfort research has primarily demonstrated that both sensation and acceptability vary with outdoor meteorological or climatological conditions and this has been applied with ASHRAE 55 [92].

2.4.3.1 Thermal Preference

De Dear and Brager offer one of the most concise definitions of thermal preference:

"a conscious desire for change in one's thermal state" [71]

With a preferred thermal state being one in which the occupant wants no change. Thermal preference is therefore the most discrete and desired form of thermal comfort metric and is therefore the most difficult to satisfy on a building scale. Preference is also the most subjective and context dependent metric, with suggested influences including culture, health, current environment, activity and season [71]

The research that has been carried out into thermal preference data generally assesses to what extent a single set of conditions can satisfy thermal preference, and how mean preferences change with respect to different external conditions. For example, it has been shown that there is a semantic offset to the ASHRAE scale dependent upon both prevailing external temperature and current indoor temperature [50, 71, 93, 94]. It has also been suggested that the ASHRAE sensation scale is fundamentally interpreted differently [95], and preferences systematically change from individual to individual [50].

Part of the adaptive hypothesis is based upon the notion that people play a role in creating their own thermal preference [71] by using physical methods within their control such as clothing, opening windows and moving furniture. This idea of "achieving comfort" as opposed to being subject to it is supported from a social perspective by Shove [85], who highlights the negative effects of increasingly converging globally standardised comfort criteria upon both social norms and energy consumption.

2.4.3.2 Variation in thermal preference

De Dear et al.'s meta-analysis of the ASHRAE RP-884 database, alongside the majority of research into thermal comfort, addresses each building as a data point in order to derive the most comfortable range of conditions within a given building, albeit by analysing responses by individual occupants within each building [71]. This approach is valuable for the development of guidelines for operational temperatures of buildings, and has led to the ability to take into account changes in external temperatures when deciding upon these set points.

However, this database alone has 21,000 *individual* responses which show the interpersonal variance of thermal preferences, which are neglected in the creation of standards for use in buildings, resulting in the notion that 80% satisfaction is a successful building when, in many other industries, such a satisfaction rate would be poor.

The recognition that thermal neutrality does not necessarily result in the desired thermal conditions led to the creation of a thermal preference scale to supplement the ASHRAE thermal sensation scale [41, 94, 96], and this method subsequently led to the development of complex behaviour characteristics showing that preference varies both with external [71] and running internal [93] temperatures. As with most current studies, these semantic offsets are being developed in order to provide a more reliable method to define comfort limits within buildings, and will work alongside post occupancy evaluations to assess why buildings are not performing to their intended comfort levels. The RP-884 database has 116 out of 160 buildings in which the preference scales is taken into account [71].

Variance of thermal preferences within a group of occupants has been acknowledged and is seen as an obstruction to comfort provision rather than an opportunity. Humphreys was one of the first to explore the range of thermally preferential conditions given a constant outdoor mean running temperature [43] with a standard deviation of 1K around a regression line for free running buildings and 1.7K for the 'Heated-Cooled Building' curve. This was assuming neutral sensations and preferred temperatures were synonymous. De Dear et al analysed the RP-884 data and showed that preferred operative temperature varied from the mean between 1.19 for HVAC building in winter, to 2.13 for naturally ventilated buildings in summer [71]. However, it must be acknowledged that these variations relate to temperature, not thermal comfort, and they represent building results rather than individual responses. Using the operational temperatures found by de Dear et al. as the mean operational temperatures, Figure 2-3 shows a representative variation in thermal preference between different sets of occupants. It could be assumed that given a single preference value within this chart, there would be a range of individual preference values that form the average preference for the building.

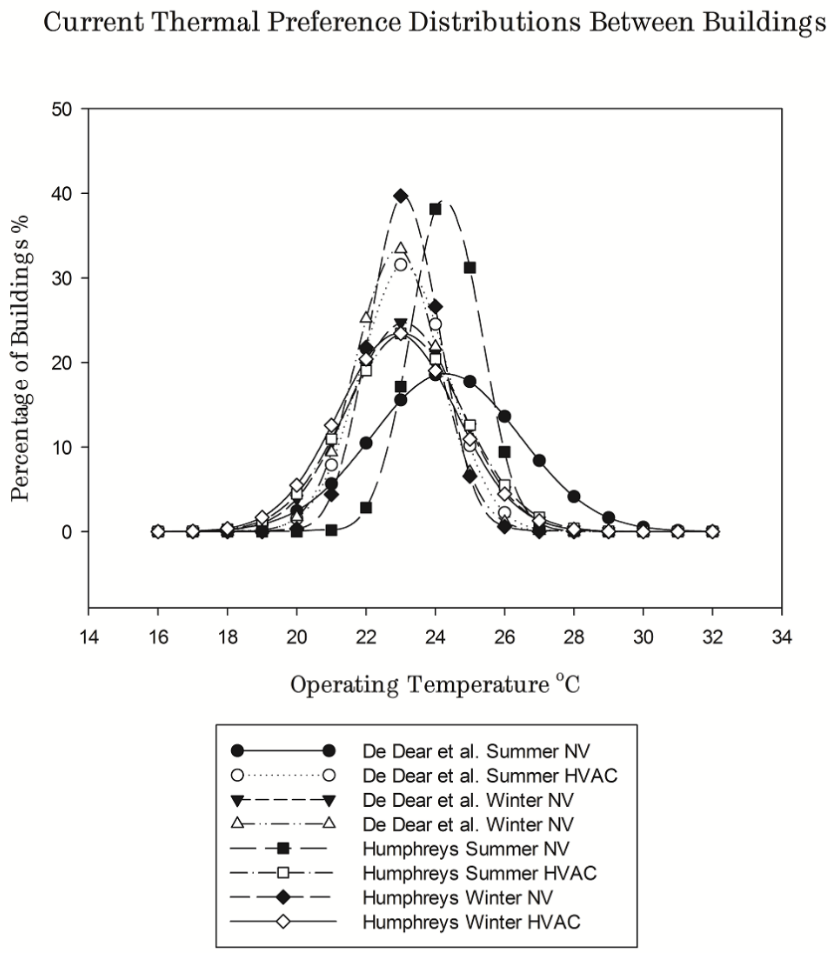


FIGURE 2-3 – THERMAL PREFERENCE DISTRIBUTIONS BETWEEN BUILDINGS, ADAPTED FROM DE DEAR ET AL.[71] AND HUMPHREYS [43]

It is possible that some of the variation of the thermal preferences within these buildings can be attributed to the semantic-artefact hypothesis proposed by de Dear et al., although running mean external temperatures are unlikely to provide a complete explanation for such a variation. Furthermore, within each of these buildings, there will be a range of individual preferences that result in the representative thermal preference given in this data.

2.4.3.3 Individual Variation in Thermal Preference

Recent statistical research has been taking a different, individualised approach to thermal comfort; recognising the importance of understanding the variation in individual comfort [42, 54, 97] as an important factor in the provision of thermal comfort to a higher level than what is currently seen as acceptable, and taking advantage of the increasing amounts of data being made available through post occupancy evaluations and thermal comfort studies.

Arens et al. submitted enquiries against the RP-884 database, the BCC database, and the SCATs database in order to assess the variation of individual comfort votes with respect to PMV. Among the conclusions drawn [54], significantly it was found that within the BCC natural ventilation study, the percentage of people wanting no change only reached 62.9% in tightly controlled PMV ranges of ±0.2 and only dropped by 2.6% when relaxing the range to ±0.7. This result demonstrates that there is plenty of room for improvement in the current approaches to comfort provisioning. Furthermore, within the BCC study [98] it was shown that, in the warm season, 27% of occupants voted no change at a ±2 thermal sensation vote and, in the cooler season, 10% of occupants voted for no change at ±3 on the thermal sensation scale. This demonstrates well that within a single set of occupants, not only is there a wide variation in their preference, but also that many occupants *prefer* to be cold, cool or warm, which is not accounted for when deriving set points and tight standards for thermal comfort.

Langevin et al. [97] have drawn upon both the data produced by the Fanger laboratory experiments and the RP-884 database field study results to produce a number of useful outcomes through the use of Bayesian techniques. In particular, the RP-884 database is reanalysed to form an equation (EQ 1.1) to predict the “percentage people no change” (PNC) at different PMVs, i.e. the percentage of people at a certain PMV that will say they would not prefer any other temperature. To the author’s knowledge, this is the only relationship that has been gathered that gives a variation of personal preference based upon individual responses to the preference scale and highlights the range of preferences found for individuals across the world.

$$PPNC = 100 - A * EXP(B * (PMV + D)^4) - (C * ((PMV + D)^2))) \qquad \text{(EQ 1.1)}$$

The constants in the equation, A-D are dependent upon method of ventilation and whether it is Summer or Winter conditions. Figure 2-4 shows the variation of PNC with PMV for each of the different conditions.

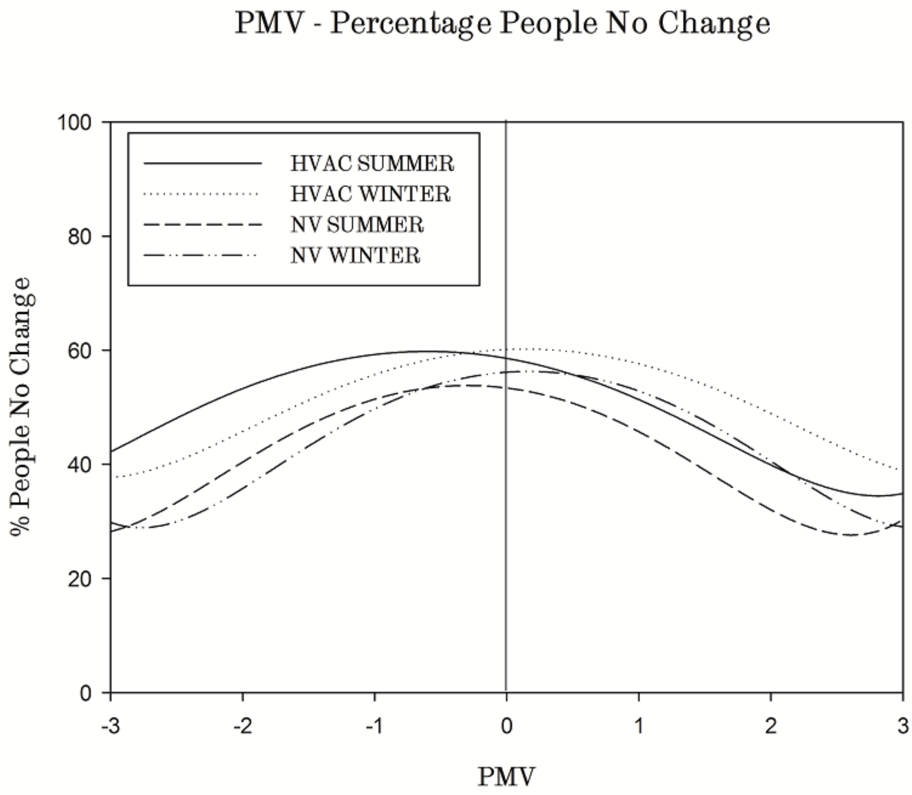


FIGURE 2-4 - PERCENTAGE PEOPLE NO CHANGE AGAINST PMV, ADAPTED FROM LANGEVIN ET AL. [97]

2.4.3.4 PMV as a design tool

Langevin's equation also demonstrates the relative power and flexibility of the PMV assessment method as opposed to the relatively simplified ATC method now incorporated in modern practice guidelines. There are three reasons why PMV will be the primary assessment method in this research:

1. Currently, ATC has only been implemented within standards as an optional approach within naturally ventilated buildings. These naturally ventilated buildings are required to have personally controllable windows by definition [83, 92]. The building being researched is naturally ventilated but without personally controllable windows.
2. PMV can be used as a design tool, allowing for flexibility of variables not included in the ATC calculations (such as clothing level, metabolic rate).
3. The PMV method allows for a variation of individual comfort conditions throughout a space to be identified. This is not currently possible with ATC models.

The flexibility of the PMV in comparison to the ATC method has been discussed further by van der Linden et al. [87], as well as its appropriate application to a moderate climate when compared to the ATC method.

2.4.3.5 Variation of comfort conditions within single buildings

PMV is the only established tool that has the ability to show varying comfort within a single building or space at a single set of external conditions. Although intended to be used to assess the vote of a large group of occupants within a building, it is theoretically possible to hypothesise that a PMV can be applied to an individual seat if a large number of people were to sit in this seat, effectively fitting a large number of people into a very small location.

Buildings using HVAC aim to create homogenous conditions throughout a building within a narrow comfort band, in order to satisfy what is seen to be the majority of people as discussed previously. Some claim this sensory deprivation is controversial [85] but it is widely acknowledged that the amount of energy needed to maintain these conditions is wasteful and inhibits efforts to reduce building energy consumption [54].

At any one time, all buildings have some degree of variation in their comfort levels. One person sitting in a seat near the perimeter is likely to be at different comfort conditions to another sitting in the centre of the same space, even if it is HVAC controlled [93]. These variations can range from differences in height within the space as shown by Kavgic et al., to local obstructions to airflow and variations in mean radiant temperature. Naturally ventilated buildings have repeatedly been shown to have varying comfort levels throughout spaces [94, 95]. Myhren and Holmberg show how a small, naturally ventilated room can still have PPD values ranging between 6% and 10% [94].

2.5 *Relevant Building Physics Literature*

This research aims to produce a realistic variation in comfort conditions within a large atrium of a building and explore how it can be exploited. A second aspect of the work looks into the possibility of turning off comfort conditioning within parts of a building over different time periods. Therefore, it is important to understand both the expected outcomes of the simulations and the physics that underlies the results. This section of the literature review will look at previous work in similar areas, whilst the physics will be covered in §5.

2.5.1 Heat transfer in atria

2.5.1.1 Natural ventilation and the Stack effect

Natural ventilation occurs when the pressure of the air inside a space differs from the air outside of that space, assuming that there are openings that link these two spaces. Within buildings there are two primary drivers of this pressure gradient; temperature and wind, and each of these have been covered extensively in literature.

Natural *convection* is defined by Hens as convection resulting from differences in fluid density caused by gradients in temperature whereby the flow pattern follows the field of temperatures [99]. Forced convection is where an imposed pressure difference causes the convection, and therefore

Hens defines wind driven convection as forced. Therefore, wind driven convection in buildings can be defined as both forced convection and natural ventilation.

It is the interaction between the roles of wind and temperature (buoyancy driven) gradients in buildings that dominate the characteristics of heat and mass flow within a naturally ventilated bottom heated building. Buoyancy driven natural ventilation alone has been researched extensively with less research into combined wind and buoyancy driven ventilation and the least in wind driven natural ventilation.

Linden et al.'s "Emptying filling boxes: the fluid mechanics of natural ventilation" forms the bedrock upon which a lot of buoyancy focussed research builds: the research numerically demonstrates the effects of different point sources of heating and inlets at different locations[100]. The BP Institute for Multiphase Flow has numerically modelled different buoyancy driven flows including both point sources [101] and distributed heat sources [102, 103] with a focus on the transitions between different conditions given a change of boundary conditions. Karadag et al. [104] have focussed upon the variation in Nusselt number caused by different floor temperatures, ceiling temperatures and room dimensions. Li [72] investigates buoyancy driven ventilation in a single zone building to derive airflow and thermal stratification, debating the accuracy of existing models previously used and Hussain and Oosthuizen [105] use computational fluid dynamics to model buoyancy driven flow in a simple atrium in Montreal.

Khan et al. provide a useful overview of research related to wind driven ventilation techniques [73] and corroborates that the literature modelling wind driven ventilation in atria is sparse. The computational analysis of wind driven ventilation in buildings researched by Evola and Popov [106] focusses on the appropriateness of different approaches available within the software programmes, using simple three dimensional scenarios.

Combined wind and buoyancy flow has a larger research base but with a more diverse range of scenarios. The work of Lishman and Woods focusses upon the transitions between and control of buildings subject to both wind and buoyancy ventilation through numerical analysis [107, 108]. Larsen and Heiselberg [109] highlight the difficulty in researching the multi-parameter flows inherent within combined wind and buoyancy driven ventilation by focussing on single sided natural ventilation. Linden [110] and Hunt and Linden [111, 112] investigate the effect of wind on point source heating comparing theoretical results to laboratory experiments: these experiments are tightly controlled to specific and simple conditions, such as small numbers of point sources and limited openings.

Displacement ventilation, where cool air enters through lower openings and warm air leaves through upper openings, has been shown to be a more efficient form of ventilation than mixed ventilation, where warm air leaves through the same high level opening as cool air enters [110]. Most naturally ventilated buildings utilise displacement stack ventilation and the volume of literature reflects this as well. However, stack ventilation does create a more stratified thermal environment and different approaches to heating the cool air result in different characteristics of the internal environment: the approaches for heating a space from the lower surface is either through point sources or distributed sources.

Single point source buoyancy driven displacement natural ventilation results in a steady state interface [101] at a height independent of the heat flux of the buoyancy source [110]. The interface is dependent upon the effective area and relative location of the lower and upper openings. The interface is caused by buoyant warm air reaching the ceiling, and being forced down to meet the air at ambient density, forming a front [100].

However when there is a distributed heat source, such as an underfloor heating system or simply through solar gain, the thermal profile of a space changes significantly. Theoretical research carried out by Gladstone and Woods [103] shows that when an opening is at some distance above the heated floor there is a mixture of both mixing and displacement ventilation. Gladstone and Woods' experiment also demonstrates that a more well mixed interior fluid results from distributed source heating and that the larger the gap between top and bottom openings, the stronger the displacement regime that dominates the initial stages of the development towards a steady state condition [103]. It is also recognised that additional drivers such as the addition of wind will dramatically affect the methods of heat distribution within a space and may lead to multiple flow regimes [97, 103, 108, 113].

There has been little research done into more complex real scenarios involving multiple openings at distributed levels with both wind and buoyancy driving forces. The effect of varying height between openings on the same side [114] has been discussed but theoretical research into more complicated scenarios has not been carried out.

2.5.1.2 Variation in conditions

Aside from CFD, the majority of building analysis tools assume that thermal conditions throughout a zone are uniform; IES-VE pro, EnergyPlus and the ASHRAE Comfort Tool[1] are all examples of this. However, as Webb shows [115], thermal comfort is a function of space, among other aspects, and therefore it is useful to acknowledge the variation in comfort throughout a space. Webb demonstrates an interaction between EnergyPlus and a developed programme called cMap whereby a single zone is split into areas of different mean radiant temperatures which can then be used as a starting point for comfort calculations. Webb acknowledges many limitations in the work including that currently it will only work in single zone models.

[1] IES-VE Pro and EnergyPlus are building simulation tools. The ASHRAE comfort tool however, is a calculator where by the user inputs environmental conditions to calculate comfort zone.

The space-dependent nature and visualisation of thermal comfort variation within a building has been addressed using environmental measurements by Pitts [116] and CFD by others [91, 93, 94]. However, from a search of current literature, there have been no studies that pull individual local conditions from models in order to evaluate thermal comfort at those positions.

3 Definition of a Smart Building

In this chapter, the need for a definition of a Smart Building is discussed before researching the drivers behind building progression. Existing work into Intelligent and Smart Buildings is reviewed before developing a definition for a Smart Building with upper and lower bounds.

3.1 *The need for definition*

Intelligent Buildings have been researched and developed over the last three decades, but in more recent literature, roadmaps and industrial reports the term Smart has started to be quoted more regularly. This seems to be the case in all aspects of the built environment sector; Smart Sensors, Smart Materials and Smart Meters within buildings are seen to be the latest, most advanced technologies in our efforts to develop high performing buildings. Smart Cities are commonly seen to be the future of the urban built environment, with increasingly populated conurbations, demanding more functionality from more constrained resources and more stringent building regulations.

However, when put into the context of buildings themselves, there is a clear confusion as to the differentiation between Smart and Intelligent Buildings. There is sparse academic literature currently recognising a distinction between the two - even though buildings are increasingly being referred to as smart. This lack of clarity in terminology does not help designers, clients or researchers.

By focusing on the key drivers behind building development past and the present, this chapter builds upon the literature covered in §1.1 to clarify the characteristics of Intelligent Buildings and bring together a definition for a Smart Building that represents a more advanced grouping, learning from and building upon the successes and limitations of previous terminology and meeting the criteria upon which a high performing building is assessed. The upper and lower bounds of a Smart Building will be defined, creating a base upon which future research can be established.

3.2 *The drivers behind building progression*

It is evident that the design and expected performance of non-domestic buildings has changed throughout history. A century ago, hospitals, offices, schools, venues and universities were robust stone and brick buildings with basic gas, water and electrical systems. Modern equivalents are being conceived, designed, and built as dynamic and technically complex buildings. In order for any change to be described as progress, it is required that the drivers for the resultant evolution have been met to a higher degree than previously. The drivers for the development of buildings can be said to revolve around adding value to a building [12]. This value will, to an extent, depend upon the context and building category, but traditionally have formed from themes relating to the cost of the building over its lifetime, and the performance, comfort and satisfaction of those within the building [25, 117]. Reducing energy consumption has now become a driver in its own right, due to increasingly stringent regulations and awareness of climate change. This is recognised in modern buildings as a significant design criterion [24, 118].

With the operating costs of a non-domestic building being significant when compared to the capital cost and a "shifting culture towards value rather than initial cost" [4] it is suggested that a more suitable representation of this driver would be its ability to maintain value over a long period of time under changing use and external conditions; its longevity. Therefore the three distinct drivers for building progression are:

1. Longevity
2. Energy and Efficiency
3. Comfort and Satisfaction

Whilst the latter two drivers are very traditional terms, they are reflections upon their broadest sense and encompass more contemporary terms such as energy effectiveness and wellbeing.

Therefore, an advanced functioning building will have its energy consumption minimised whilst consistently allowing the maximisation of the performance, comfort and satisfaction of its occupants over a long lifetime.

3.3 *Methods to Achieve Progress*

The implementation of the changes required to meet the drivers has largely been enabled by increasing knowledge, research and the availability of new materials and technologies, such as rapidly evolving communication systems [12, 20]. It is possible to express the changing genres and aspects of buildings through the different levels shown in Figure 3-1, which demonstrates that as buildings have progressed there are four aspects that vary:

1. the methods by which building operation information is gathered and responded to (*intelligence*),
2. the interaction between the occupants and the building (*control*),
3. the buildings physical form (*materials and construction*) and
4. the methods by which building use information is collected and used to improve occupant performance (*enterprise*)

In different categories of building, these four methods are focussed upon and utilised to different extents. Although each method has developed over time to be more effective, the methods have largely been developed independently of each other.

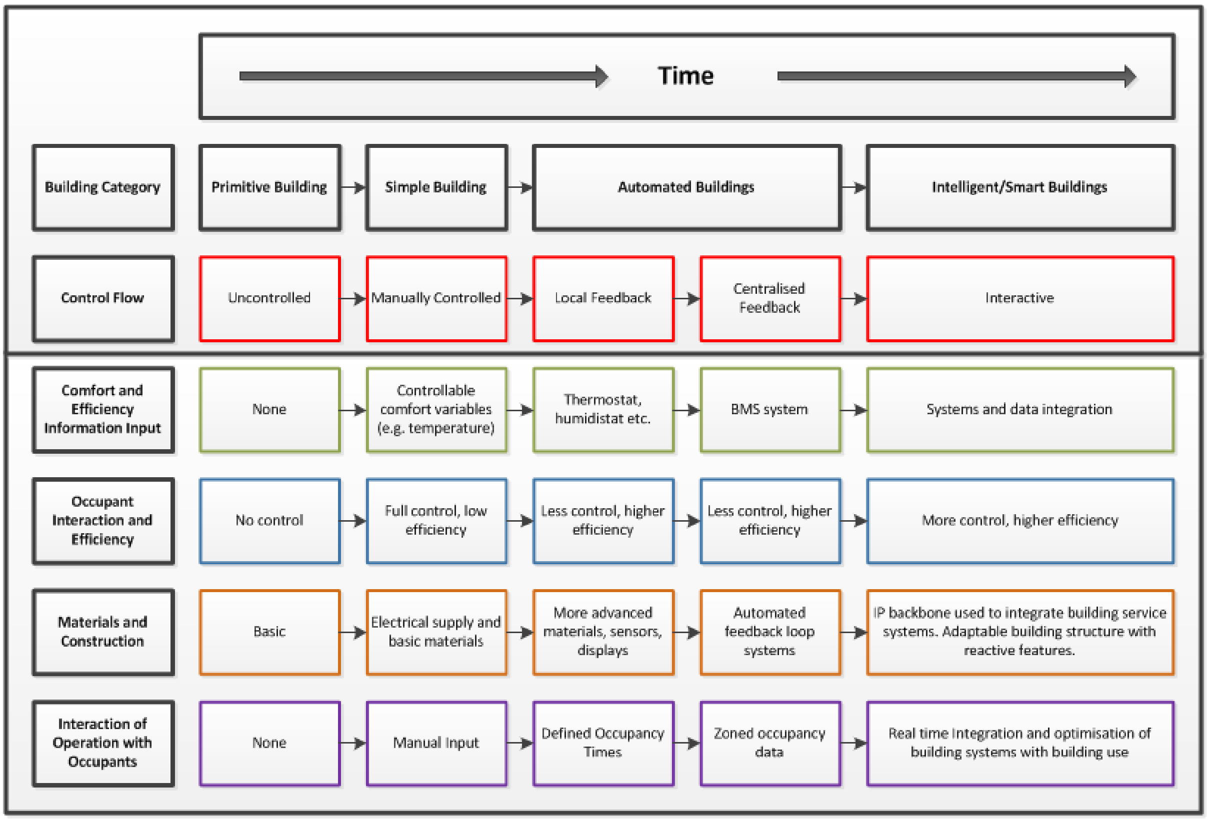


FIGURE 3-1 - BUILDING PROGRESS

3.4 *Progression from Intelligent Buildings*

Applying the term *Smart* to buildings has been increasingly used in both industrial reports [26, 28, 119] and also in the recent academic literature [21-23, 120-122]. This increasing use of new terminology demonstrates that current terminology does not cover all aspects of the most advanced buildings and industrial pressure to create a distinct advancement in building technology. However, the lack of a clear definition to what a Smart Building actually is, results in an unclear end goal with few methods by which it can be achieved. It is a similar situation to that surrounding the definition of zero carbon homes [123] or the confusion and ambiguity incurred when referring to something as *sustainable*.

The need to define a Smart Building is similar to the need to define Intelligent Buildings in the 1980s; in order to put a clarification on a term that was most probably developed “to sell or rent more floor area in commercial and/or office buildings” [R.Geisler, 1989 as quoted by 124].

Just as Intelligent Buildings were developed from automated buildings, a concept supported by the CABA Building Intelligence Quotient Programme [15], Smart Buildings are developed upon Intelligent Building concepts [26, 27]. Katz and Shopek [15] show that Intelligent Buildings contain aspects of automation and similarly intelligence is an important aspect of Smart Buildings [21, 64, 125]. Automation in buildings requires ‘a lot of “*intelligent*” devices’ [126] and Intelligent Buildings are increasingly using a number of *smart* devices, materials and sensors [124, 127, 128].

This development from the use of *intelligent* to *smart* sensors within buildings is just one example of the progression towards a *smart* built environment [117]. Deakin and Al Waer [129] demonstrate the transition from *intelligent* to *smart* cities and Fadlullah et al. [130] show the use of *intelligent* systems within an overarching *smart* grid.

3.5 *Creation of definition*

The definition of a Smart Building will take into account the recognised need for holistic and integrated design, taking into account both the current themes described in literature, the drivers for building progression and the methods through which these can be achieved:

Smart Buildings are buildings which integrate and account for intelligence, enterprise, control, and materials and construction as an entire building system, with adaptability, not reactivity, at the core, in order to meet the drivers for building progression: energy and efficiency, longevity, and comfort and satisfaction. The increased amount of information available from this wider range of sources will allow these systems to become adaptable, and enable a Smart Building to prepare itself for context and change over all timescales.

Figure 3-2 shows the diagrammatic representation of the author's Smart Building definition.

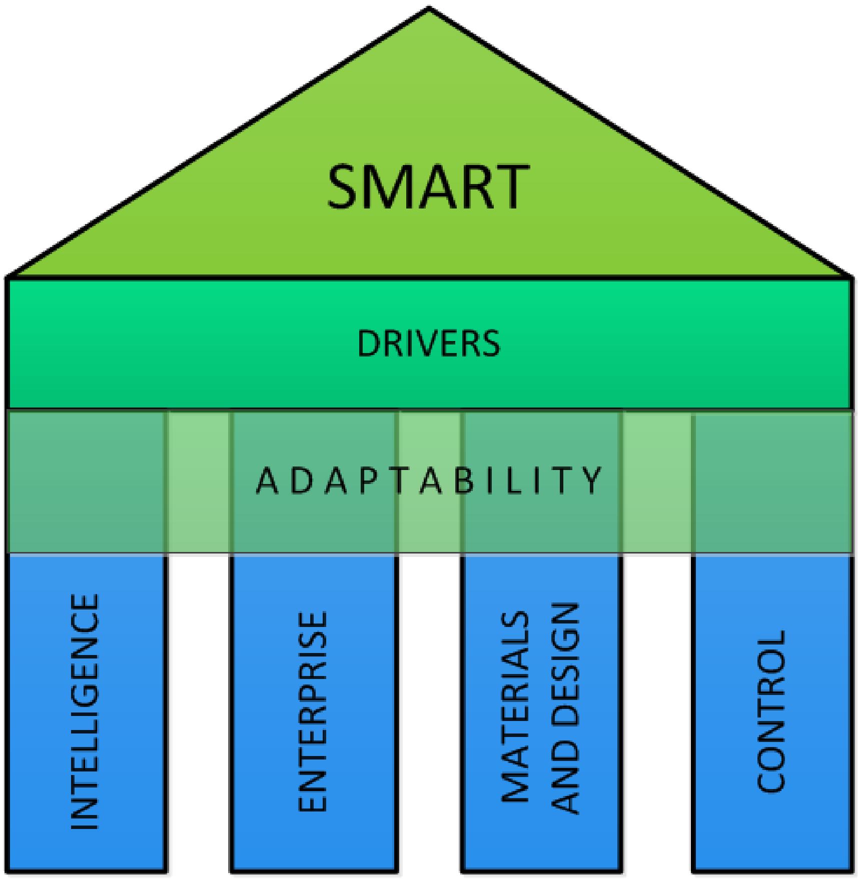


FIGURE 3-2 - FEATURES OF A SMART BUILDING

The four methods that meet the drivers for building progression, suggested in §3.3, can be seen to be the four pillars in Figure 3-2. However, at the heart of the definition of a Smart Building is adaptability.

3.5.1 Adaptability

Adaptability within, and integration between all aspects of the building will allow the differentiation between previous generations of building and Smart Buildings. Adaptability utilises information gathered internally and externally from a range of sources to prepare the building for a particular event before the event has happened, which is fundamentally different to being reactive. A Smart Building is able to adapt its operations and physical form for these events. Intelligent Buildings are generally reactive; Smart Buildings are adaptive. Examples of adaptability are the ability to account for:

- different people's perceptions of comfort at different times of day and different times of year,
- changes in occupants or building use,
- varying occupancy data characteristics and
- varying yearly average external weather conditions,

whilst maintaining or increasing energy efficiency and occupant satisfaction.

Creating an adaptable building through the design and integration of the four methods in Figure 3-2 in order to meet one or more of the drivers can be defined as a *smart* system. Figure 3-3 shows the different timescales on which *smart* adaptability operates. It is not new for adaptability to be associated with buildings, but the use of integrated adaptability as opposed to reactivity is a significant difference between Intelligent and Smart Buildings. The ability to adapt in response to information gathered from building use is essential to a Smart Building's successful operation.

Recent intelligent building systems research, such as intelligent agent controllers, can be adaptable and autonomous as opposed to traditionally reactive intelligence [131]. The author sees this as a method through which intelligence can be adaptable, as required in Figure 3-2, and would be used alongside the 3 other methods to create a Smart Building. If a Smart Building is not performing to its design standard, the building systems can gather information on why and adapt to perform to the intended level in future similar conditions.

Adaptability for the long term will predominantly evolve around the materials and physical design of the building, although any intelligence and enterprise infrastructure must be able to accommodate long term change.

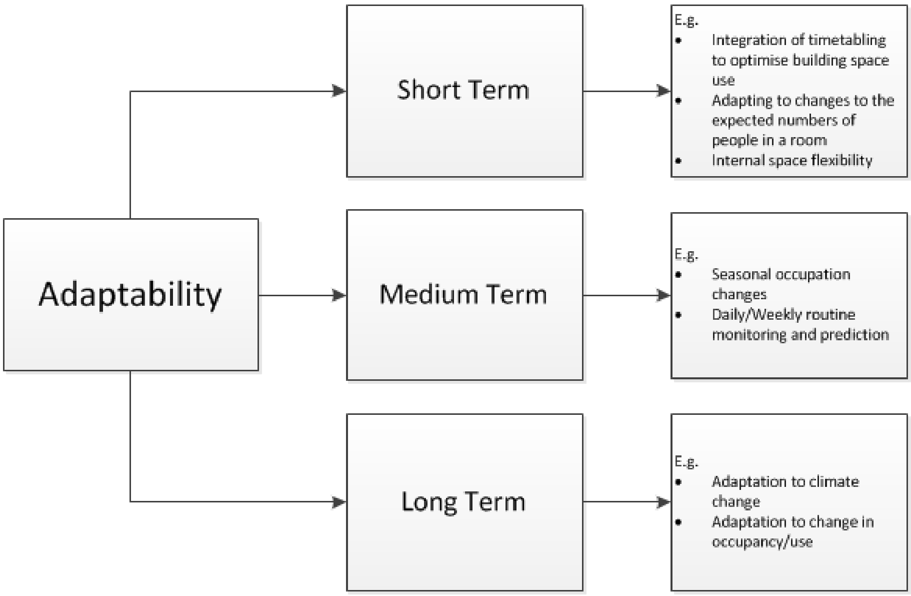


FIGURE 3-3 - ADAPTABILITY OVER DIFFERENT TIMESCALES IN A SMART BUILDING

3.5.2 Control within Smart Buildings

Smart Buildings are those which reconcile both human control and automation in order to achieve the drivers for building progression. The recognition of this need is addressed in recent research [42, 132]. The aim of control within a Smart Building is to provide occupants with information so that they can adapt to the building, as well as the building adapting to their preferences and requirements.

3.5.2.1 Examples of Control within Smart Buildings

- Influencing adaptive comfort by warning occupants of the building what the likely temperature is going to be within the building before they set off from home.
- Use real time environmental information to enable occupants to be directed to an area within their personal comfort preferences. For example, in a library, informing occupants on arrival of the varying conditions in each area.

By contrast, an Intelligent Building may collect information about current weather conditions and react to them by modifying HVAC operation with little control given. Occupants may be given a method to feedback on personal comfort and therefore indirectly control their own environment [133], or they may be given opportunities to open windows, but if conditions within the building fall outside of designated comfort conditions, then the building's intelligent systems will implement changes to rectify this.

3.5.3 Enterprise within Smart Buildings

Enterprise is an emerging theme within literature referring to Smart Buildings. Singer [134] and Powell [28] of the GSA Public Building Service define a Smart Building as one which "integrates major building systems on a common network" and demonstrate the need for an enterprise system to be integrated within the previously integrated *intelligent* system. Enterprise in the context of non-domestic buildings consists of a combination of hardware and/or software used to overcome fragmented, non-compatible, non-proprietary legacy systems [135] in order to allow the building operation to be optimised towards the building function. Enterprise is any method through which building *use* information is collected; e.g. room bookings in a university or cinema film schedules. Integrating enterprise with the BMS and real time building systems creates a huge potential for both energy effectiveness and comfort provisioning by using context related data which already exists but is not used for the purpose of improving building performance.

Robey et al. emphasise the benefits of real time information in the role of enterprise to increase the operational efficiency of a medium to large organisation, while GSA suggest that enterprise consists of such elements as business integration, enterprise management and dashboards. Enterprise systems and architecture integrated into real time building operations, using middleware, are beyond the scope of Intelligent Buildings, but form an aspect of Smart Buildings.

3.5.3.1 Examples of Enterprise within Smart Buildings

- Using a room booking system in a university or school, for example, in order to arrange rooms in specific areas of a zoned building, allowing the rest of the building to be uncontrolled. Upon entering the building the occupants would be informed as to where their booked room is located, rather than pre-booking a specific room.
- In a hot-desking office building, specific occupant-tailored suggestions could be made as to the area in which they are most likely to be comfortable based upon previous feedback (such as "too hot" or "too cold" options on the desk or computer) and any adaptive comfort variables which can be recorded, such as external conditions.
- When a room is booked, for example a meeting room, the number of people who are likely to attend will be input into the enterprise system and this will adjust any operational system requirements in order to accommodate the specific number of people; controlling the heating, cooling and ventilation in order to maximise productivity and achieve conditions which are most likely to be comfortable.

By contrast, an Intelligent Building enterprise system may allow occupants to book a room and if no one is within the room after a certain period a PIR sensor will turn the lights and computers off. If the room is highly occupied then the sensors within the room will activate changes to rectify the unaccounted for heating supplied by the occupants themselves.

Using available information and occupants choices in a way that will allow the operation of a building to be adapted beforehand rather than reacted to afterwards will allow greater comfort and reduced energy consumption, which contrasts to the traditionally intelligent method of heating a room if it is considered too cold, or cooling a room if it is considered too hot. Within the building, *intelligent* control systems such as feedback loops are still used to allow Smart Buildings to build upon the decades of research and experience, to react to unaccounted-for events and discrepancies, and to provide the interoperability of the building systems and components.

3.5.4 Materials and Construction within a Smart Building

As defined upon introduction, the materials and construction feature within the smart building definition represents the built form. The construction of a Smart Building needs to reflect and house the smart functions within it. A Smart Building is constructed of materials and contains features which will allow for accommodation of changes in use and climate. The internal structure should also reflect the dynamic nature of the building by being adaptable to the needs of the occupants. An example in practice can be seen in 30St Mary Axe, which was designed so that that the core did not need to resist wind loads, allowing for an open planned steel structure that provides adaptable space when combined with the regular internal planning grid [136].

3.5.4.1 Examples of Materials and Construction within Smart Buildings

- The building structure itself could be adaptive to future climate expectations through the ability to replace features in the future to account for change. Established precedence in this area are the concepts of Design for Adaptability and Deconstruction (DfAD) and Design for Deconstruction [113].

- Based upon occupancy data available from the enterprise systems, a Smart Building may be able to close zones during periods of known low occupancy. This requires the internal structure to be adaptable in order to maintain value to the occupant.

By contrast to these examples, Intelligent Buildings have predominantly relied upon the intelligent systems within them, rather than addressing the construction itself. An Intelligent Building may utilise PIR sensors to recognise when a zone is not occupied and reduce conditioning of this zone. A single person utilising a zone, however, could result in comfort heating appropriate for dozens of people. Smart Buildings give occupants control whilst keeping the energy consumption per occupant hour to a minimum.

3.6 *Smart Building Concepts*

Smart Buildings are Intelligent Buildings with integrated aspects of enterprise, control and materials and construction, implemented both individually and as a system to be adaptable.

Smart Buildings are occupant-based, creating active participants [137] by incorporating feedback both to and from occupants about their building use, alongside providing methods for inherent control through integrated enterprise and intelligent systems. The building empowers the occupants to make their own comfort decisions whilst maintaining regulated control. When this manual control is not possible, the occupant should be informed.

The role of learning and prediction in a Smart Building is important but needs to be clarified: In a Smart Building, learning will develop over time through the building systems interpreting data from past usage and adapting, allowing the choices of the occupants to be used for the purpose of creating a higher level of comfort and satisfaction. Prediction in a Smart Building will rely upon the integration of enterprise and the intelligent operational systems in the building. This will provide previously available but unused useful information through which energy savings can be made whilst potentially improving comfort. The prediction element in a Smart Building could therefore be termed more accurately as “informed prediction”. Other forms of prediction are likely to be used in future generations of building.

3.7 *The Upper Bounds of Smart*

As discussed above, the lower bounds of Smart Buildings are the upper bounds of Intelligent Buildings; the ability to integrate intelligence, enterprise, control, and materials and design in an adaptable manner to allow the building to prepare for event before they occur.

In order to avoid similar confusion in the future, it is important to attempt to define the upper bounds of a Smart Building. The author believes that less informed prediction will be significant in the next generation of building. As opposed to Smart Buildings, predictions will be decided through Artificial Intelligence systems. The building systems may be able to adapt comfort settings which will be dependent upon more ambiguous forms of data collected by new technologies. The author believes that future building development will create buildings that build upon Smart Buildings, using new technologies, processes and knowledge. Figure 3-4 expands upon Figure 3-1 to draw upper and lower bounds to the definition of Smart Buildings.

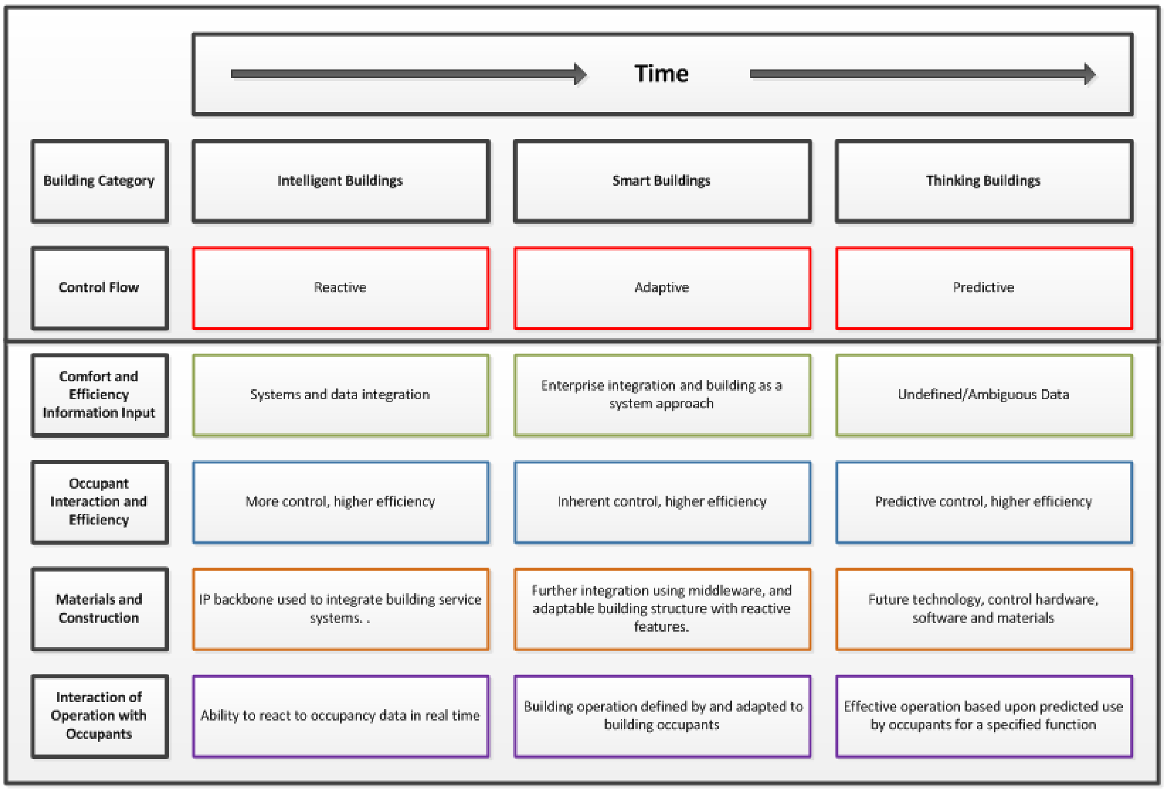


FIGURE 3-4 - UPPER AND LOWER BOUNDS OF A SMART BUILDING

3.8 *Chapter closing remarks*

Fragmentation and a lack of clarity within the building sector will create confusion rather than direction. Non-domestic buildings should aim for user comfort and satisfaction, energy reduction, resource efficiency and sustainability into the future. The definition of Smart Buildings given in this research builds upon the foundations set by previous generations of building design, including Intelligent Buildings. Research into Intelligent Buildings has advanced significantly since the 1980s and Smart Buildings combine some of the more recent research with a more holistic view of buildings.

Smart Buildings are buildings which integrate and account for intelligence, enterprise, control, and materials and construction as *an entire building system*, with adaptability, not reactivity, at its core, in order to meet the drivers for building progression: energy and efficiency, longevity, and comfort and satisfaction. The increased amount of information available from this wider range of sources will allow these systems to become adaptable, and enable a Smart Building to *prepare itself* for context and change over all timescales. By contrast, Intelligent Buildings meet the drivers to building progression by focussing on intelligent systems which reactively utilise information; control, enterprise, and building materials and construction are developed largely independently of the intelligent systems.

4 Case Study 1: The Information Commons

The Information Commons (IC) is introduced and the hypothesis of this research case study is presented before analysing current building performance. A pilot study is then carried out before presenting and discussing the results. Suggested improvements that could be made to the process are presented at the end of the chapter.

4.1 *Summary of research*

This work proposes a method through which Smart Buildings can facilitate and increase a building's ability to vary its occupiable capacity, and therefore its energy consumption, with occupancy. The opportunity is established using energy and occupancy data, with considerations of occupant satisfaction, before running a pilot study to demonstrate possible savings. It is proposed that Smart Buildings should have the ability to use the metric of energy use per occupant hour to convey occupant-based energy efficiency.

The results show an opportunity for significant savings to be made within non-domestic buildings with extended opening hours and varying occupancies. The work exemplifies a process through which functionality and design of a building can be taken into account when developing an occupancy based capacity change. Finally, recommended improvements in design of future buildings looking to utilise this method as a means of saving energy without compromising value to the occupant are suggested.

4.2 *Introduction to the chapter*

At the heart of energy performance criteria has been a version of the Energy Use Intensity (EUI) metric. A key benefit of this metric is that it can be used as a benchmark against which the building can be designed, as well as an evaluation method.

Increasingly however, it has been recognised that EUI as it stands is not a comprehensive measure of the energy effectiveness of a building, and that there are significant advantages to tailoring a building to the occupants themselves [40, 71, 138]. Nguyen and Aiello give a thorough review of extensive studies into occupancy driven energy consumption showing that the effective implementation of occupancy measuring techniques will allow for between 10 and 40% reduction in total energy use in buildings.

Smart Buildings offer the opportunity to realise more tailored metrics: their ability to collect and adapt to data from multiple sources, alongside the reconciliation of human and automated control, enables methods of building management not previously available. One example of increased information availability is spatial and temporal occupancy figures, where trends can be combined with informed data from the integration of time tabling enterprise systems to modify the Building Energy and Comfort Management Systems (BECS) [40]. These trends could be slight variations in occupancy dependent upon time of year, or they could be significant diurnal swings in occupancy during a 24 hour access building. The potential of this further occupancy data can increase the extent to which a building can adapt in innovative ways.

4.3 *Hypothesis*

The research in Chapter 2 shows the ability for buildings to vary their energy consumption with occupancy location, density and activity. However, there has been little research into the use of data assimilation to facilitate the reduction of the base-load energy consumption. An unoccupied but comfortable building will use a base-load of energy. Although possible with buildings open 24 hours for the convenience of their occupants, a more realistic scenario would be a significantly under occupied building, which would need to maintain comfortable conditions for a smaller number of occupants; such as during out of hours working [139]. Furthermore, a building that is unoccupied and unconditioned can still use a significant amount of energy if good energy behaviour is not adhered to [27, 30]. Pout et al. show how modelled building loads closely matching actual monitored loads during peak hours but fail to demonstrate the high energy consumption during out of hours periods [140].

This research proposes that the increased amount of data available to Smart Buildings can not only influence the energy consumption attributed to occupancy density within a given space, but also facilitate the ability to reduce base-load energy consumption through the correlation of occupiable space to occupancy levels.

Although currently physically possible, it would be highly inconvenient for any facilities managers and occupants to coordinate the ramping down of zone energy consumption to the distribution of occupants throughout the building. This research hypothesises that Smart Buildings can facilitate the concept and therefore endeavours to show the potential savings that could be available.

By integrating the building management system with expected occupancy data, it would be possible to close functionally non-unique zones within the building and reduce the base load energy consumption required for that zone; effectively modifying the occupiable space of the building with the occupancy.

In order to implement this idea, a smart building would need to be aware of:

- Current and future occupancy – through prediction or timetabling
- Historical trends relating occupancy in different parts of the building to actual energy performance
- Functionality requirements and locations within the building
- Granular energy load data by zone and type (i.e. small power, clean power and lighting)

Furthermore, in order to have this as a dynamic relationship between occupants and the building, the occupants would need to know in advance:

- When areas of the building would be closing and for how long
- Which suitable places are there for them to carry out their desired function

Within this investigation, a case study university building shall be used. This building is *not* a Smart Building but would benefit from being one. Therefore, the potential impact that could be made on this building's performance if it were smart is being investigated. The occupancy and energy profiles are compared in order to identify the potential savings and a comparison of satisfaction and occupancy is carried out to assess reasonable levels of space needed to maintain satisfaction levels. A pilot study demonstrates the impact of closing two zones during a 2 week period of low occupancy. The discussion will address the requirements needed in order to implement this as part of typical operation within other buildings with varying occupancy levels.

4.4 *Characteristics of the Case Study Building*

4.4.1 Case Study Building

The Information Commons, shown in Figure 4-1, is a multi-award winning Sheffield University building in the UK. The building has an F level Energy Performance Certificate classification. This likely to be a low value due to the 24 hour occupied times not being accounted for within the standard occupancy scenarios used within the EPC process, alongside the large size of the building.

FIGURE 4-1 – THE INFORMATION COMMONS, SHEFFIELD, UK

The Information Commons (IC), opened in 2007, was seen as a unique, leading environment which provides a flexible space to facilitate learning. The building has 1300 workstations spread over 7 storeys. The IC is The University of Sheffield’s largest library, containing numerous flexible spaces available for silent and quiet study and supplemented by a number of bookable small rooms and seminar rooms alongside spaces for permanent staff offices. The building reaches capacity during most term time dates, which is testament to its effectiveness. It is open 24 hours a day, 365 days per year and is run predominantly upon electricity, supplemented by low grade heat from the district heating system.

The building has an online room booking system for staff and students, a computer booking system for students only and methods through which occupancy and the distribution of computer users can be measured.

Although the function of the building has been fulfilled, the open, flexible nature has come at a cost of inflexible energy consumption. The building is cooled throughout the year. This cooling is achieved via a single air blast cooler running constantly, and two chillers which are used when required. The other primary electricity use is for small power, including computing, lighting and services.

Currently PIR sensors are used to reduce lighting load. This results in the lights turning off after 30 minutes of inactivity. However, with frequent tours of the building by cleaners and security staff it is recognised that this method is not fully effective. The ventilation rate is determined by return air temperature and CO_2 concentration. Computers will automatically turn off after 20 minutes of inactivity when logged off. Occupancy of the building is monitored through an entry gate system where students use their individual student cards to gain access to the building.

Each floor has between 3 (ground floor) and 6 (first floor) zones apart from floors 5 and 6 which are single zones. Each zone is served by a single air conditioning unit which supplies air to the zone through numerous floor grates, containing low powered fans. Figure 4-2 shows a simple schematic of the building.

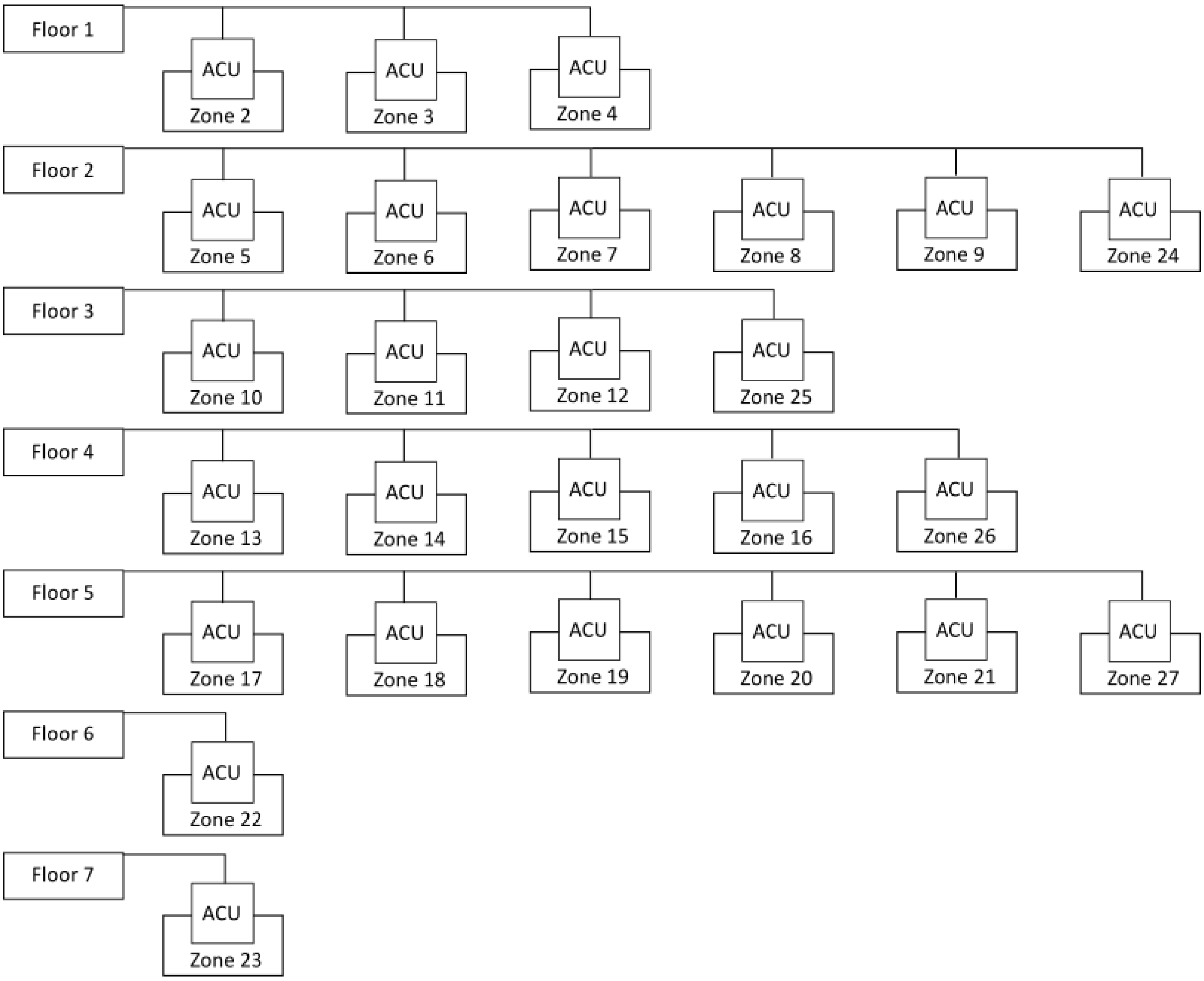


FIGURE 4-2 - SIMPLE SCHEMATIC OF THE INFORMATION COMMONS ZONES

Within this case study, an initial investigation into current occupancy and energy trends will establish an opportunity for innovative methods of energy saving. This will then be supported by a pilot study run over 2 weeks to demonstrate easily achievable energy savings. This will conclude with a discussion on how future buildings can be designed to accommodate a more adaptable space utilisation policy.

4.4.2 *Energy use and occupancy for the IC*

The purpose of the IC is to facilitate learning. This is achieved by providing a range of spaces which are available for 24 hours every day to suit a large variety of student working styles. In order to do this, a large amount of energy is utilised by the building to ensure that all spaces are “comfortable” which is conducive to a productive working environment.

However, in light of its purpose, it is clear that at some times of day and year (when occupancy is high), the building is more energy effective; the building is less energy effective when there is a single occupant than when it is full.

To quantify this, the energy consumption and occupancy over four selected weeks were attained for hour long time intervals. The weeks chosen, shown in Table 4.1, are representative of the four main occupational cases during a year within the university library: the beginning of term, mid-term, holiday period and exam period. The historic energy data was available through the Schneider Energy Remote Monitoring (ERM) system used by the university, whilst the occupancy was available from data created by the swipe card entry system. Figure 4-3 shows the energy consumption over the four weeks varying between a base-load of 160kW-240kW and a consumption reaching over 400kW at peak times. Figure 4-4 shows a heat map representation of this data using the key in Table 4.2. The colour coded data bins have been chosen to represent an even range of energy consumptions within each denomination.

TABLE 4.1 - REPRESENTATIVE DATES FOR DATA

	Week Comparison	Represents
1	3rd–9th October 2011	Beginning of Term
2	24th-30th October 2011	Mid Term
3	26th December 2011 – 1st January 2012	Holiday Period
4	16th-22nd January 2012	Exam Period

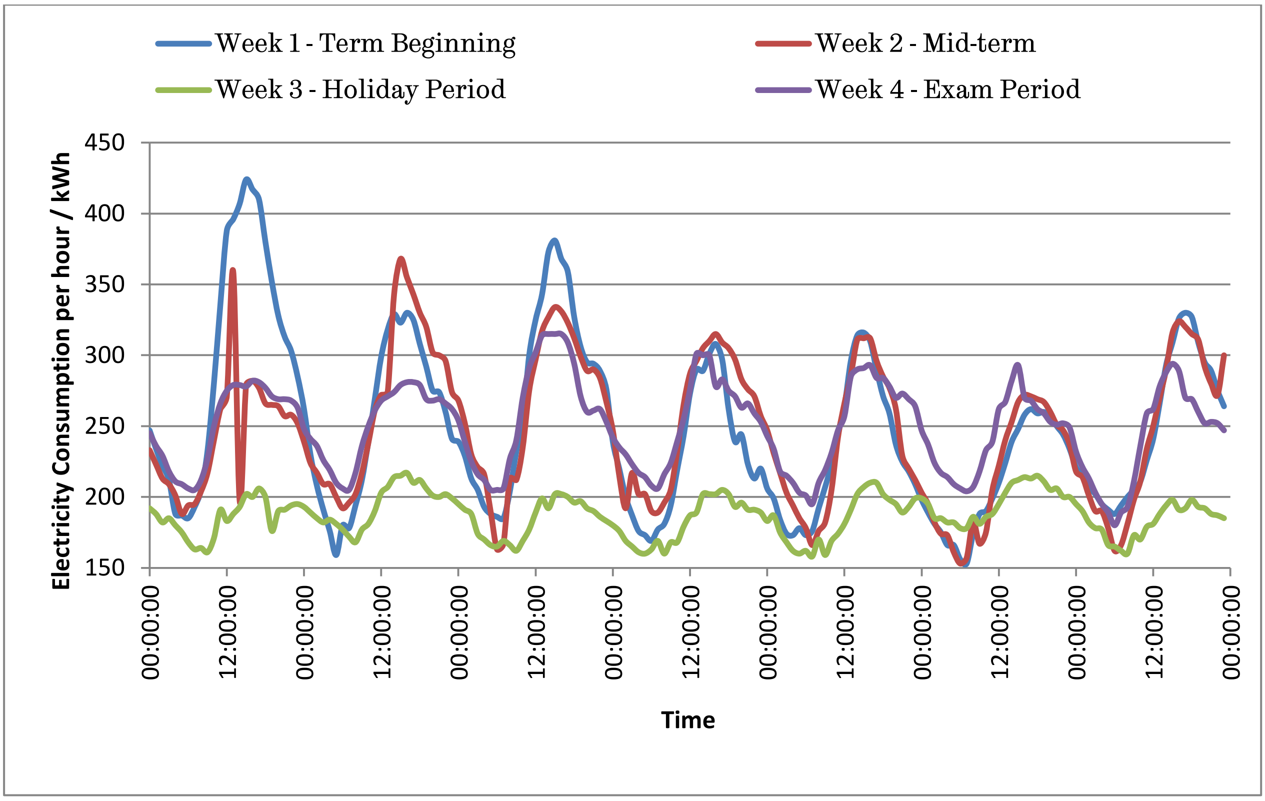


FIGURE 4-3 - ENERGY CONSUMPTION WITHIN THE INFORMATION COMMONS

TABLE 4.2 - KEY FOR FIGURE 4-4

kWh	Energy Consumption
0	Minimum
80	Low
160	Medium
240	High
320	Very High
400	Maximum

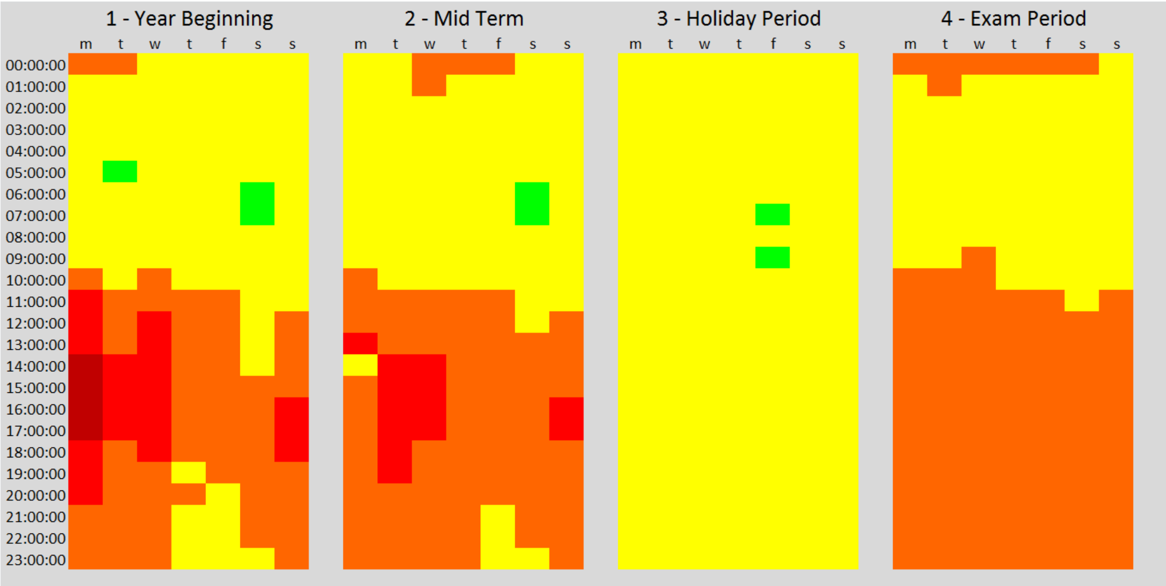


FIGURE 4-4 - VISUAL REPRESENTATION OF ENERGY CONSUMPTION WITHIN THE INFORMATION COMMONS

When constructing a similar representation of occupancy levels, the management staff working to run the Information Commons proposed classifications for the rating of perceived building performance against capacity, shown in Table 4.3; the validity of these assumption are tested in §4.5. Figure 4-5 and Figure 4-6 shows this visualisation of occupancy over the four weeks, demonstrating fairly predictable trends: exam period being the busiest time, and the beginning of the week being busier than the end as students work to meet deadlines later on that week. The most interesting areas are those in the sub-optimal zone where the building has less than 600 occupants. Quite often, especially in the holidays, this value reaches less than 100 occupants in a building designed for a factor of 10 times this.

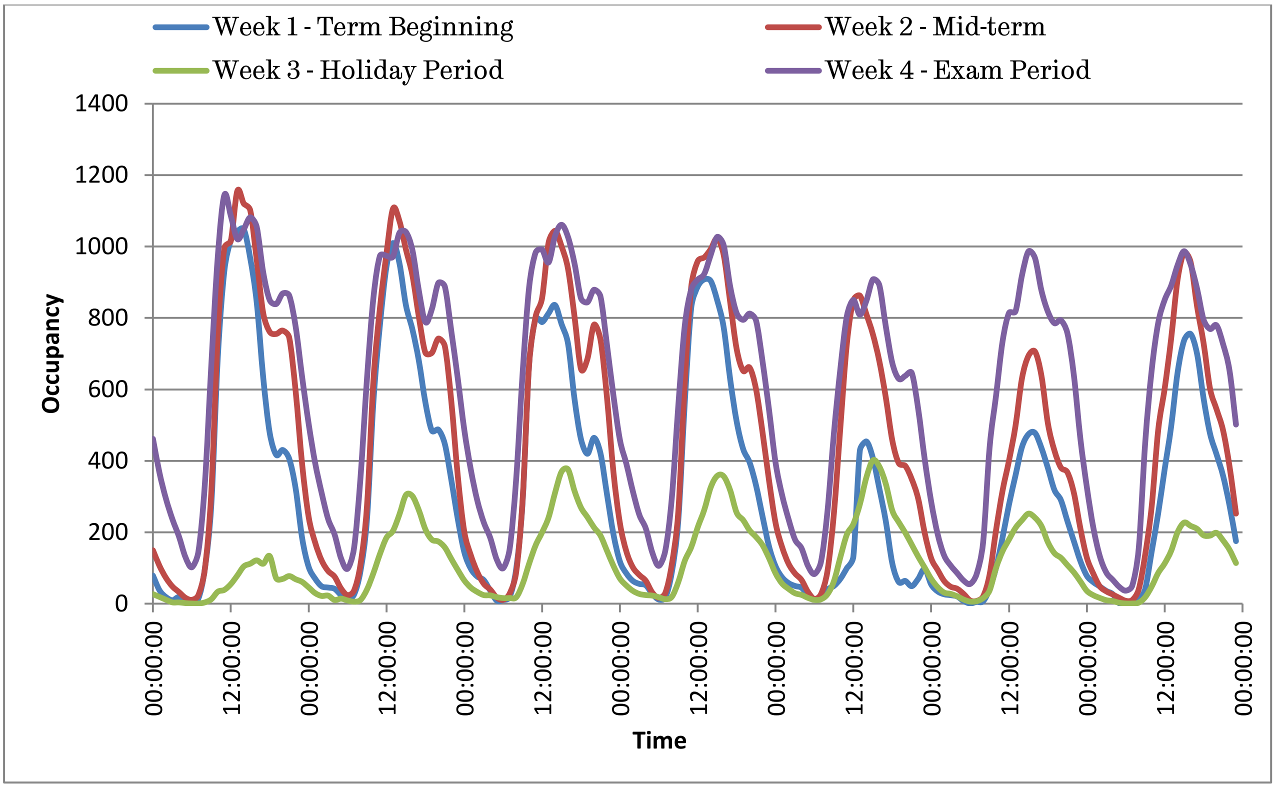


FIGURE 4-5 - OCCUPANCY WITHIN THE INFORMATION COMMONS

TABLE 4.3 - KEY FOR FIGURE 4-6

Minimum Occupancy	Maximum Percentage of Capacity	Classification
0	46	Suboptimal
600	69	Optimal
900	81	Busy
1050	92	Full
1200	100	Overfull
1300		Dangerous

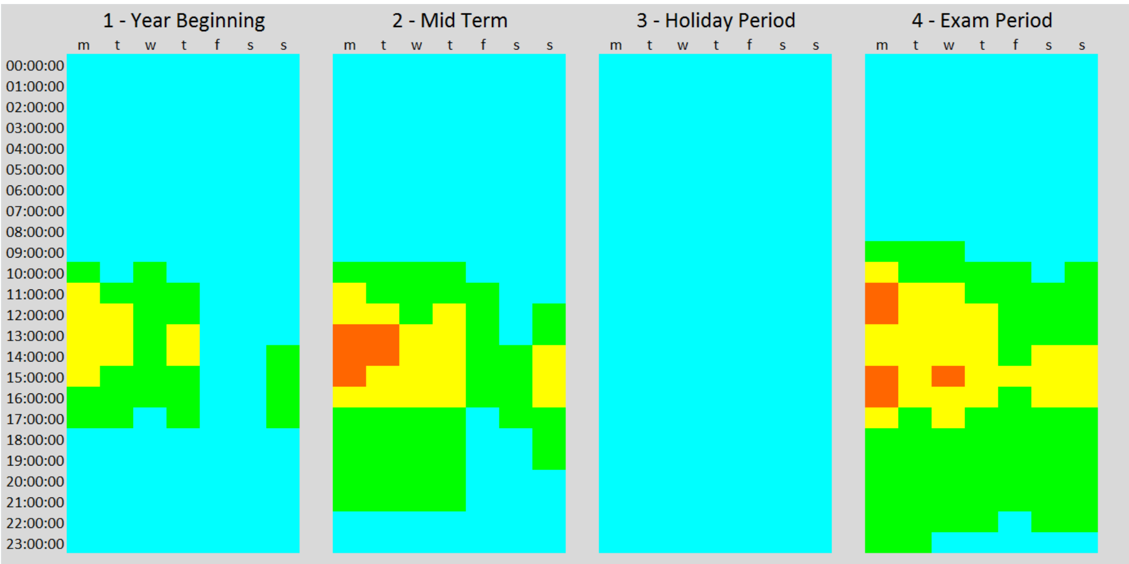


FIGURE 4-6 – VISUAL REPRESENTATION OF OCCUPANCY LEVELS WITHIN THE INFORMATION COMMONS

Section 2.3 reviewed current metrics for building energy performance, highlighting the development of the viewpoint that current EUI based metrics are unable to fully describe the energy performance of a building. The data available within the IC allows a new metric to be proposed for Smart Buildings that are able to consistently collect and analyse this data. Figure 4-7 and Figure 4-8 build upon the occupancy and energy readings to propose a new metric for building energy efficiency: energy use per occupant per hour (kWh $person^{-1}$ $hour^{-1}$). By using this metric, it can be seen that during suboptimal periods the energy footprint of an individual person using the IC can approach 1000 times more than that of a person during maximum capacity.

The average energy consumption per occupant-hour, when the building is "optimal" or above, during these four days is 0.72kWh $person^{-1}$ $hour^{-1}$. In contrast, the average for "sub-optimal" energy usage is 3.34kWh $person^{-1}$ $hour^{-1}$; nearly a factor of 5 higher. However, the building is suboptimal 70% of the time, and therefore, for example, if the energy consumption per occupant-hour was reduced by half when in suboptimal occupancy states, the energy saved would be 31% of the total building energy consumption over the four days used. This will be primarily due to inefficient use of space and resources in the building.

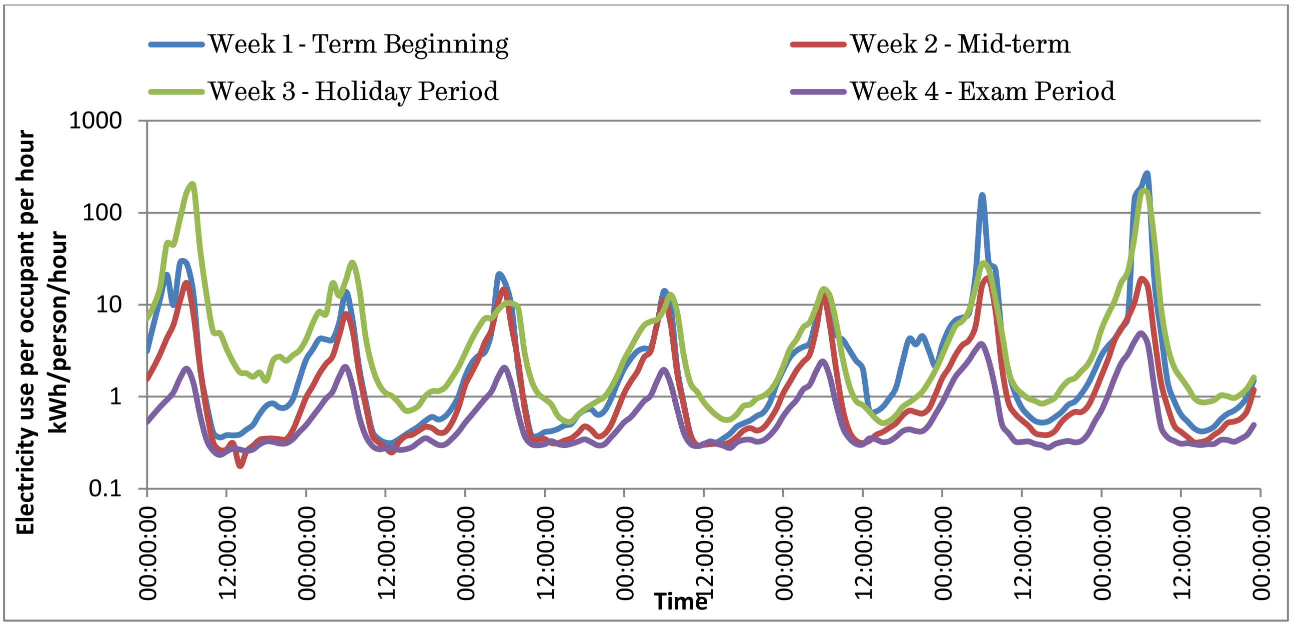


FIGURE 4-7 - ELECTRICITY USE PER OCCUPANT HOUR IN THE INFORMATION COMMONS

TABLE 4.4 - KEY FOR FIGURE 4-8

kWh per Occupant Hour
<0.3
0.3-1
1-3
3-10
10-30
30-100
>100

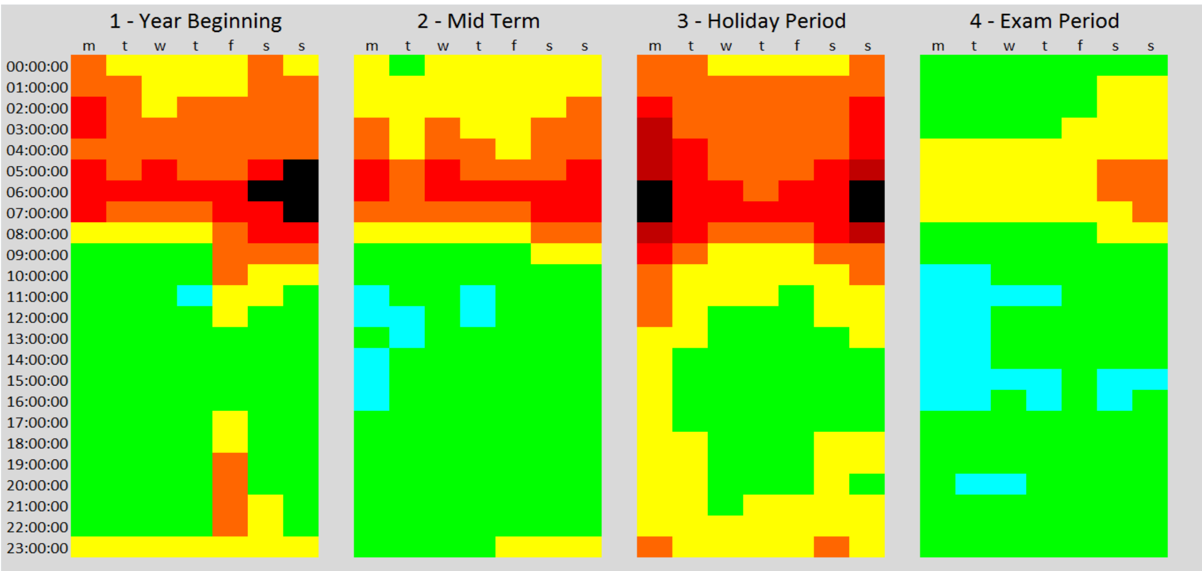


FIGURE 4-8 – VISUAL REPRESENTATION OF ELECTRICITY PER OCCUPANT HOUR WITHIN THE INFORMATION COMMONS

4.5 ***Validation of Capacity Classifications***

Although the experience of the staff within the building must have some authority given to it as justification of levels, it was seen as important to objectively validate these numbers, focussing on the optimal and sub-optimal classifications. It was hypothesized that when breaching the optimal capacity, student satisfaction would decrease noticeably as the number of spaces available was reduced and some facilities would approach capacity level. Furthermore, it was predicted that when approaching sub-optimal level, the energy usage per occupant would increase at a higher rate, thus running the building sub-optimally.

To validate these predictions, 23224 votes were taken over a period of 12 weeks asking the students in the IC whether they were “Satisfied with the Services Provided by The IC”. This question was chosen in order to disassociate the influencing factors on students’ perception of the building beyond the services that it provides; for example the students’ personal working anxieties.

The question was delivered via two interactive touch screens placed at the exit to the IC, with three possible answers represented by a range of faces from happy to sad. This method was chosen to simplify the process and engage more students in the vote.

The resultant cubic trend line can be seen in Figure 4-9, where the Satisfaction Rating is a ratio of Good, Average and Poor votes developed based upon the mean of the ordinal data. Hours in which less than three votes were cast were removed from the data as they did not provide reasonable representations of the satisfaction within the building. Figure 4-9 therefore clearly shows that the given percentage by the staff within the building for the upper limit of the optimum running capacity (shown by the vertical line) of the building is reasonable.

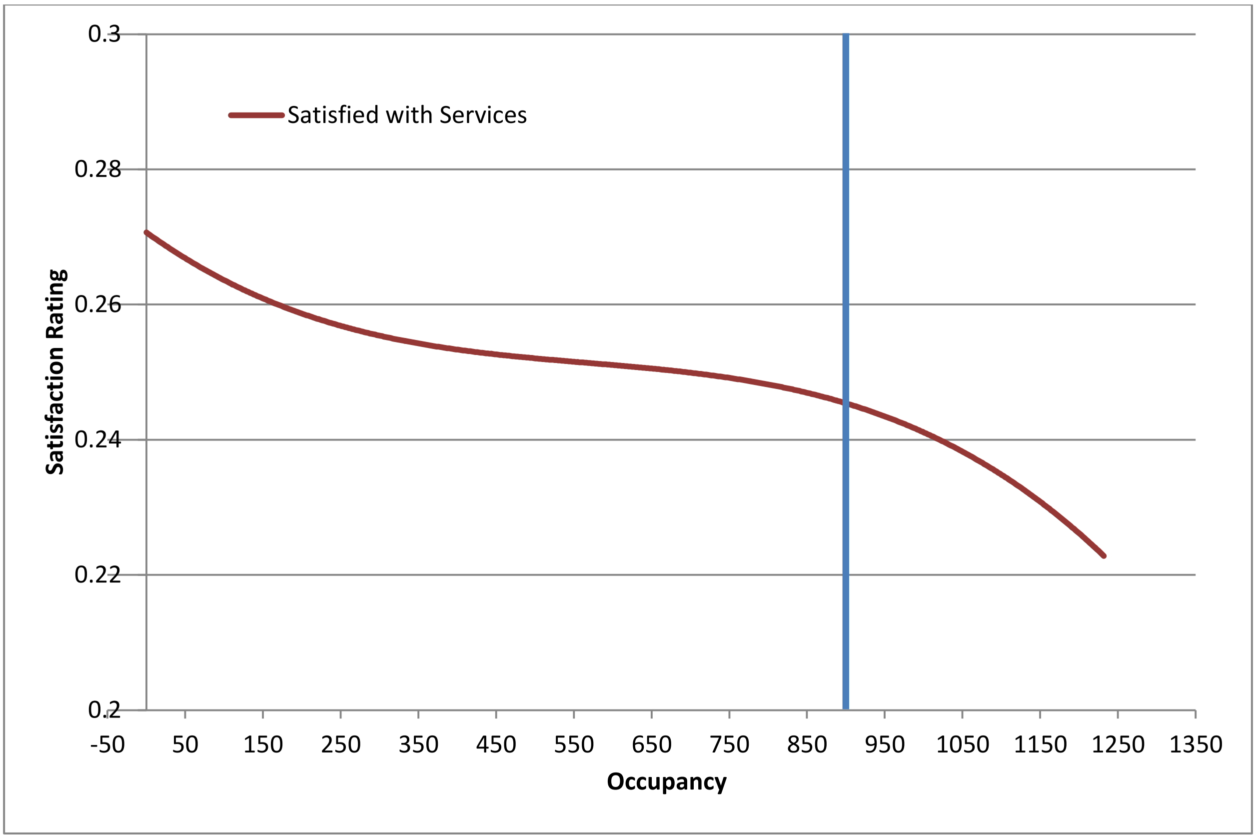


FIGURE 4-9 - COMPARISON OF OCCUPANCY LEVEL AND SATISFACTION RATING

In order to validate the lower boundary of the optimum running capacity of the building, the total energy use, and the energy use per occupant hour was correlated against the same occupancy data used in Figure 4-9. The results shown in Figure 4-10 show that the when fewer than 600 people are using the building, the energy use per occupant hour increases significantly and therefore the suggested lower bound for optimal capacity (shown as a vertical line) can be seen as appropriate.

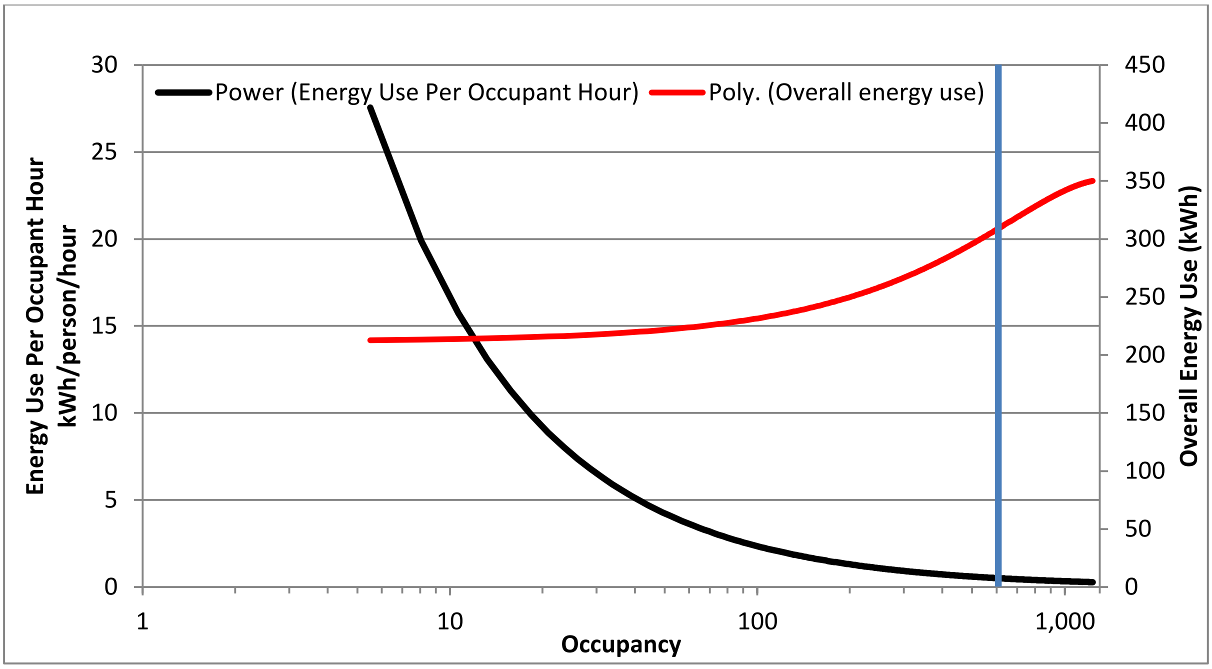


FIGURE 4-10 - VARIATION OF ENERGY USE PER OCCUPANT HOUR AND TOTAL ENERGY CONSUMPTION WITH OCCUPANCY

4.6 *Pilot Study*

In order to investigate the scale of the real savings that could be made within the IC, a pilot study was carried over one week during the summer vacation period (9th -16th September 2013). This week has consistently been sub-optimally occupied for the entirety of its duration over the past three years and so it was anticipated that the building would again be relatively under occupied. This form of basic trend analysis would be more automated if the principle was implemented into a building energy strategy. The data available within this study was limited to air handling unit, chiller and total building energy use at 1 hour intervals. Using this data it was hoped that a change in consumption could be seen between the pilot week and the weeks either side when turning off zones 22 and 23 of the building. However, as can be seen by Figure 4-11, which shows the building energy use without that of the rooftop air handling unit or chillers, the results were inconclusive. The variations shown are largely representative of the variations in weather conditions over the three weeks, with the pilot week particularly cold in comparison to the first week. A longer study period may have warranted the use of degree day normalisation but this process is not reliable for such small time periods. Furthermore, it is difficult to diagnose the reason for any variation in energy usage with any certainty with a number of variables affecting the data, such as small variation in occupancy and the quantity of direct solar radiation.

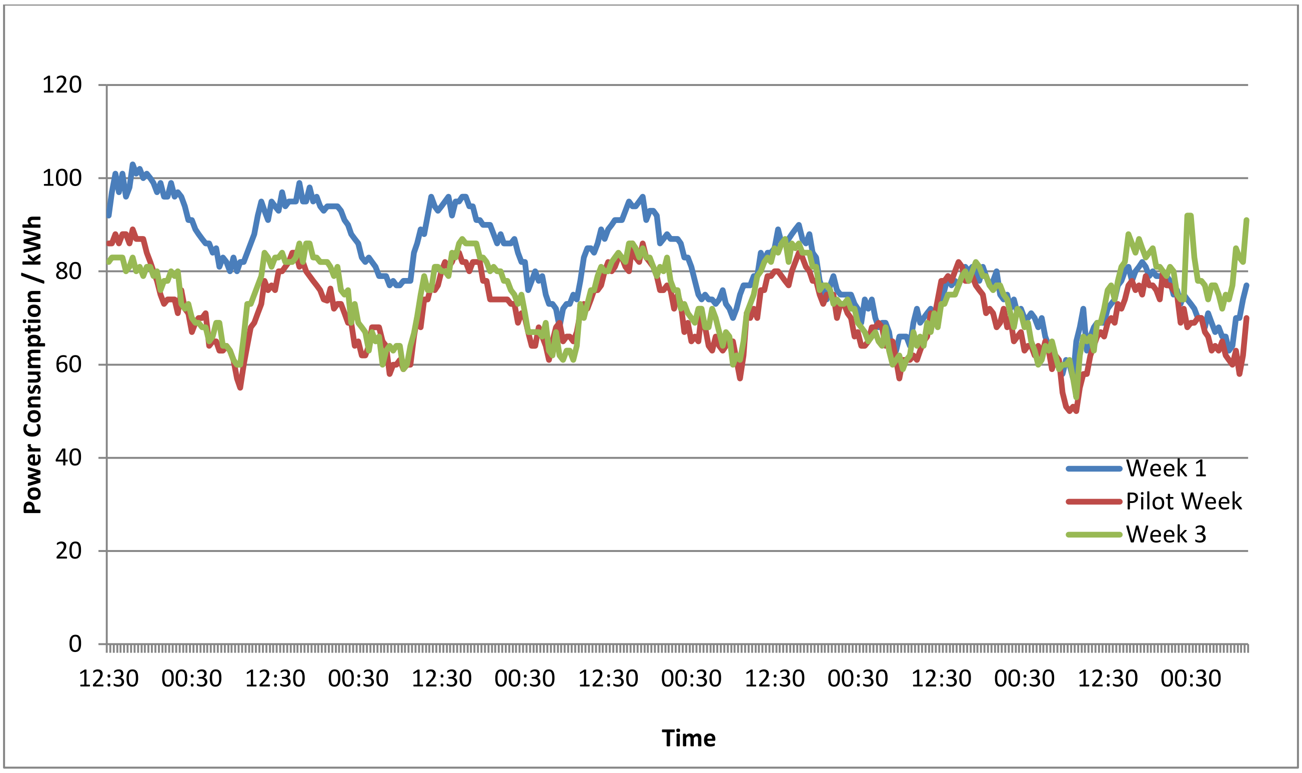


FIGURE 4-11 - PILOT 1 RESULTS COMPARING THE TOTAL BUILDING ENERGY USE (WITHOUT AIR HANDLING UNITS AND CHILLERS) OVER THE PILOT WEEK AND THE WEEKS EITHER SIDE OF IT

It was requested that The University of Sheffield upgrade the metering system to a more useful one as part of a campus wide energy metering upgrade. This upgrade resulted in an increase from 3 energy meter readings for the building to 53, enabling metering data to be collected in real time at a distribution board level for power, clean power and lighting. Clean power is that used for small plug loads such as computers, photocopiers and charging electronics.

With the increased energy data granularity available, another pilot study was proposed to run during the Christmas vacation period (18th Dec 2014-January 3rd). A two week period was studied to reduce susceptibility to temperature variations and similarly to the initial pilot study, the weeks have consistently had low occupancy levels within the building. The following methodology and results address the second pilot study only.

4.6.1 Methodology

Initially, suitable spaces needed to be identified to be closed. Such a space must be able to be:

- Turned off without losing any unique function available within the building.
- Isolated from the rest of the building
- Monitored independently of other areas of the building

These criteria, when applied to other buildings, will result in a number of different spaces dependent upon function, zoning strategy and metering systems. The spaces chosen in this study were the 5^{th} and 6^{th} floor computing spaces. These floors were chosen because they occupy an entire zone each, meaning that the services provided to the rooms could be switched off with minimal impact on occupied spaces, and the energy reductions could be monitored independently of other occupied spaces. On these two floors, there are 118 work stations with computers in total.

The 5^{th} floor was quiet study computing, and the 6^{th} floor was silent study computing. There was no other silent study computing available in the building, and therefore some of the computers were moved to the balcony region of another silent study area. New quiet touch keyboards were installed to minimise any impact upon the existing silent study space.

The premise of a Smart Building defined in Section 2 requires the engagement of occupants through the transfer of information, enabling adaption to future changes in operation. In a Smart Building, this could be through dynamic timetabling delivered through screens or mobile devices but in this study the occupants of the building were informed of future closures through information screens operating throughout the building. Signs were placed on the access routes to the floors and the room doors themselves. The doors were locked to ensure no one entered the rooms. They were not however informed of the reason behind the closure; areas are periodically shut off for maintenance and cleaning. The justification for this was to remove any subjective opinions of the university sustainability agenda.

During the two week period the following energy saving methods would take place:

1. the lights would turn off due to inactivity and remain off throughout,
2. The computers would also turn off automatically when not in use.
3. The HVAC units located within the respective rooms were put into frost protection mode. This was achieved remotely through the Estates and Facility Management Team at The University.

4.7 *Results*

The second pilot was successful in demonstrating the potential for energy saving. However, a number of issues were discovered in the data; these shall be explained. Firstly, on the penultimate day of the study, the rooms were accidently opened by the library staff. Although this was not intended, it had an unexpected positive incite as it did demonstrate an estimate of the energy consumption of these rooms had they not been closed.

Figure 4-12Figure 4-13Figure 4-14 show the power, clean power and lighting respectively delivered to each of the floors 5 and 6. Clean power is provided to the plug sockets in the rooms and therefore powers the computers primarily. Clean power is separated from overall power, which primarily provides power to the HVAC units in the rooms, as the majority of clean power is not removed but shifted to other areas of the building.

It can be seen in Figure 4-12 that the HVAC units on floor 5 were remotely switched to frost protection mode on the morning of the 23rd December 2014. However, the study revealed a fault in the HVAC system on floor 6 and therefore the power consumption here was higher than expected. Therefore, in order to quantify the results from this study, it is assumed that due to the similarities in room and function that the power consumption would both be equal to floor 5 if the equipment had not been faulty.

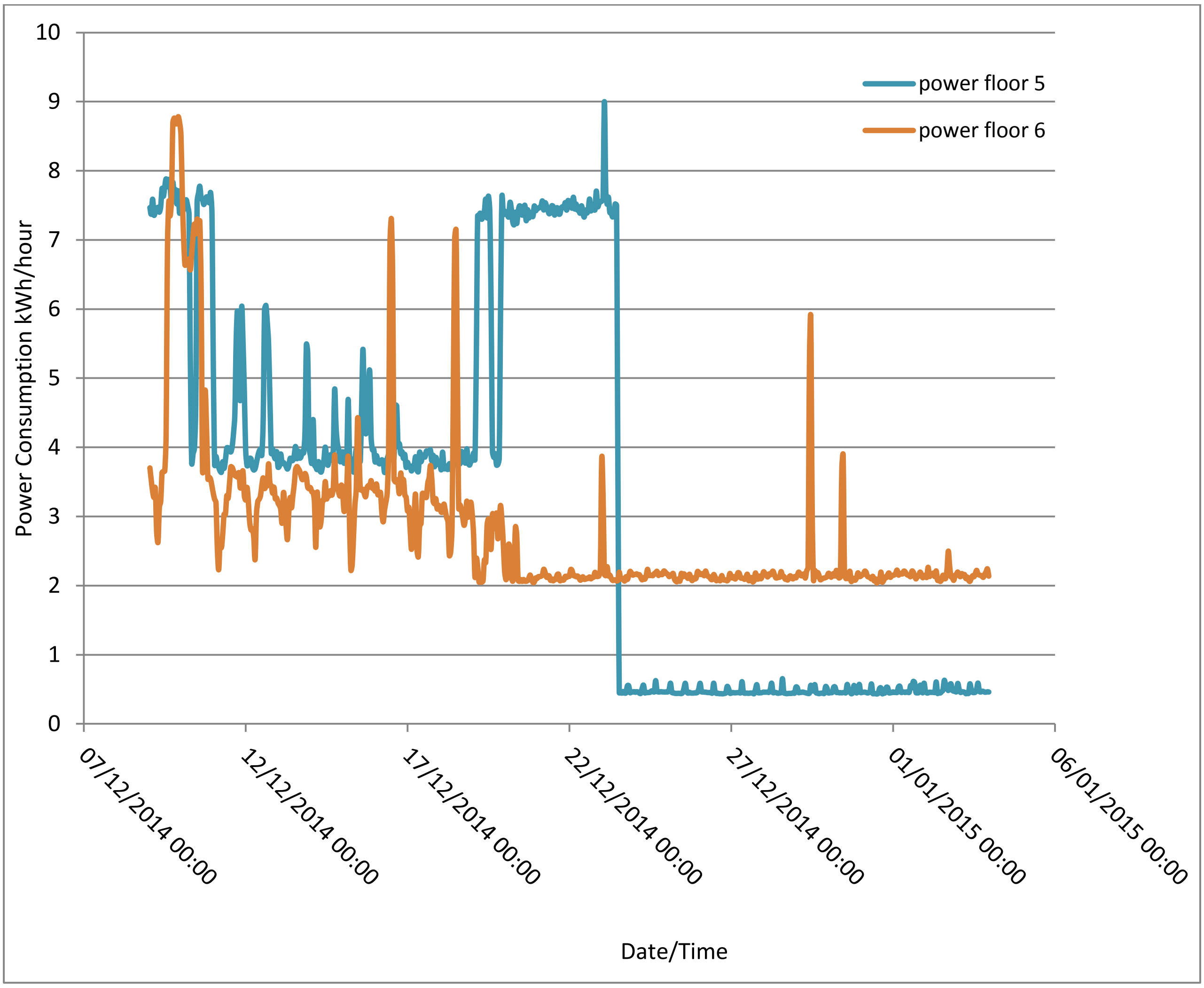


FIGURE 4-12 - POWER CONSUMPTION DURING THE PILOT STUDY

Figure 4-13 shows the clean power consumption within the floors reduced to its minimum value over the two weeks. It is unclear what the remaining power consumption is being used for. It should be noted that the rooms were locked two days prior to the HVAC being turned off, hence the earlier drop in power consumption in Figures 8 and 9. Although interesting to see, the overall energy gains from a reduction in clean power will be limited to communal equipment, such as the photocopier, and any standby computer time as other energy use will be shifted to other areas of the building.

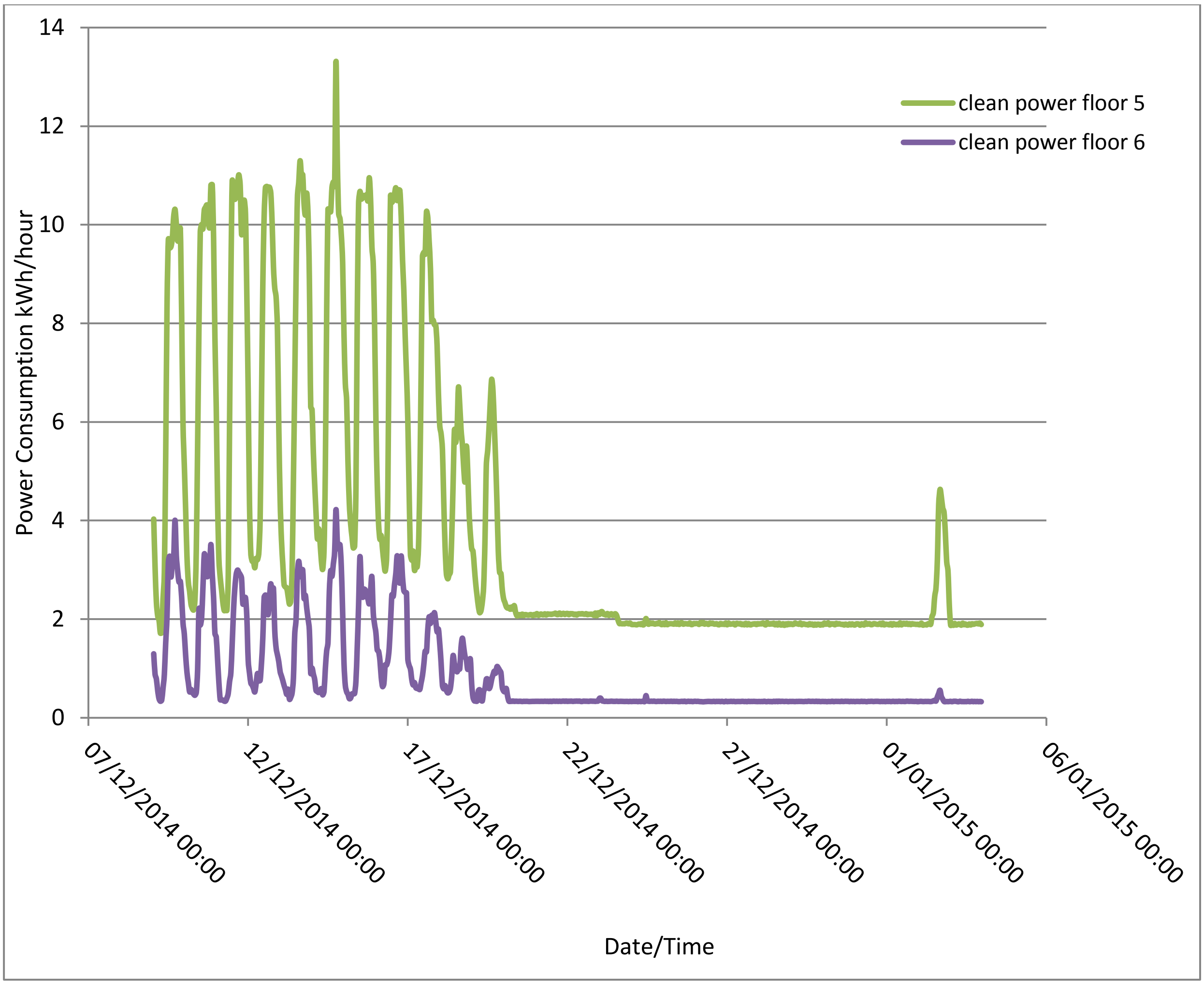


FIGURE 4-13 - CLEAN POWER CONSUMPTION DURING THE PILOT STUDY

Figure 4-14 shows that the lighting consumption within the building was slightly more erratic than the other two power forms. From the results, it was found that the lighting sensors on floor 5 did not work as anticipated, meaning that the lighting consumption patterns operated as usual. Floor 6 operated as expected for the majority of the time; at a small base load level with a few peaks as the hallway lighting outside the rooms and in the stairwell were triggered. However, there were unexpected prolonged periods of higher load intensity towards the latter stages of the study. This coincides with the slow return of higher occupancies to the building. In a building which was specifically designed to operate with varying capacity, this load would be avoided. For the purpose of this study, the floor lighting levels were assumed equal to those on floor 6, including the periods of higher consumption. This is reasonable since Floor 6 has the same floor area and lighting design as Floor 5.

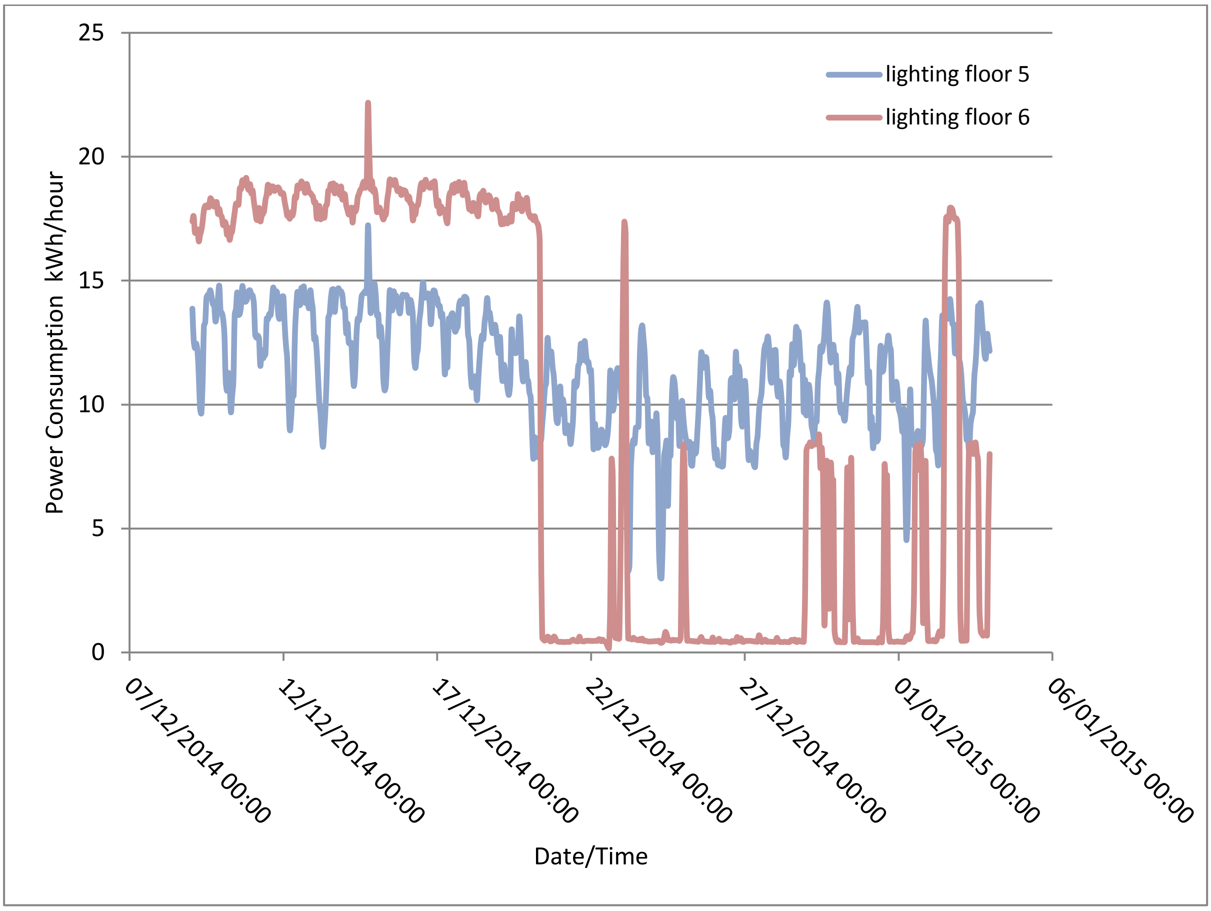


FIGURE 4-14 - LIGHTING POWER CONSUMPTION DURING THE PILOT STUDY

4.8 *Savings*

In order to quantify the energy savings over the two week pilot, a comparison was made to the sub-optimal periods in the two weeks leading up to the study. There were 114 hours operating at suboptimal times during this period (named the control) and 242 during the study. Table 4.5 summarises the key findings:

TABLE 4.5- ENERGY SAVING COMPARISON OF PILOT STUDY TO CONTROL

	Control	Study[123]
Number of hours	114	242
Total Energy Use[4] / kWh	7649.1	2681.5
Average power / kW	67.1	9.5

[1]Assuming Floor 5 lighting = Floor 6 lighting
[2]Assuming Floor 6 power = Floor 5 power
[3]Disregarding the day when the rooms were accidently opened
[4]Disregarding clean power reductions as these would be displaced to other rooms

Assuming a reasonable electricity tariff of £0.11 per kWh, the savings made over the two weeks amounted to £1,530. Realistically, this building could utilise this method during every sub-optimal capacity night and would therefore save approximately £24,600 annually based upon 2012-2013 occupancy figures.

4.9 *Discussion*

The initial investigation into the energy use characteristics of the information commons demonstrates the benefit of using a more relevant energy performance metric of energy use per occupant per hour for buildings with highly variable occupancy levels. The current standards that normalise energy use intensity metrics by taking into account longer occupancy hours do not suffice when looking at energy effectiveness. During sub-optimal times the energy use per occupant hour increases significantly, reaching above 100kWh per occupant per hour in holiday periods (Figure 4-7) and between 0.2 and 30kWh per occupant per hour during term time (Figure 4-10). In the year 2013-14, the IC was sub-optimally used for 71% of the time, during which the average occupancy was 218 people. Theoretically, satisfaction could be maintained if a corresponding average of 75% of the building was closed down during these periods. Assuming that an average baseline energy consumption of 150kW was impacted proportionately, the energy saving potential over the year would be approximately 700MWh, or 33% of the total energy consumption.

This potential reduction is only achievable when the factors limiting its success if implemented in the IC currently. Therefore much importance of this study lies in the identification of improvements required if the building was designed to accommodate this concept.

4.10 *Improvements and Developments*

The occupancy of the building after the 5th and 6th floors were closed was still sub-optimal for the majority of the time. Therefore the potential energy savings that could be made in similar sized buildings with similar occupancy fluctuations is much larger. There are two primary features of a building design that will enable energy saving through this method:

1. Distributed functionality: by reducing the number of unique spaces within a building, the designer will enable occupants to achieve their purpose within a building that has reduced capacity. The recent increase in flexible working spaces and organisations' work policies [61, 63] through the introduction of tele-working, hot-desking and activity based working. These working policies would feasibly be complimented by a buildings ability to accommodate varying occupancies.

2. Zoning and spatial layout: The ability to vary energy levels whilst maintaining functionality depends upon the zoning of the building. Zoning is currently based upon aspects such as HVAC requirements, solar gains, temperature stratification and spatial activities [65]. If the ability to close areas of the building off without losing functionality was also considered when zoning then the ability to control energy consumption can be more closely coupled with expected occupancy.

If these principles were applied to the IC, allowing for complete functionality of the building at 20% capacity and having the ability to incrementally close down 10% of the building at a time, then the energy use per occupant hour shown in Figure 4-10 would be modified to become similar to that in Figure 4-15, assuming a base load consumption of 150kW. This data is based upon 2,015 hours of data, in which 53% were optimal or above, yet during these hours a potential 17% of energy could be saved by varying capacity as described above. When implemented over the entire year, where the building is at sub-optimal capacity for approximately 70% of the time, this energy saving value will increase.

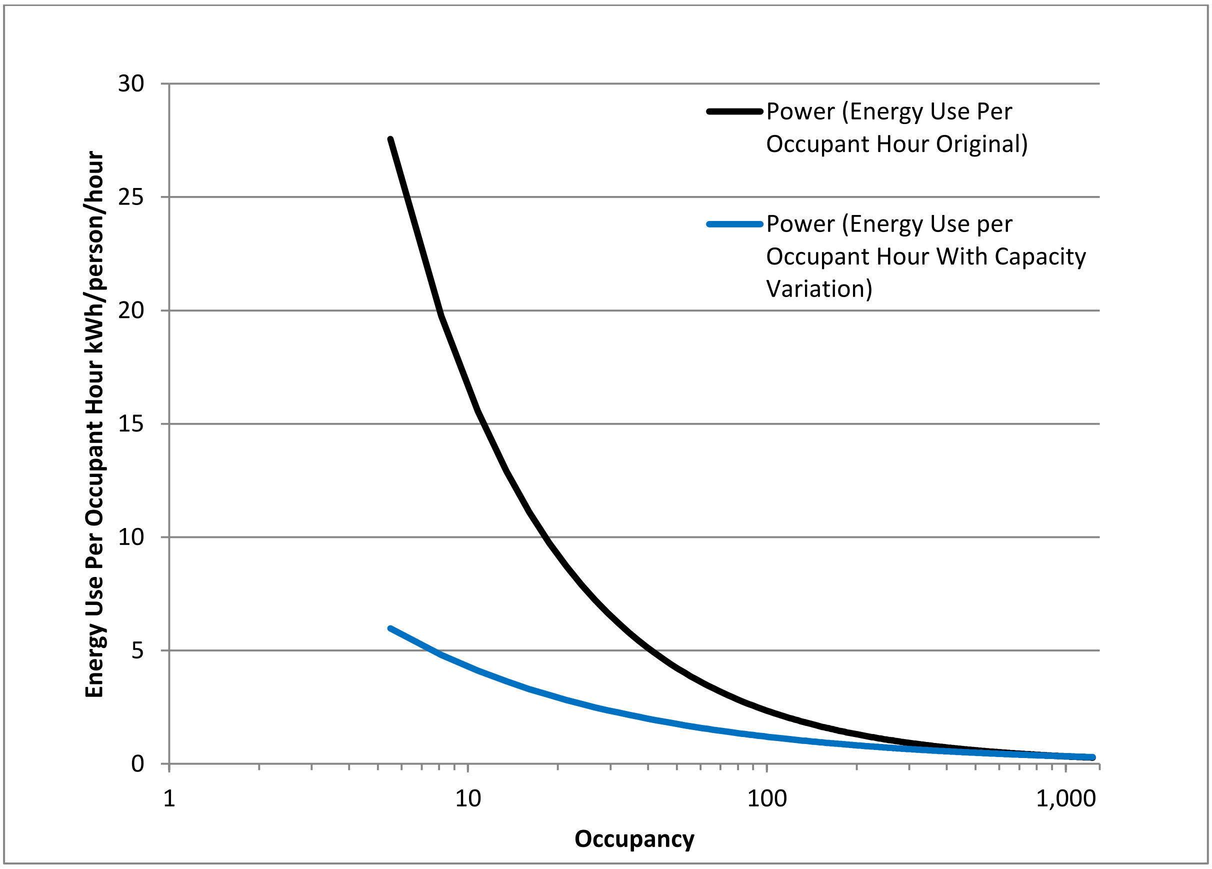


FIGURE 4-15 - THE EFFECT OF CAPACITY VARIATION ON ENERGY USE PER OCCUPANT HOUR

4.11 *Conclusion*

This study has identified that for buildings with large variations in occupancy and distributed functionality, there is the potential to tailor energy consumption to the number of occupants by reducing the capacity of the building itself. Although the IC is not a Smart Building, it has been shown that smart use of available information could improve building energy performance. The work of previous authors into the role of occupancy in tailoring building energy use has been supplemented by proposing a method through which base-line energy consumption can be step-reduced. The study has proposed that Smart Buildings will enable building performance metrics to become more occupant centred, proposing that energy use per occupant hour is a more representative metric, addressing the energy footprint of individual occupants of a building over given time periods.

A pilot study run within the Information Commons in Sheffield has shown that this approach on the IC's energy performance, but has also highlighted areas in which future buildings can be designed to increase the buildings ability to correlate capacity to occupancy.

This concept is both old and new; it is known that turning an area off saves energy, but it is novel because the implementation of this technique dynamically through a year can be facilitated by a Smart Building approach.

5 Literature review and theory of modelling methods

The two main modelling tools in this research are IES-VE Dynamic Building Simulation and Ansys FLUENT Computational Fluid Dynamics. This chapter introduces each package, indicating their usefulness to different aspects of the research, their calculation methods and a literature review of their application to building atria.

5.1 *IES-VE*

IES Virtual Environment (IES-VE) is a software package used for dynamic building energy simulation. It consists of a suite of integrated analysis tools that enable the assessment of building performance over large timescales with relatively small computing power when compared to CFD. The capabilities of IES range from legal compliance, financial and environmental cost to comfort and energy performance. The software allows easy integration of real weather files and dynamic control of openings dependent upon measured variables.

Together with its wide adoption within industry, the capability of IES to give an initial estimate of building performance with dynamic weather inputs, whilst using minimal resources were the primary reasons for choosing this software for the initial stages of the building modelling. As it is not possible to test on the Diamond, due to it being under construction, or to create scale models of the building, due to a lack of available equipment, the IES model is seen to be a reasonable method to represent the overall performance of the building which can then be modelled in more detail through CFD. As Augenbroe corroborates [141],

> "The primary objective of their use is to conduct a performance
>
> analysis that informs for instance a pending design decision" [141]

Building simulation in this part of the research is used as a precursor to a more in depth analysis of the case study building in order to inform criteria to be used in the CFD analysis.

Although there are 24 integrated packages with IES, the modules used within this modelling are ModelIT (Building Modeller), Suncast (Solar Shading Analysis), ApacheSim (Thermal and Energy Simulation), Macroflo (Multi-zone air movement) and VistaPro (Advanced Analysis).

5.1.1 *Building Simulation of large buildings and atria*

Building simulation has predominantly been reported in the literature for one of two purposes in relation to individual building design: either to model various design characteristics over long timeframes to discover relative performance benefits (e.g. [142-144]); or to couple with CFD methods to create long time-scale, tractable building models [145, 146]. There are a number of different packages available such as Energy Plus, TRNSYS and IES-VE, they are all primarily used in the design development stage within industry [147].

The subjects of building simulation studies have predominantly been either single room studies but there have also been a number of larger naturally ventilated spaces modelled [145, 148, 149]. The latter are often the subject of the coupled approaches with CFD. Zhang et al. [145] used the Energy Plus nodal model software to model natural ventilation within a $2400m^2$ space before inputting multiple variables into Fluent. The study successfully modelled the space over an annual cycle, reducing the time requirement from 46 to 8 days, which is still a very resource intensive simulation. Göçer et al. [149] simulated an example atrium building by combining EnergyPlus with Fluent and COMIS, an airflow simulation tool. The latter tool was used because EnergyPlus did not have a native ability to model any form of stack ventilation. IES-VE's Macroflo integrated module does allow for stack ventilation to be accounted for when a space is split into a number of elements in the vertical plane [150]. More recently, Morshed successfully used IES-VE building simulation and CFD to model a naturally ventilated tall teaching space [151].

Building simulation programmes provide complimentary information to CFD due to different characteristic time-scales and granularity of information. There are a number of methods through which the two software packages can be coupled. Zhai et al. [152] summarise these methods clearly into two categories; static and dynamic. The latter performs continuous exchanges of information between the models, such as wall temperatures and inlet conditions, whilst the latter performs one or two stages of information transfer, defined as one-step and two-step static transfer. Zhai et al.

recommend that static coupling is suitable for models that are not too accuracy dependent. Furthermore, one-step modelling is suitable to simulations where the CFD is solving steady state solutions whereby transient conditions are not considered. One-step coupling between IES-VE and Fluent is used in this research.

5.1.2 Mathematical methods utilised

The modules of IES-VE that are used within this research allow for the measurement of radiation, airflow, energy input and heat transfer. The variables that are important to outputs of the model are: air temperature, air velocity, mean radiant temperature, energy input, diffuse and direct radiation.

An element of the IES model consists of walls, floor and ceiling. There are 29 constructed within the atrium, with some including windows and many with their ceilings and floors defined as holes, allowing for air movement between elements. Heat transfer and balance within an element is calculated within IES-VE though the finite difference approach. This approximation distributes nodes within the element at which temperature is calculated. These temperatures are dependent upon the local node spacing via Equation 5-1:

$$\frac{T_{n-1}-2T_n+T_{n+1}}{{\delta_n}^2} \qquad (5\text{-}1)$$

Where T_n is the temperature in Celsius at node n, and δ_n is the local node spacing (m). The nodal spacing is in turn dependent upon the chosen time step based upon the Fourier number:

$$F = \frac{(\frac{\lambda}{\rho c_p})\Delta}{{\delta_n}^2} \qquad (5\text{-}2)$$

Where λ is the conductivity of the air, ρ is the density, Δ is the simulation time-step and c_p is the specific heat capacity of air. Within each element there are two significant assumptions made; the thermophysical properties (λ, ρ and c_p) remain constant throughout the element; and the air within the element is fully mixed (IES refer to this as the stirred tank representation), meaning that a single temperature (T_a) represent the entire bulk air temperature. This is an obvious limitation to the study of specific comfort conditions throughout a space and is the reason that CFD is being used as the more advanced modelling technique.

Although the walls to the atrium are modelled as adiabatic due to large amounts of insulation between naturally and mechanically ventilated sections of the building, the floor of the atrium and the balconies contain significant thermal mass as specified by the building engineers. Therefore it is important to understand how the convective heat transfer is modelled within ApacheSim. Equation 5-3 is used for forced convection aspects:

$$\boldsymbol{Q} = \boldsymbol{K}(\boldsymbol{T_a} - \boldsymbol{T_S}) \quad (5\text{-}3)$$

Where Q is the heat flux (W/m^2), K is a constant found experimentally, and T_S is the surface temperature. For natural convection components of convection, Equation 5-3 is linearised to form Equation 5-4.

$$\boldsymbol{Q} = h_c(T_a - T_S) \quad (5\text{-}4)$$

Where h_c is the heat transfer coefficienct and to simplify the calculation this value remains constant throughout the simulation based on typical values of temperature difference. This fixed coefficient is specified by the CIBSE 'simple model' as 3.0. This is an assumption that is not always accurate and is one of the main drivers behind the work into automated coupling of CFD and building simulation, as the CFD models accurately calculate the h_c values that can then be fed back into the building simulation model which can, in turn, feed back more accurate wall temperatures, along with other outputs previously discussed [152, 153].

Within the atrium it is important to acknowledge the methods and shortcomings on the IES-VE approach to air flow within large atria. If the atrium was modelled as a single zone, much like a room, then there would be no variation in temperature throughout the space.

There are two approaches to heat transfer by air movement between elements in IES-VE used within a naturally ventilated space: pre-specified air exchanges from the wind coming through the louvres and buoyance driven flow integrated into the calculation through the MacroFlo module. The former method is specified by the weather file but is altered during the year by the louvre opening profile whereas the latter is calculated within the MacroFlo. The heat transfer rate from air entering an element is:

$$\boldsymbol{Q} = \dot{m} c_p (T_i - T_a) \quad (5\text{-}5)$$

Where $\dot{m}$ is the mass flow rate of the air and T_i is the temperature of the incoming air stream.

The MacroFlo module is used within the model to calculate the air exchanges between the different elements throughout the atrium space. This module enables the stack effect to be modelled.

Buoyancy driven flow within MacroFlo still assumes constant density and therefore the pressure varies linearly with height of the element. However, air density varies between elements when combined with the Apache heat transfer calculations and therefore the stack effect can take place.

The main limitation of MacroFlo and ApacheSim for the modelling of stack ventilation of this atrium is that there are numerous high level louvres, which have external air flowing into them. In a typical building, assuming relatively low inlet velocities, you would expect downdrafts as this air meets the warm internal air and falls immediately, having little impact on the temperature of the air further away from the opening. However, in IES-VE this incoming air has a significant impact upon the T_a under the fully mixed assumption. The effect being that only the middle elements away from the openings display good stack effect results. However, since the balconies are separate elements to those adjacent to external openings, the comfort values obtained can be assumed reasonable representations.

5.1.2.1 Diffuse solar

Within this work, an important factor that is used is the solar gain through diffuse radiation entering the atrium through the glazed surfaces. ApacheSim reads the diffuse solar radiation measurements from the inputted weather file, which is in this is a weather file for Sheffield. ApacheSim then uses equations 5-6 and 5-7 to calculate the diffuse sky (I_{sdiff}) and diffuse ground (I_{gdiff}) solar flux:

$$I_{sdiff} = I_{hdiff} cos^2\left(\frac{\beta}{2}\right) \quad \textbf{(5-6)}$$

$$I_{gdiff} = \rho_g I_{hglob} sin^2\left(\frac{\beta}{2}\right) \quad \textbf{(5-7)}$$

Where I_{hdiff} is the diffuse sky solar flux on the horizontal plane which is read from the weather data file. β is the inclination of the surface and assumes isotropic diffuse radiation. ρ_g is the solar reflectance of the ground, which is assumed to be the standard value of 0.2 for a temperate climate, as in CIBSE guide A2. I_{hglob} is the total solar flux that falls on the ground and is dependent upon the solar altitude, α, the solar flux measured perpendicular to the beam, I_{beam} and I_{hdiff} through equation 5-8:

$$I_{hglob} = I_{hdiff} + I_{beam} sin\alpha \quad \textbf{(5-8)}$$

5.1.2.2 Building Air Flow and Heat Balances

Natural ventilation requires a software programme to be able to link air flow and heat balances, since they are inter-dependent. Therefore within IES VE-Pro, data is exchanged between Macorflo and ApacheSim dynamically. The stirred tank model assumption in ApacheSim is important in this process as any air transported to an adjacent element is assumed to be at the mean air temperature of the origin element. This assumption, and associated air density, defines the buoyancy force calculated within Macroflo.

5.2 *Ansys FLUENT Computational Fluid Dynamics*

This section covers an overview of computational fluid dynamics (CFD). A short history of CFD development is followed by a summary of the applications of CFD within large naturally ventilated buildings modelling and research. The governing equations and methods available within the ANSYS FLUENT package are introduced.

5.2.1 General History of CFD modelling

CFD employs numerical analysis and simulation of fluid processes to build upon the vast wealth of knowledge developed around fluid mechanics and dynamics; from Newton's law of viscosity for Newtonian fluids in the 17th century to the development of the Navier-Stokes Equations in the 19th Century and Richardson's [154] methods of solving Laplace equations using iterative techniques in 1910. Although his work was not specific to fluid dynamics, the techniques developed formed the basis for some of the first used in within computationally solved fluid dynamics problems on the ENIAC (Electronic Numerical Integrator And Computer) in 1940 [155]. CFD has only been widely possible since the 1960's with the development of high speed digital computers but its usefulness has always been constrained to the availability of computational resources; Kawaguti used a mechanical desk calculator for 20 hours a day for 18 months to solve the flow around a cylinder in 1953 [156] and to this day, the complexity of models is limited by available computing resources, with 3D building models demanding huge resource requirements.

The ultimate goal of CFD is to be able to model a scenario accurately. This then allows for the relatively time and cost efficient study of the effect of changing variables on that model, compared to running the equivalent number of experimental cases. However, the ability to trust a CFD model without validating it experimentally has still not been achieved and Richard Hamming's quote is relevant to modern day modelling:

"The purpose of computing is insight not numbers." [157]

5.2.2 *Application of CFD modelling for large buildings and atria*

Although there are currently no published comprehensive reviews of the application of CFD to building air flow modelling, some aspects of the following were obtained from Cook [158] and Jones and Whittle [159].

The applications of CFD were initially limited to the aerospace and automotive industries. Early applications to modelling of building airflow began to emerge in the 1970's and 1980's. The first recognised studies were carried out by Nielsen et al. in 1974 [160] and 1979 [161] in which the standard k-ε turbulence model was implemented to model the transport of kinetic energy and its dissipation rate, and the latter study included buoyancy terms. Within Nielsen et al.'s 1979 article, it was stated that the predictions were satisfactory for design purposes.

Over the following decades the depth of study into the suitability of different CFD approaches to buildings was increased substantially as more computer power and resources became available to researchers. In the 1980's steady state and transient simulations were shown to be suitable to model complex turbulent flows [162] by Broyd et al., Waters used CFD to model a number of buildings, including atria[163], to measure temperature and air movement and Davidson [164] used a finite difference method to model three dimensional buoyancy driven turbulent plumes within a room.

In 1992 Jones and Whittle concluded that the finite volume discretisation method was both suitable for modelling buildings and favourable over the finite element approach due to its less resource intensive calculation methods, especially with unstructured meshes overcoming its inability to model complex geometries [159]. In 1992 the RNG k-ε model was introduced [165] and this was followed by the development of the Realizable k-ε model in 1995 by Shih et al. [166]. Although relatively new, the latter model has been shown to outperform both RNG k-ε and standard k-ε for many applications [167]. After the early 90's, research into the validity of CFD for modelling buildings focussed upon the accuracy of varying models as opposed to the applicability of CFD to buildings and with increasing computing power, different building geometries and applications could be investigated.

The modelling of atria in CFD is a field that has been increasingly researched in the since the 1990's. The reasons for the increased focus are that:

i) a well-designed atrium can save energy and meet more stringent environmental standards through the use of buoyancy driven natural ventilation [168, 169],

ii) atria are recognised as being aesthetically pleasing and provide a central social space within a building[149, 170] and

iii) atria allow deep daylight penetration into a large building, further increasing energy performance, aesthetics and morale of occupants[170, 171].

However, atria are seen to be a difficult problem within CFD due to the strong buoyancy forces involved in stack ventilation with a significant amount of work done in the area of varying degrees of complexity.

In 1994 Gan and Awbi [172] developed the CFD programme VORTEX which used the k-ε turbulence model and SIMPLE algorithm. This was then applied by Awbi [173] to a 3D atrium model in 1996 to verify that CFD can be used to model stack ventilation in atria. Although not specifically working on atria, Malcolm Cook's work in the 1990's revolved around the validation of techniques for the modelling of buoyancy driven flow within naturally ventilated buildings using 2D and 3D models in the CFD programme CFX [158, 174]. It was shown in this work and confirmed with personal communication [175] that pseudo time dependent features of CFD programmes, use of under-relaxation factors, the RNG k-ε produced reasonable results when compared to experimental work.

In 2003, Jiang and Chen concluded that the Large Eddy Simulation model is more accurate than the RANS models for modelling buoyancy within a space, but they were not working with an atrium, but with a simplified 2D space[176]. However, in 2009, Liu et al. validated the use of CFD against scale models of an atrium [168]. Within this work, the Center for Education in the Green Building , Taiwan, is modelled using both reduced scale air models and CFD. The RNG k-ε was shown to be the most suitable model to model the heated areas of the atrium. This research also showed the large impact of external air temperatures on the internal conditions.

In 2009, Cable et al. further confirmed that a number of different turbulence models lead to reasonable results matching full scale experimental results from an atrium at Concordia University in Montreal [66]. This was the first of many useful research articles presented on this atrium, with the others being carried out by Hussain and Oosthuizen [105, 169, 170, 177], and Rundle et al. [178] between 2011 and 2012. This work validated the use of CFD for capturing buoyancy driven stack ventilation and the associated temperature and velocity variations throughout the space [178]. It compared different turbulence models, concluding that although all of the two equation models were reasonably accurate compared to experimental results, the SST k-ω model was the most accurate [170]. It was also the first time CFD had been used within an atrium to evaluate thermal comfort conditions using the PMV and PPD metrics when modelling a steady state condition, demonstrating the effect of design criteria, such as the inclusion of a chimney, on thermal comfort conditions [105]. Importantly, in this research, it was acknowledged that the CFD simulations needed to be modelled as steady state due to resource constraints. The atrium that was modelled was three storeys high and very simple .

More recently, Ray et al. modelled a four storey atrium at MIT in the CFD programme Fluent, comparing three turbulence models (k-ε , RNG k-ε , and LES) against full scale experimental measurements. [179] Transient conditions were used to calculate an assumed steady state condition and found that all turbulence models performed reasonably against measured data. Kayne and

Agarwal also used Fluent to model mixed convection in an atrium, and compared the results against the Concordia atrium building [180], comparing k-ε realizable and SST k-ω models. It was found that the former was most suited to the task, although it was acknowledged that an element count just below one million was resource intensive and that the model would have benefitted from a higher mesh density.

Although there has been a significant amount of work done to validate the use of CFD in atria, all of which confirm the appropriate use with care, the only thermally applied aspect to the research that can be found by the author is a single study recognising variations in thermal comfort throughout the space. Considering that atria are well known to have a large variation in comfort conditions due to natural ventilation and thermal stratification, it is recognised to be an area that has not yet been explored fully.

5.2.2.1.1 ANSYS Fluent

There are three elements of modelling in CFD, common to all projects: the pre-processor, the solver, and the post processor. Ansys Workbench allows for all three of these elements to be combined into the same graphical user interface, which assists with workflow. For this project, ANSYS Workbench 14.5 has been used. DesignModeller and Meshing Editor were used to carry out the pre-processing tasks of geometry and mesh creation. The solver chosen was Fluent and post processing was carried out using a combination of Fluent's inbuilt abilities and CFD-Post.

As well as being usefully integrated in the Ansys Workbench environment, each software package is powerful in its own right and has been used extensively in research and industry. The solver was the only element that needed any thought, as CFX is also included within Workbench and has been used to model buildings in literature. CFX uses a finite element approach and Fluent uses a finite volume approach to solving the partial differential equations. A detailed comparison is not required as both are seen to be sufficiently accurate and are able to handle unstructured meshes well. Fluent was chosen due to available expertise within the University and prior experience. The Finite Volume Method will be discussed in more detail in later sections.

5.2.3 Governing Equations

Within a Newtonian, compressible fluid, the fundamental governing equations of fluid dynamics dictate that mass, momentum and energy are conserved. The governing equations are a number of partial differential equations that are complicated to solve. This thesis will not derive these governing equations as this can be found in one of many CFD reference books (e.g. [181, 182]) but it is important to understand how the governing equations are used within the finite volume method to solve fluid flow. The following sections give a brief overview of the utilisation of each governing equation.

5.2.3.1 Continuity:

$$\frac{\delta\rho}{\delta t} + \nabla\left(\rho\vec{V}\right) = S_M = 0 \qquad (5\text{-}9)$$

Where ρ is the density, $\vec{V}$ is the vector velocity field ($\vec{V} = u\vec{\imath} + v\vec{\jmath} + w\vec{k}$) and S_M is a momentum source term, which is equal to 0 in this case as there are no user defined functions or mass added from the dispersed second phase.

5.2.3.2 Momentum

The three momentum governing equations were originally defined in terms of viscous stresses equations correspond to the Cartesian axes.

$$\rho\frac{Du}{Dt} = -\frac{\delta p}{\delta x} + \frac{\delta\tau_{xx}}{\delta x} + \frac{\delta\tau_{yx}}{\delta y} + \frac{\delta\tau_{zx}}{\delta z} + S_{M_x} \qquad (5\text{-}10)$$

$$\rho\frac{Dv}{Dt} = -\frac{\delta p}{\delta x} + \frac{\delta\tau_{xy}}{\delta x} + \frac{\delta\tau_{yy}}{\delta y} + \frac{\delta\tau_{zy}}{\delta z} + S_{M_y} \qquad (5\text{-}11)$$

$$\rho\frac{Dw}{Dt} = -\frac{\delta p}{\delta x} + \frac{\delta\tau_{xz}}{\delta x} + \frac{\delta\tau_{yz}}{\delta y} + \frac{\delta\tau_{zz}}{\delta z} + S_{M_z} \qquad (5\text{-}12)$$

In this research, the only sources will be gravity in the z coordinate. These scalar equations are the Navier-Stokes equations in non-conservation form, meaning that the finite control volume is moving with the fluid. However, as the control volume elements are fixed in the mesh and do not move within the fluid in fluent, the conservation form is needed. This is achieved by writing the left sides in terms of the local derivative and reducing to the form that Fluent uses within its calculations:

$$\frac{\delta(\rho u)}{\delta t} + \nabla\left(\rho u\vec{V}\right) = -\frac{\delta p}{\delta x} + \frac{\delta\tau_{xx}}{\delta x} + \frac{\delta\tau_{yx}}{\delta y} + \frac{\delta\tau_{zx}}{\delta z} \qquad (5\text{-}13)$$

$$\frac{\delta(\rho v)}{\delta t} + \nabla\left(\rho v\vec{V}\right) = -\frac{\delta p}{\delta x} + \frac{\delta\tau_{xy}}{\delta x} + \frac{\delta\tau_{yy}}{\delta y} + \frac{\delta\tau_{zy}}{\delta z} \qquad (5\text{-}14)$$

$$\frac{\delta(\rho w)}{\delta t} + \nabla\left(\rho w\vec{V}\right) = -\frac{\delta p}{\delta x} + \frac{\delta\tau_{xz}}{\delta x} + \frac{\delta\tau_{yz}}{\delta y} + \frac{\delta\tau_{zz}}{\delta z} + \rho g_z \qquad (5\text{-}15)$$

Within the Navier-Stokes equations there are unknown viscous stress components, and the most useful forms of these equations require a suitable model for representing these. Within Newtonian fluids, viscous stress is proportional to local strain rate. In fluent, this relationship is represented through:

$$\bar{\bar{\tau}} = 2\mu\left(\nabla\vec{\mathrm{V}}\right) - \frac{2}{3}\nabla\vec{\mathrm{V}}l \qquad (5\text{-}16)$$

Where μ is the molecular viscosity and l is the unit tensor. The second term on the right is the effect of volume dilation, relating stresses to volumetric deformation.

5.2.3.3 Energy

The energy equation needs to be solved when heat is being transferred and in high speed flows. Ansys Fluent solves the energy equation in the following form:

$$\frac{\delta}{\delta t}(\rho E) + \nabla\left(\overrightarrow{V}(\rho E + p)\right) = \nabla\left(k_{eff}\nabla\mathrm{T} - \textstyle\sum_j h_j\vec{J_j} + \left(\bar{\bar{\tau}}_{eff}\vec{\mathrm{V}}\right)\right) + S_h \qquad (5\text{-}17)$$

The second term on the right hand side represents species diffusion, and in this case only a single species is used, meaning that this term can be discounted for the current problem. The third term represents viscous dissipation which is usually neglected in macro-scale geometries as it has little impact upon results. Furthermore, S_h represents source terms such as heat given off through chemical reactions or volumetric heat sources, which are not present in this case. Therefore, the equation reduces to:

$$\frac{\delta}{\delta t}(\rho E) + \nabla\left(\overrightarrow{V(}\rho E + p)\right) = \nabla\left(k_{eff}\nabla \mathrm{T}\right) \qquad (\text{ 5-18 })$$

Where k_{eff} is the effective conductivity, which is the sum of the thermal conductivity and the turbulent thermal conductivity. The remaining term on the right hand side of the equation represent energy transfer due to conduction. The specific energy e (kj/kg)is represented by:

$$e = h - \frac{p}{\rho} + \frac{\vec{V}^2}{2} \qquad (\text{ 5-19 })$$

Where h is the sensible enthalpy.

The total energy E (kJ) is therefore:

$$E = m\left(h - \frac{p}{\rho} + \frac{\vec{V}^2}{2}\right) \qquad (\text{ 5-20 })$$

Within these governing equations there are seven unknowns; four thermodynamic variables (pressure, internal energy, temperature, density) and three viscous stress components. By assuming that the fluid is in thermodynamic equilibrium, the two equations of state (5-18 and 5-19) can then be used to create the final two equations needed to close the set of equations and enable each variable to be calculated.

$$p = p(R, T) \text{ (5-21)}$$

$$i = i(\rho, T) \text{ (5-22)}$$

5.2.4 Turbulence Models

Air flow within buildings is turbulent and therefore when modelling a building in CFD, an understanding of the turbulence models used is important. The governing equations presented in sections 5.2.3.1 to 5.2.3.3 represent exact laminar flow. The final state of turbulence is random and chaotic and could only be modelled using the exact governing equations if the mesh size and time step were small enough, which is far from being practical. Therefore, turbulence models are required within CFD packages. Fluent offers a number of different packages, none of which have been developed specifically for flow within buildings, but many are applicable.

As described previously, the majority of research involving CFD modelling of atria has demonstrated the applicability of different turbulence models; the results largely suggesting that all two equation turbulence models are relatively well performing when modelling atria air flows. Consistently, the Ralizable $k\!-\!\varepsilon$ and RNG $k\!-\!\varepsilon$ out-perform the standard $k\!-\!\varepsilon$ model. Some research into the SST k-ω has shown that this model could offer slightly more accurate results. In this section, these different models are summarised.

All four of the models above belong to the family of two-equation models which solve two separate transport equations to obtain turbulent kinetic energy and its turbulent dissipation rate (for the Standard, RNG and Realizable $k\!-\!\varepsilon$ models) or the specific dissipation rate (for the SST k-ω model).

The standard $k\!-\!\varepsilon$ model was developed by Launder and Spalding [183] in 1974 as an advancement from the Spalart-Allmaras model, which solved a single transport equation for turbulent viscosity. The advantage of the standard $k\!-\!\varepsilon$ model is that the length scale can be accounted for, enabling transitions from wall bounded to free shear flow to be modelled. The RNG $k\!-\!\varepsilon$ model was devised by Yakhot and Orszag [184] in 1986 and represents the effects of smaller eddies in terms of larger turbulence scales through a statistical technique called Renormalization Group Theory (RNG). This adaptation improves accuracy for swirling flows and rapidly strained flows [167].

The Realizable $k\text{–}\varepsilon$ model, developed by Shih et al. in 1994 [166], as with many developments of turbulence models, looks to improve the transport equation for ε, which is commonly seen to be a limitation of the standard $k\text{–}\varepsilon$ model [181]. It derives the dissipation rate from an exact and dynamic equation for the transport of the mean-square vorticity function. This model is widely seen to be superior for a number of cases, including boundary layers under strong adverse pressure gradients. The full calculation methods utilised by Fluent in implementing the Realizable $k\text{–}\varepsilon$ model can be found in [167].

5.2.5 Discretization

In order to solve the governing equations, CFD employs discretisation techniques. Discretisation methods come in three forms, finite difference (FDM), finite element (FEM) and finite volume (FVM) methods. FDM is used by IES-VE Apache Sim to solve heat transfer, but the majority of CFD packages use FVM.

The finite volume method requires three main steps:

I. Grid generation: where the domain is divided into discrete control volumes, each containing a nodal point at its centre. Structured quadrilateral based grids offer the most efficient use of space and therefore resources, but unstructured tetrahedral meshes are often required in large, complex geometries and have recently become much more stable.

II. Discretisation: The governing equations are integrated over the control volume to create discretised equations for each variable at each nodal point.

III. Solution of equations: for a discretised 3D volume involving convection and diffusion, Fluent uses the following linearised form to find a solution for a property ϕ at a node P:

$$a_P\phi_P = \sum_{nb} a_{nb}\phi_{nb} + b \quad (5\text{-}23)$$

Which describes the sum of the products of the neighbouring cells (nb) linearised coefficients (a_{nb}) and values of property ϕ_{nb}. b is a source term which is particularly important when the face of a control volume is (for example) a heated wall, whereby the wall is defined as the flux.

The non-linearised discretised equation for property ϕ takes the form below:

$$\frac{\delta\rho\phi}{\delta t}V + \sum_f^{N_{faces}} \rho_f \vec{\mathrm{V}}_f\, \phi_f \vec{A}_f = \sum_f^{N_{faces}} \Gamma_\phi\, \nabla_{\phi_f} \vec{A}_f + S_\phi V \qquad (5\text{-}24)$$

Which describes the sum over all (N_{faces}) faces (f) of each of the control volume. $\rho_f\vec{\mathrm{V}}_f\vec{A}_f$ signifies the mass flux through the face, Γ_ϕ is the diffusion coefficient for property ϕ, ∇_{ϕ_f} is the gradient of the property at each face and V is the volume. S_ϕ is the source term.

Although Fluent stores each property at a nodal point, it is clear from Equation 5-18 that the face values are required in problems involving convection. There are a number of techniques available within fluent to calculated these values, the most common of which are first and second order upwind schemes. Upwinding means that flow direction is known and values for ϕ_f are found using upstream centre node values.

In first order upwind modelling schemes, the face value of a property is assumed to be equal to that of the node of an upwind cell. This assumption can be valid for flows where the flow is parallel to the control volume, such as laminar flow, and is often a good method to provide initial calculations with high convergence rates [185]. However, within more complex flows, for example using unstructured tetrahedron meshes with turbulent flows, the second order upwind scheme generally provides more accurate results. In this scheme, cell face property values are calculated through Taylor series expansion of cell centred solution about the cell centroid. The allows for the gradient of property ϕ and the distance from the upstream cell centroid to be accounted for in the calculation of ϕ_f.

Within a pressure-based solver the spatial discretisation of the momentum equation to find the pressure located at the central nodal point also requires the pressure at the wall of the cell to be known. Therefore an interpolation method is needed, the most suitable of which is the Pressure Staggering Option (PRESTO!) Scheme for its effectiveness at modelling high-Rayleigh-number natural convection [185]. PRESTO! Uses the discrete continuity balance for a staggered control volume about the face to compute the face pressure [167].

5.2.6 Near Wall Treatment

When modelling in CFD, the modelling of the near-wall region requires special care and attention if the results are likely to be highly dependent upon its effect. In underfloor heated, buoyancy driven flow, the modelling of the region near the heated wall is important to ensure heat is transferred correctly.

When turbulent air flows across a wall, a boundary layer is formed consisting of three layers:

I. The laminar sublayer, where the wall shear stress is assumed to be caused by viscous forces alone.
II. The log-law region, where the fluid velocity can be described as a logarithmic function of the distance from the wall
III. The outer layer, where the boundary layer merges into free flow.

The first two layers can be represented by Figure 5-1.

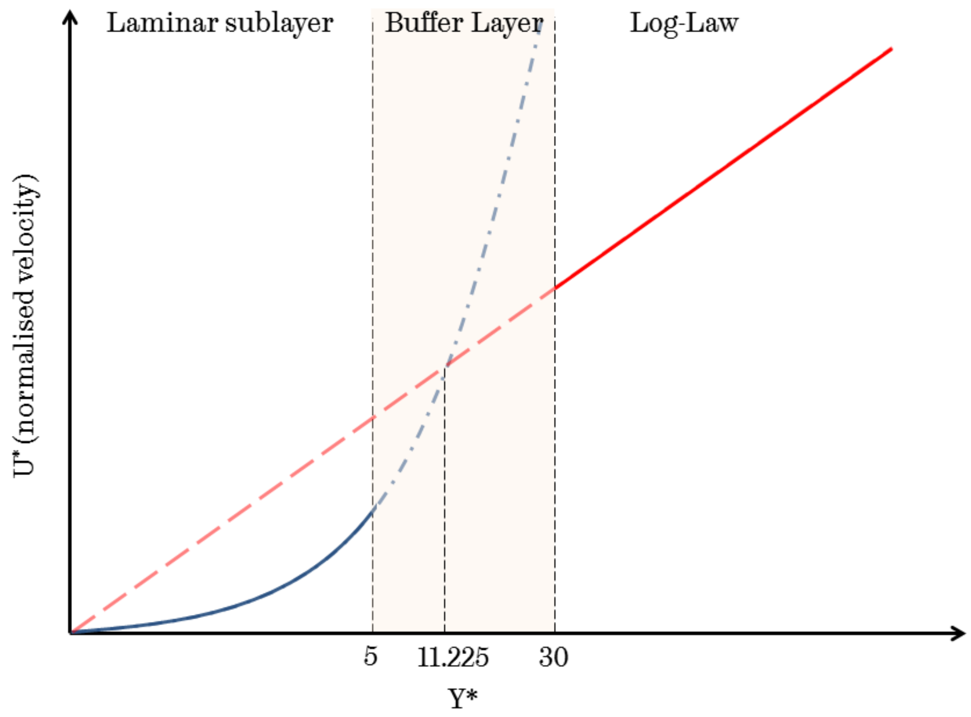


FIGURE 5-1 - THE NEAR WALL VELOCITY PROFILE

There are two main types of wall treatment commonly used within Fluent: low-Re models and high-Re wall functions. If it is important within the model to have a precise profile of the velocity of thermal profile of the boundary layer, then the first nodal point needs to be below a y^* value of 5 (ideally ≈ 1) and therefore a low-Re wall modelling technique needs to be used. However, if detailed wall-bounded effects are not a necessary then high-Re wall functions can be used.

It must be noted that conventionally in literature, the normalised distance from the wall is known as the y^+ value:

$$y^+ = \frac{\Delta y_P}{v}\sqrt{\frac{\tau_w}{\rho}} \qquad (5\text{-}25)$$

Where y_P is the distance of the first node from the wall and v is the velocity parallel to the wall. However, with the laws-of-the-wall calculations for velocity and temperature ANSYS Fluent uses a slightly different value, y^*:

$$y^* = \frac{\rho C_\mu^{\frac{1}{4}} k_P^{\frac{1}{2}} y_P}{\mu} \qquad (5\text{-}26)$$

Where k_P is the turbulent kinetic energy at nodal point P and C_μ is a constant. Largely, these two variables give very similar values and are widely interchanged in literature. However, it is important to recognise that the value at which each defines the intersection of the linear (laminar) normalised velocity variation and the log-law layers vary slightly. This occurs at a value of $y^+ = 11.63$ and $y^* = 11.225$. When $y^* > 11.225$ the flow is turbulent and a wall function should be used[181].

The standard wall functions described above for ε-based models are only suitable when the mesh is entirely in the log-law region of the boundary layer. However, this can sometimes be hard to achieve. For example, flow across a large building floor often has varying y^* values. With a constant value of y_P, a point at which there is little circulation due to proximity to an obstacle, will have a much higher y^* value than at an area with close proximity to an inlet or recirculating flow. Fluent provides different methods to approach this situation.

I. The scalable wall function overcomes problems in the inconsistencies in finely meshed grids by forcing the use of the log-law in combination with standard wall functions. This is achieved by imposing a y^* value of 11.225 when the actual y^* value is less than this value. This method reduces mesh dependency of the formulation significantly, which in complex demonstrative models is useful.

II. Enhanced wall treatment blends separate models in the two-layer approach by use of a damping function suggested by Kader [186]. It is applicable to k-ε models and models both laminar near wall flows and, through the use of a blending function, transforms into the log law as y^* values become higher. This treatment is most suitable when $y^* < 5$ and will be identical to the standard wall function when $y^* > 30$, but shouldn't be used if $5 < y^* < 30$.

III. Enhanced wall functions are used for the k-ω turbulence models as they are already low-Re models. Therefore, the enhanced wall function is used to blend the existing near wall ability into the log-law for higher y^* values.

5.3 *Concluding remarks*

There are numerous software packages available to model buildings. However, it is important to understand both the methodologies and limitations of the software being chosen, in order to recognise what is being shown by the results. This chapter has shown the challenges associated with modelling atria and has shown the relevant numerical simulation methods used by the two selected software packages and the complimentary features of each.

6 Development of Case Study 2: The Diamond

The Diamond is introduced before the research method used is presented. IES-VE Pro is used to develop input boundary conditions for the computational fluid dynamics (CFD) model. The development of the CFD model is then presented.

6.1 *Introduction*

The hypothesis for this research is that within a single naturally ventilated (with no personal window control), underfloor heated atrium there will be a range of comfort conditions, alongside a range of comfort preferences throughout the occupants that are using the space. Adhering to the adaptive comfort hypothesis, the author believes that occupants can achieve their own comfort by being informed about the warmer and cooler locations throughout the space, given the availability of relevant information. Although the formation of this information is out of the scope of this study, it is envisaged that it could be shown on dashboards, but is more likely to be personalised through mobile devices. The concept of individually based individual environments has been envisaged as the future of comfort provision by many researchers such as de Dear et al. and van Hoof [80, 187]. This work is attempting to demonstrate the realisation of this vision.

By allowing for occupant choices, it is hoped that both comfort levels and energy efficiency of buildings can be increased.

6.1.1 Energy use and comfort:

The energy use of the building being studied is via underfloor heating, supplied by a district heating system. This system would usually be used to ensure that conditions throughout the space are heated enough to make 80% of spaces thermally acceptable, and therefore in the absence of heat generating occupants, it is likely that the energy use of the underfloor heating would increase.

However, this research will investigate whether at low occupancies the building can be allowed to thermally drift, whilst maintaining an appropriate number of spaces that are thermally preferable or acceptable. If it is known where these spaces are, then it is hypothesised that occupants can use the comfortable spaces since they will know where they are located through the information given to them.

Thermal comfort is influenced by metabolic rate, clothing level and other personal factors. Rather than attempt to define all variables that result in a person's comfort in order to select building operation parameters, this research will assume that diversity exists; initially using existing ranges of preference values.

This research aims to find a typical range of conditions expected within an atrium building, which will allow the prediction of the maximum increase in comfort rate when occupants sit in places most comfortable to them when compared to a random arrangement of occupants. Although a circulation space, for students using the rooms in the building, the atrium also serves as a workplace with 385 workstations spread across four floors where typically low activity-level work will be carried out. When at low occupancies, it is expected that the majority of occupant *preferences* can be met, whilst when at full capacity it is believed that a larger number of preferences will be met whilst a higher level of overall acceptability will be achieved.

Figure 6-1 shows a demonstrative graphical representation of the hypothesis. For the purposes of this demonstration only it is assumed that there is a Gaussian distribution of both comfort and workstation conditions. In reality, the work station variation will depend upon each specific building. It can be seen that the thermally drifting workstation distribution, although shifting by 1 PMV to the colder side of neutral, still allows acceptable comfort conditions for all occupants when nearly half the workstations have conditions classed as unacceptable (those shown in the shaded area).

Furthermore, at high occupancy levels:

- If the distribution of workspace comfort conditions is known within the building;
- And the variation of acceptable ranges of comfort within the occupancy are known;
- It is possible that the comfort variation can be matched to the variation in conditions within the building, thus increasing rates of comfort

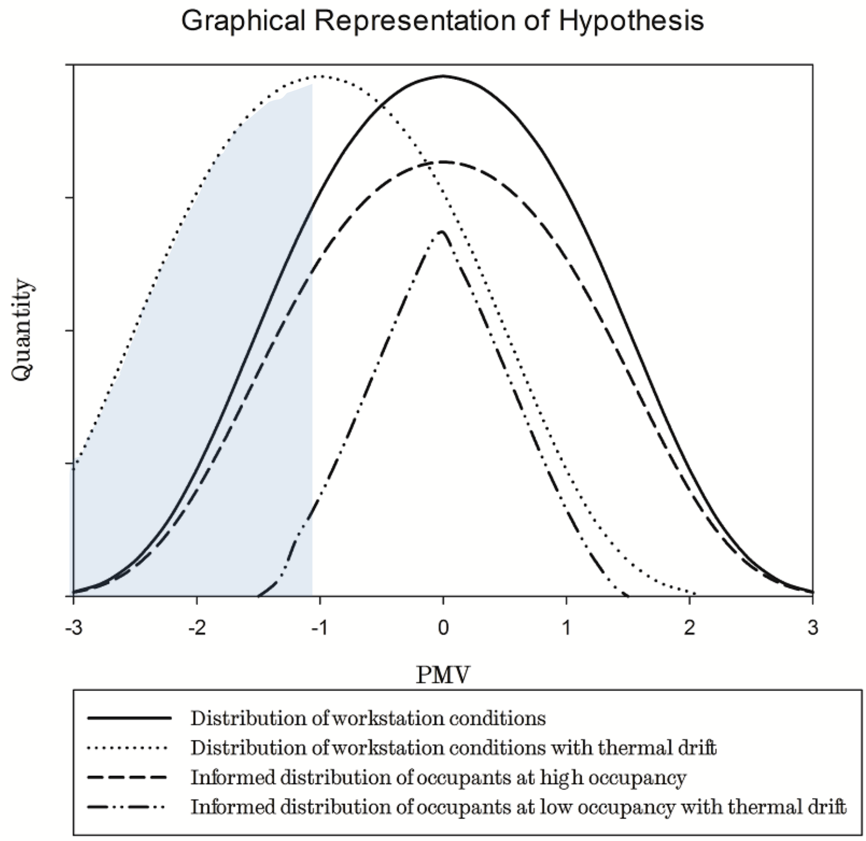


FIGURE 6-1 - GRAPHICAL REPRESENTATION OF THE HYPOTHESIS

6.2 *Method*

This research will look into initial tests of the hypothesis by use of a case study building; specifically the atrium of a building called 'The Diamond' in Sheffield. Since the building is under construction and therefore no real data can be pulled from it, two modelling techniques shall be used:

I. Building Simulation shall be used to model the building over a year using real weather files from Sheffield. The purpose of this model shall be to create a realistically running building which can output appropriate boundary conditions for a CFD model. It will also be used to validate the CFD model to some extent.

II. A CFD model will then be created to model the atrium in order to further understand the variation in conditions throughout the space and investigate the feasibility of this novel approach to demand side energy management.

The purpose of this modelling is *not* to gain specific understanding about how this building operates but to develop an understanding of the variation in comfort levels in a large building space. As the building is so complex and currently does not exist, specific validation using saltwater models or experimental techniques will not be carried out. However, it *is* important to have confidence that the model is representative of a functioning building and therefore the following features of the model will be investigated:

- Reasonable correspondence between both Building Simulation and CFD models
- The presence of heat transfer and buoyancy flow demonstrated in all CFD models.
- Air movement and heat transfer should be seen in all meshed zones.
- Unusual air movements in the CFD model should be explained through building physics, previous studies and theoretical work.
- Within both models, the resultant temperature ranges and the air velocity should be justifiable.

6.3 *Building Information*

The case study building shown in

Figure 6-2, named The Diamond, is a new University of Sheffield multi-use facility for the Faculty of Engineering. The Diamond, designed by the Twelve Architects practice, is a six storey building, with an atrium running 83.5m east to west on the top four floors, spanning between 12.4m and 23.1m in width. Three pods are suspended in the atrium, each of which is mechanically conditioned within, but there are unconditioned spaces on the top of the pod. There are balconies on the 2nd and 3rd floors of the atrium. The layouts are shown in Figure 6-3 to Figure 6-6.

FIGURE 6-2 - ARTISTS INTERPRETATION OF THE NEW ENGINEERING BUILDING

FIGURE 6-3 - 1ST FLOOR LAYOUT

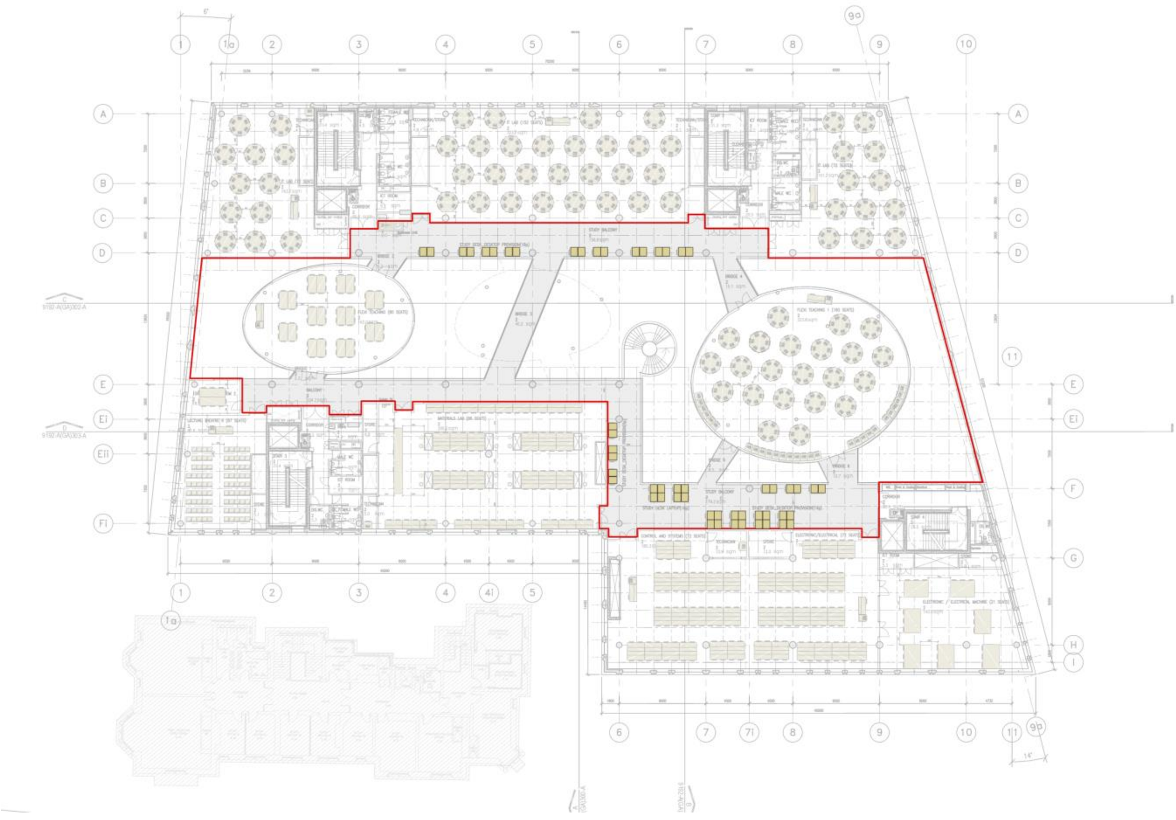


FIGURE 6-4 - 2ND FLOOR LAYOUT

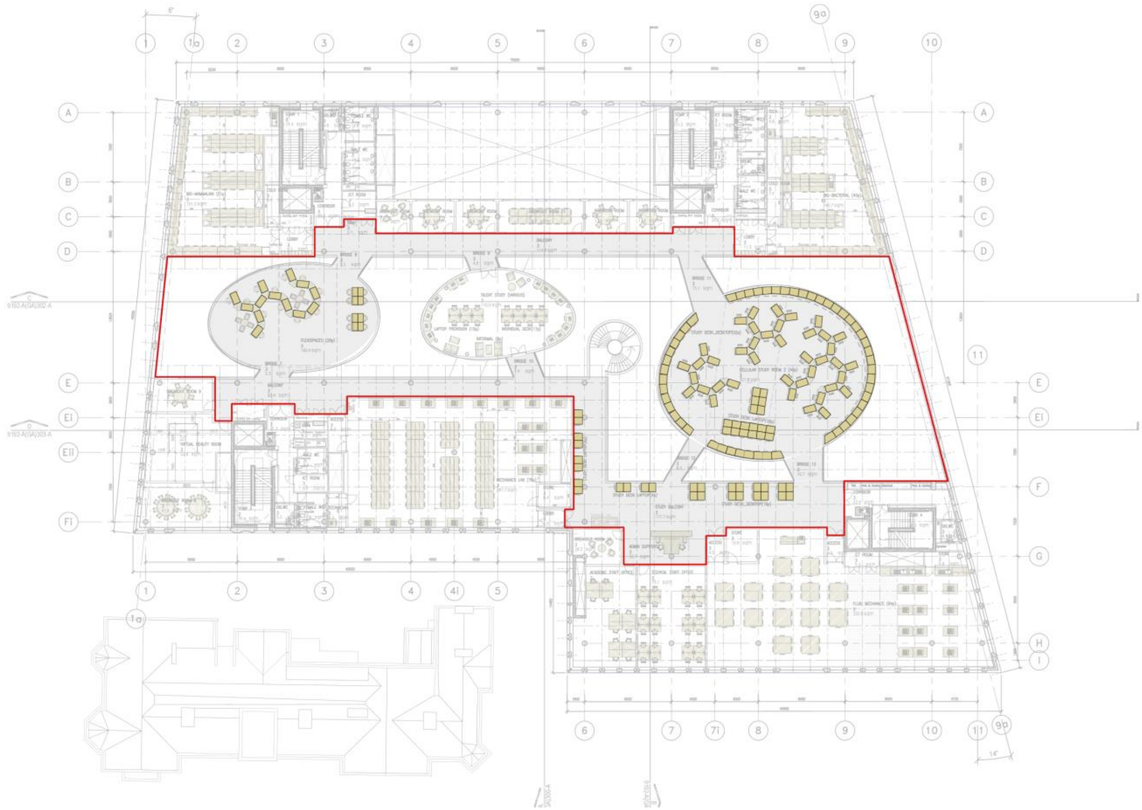


FIGURE 6-5 - 3RD FLOOR LAYOUT

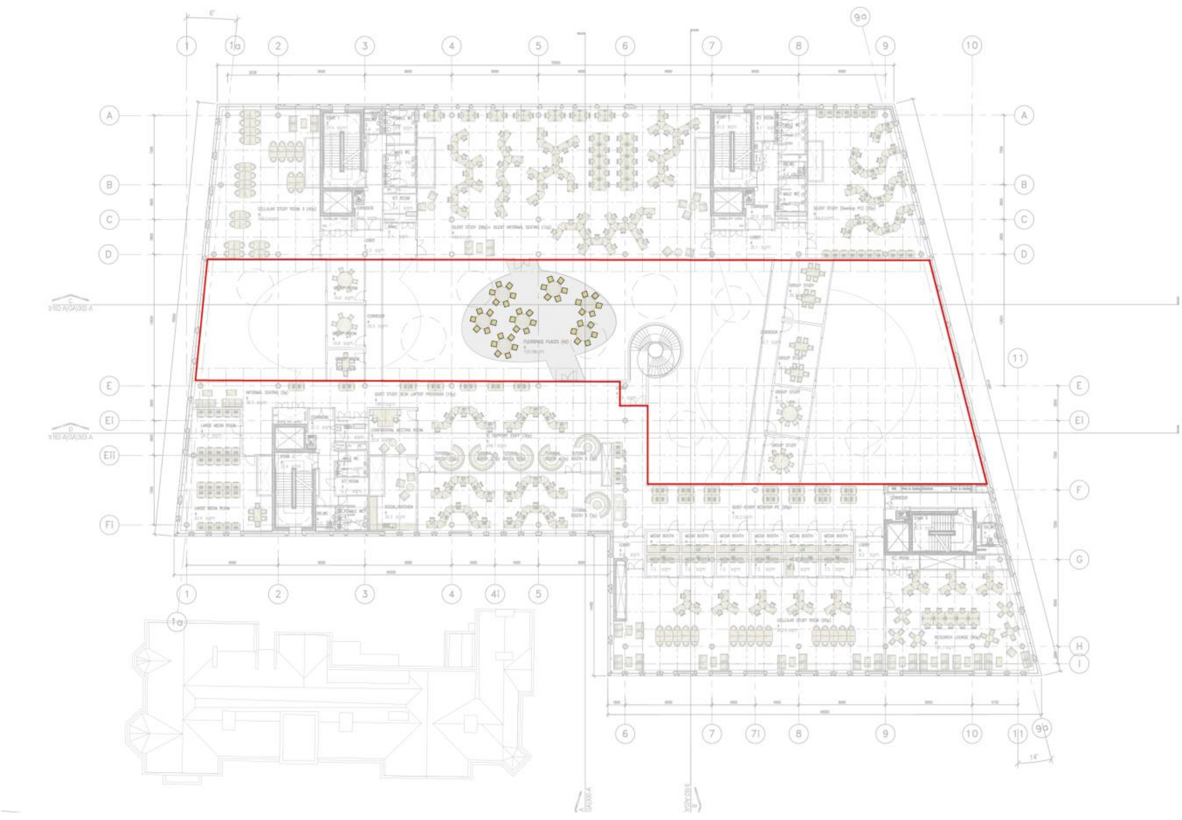


FIGURE 6-6 - 4TH FLOOR LAYOUT

Figure 6-3Figure 6-6 show that workstations and social spaces are spread throughout the balconies (82 seats), pod tops (180 seats) and atrium floor space (123 seats). Some of these workstations have computers and some are desks only. The students use these areas for general study and therefore there are no specific classifications assigned to any of the workstations.

The atrium has underfloor heating, supplied by a district heating system, and is naturally ventilated. Air passes through each of the end facades, which are formed of a lattice of louvres, opaque and glazed panels. Air outlets are in the roof space of each façade, as well as on the sides of the roof up stand. The ventilation rate is controlled automatically using the difference in temperature between external and internal conditions. The extents of openings are defined by the building engineers, shown in Table 6.1.

TABLE 6.1 - OPENING SIZINGS

Temperature Difference T_{in}-T_{out} (^oC)	Required Low Level Openings (m^2)	Required High Level Openings
$\Delta T \geq 9$	1.41	1.9
$9 > \Delta T \geq 6$	4.7	6.3
$6 > \Delta T$	11.8	15.9
$When\ T_{in} > 23$	24 East/ 47 West	96

The lower level openings are those located on floors 1-4, and the high level openings are those located around the roof upstand, and on the roof level on the east and west façades. These openings are louvres, placed in a lattice formation, spread across all floors, as shown by Figure 6-7 below, displaying the east façade of the atrium.

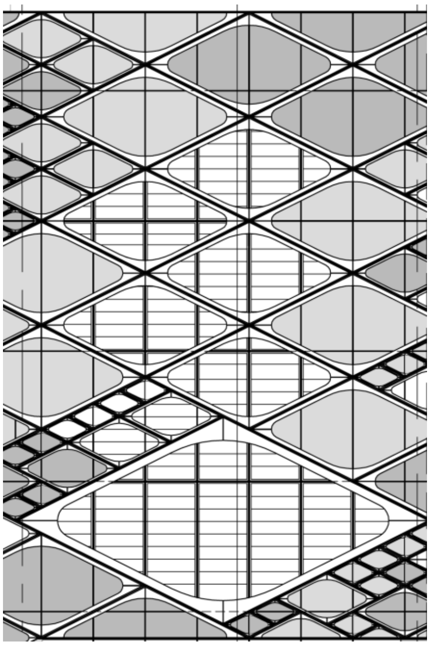


FIGURE 6-7 - FACADE LATTICE

6.4 *IES-VE Model creation*

As The Diamond is still in construction, a building simulation model has been created using IES-VE Pro. The model was created to adhere to the initial specifications set by the building engineers. The openings modelled in IES were defined with comparable areas to those designed by the architects and distributed throughout the two end façades, as shown in Figure 6-8.

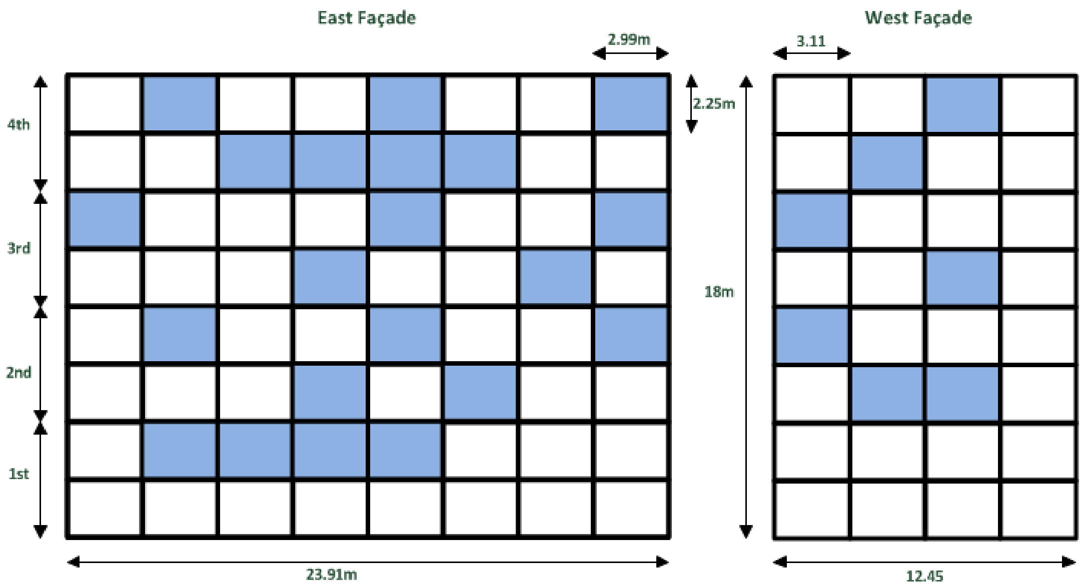


FIGURE 6-8 - IES VE-PRO OPENING LAYOUT

The opening profile relationship described in Table 1 was used through the following function:

$$IF(ta > 23,1, IF(ta - to > 9, x_1, IF(ta - to > 6, x_2, x_3)$$

Where x_i represents each state of opening required satisfying Table 6.1 consisting of defined fractions of opening for each group of openings. A realistic occupancy profile was applied to the atrium, given its 24 hour opening times and strong relationship between occupancy and university lecture time tables.

As described in §5.1.2 IES VE-Pro is unable to produce a variation in temperature within a single element of the model. However, stack ventilation is fundamental to the operation of the atrium, and therefore each floor was divided into two layers, and these layers were then subdivided along the length of the atria to account for the pods placed within the space. Lastly, the balconies were designed as separate, two layered, elements so that the comfort measurements would be more realistic, taking into account air flow patterns between the main space and the corridors.

In order to simulate the stack effect in IES VE-Pro, each of the floors and ceilings of the elements (except for the respective ground floor and roof elements) are classified as a 'hole' which allows air to be exchanged through it freely. MacroFlo also enables the cross ventilation of the building due to the splitting of elements along the length of the atrium.

6.4.1.1 Selection of model features

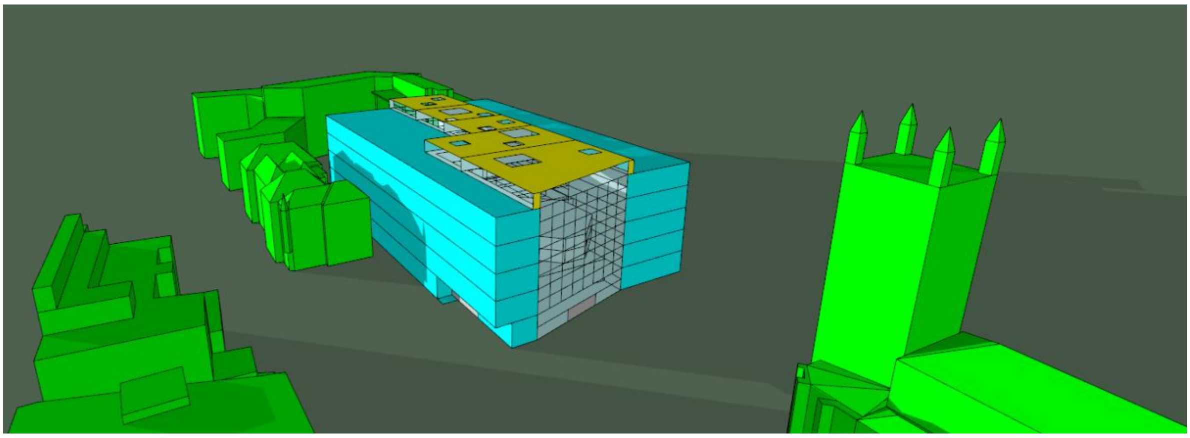


FIGURE 6-9 - IES-VE PRO MODEL WITH SURROUNDING BUILDINGS

As shown in Figure 6-9, surrounding buildings were also included in the building simulation model. It can be seen that the single atrium has been split into a number of layered zones, each of which is half a floor in height. This allows for stratification of conditions to be taken into account and a well performing building to be confirmed through the use of the PPD metric, where ASHRAE 55 [77] defined limits for discomfort were met in occupied zones.

The mechanically ventilated areas of the building, adjacent to the atrium, were also modelled, but were deactivated to create an adiabatic assumption on the atrium internal walls.

6.4.1.2 Case date selection

Direct solar radiation impacts upon thermal comfort. In the initial CFD model, the radiation models shall not be used. Therefore, the cases to be used will be cloudy days with no direct solar radiation. Furthermore, no direct solar radiation allows for predictable and evenly distributed mean radiant temperatures. This can be indicated within the IES model by comparing the difference between internal air temperature and average mean radiant temperature (MRT) ($\boldsymbol{\alpha = MRT - Air\ Temperature}$6-1) for the hours before and after the given case condition, as shown in Table 6.2.

$$\alpha = MRT - Air\,Temperature \quad \textbf{6-1}$$

$$\Delta\alpha = (\max\alpha - min\alpha)_{n-1}^{n+1} \quad \textbf{6-2}$$

Where n represents the hour used as a case study condition. This is calculated using the set point conditions discussed in the next section.

A variety of conditions will be used in order to model different seasonal conditions. Naturally, the highest potential for energy reduction will be during cold seasons with the higher energy input from the heating system. The variety of conditions will establish the extent of this.

For each case to be chosen, days with a smooth and low variation in ambient internal temperature will be chosen to allow for a steady state assumption to be made in the CFD model. Although this is not fully representative of the dynamic nature of a building, the running mean conditions during a thermally stable day are suitable for an investigation into the variation of conditions throughout a space.

Table 6.2 shows the three cases selected and the variables representative of the required conditions introduced previously.

TABLE 6.2 - CASE DATE VARIABLE OUTPUTS FROM IES

Case	1	2	3
Date	18th November 2011	18th February 2011	4th August 2011
Time	15:00	15:00	15:00
External dry-bulb temperature	12.6	5.4	16.3
Direct solar radiation	0	0	0
Diffuse solar radiation	32.49	50.22	108.68
α	1.02	3.29	0.54
$\Delta\alpha$	0.17	0.07	0.04

6.4.1.3 Model evaluation or testing

One required output of the IES model is the energy input associated with a well performing model. This energy input is comprised of the underfloor heating requirement, the solar gain and the internal gain provided by the occupants themselves.

There is no specific way to model underfloor heating in an atrium within IES. Therefore the method used here has been advised through personal contact with an industrial expert [188]. A set point temperature is assigned to the lowest level of the atrium, with all other levels having no space heating associated with them. The energy used to maintain this lower floor condition is therefore the equivalent energy needed to be transferred into the atrium by the underfloor heating.

In order to assess an appropriate set point temperature to use in the atrium, two metric were taken into account. Since the building will be open twenty four hours a day, the yearly mean PPD would be compared. Furthermore, it is expected that occupancy profiles will be similar to that of the IC and therefore, the percentage of hours exceeding 10% people dissatisfied between 08:00 and 22:00 was compared. The summaries are shown in Table 6.3.

TABLE 6.3 - COMPARISON OF PERFORMANCE OF DIFFERENT SETPOINTS WITHIN IES

Setpoint - ^oC	Percentage PPD >10% during most occupied hours	Mean PPD over one year
20	9.07	25.92
21	7.91	16.06
22	7.86	16.2

It can be seen that 21^{o}C and 22 ^{o}C produce similar results. Therefore, for the first case condition on November 18th 2011, these two variables were applied over a single day. Table 6.4 shows that a setpoint of 21^{o}C performs better and therefore this setpoint was chosen for the model.

TABLE 6.4 - COMPARISON OF BEST PERFORMAING SET POINTS OVER A SINGLE CASE DAY

Setpoint - ^{o}C	Percentage PPD >10% during most occupied hours on 18th November 2011	Mean PPD over 24 hours 18th November 2011
21	1.02	5.53
22	4.21	5.94

The internal gains provided by the occupants are set to be 50 Watts sensible heat gain per person. The density of occupation is 1 person per $5m^2$ and the occupancy profile for the atrium itself reflects a typical university schedule whereby there will be numerous people in the atrium between lectures, shown in Appendix 2.

The internal gains provided by lighting assumes dimmable fluorescent lighting with a maximum sensible heat gain of $8W/m^2$ as is the default setting within IES-VE Pro: this value is aligned with the CIBSE Guide A data which suggests a value between 8 and 12 W/m^2 for fluorescent lamps with high frequency ballasts [189]. The internal gain provided by equipment is defined to be $10Wm^{-2}$ and varies with occupancy profile, representing workstation computers and laptops. This value is also reasonable when compared with CIBSE Guide A.

6.4.1.4 IES Results

The building simulation model was used to define inputs for a CFD model. It is becoming more common to use both building simulation and CFD in the design of buildings, as CFD can provide higher granularity and more detailed variations in conditions and air flow.

The primary outputs from the IES model needed for initial modelling are the volume flow rates passing through the openings on the façades and the energy input into the building from space conditioning, solar gain and internal gain, consisting of people sensible gain, equipment gain and lighting sensible gain. This allows for the comparison of the CFD model to the IES model to ensure they correlate. The percentage space heating contributing to the total energy input in each case is needed to show the degree of control of energy consumption available to the building. Table 6.5 shows these outputs.

TABLE 6.5 - OUTPUTS FROM IES-VE PRO

Output	November 18th	February 18th	August 4th
Energy input (kW)	124.67	322.18	78.35
Heat flux (W/m^2)	93.00	240.35	48.45
Energy attributed to space heating (%)	57.11	81.64	0
Volume flow rate east façade (m^3s^{-1})	3.99	9.96	4.50
Volume flow rate west façade (m^3s^{-1})	0.81	3.21	4.74

Although it may seem counterintuitive that on a colder day, there is a higher volume flow rate into the building, this is due to varying wind conditions and a limited number of set opening sizes in the control algorithm for the louvres. The actual volume flow rates within these cases are relatively low with air change rates reaching up to 1.83 air changes per hour for the atrium, which are reasonable for maintaining air quality in a non-domestic building.

Figure 6-10 shows the source of energy input in each of the three cases chosen. It can be seen that whilst internal gain remains constant due to consistent occupancy and lighting levels, the solar and space conditioning levels vary with external conditions. As previously specified, all solar gain in these models is through diffuse radiation, suggesting complete cloud coverage during the day. Therefore, the increase in solar gain between cases can be explained by an increase in total extra-terrestrial radiation between the different seasonal conditions. The increase in space heating therefore is the primary method to counter a decreasing temperature of incoming air and has the most potential to reduce total energy consumption.

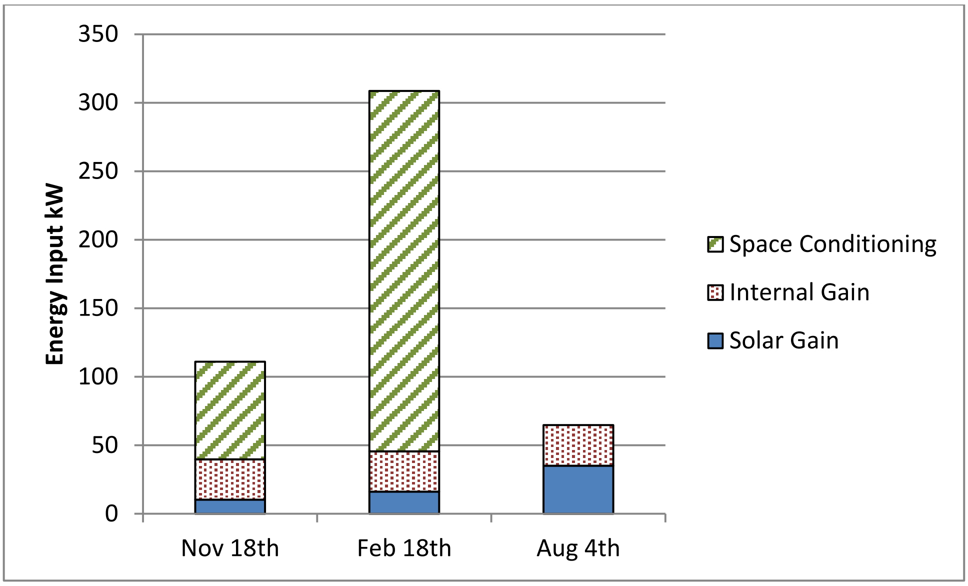


FIGURE 6-10 - CONTRIBUTION OF DIFFERENT SOURCES TO ENERGY INPUT FOR EACH CASE

The outputs shown above, alongside the external air temperature shown in Table 6.2 will be used to define the CFD model.

6.5 *CFD Model Creation*

6.5.1 Definition of purposes for modelling

The purpose of the CFD model in this research is to provide a reasonable representation of the variation of conditions within the atrium. In order to achieve the aims of the research, the accuracy of the model only needs to be high enough to provide a realistic variation in conditions and therefore some aspects of the model have been chosen for resource efficiency and simplicity and will be highlighted in the following sections.

6.5.2 Geometry and Mesh generation

The CFD model uses the dimensions from the architectural drawings. The inlets are represented as rectangular instead of diamond in shape for ease of meshing; however, the inlets have the same area as those specified in the architectural drawings with an equivalent distribution and therefore should not impact upon results. It is acknowledged that the actual opening sizes vary depending upon louvre angle, but in this model, the inlets are modelled as inlet velocity boundary conditions where the mass flow rate of air entering the space is specified. The outlets are modelled with the equivalent size required by the assumed control strategy in Table 6.1 and distributed evenly over the roof outlet area.

For the main body of the fluid, an unstructured mesh was used, with element size increasing with height to reduce the total number of elements needed, shown in Figure 6-11. Sweep meshing techniques were used on the balconies and structured surface meshes. In order to control near wall mesh metrics next to the heated floor, a wedge-based, 10 layer structured mesh was placed within 15cm of the heated floor, as shown in Figure 6-12.

For simplicity, the obstacles within the space, such as furniture, occupants, staircases and balcony railings have not been modelled. The inclusion of these obstacles would require a much higher number of elements in the mesh, requiring more resources than are available. This simplification of the model is significant since local comfort conditions are likely to vary with nearby obstacles. However, this research requires a representative variation of conditions throughout a space, which can be provided without their inclusion. This limitation is discussed further in Chapter 8.

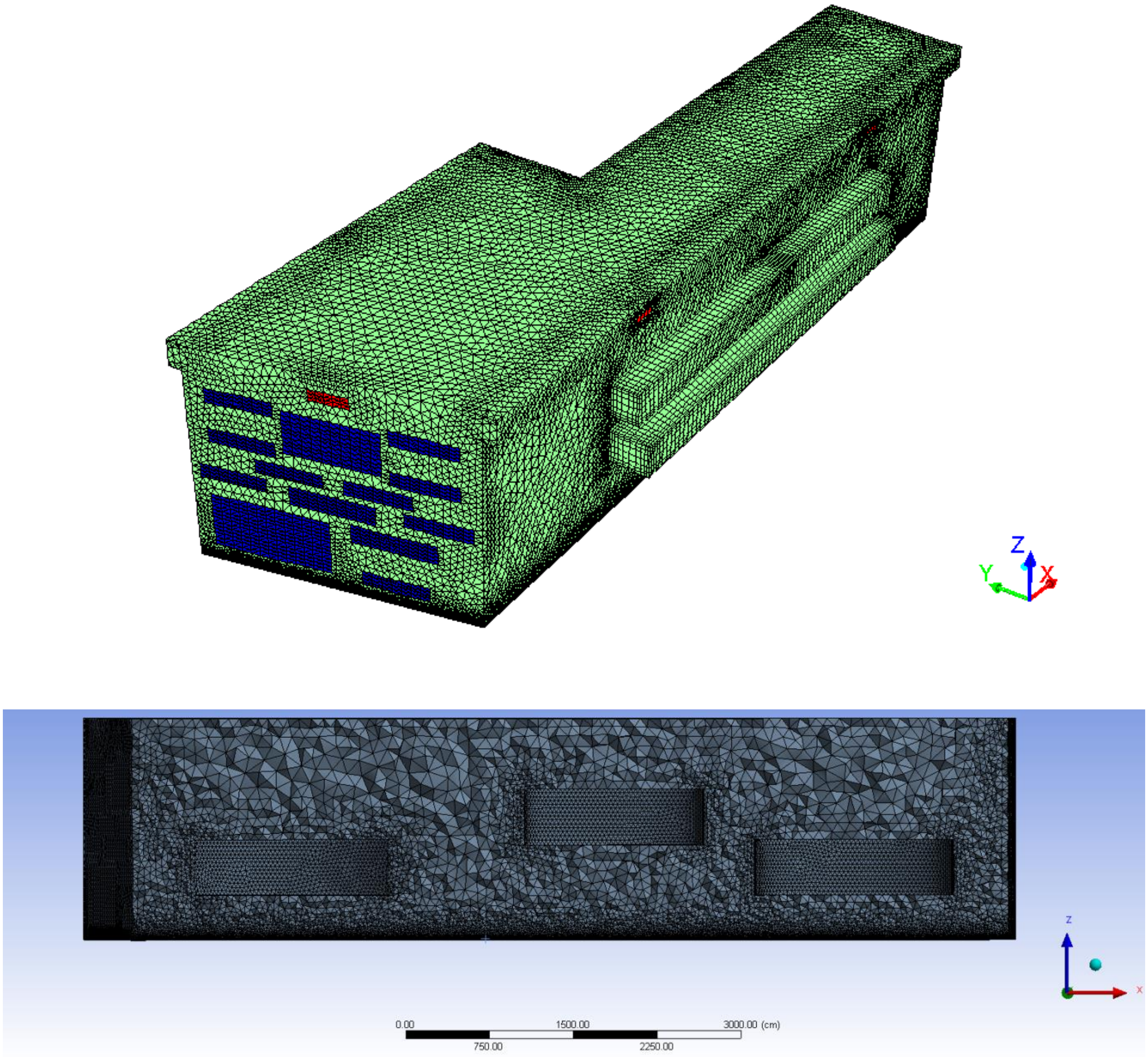


FIGURE 6-11 - MESH STRUCTURE OF THE CFD MODEL

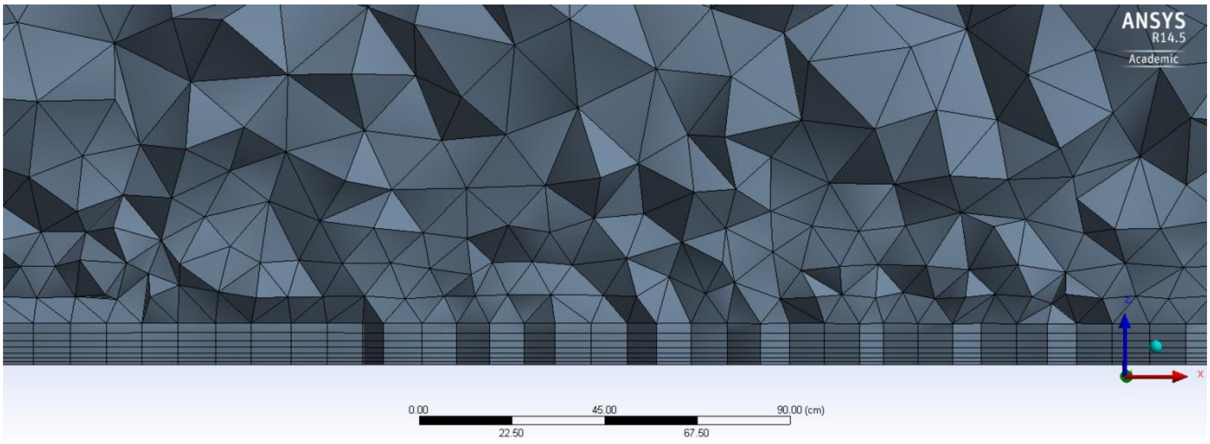


FIGURE 6-12 - NEAR FLOOR MESH STRUCTURE

6.5.3 Turbulence Model

The selection of the turbulence model and wall function was based upon the following criteria:

I. Previously researched accuracy of the model on buoyancy driven flow, preferably within large scale atria models.

II. The required near-wall mesh size of the turbulence model when combined with the required wall treatment against resources available.

III. The ability for the model to converge during modelling trials.

Although SST k-ω models are seen as an accurate method to model buoyancy driven flows within CFD, they require the mesh y^* values to be in the region of 1 [190]. The complexity and scale of the model results in a large variation in air flow velocities adjacent to the heated floor surface, resulting in a high variation of y^* values. Therefore, it is very resource intensive to create a model with a Y* values in the region of 1, which are required for the SST k-ω model, within the resources available.

Of the remaining turbulence models, the realizable k-ε has been shown to be the most accurate, as discussed in Section 5.2.4. The wall treatments available for k-ε models with varying y* values are the enhanced wall treatment and the scalable wall function. The former recommends that y* values should be less than 5. With a very refined mesh, the y* values ranged between 0.2 and 70, and the simulation was unable to converge, even when the relaxation factors were manipulated. Therefore, the scalable wall function was implemented, which resulted in the y* values varying in a similar manner to the example plot in Figure 6-13.

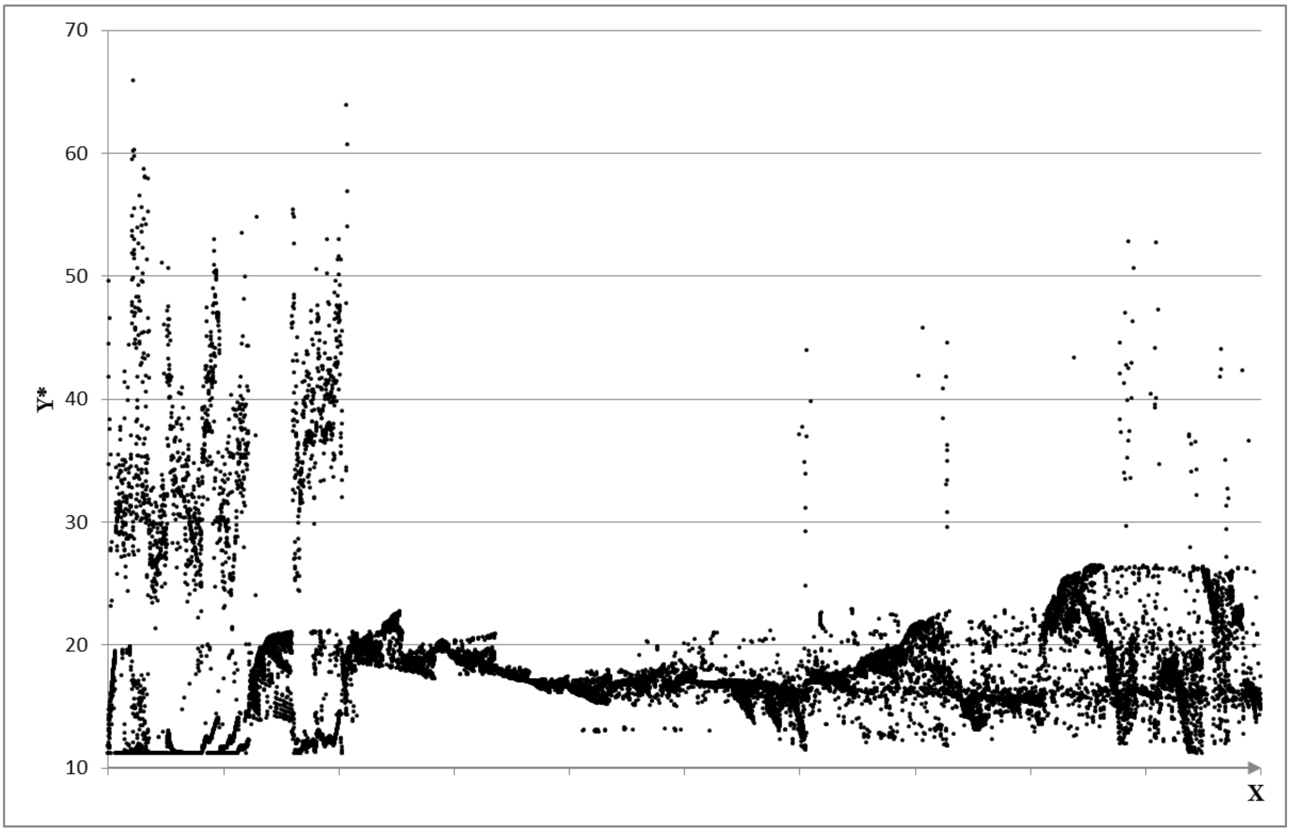


FIGURE 6-13 - AN EXAMPLE DISTRIBUTION OF Y* VALUES ALONG THE FLOOR OF THE BUILDING

It can be seen that any Y* values below 11.225 are treated as Y*=11.225 and will therefore be treated within the log-law of the standard wall function. This allows the simulation to converge and allows for the element number to be limited to approximately 26 million, which is solvable using a high performance computer cluster within five days. The exact plot will vary between specific cases due to changes in velocity, but the mesh is maintained throughout the different cases.

Following a similar approach to Shafqat and Oosthuizen [105], steady state conditions have been chosen since real building temperature changes occur over relatively long periods of time, and modelling time dependent conditions would be very resource intensive and beyond the scope of this research. The Pseudo Transient criterion is used to aid convergence.

Convergence was judged to have been achieved when point monitored flow variables varied by less than 1% over the last 100 iterations, the mass balance was within 0.002kgs^{-1} (total mass:

28873.55kg) and the energy residuals reached 0.1%. The point monitors used in each simulation were:

- Average y+ value over heated floor
- Average Nusselt number over heated floor
- Average static temperature at two points in the middle of the atrium space
- Average velocity through a 1m high surface at both east and west ends of the atrium, perpendicular and adjacent to the heated floor.

6.5.4 Boundary Conditions

Inlets are classified as velocity inlets used to create equivalent volume flow rates to the IES building simulation model. One may question the use of constant boundary conditions imposed directly onto the openings of the model, with air flow upstream of the building usually modelled. However, since the inlet conditions of the model can be estimated through building simulation, this method allows for generic modelling of the building conditions without using excessive resources; the early stage of the investigation into this technique does not require precise modelling. The method is similar to that used by Cook et al. [118] Outlets were modelled as pressure outlets. All walls apart from the floor were modelled as adiabatic as they are highly insulated from the mechanically ventilated rooms adjacent to the atrium space. The floor was modelled as a steady temperature; as this is the control condition for the underfloor heating system, with an initial value chosen to give a heat input similar to the Building Simulation model.

6.5.5 Inspection of Model

Although it has been previously acknowledged that the purpose of this model has not been to create an entirely accurate model, the airflow and heat transfer within the building should be realistic. Therefore, this section will investigate the model's performance.

Figure 6-14, Figure 6-15 and Figure 6-16 show a contour plot of temperature z (vertical) and x (longitudinal) velocities at a cross section of the atrium. The case being modelled here is Case 1 (12.6^{o}C external temperature, November 18th, 2012) with a 310K floor temperature. The scale has been trimmed slightly in the temperature plot as the very thin layer of air immediately adjacent to the floor is close to the floor temperature, which is unrealistic, considering the heat input accounts for all internal and solar gains to the space. Furthermore at the lower end of the scale, the cold air coming into the space quickly warms as it reaches occupied areas and so to demonstrate the special temperature variation more clearly, this has been clipped.

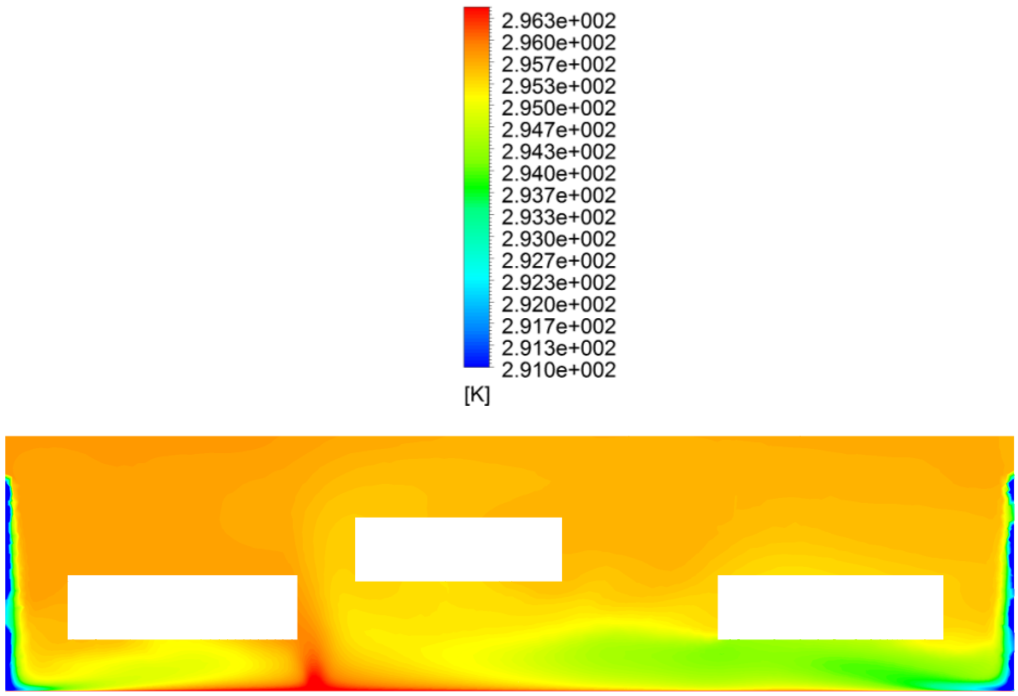
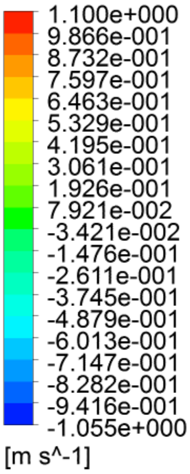


FIGURE 6-14 - TEMPERATURE CONTOURS X DIRECTION CASE 1 310K FLOOR TEMPERATURE



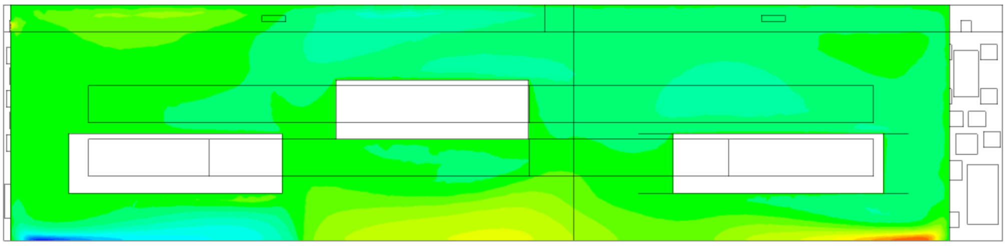


FIGURE 6-15 - X (LONGITUDINAL) VELOCITY CONTOUR PLOT AT CROSS SECTION

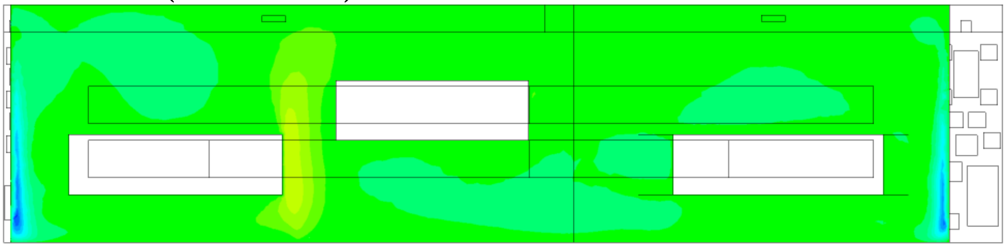


FIGURE 6-16 - Z (VERTICAL) VELOCITY CONTOUR PLOT AT CROSS SECTION

Cold air enters the building, it is comes into contact with the warm plume of air within the building, causing a downdraft to be created whereby the cold air travels adjacent to the glazing as it descends. Although not a good design characteristic, the downdraft is a common occurrence within large glazed buildings. In this case, the use of mid pane louvres will aid this movement by physically deflected the air down once it enters the building.

Upon reaching the floor of the atrium, the air moves along the heated floor, gaining heat until a stagnation point is reached, where opposing directions of flow meet each other. At this point, the wind driven forced horizontal convection supplements the buoyancy of the heated air, causing it to rise. The velocities or air involved in both longitudinal and vertical flow are predominantly in acceptable values between 0 and 0.4ms^{-2}. The only areas that pose a significant threat to thermal comfort conditions are those at the base of the cold downdraft. There are a number of seats located in this area.

The warm column of air is a characteristic of the atrium result in an interesting distribution of air where by it is not quite reflective of a point source of heating, but is much more concentrated than comparable studies with distributed heat sources. A point source of heating will tend to result in a clear plume of air being formed, as described by Linden [100]. In this case, a warm plume can be seen, with an approximate 2K difference in temperature, but the shape of the plume is distorted by the external force of the wind, and the pods.

Figure 6-17 shows the velocity and temperature distribution along the widthways cross section of the building at halfway along the length. The velocity of air flow in both horizontal and vertical directions is slow, but at a cross section 40m away from the external openings, this could be expected. The circulation patterns show two eddies forming with air rising near to the wall, not passing the obstructing pod and circulating back towards the floor. This is due to localised convective flow of the warmer plume of air above the pod. However, this results in an interesting flow distribution in the balcony spaces; only one balcony has significant air movement. Although not part of this work, such a condition should be investigated further when implementing ventilation strategies similar to this.

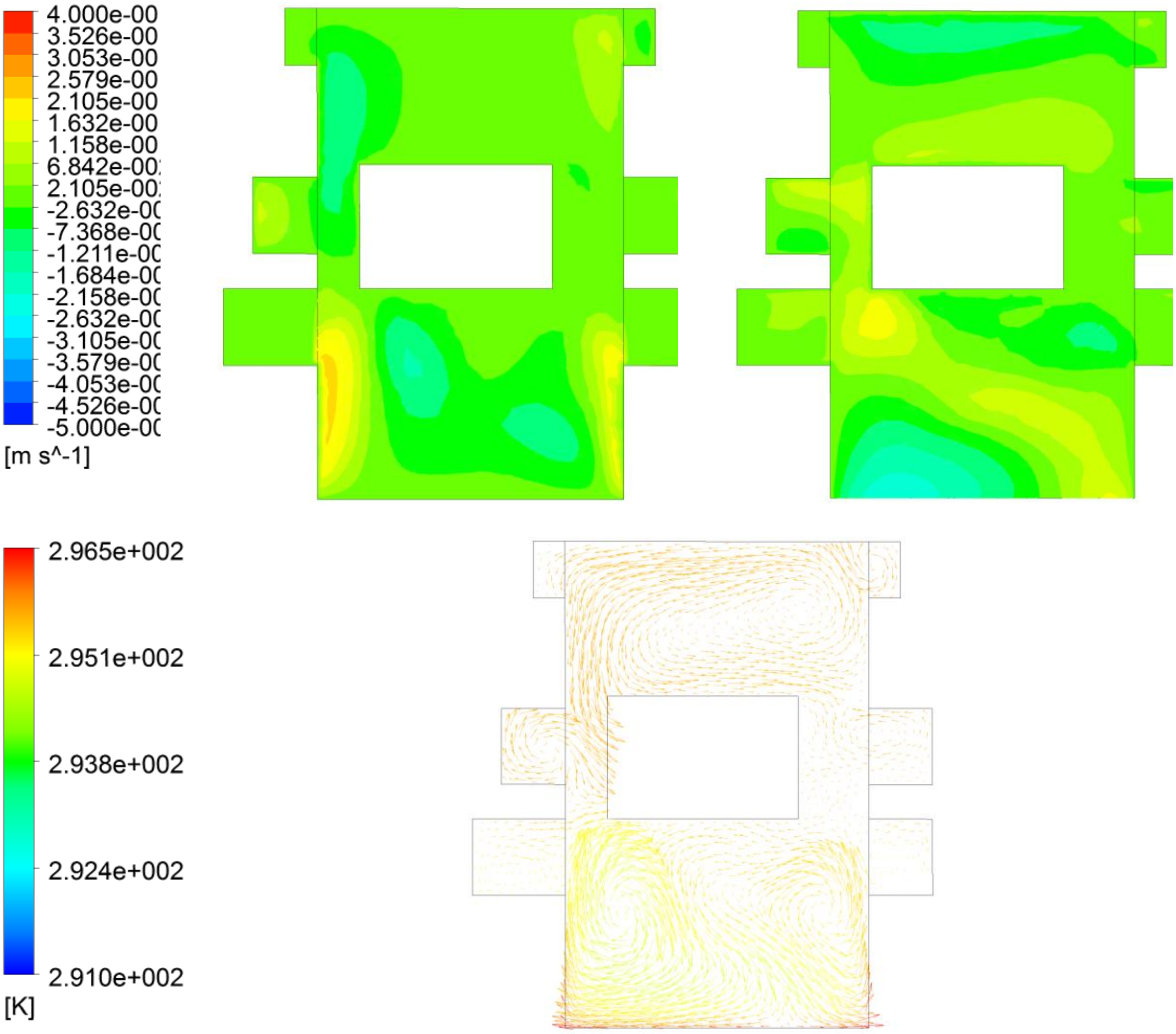
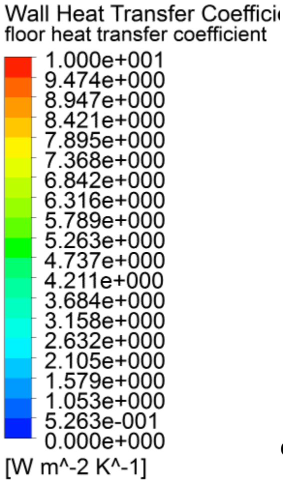


FIGURE 6-17 - CLOCKWISE FROM LOP LEFT, Z (VERTICAL) VELOCITY CONTOURS, Y (HORIZONTAL) VELOCITY CONTOURS AND TEMPERATURE COLOURED VELOCITY VECTORS

Figure 6-18, Figure 6-19 and Figure 6-20 show the convective heat transfer coefficient and heat flux properties of the floor along with the associated flow pattern of air 0.5m above floor level. It can be seen that by setting the floor to be a constant temperature, the heat flux varies over the floor with the changing heat transfer coefficients resulting from the flow patterns over through the atrium. In reality the heated water underfloor heating system would struggle to have enough control to maintain a constant floor temperate over the entire floor, but it is a better assumption than the alternative. The average heat flux over the floor area is 65.37W/m^2.

Figure 6-21 shows the correlating floor Nusselt numbers for the line shown in Figure 6-18. These demonstrate that a large amount of convection heating is taking place in the atrium. The values of Nusselt number throughout the space are predominantly between 90 and 125, with higher values at the points where the downdrafts meet the floor.



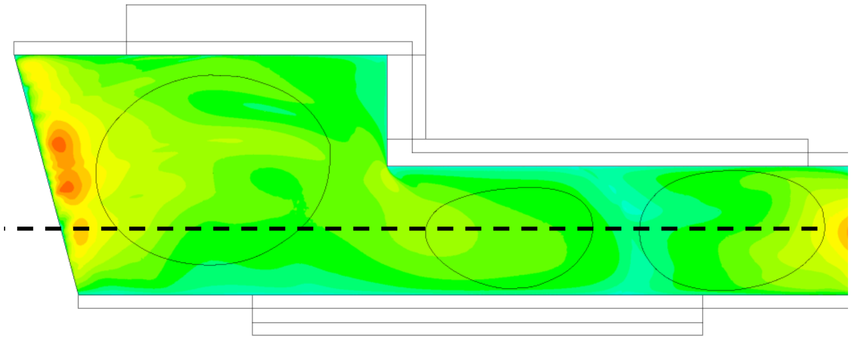
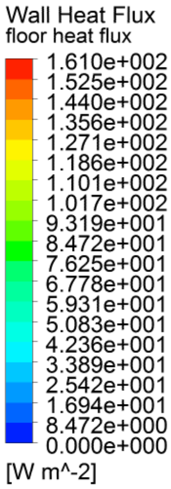


FIGURE 6-18 – HEATED FLOOR CONVECTIVE HEAT TRANSFER COEFFICIENTS



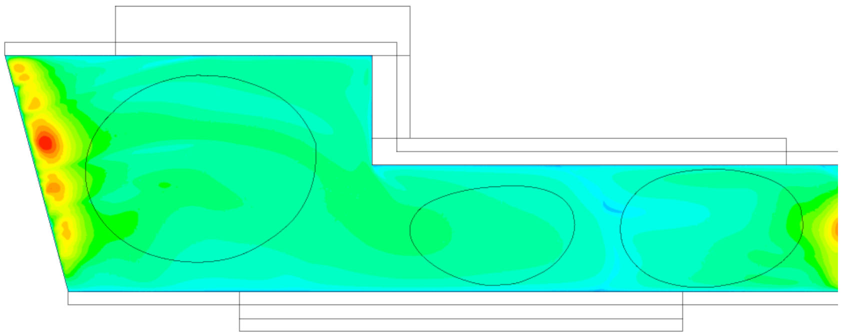
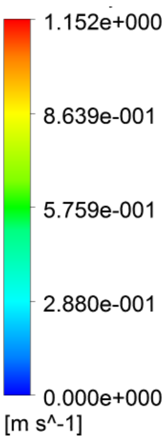


FIGURE 6-19 - HEATED FLOOR HEAT FLUX



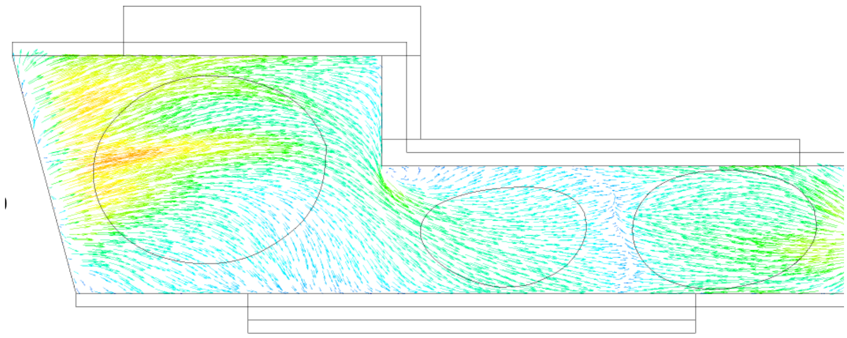


FIGURE 6-20 - VELOCITY MAGNITUDE TANGENTIAL VECTORS AT 0.5M ABOVE FLOOR LEVEL

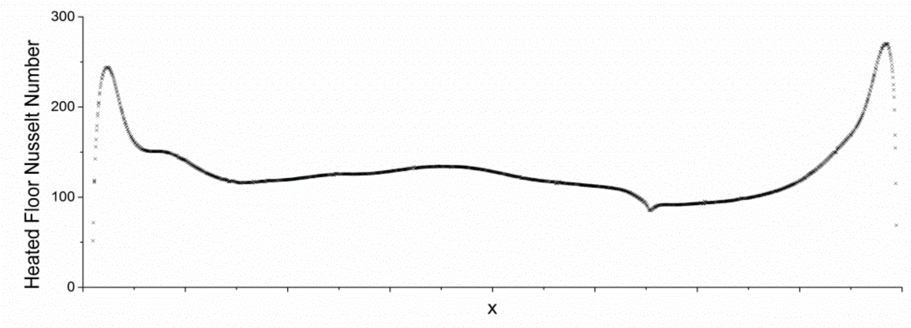


FIGURE 6-21 - NUSSELT NUMBER VARIATION AT HEATED FLOOR ALONG CENTRE LINE

From inspection of the model, it can be shown that, given the input conditions, the atrium is behaving in a realistic manner. Buoyancy is demonstrated by the formation of a plume and the downdraft of cold air as it enters the building. Furthermore, convective heat transfer occurs, demonstrating that the meshing of the model and choice of turbulence model are working. Although the temperatures present in this case are reasonable, the important performance aspect is that the model is transferring heat and mass in a realistic manner.

7 The Diamond: Results and Discussion

The method of results collection is described before presenting the results of the second case study building, The Diamond. Aspects of individual results are discussed throughout before discussing all of these results at the end of the chapter. The discussion relates only to these results on their own merit. Chapter 8 discusses these results alongside those from Chapter 4 in the context of the entire thesis.

7.1 *CFD Results collection method*

In order to collect variable data from each of the 385 workstations, the Cartesian coordinates of each was measured from the architectural drawings. The points used were 0.9 meters above ground level to account for seated working occupants. These were then imported as points into Fluent as a script. Vertex average velocity magnitude and vertex average static temperature surface integrals were then measured.

Figure 7-1 shows the variation of static temperature and velocity magnitude at the workstations throughout the atrium in Case 1 at a 310K floor temperature (resulting in 65.35Wm^{-2} heat flux). Each workstation was assigned a number from 1-385. The exact coordinates of each workstation is in Appendix A1 but they are numbered from bottom floor to top floor. From this figure it can be seen that in this case, there is a lot more variability in the temperature conditions at the lower workstations with an average lower temperature than those at the higher levels. Equally the lower level workstations are subjected to a more variable and on average higher level of air velocity, although the levels themselves are not exceedingly high, with a maximum of 0.69ms^{-2}.

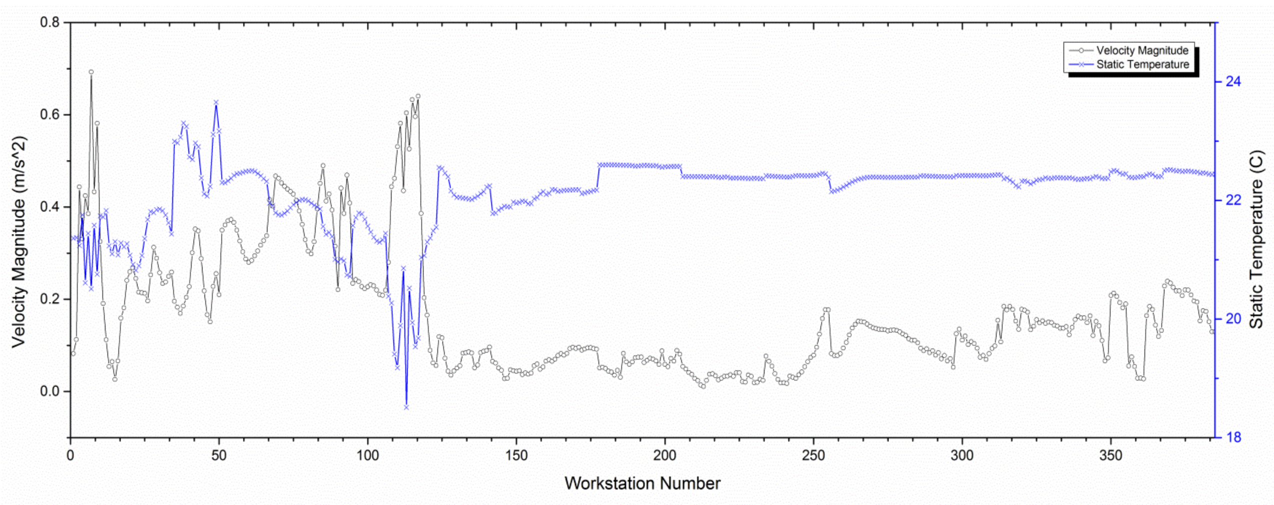


FIGURE 7-1 VARIATION OF STATIC TEMPERATURE AND VELOCITY MAGNITUDE BETWEEN WORKSTATIONS

It is interesting to see that the lower levels are subject to conditions less conducive to a comfortable thermal environment. In order to calculate the PMV conditions available for each workstation the exported data was then imported into a spreadsheet which contained three main stages of processing:

I. Calculation of PMV values

For each workstation the velocity and temperatures values were combined with the mean radiant temperature previously discussed in 6.4.1.2., the clothing level, metabolic rate and humidity levels.

It is acknowledged that metabolic rates, clothing levels and, to a lesser extent, humidity variation have an impact on thermal comfort. However, in this research, where a reasonable distribution of comfort conditions is desired, metabolic rates, clothing levels and humidity are maintained at an assumed constant. For each workstation's PMV calculation the values in Table 7.1 have been used. These have been chosen based upon existing guidelines [89, 90] for sedentary activity and winter clothing levels. The impacts of these assumptions will be discussed in subsequent sections.

TABLE 7.1 - ASSUMED THERMAL COMFORT PARAMETERS

Variable	Value
Metabolic rate	1.1
Clothing level	1 clo
Humidity	50%

The resulting PMV distribution by individual workstation for Case 1 at 310K floor temperature is shown in Figure 7-2. It can be seen in this case, with relatively small variations in wind velocity, the comfort conditions reflect variations in temperature conditions quite closely.

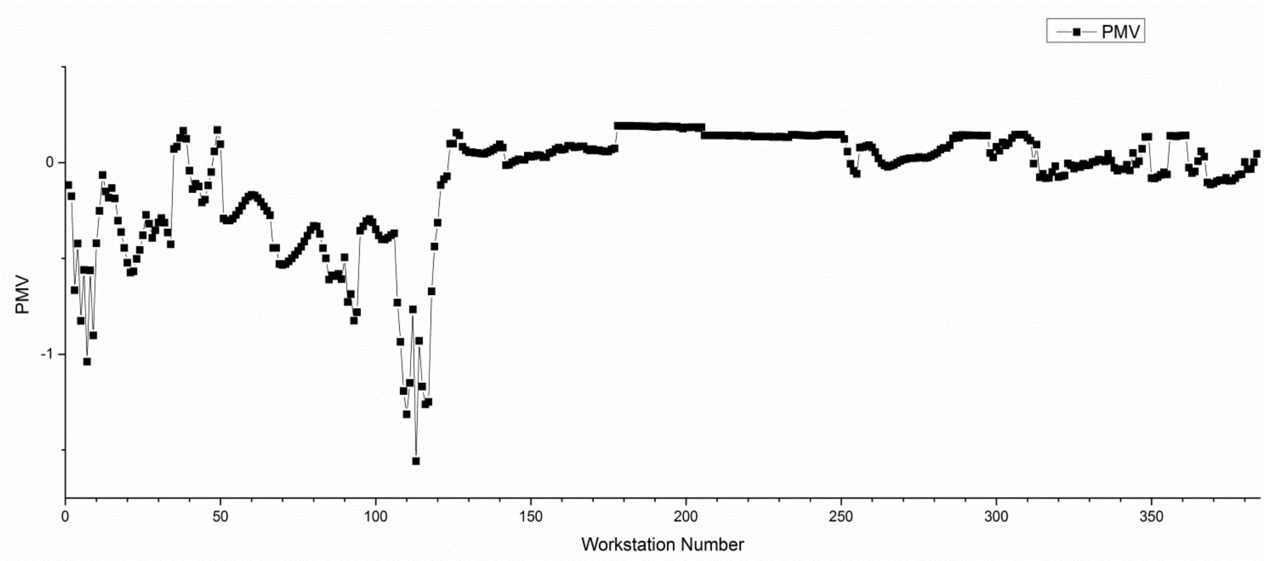


FIGURE 7-2 - VARIATION OF PMV WITH WORKSTATION

II. Calculation of the random distribution of occupants and corresponding probable comfort ranges.

The workstations were grouped into bins of PMV values rounded to 0.1 to give a number of workstations per discrete value of PMV. The random distribution of occupants throughout the workstations is calculated to be directly proportional to the number of workstations at any given PMV (i.e. a 100:50 split of workstations between two PMV values would result in 75 occupants being split 50:25 respectively.). Once calculated, it is possible to calculate the probable number of dissatisfied occupants sitting in this PMV condition. Figure 7-3 shows this random distribution of occupants at medium occupancy in Case 1 at 310K. The PMV range has been reduced to ±2 because if there were conditions beyond these the vast majority of people would find it very uncomfortable should they happen to sit there. As can be seen, the distribution simply reflects the variation in workstation conditions.

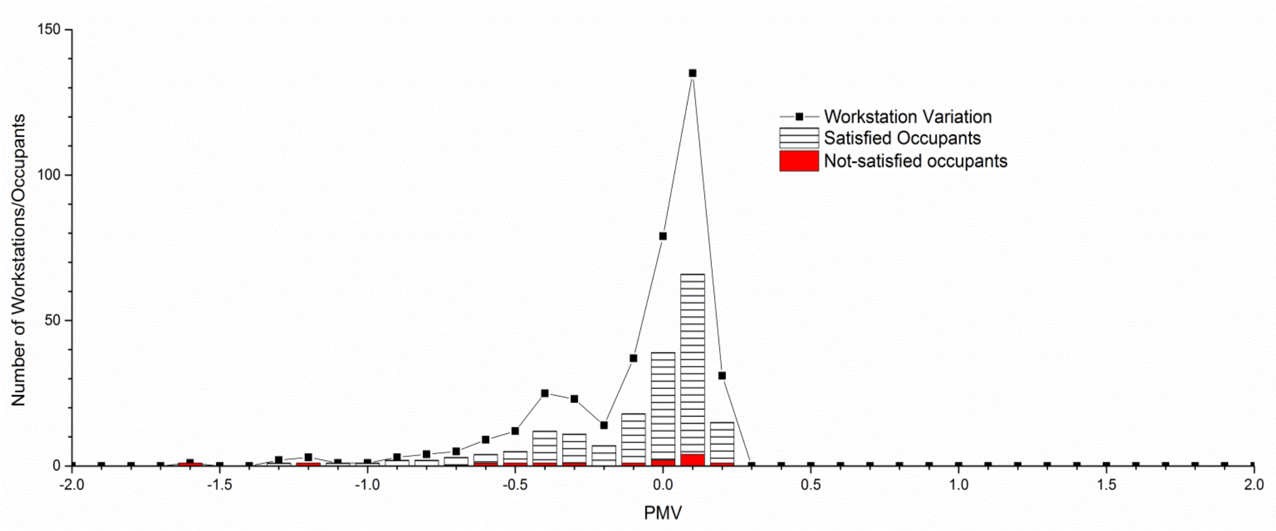


FIGURE 7-3 - RANDOM DISTRIBUTION OF OCCUPANTS AND ASSOCIATED SATISFACTION

Furthermore, building upon the work of Langevin [88], the number of people likely to want change, given the opportunity, can be demonstrated through a similar method, as shown in

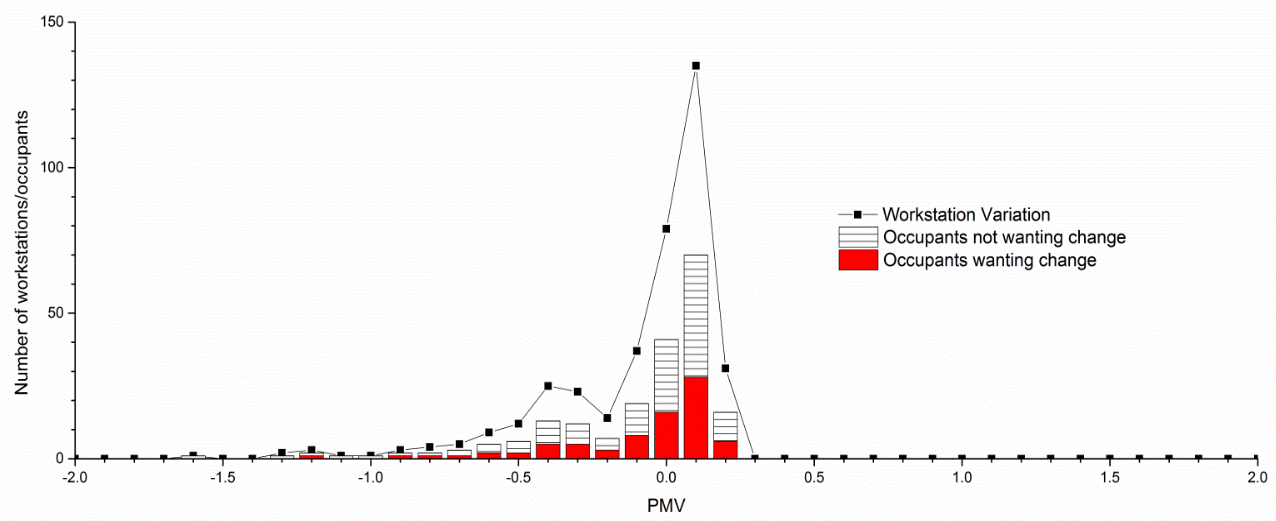


FIGURE 7-4 - RANDOM DISTRIBUTION OF OCCUPANTS AND ASSOCIATED PREFERENCE

III. Calculating the informed distribution of occupants and corresponding probable comfort ranges

The allocation of informed occupants is achieved through the following method:

1. Start with the workstations at the most prevalent comfort condition,
2. Using Fanger and Langevin's equations estimate how many of the occupants would be satisfied or wanting no change in that thermal condition
3. Allocate this number of occupants to these workstations
4. Repeat the process with the next most prevalent comfort condition within the building.

Initially it is assumed that when informed of suitable locations, an individual will choose a location suggested to them. This is not implying that there is only one seat suitable for each person as in the majority of cases an individual entering the building would have a number of suitable spaces available to them. Figure 7-5 shows how this can be applied to both satisfaction and preference probabilities. It can be seen that, since the most probable comfort condition at which an individual is likely to be comfortable is close to 0 PMV, when informed, all of these workstations can be occupied.

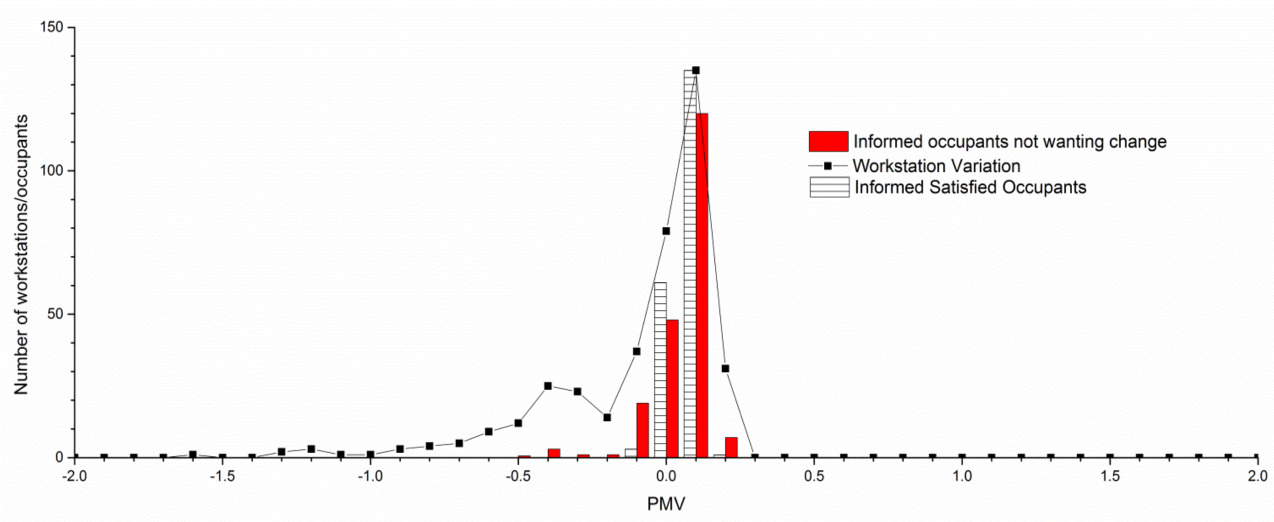


FIGURE 7-5 INFORMED DISTRIBUTION OF OCCUPANTS AND ASSOCIATED SATISFACTION AND PREFERENCE

7.2 *CFD Model Performance*

7.3 *Variation in Workstation Conditions*

Figure 7-6, Figure 7-7 and Figure 7-8 show the variation in workstation comfort conditions for different floor temperatures (in Kelvin) within the different cases; November 18th, February 18th and August 4th 2012. It can be seen that over all three cases, throughout all floor temperatures, there is a skewed colder tail to the workstation variation due to the increased velocities and of cooler air. The impact of the temperature of external air temperature can be seen by comparing the height of this skewed tail, with the 5.4°C external air temperatures in Case 2 producing a larger number of cool conditions in contrast to the 16.3°C external temperature in Case 3.

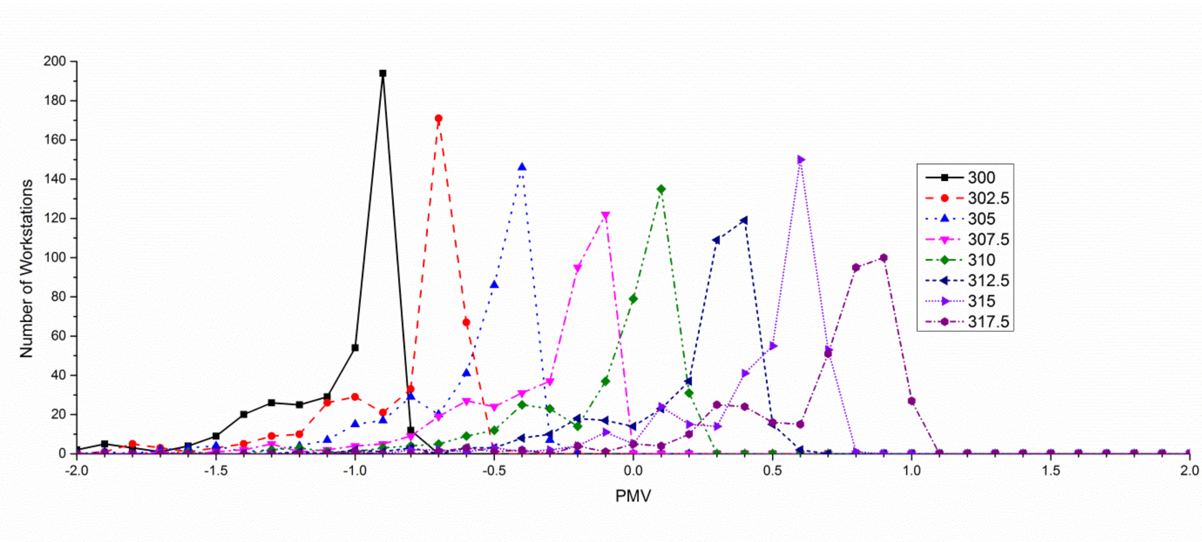


FIGURE 7-6 – CASE 1 WORKSTATION THERMAL COMFORT DISTRIBUTION AT VARYING FLOOR TEMPERATURES

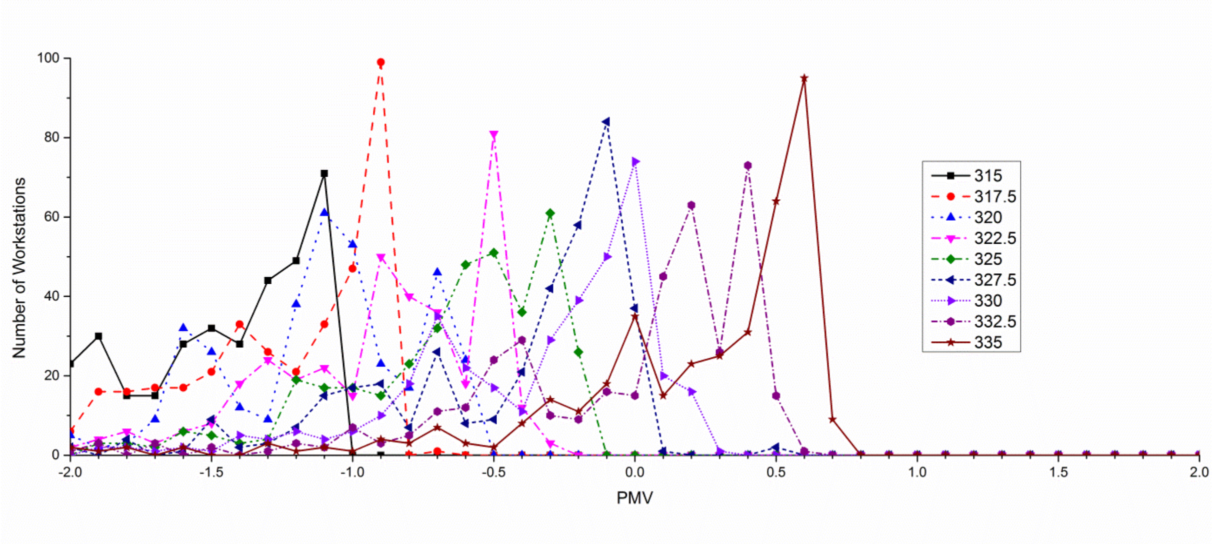


FIGURE 7-7 – CASE 2 WORKSTATION THERMAL COMFORT DISTRIBUTION AT VARYING FLOOR TEMPERATURES

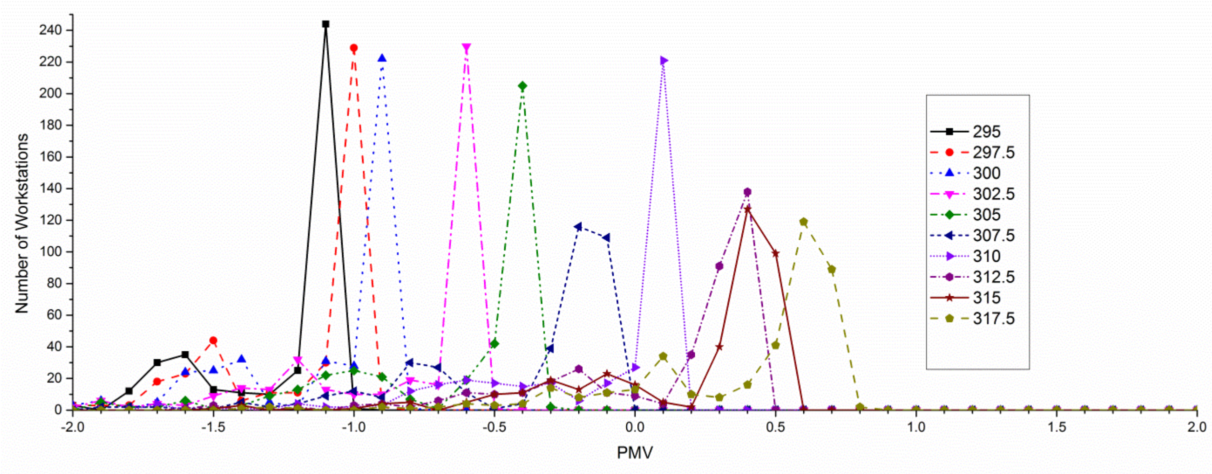


FIGURE 7-8 – CASE 3 WORKSTATION THERMAL COMFORT DISTRIBUTION AT VARYING FLOOR TEMPERATURES

To choose the conditions at which optimum conditions are achieved, it is useful to refer back to ASHRAE 55 and BS ISO 7730, which both classify buildings into A,B and C categories depending on the range of PMV conditions within their internal environment. Category A buildings have PMV ±0.2

(PPD ≤ 6%), B have PMV ±0.5 (PPD ≤ 10%) and C have ±0.7 (PPD ≤ 20%). Figure 7-9 shows, for each case, the number of workstations at each floor temperature that fall between a PMV of ±0.2 and ±0.5 within the atrium.

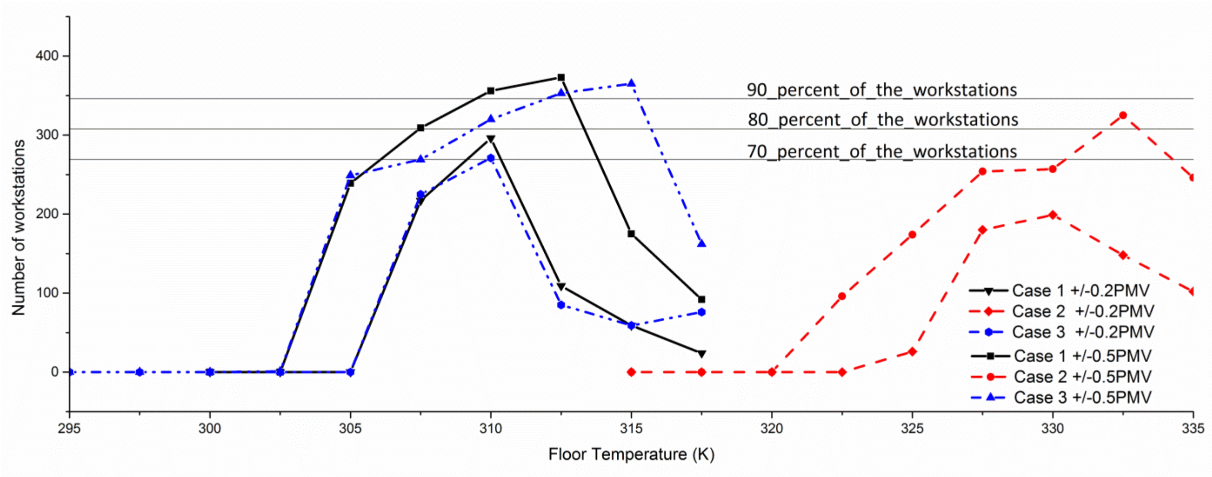


FIGURE 7-9 - VARIATION OF NUMBER OF WORKSTATIONS BETWEEN +0.5 AND -0.5 PMV AT DIFFERENT FLOOR TEMPERATURES FOR EACH OF THE CASES

Firstly, it can be seen that with a naturally ventilated and underfloor heated atrium, the range of conditions is inherently going to vary much more than typically accepted levels. According to current standards, this building does not meet the specification for a naturally ventilated building which would then allow for adaptive comfort allowances to be made since windows are not manually operated and therefore would officially be classed as a low comfort building, especially when dealing with cold external temperatures. However, for the purposes of this study, the conditions at which would be classed as best performing need to be chosen to study and compare with colder conditions.

The conditions chosen were those which produced the highest number of workstations within PMV ±0.2, apart from in Case 2 where the number of workstations in this region was low, and the corresponding number of PMV ±0.5 workstations was below 70%. In this Case, the condition chosen was that which produced the largest number of PMV ±0.5 workstations. Table 7.2 shows the summary of conditions chosen to represent the most comfortable state within the atrium for each case. Table 7.2 also defines the low temperature conditions to be used. Since the summer case (Case 3) has no space conditioning, there is no potential for energy saving to be made through heating reduction. Therefore, no lower temperature case is used for case 3.

TABLE 7.2 - OPTIMUM AND LOW FLOOR TEMPERATURE CONDITIONS

Case	Floor Temperature Producing Best Conditions (K)	Low Floor Temperature Condition (K)
1	310	300
2	332.5	322.5
3	310	

Figure 7-10 shows the variation of heat flux from the floor of the CFD model at each floor temperature compared to the heat input provided by the IES model.

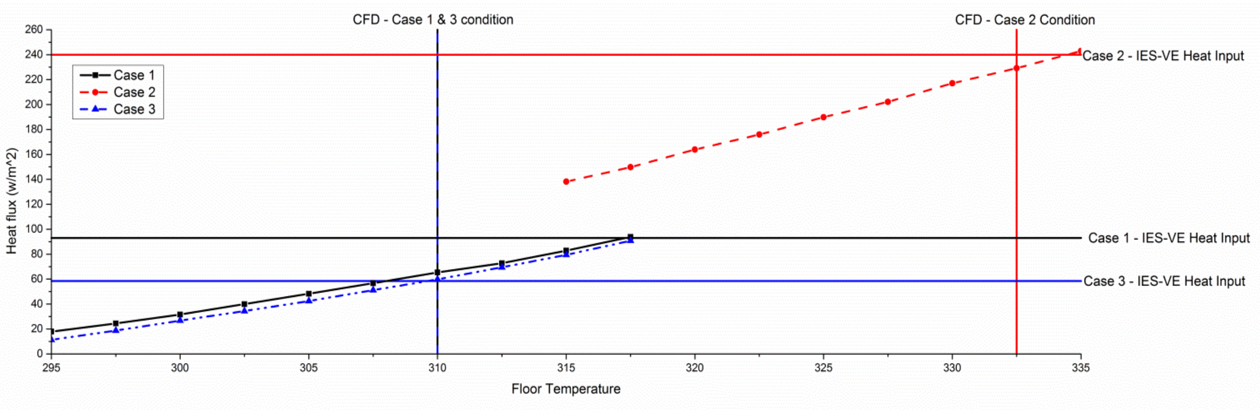


FIGURE 7-10 - COMPARISON OF CFD FLUX CONDITIONS AGAINST THOSE DERIVED FROM BUILDING SIMULATION

This shows a relatively good agreement between conditions in cases 2 and 3, but is 27.6Wm^{-2} lower in the case 1 CFD model than the IES model. This difference is not unexpected since the IES model can only measure PMV values as uniform within the 29 elements of the model, whereas the CFD model's higher granularity accounts for varying conditions throughout the space. This figure does demonstrate however that the method through which the atrium is heated, representing all heat inputs, returns heat fluxes in the expected region.

7.4 ***Variations in temperature and velocity***

The images taken from all models in this section are mid-plane sections at y=-6m for the zx plane and x=-40m for the zy plane as shown in Figure 7-11

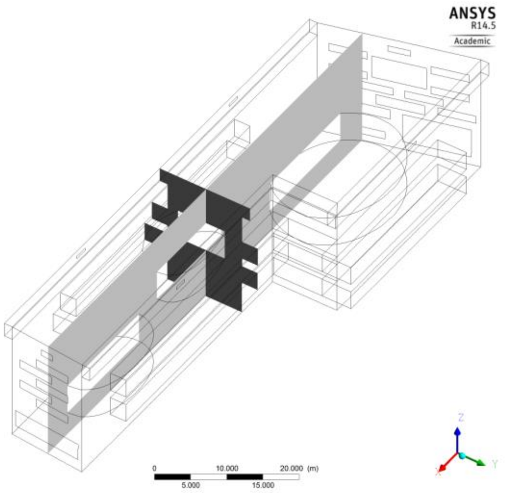


FIGURE 7-11 - MIDPLANES USED FOR COMPARISON OF CASES

Table 7.3 shows temperature distributions in each of the cases at both optimal and low temperature conditions. The ranges have been clipped slightly to demonstrate the variation in conditions throughout the bulk of the space. For maximum temperatures, refer to the initial boundary conditions set for each case. Table 7.4 shows the vertical velocity distributions of each of the cases at optimum and low floor temperatures.

TABLE 7.3 - TEMPERATURE DISTRIBUTIONS IN CASES AT OPTIMUM AND LOW FLOOR TEMPERATURES

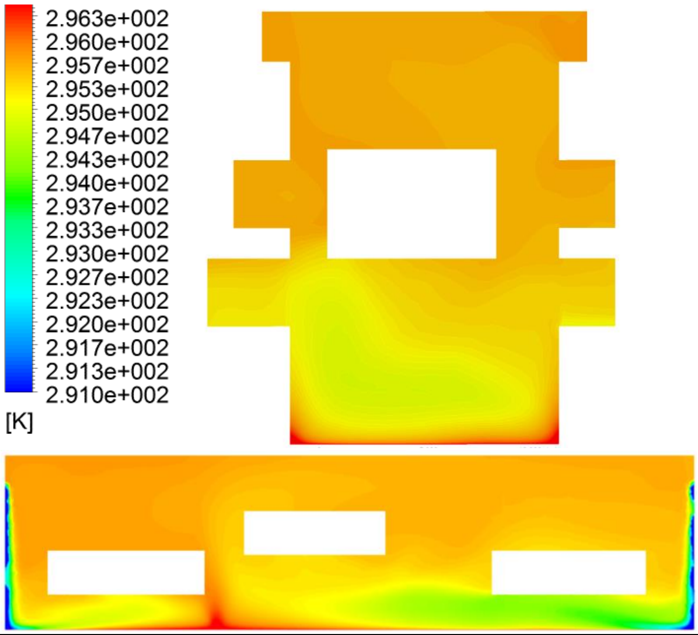
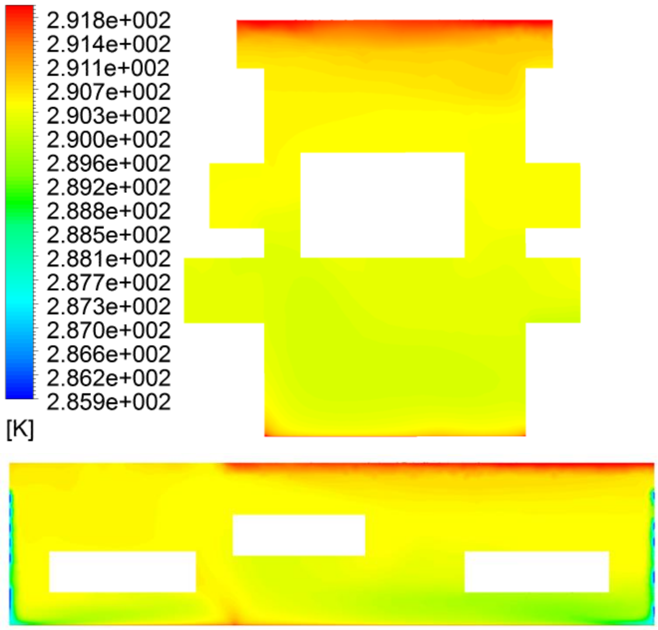
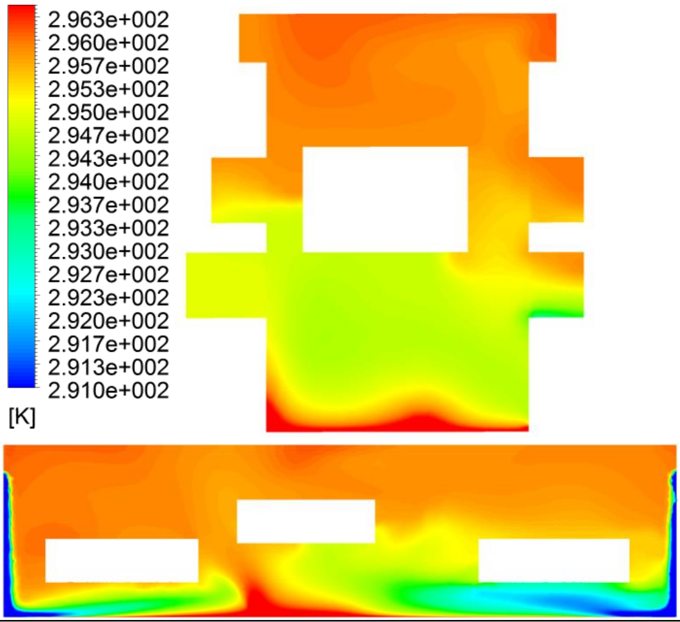
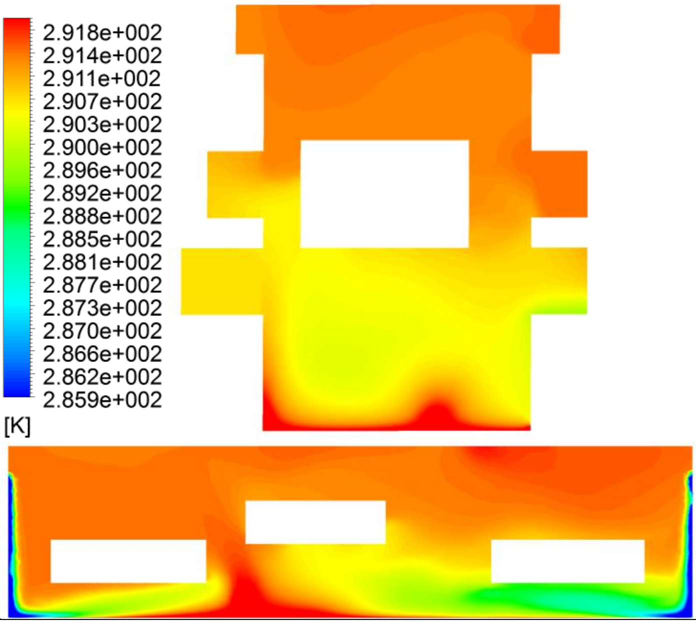
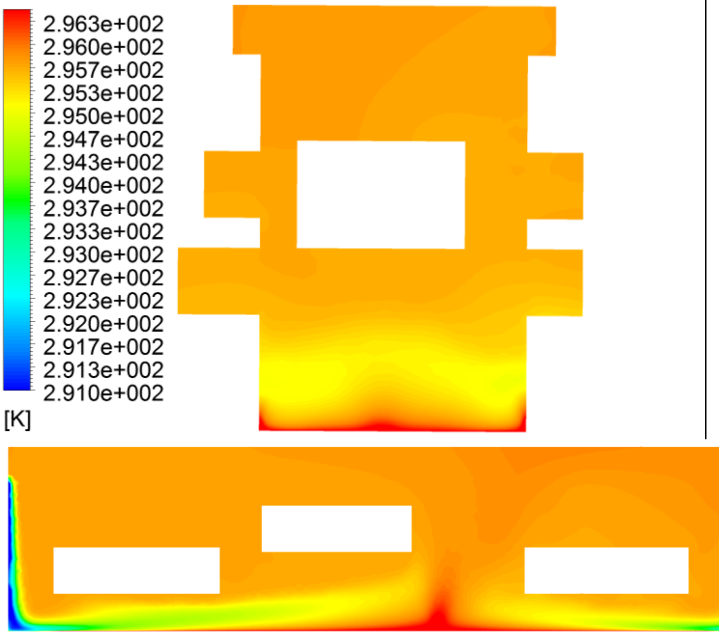
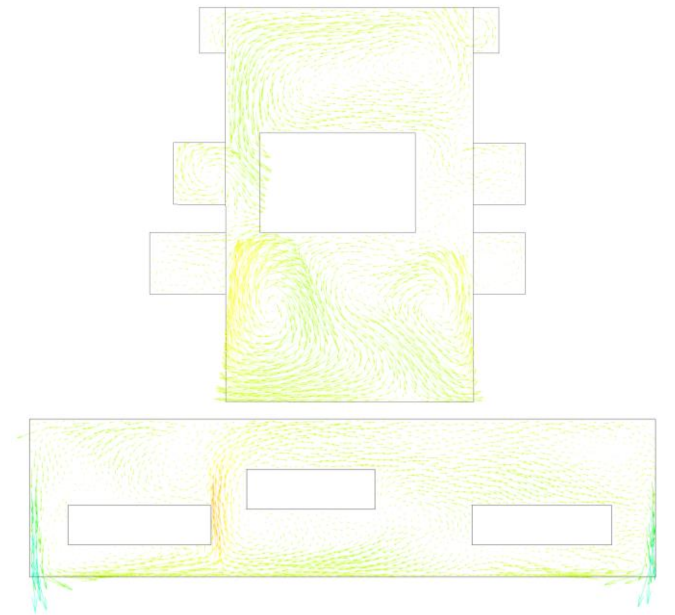
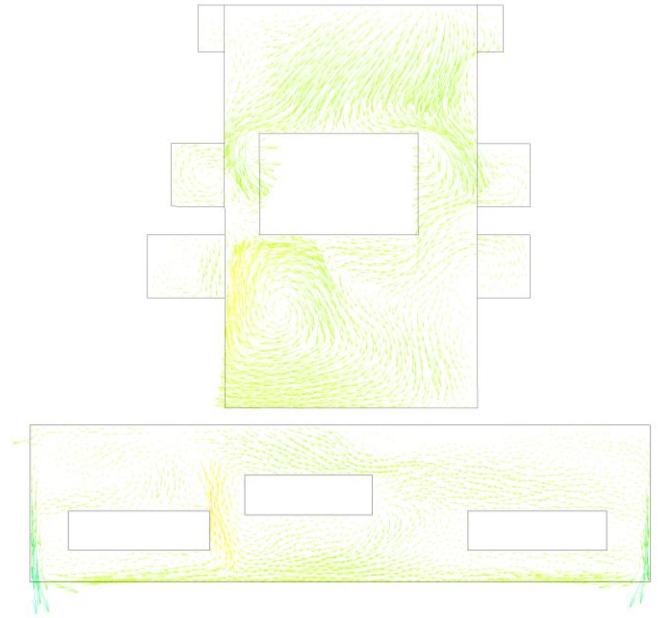
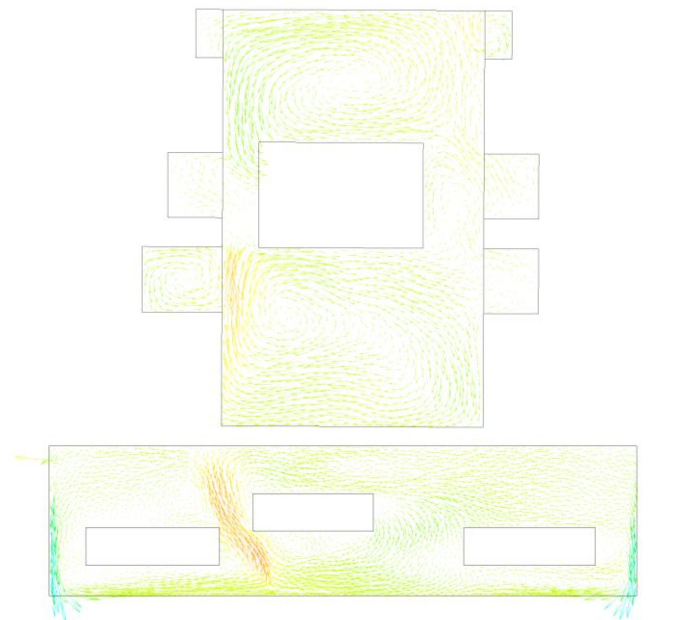
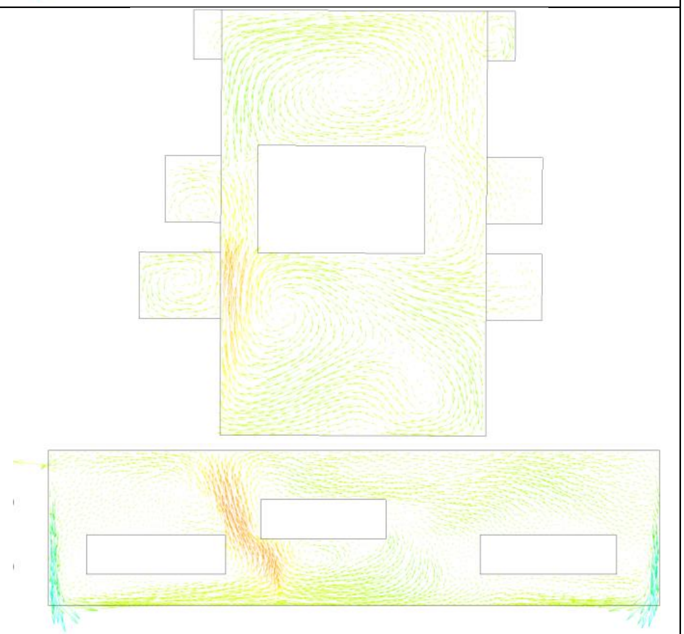
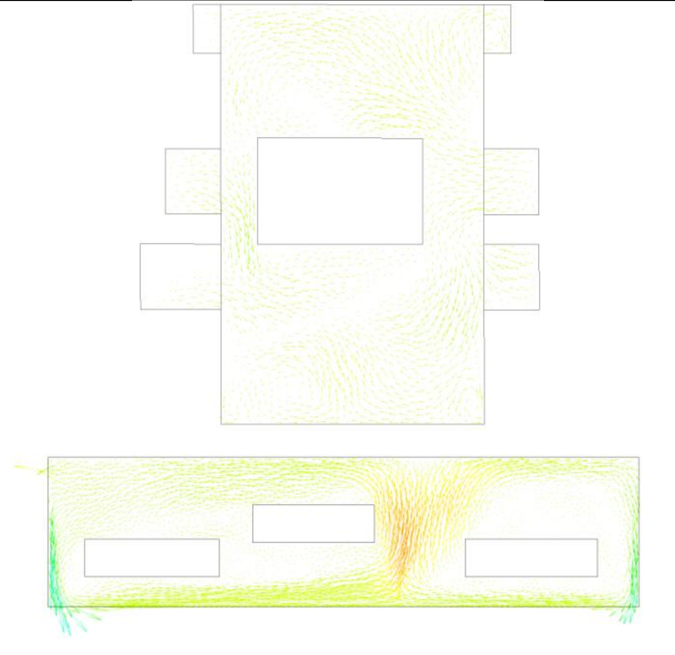
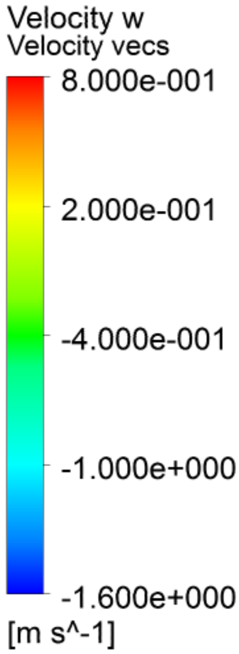
	Optimal temperature condition	Low temperature condition
Case 1		
Case 2		
Case 3		

TABLE 7.4 - VERTICLE VELOCITY DISTRIBUTIONS IN CASES AT OPTIMUM AND LOW FLOOR TEMPERATURES

	Optimal temperature condition	Low temperature condition
Case 1		
Case 2		
Case 3		

The cold air can be seen to enter through the louvres at low velocity. The dense cold air immediately falls to the floor in a downdraft, before coming into contact with the hot surface. As it travels across the surface, heat is transferred to the air, which then rises. The effect of forced ventilation by the wind can be seen as opposing flows of air meet at a point in the building, causing a point of relative stagnation.

Across all models, thermal stratification can be seen. When point source heating occurs, a plume is expected to form with a clear divide between warmer and cooler air. However, using a distributed heat source, such as underfloor heating, creates more gradual transition between cool and warm conditions is seen with more mixing. In this case, the wind creates forced convection, effectively creating a “pseudo-point” source of heating which create plumes, particularly in cases 1 and 2.

It can be seen that there are clear areas of varying conditions throughout the space caused by:

- The incoming cool air
- The stagnation of air near to the floor
- Thermal stratification
- Flow around the pods and balconies.

For smart buildings, the characteristic temperature distribution within the building at different external conditions is useful to know as it enables a better prediction of future comfort variation when the weather forecast is known. Although these CFD models are steady state samples of conditions within a space, the following trends can be seen:

Reducing the floor temperature by 10^{o}C in moderate external conditions has a larger impact on temperature variation than the same temperature difference during colder external conditions.

This is due to the percentage change in heat input being larger in the case 1 than case 2. In case 1, reducing the floor temperature by 10^{o}C results in a 51.68% reduction in total heat flux, accounting for almost all of the heating contributed by underfloor heating (57.11%). Within case 2, the same temperature change results in a 23.21% reduction in heat flux, which is 28% of the estimated space heating requirement. The importance of this result is that the potential for energy saving in during colder conditions is higher.

Forced ventilation characteristics have an impact on the distribution of thermal conditions throughout the space.

Case 3 is the only case in which the volume flow rate of air entering through the west façade is larger than the east façade. This results in a shift from the west side of the building being warmer, to the east side of the building being warmer. This will have a particular impact upon the seating on top of the lower two pods, and the ground floor.

Warmer external environments result in less extreme variations in thermal conditions.

In both cases 1 and 2, a clear plume is formed by effectively point source heating due to the dominance of wind driven flow over buoyancy driven flow. This plume entrains air within it and creates a pressure barrier between the cold lower levels and the warm upper levels. When the incoming air is colder, it would be expected that the separation between the two would be more extreme and this can be seen in Case 1 in comparison to Case 2.

7.5 *Comparison of informed and uninformed occupants*

In the following sections, a number of different results graphs will compare informed and uninformed occupants. Informed occupants are those that locate themselves in a workstation that has been suggested to them whereas uninformed occupants are equally distributed throughout a space. Both satisfaction and preference are addressed based upon Fanger's [70] and Langevin's [88] work respectively. The different occupancy scenarios defined in Table 7.5. Optimal and low floor temperature conditions are the same as those defined in Table 7.2.

TABLE 7.5 - OCCUPANCY SCENARIOS

Occupancy Level	Number of occupants using the 385 available workstations
High	370
Medium	200
Low	100

7.6 *The potential impact of informed occupants on satisfaction levels*

When the building is at high occupancy it is hypothesised in this research that levels of thermal comfort can be increased by informing occupants about the most comfortable places to sit based upon their preferences. Figure 7-12 shows how satisfaction levels can be increased at high occupancy, optimal temperatures.

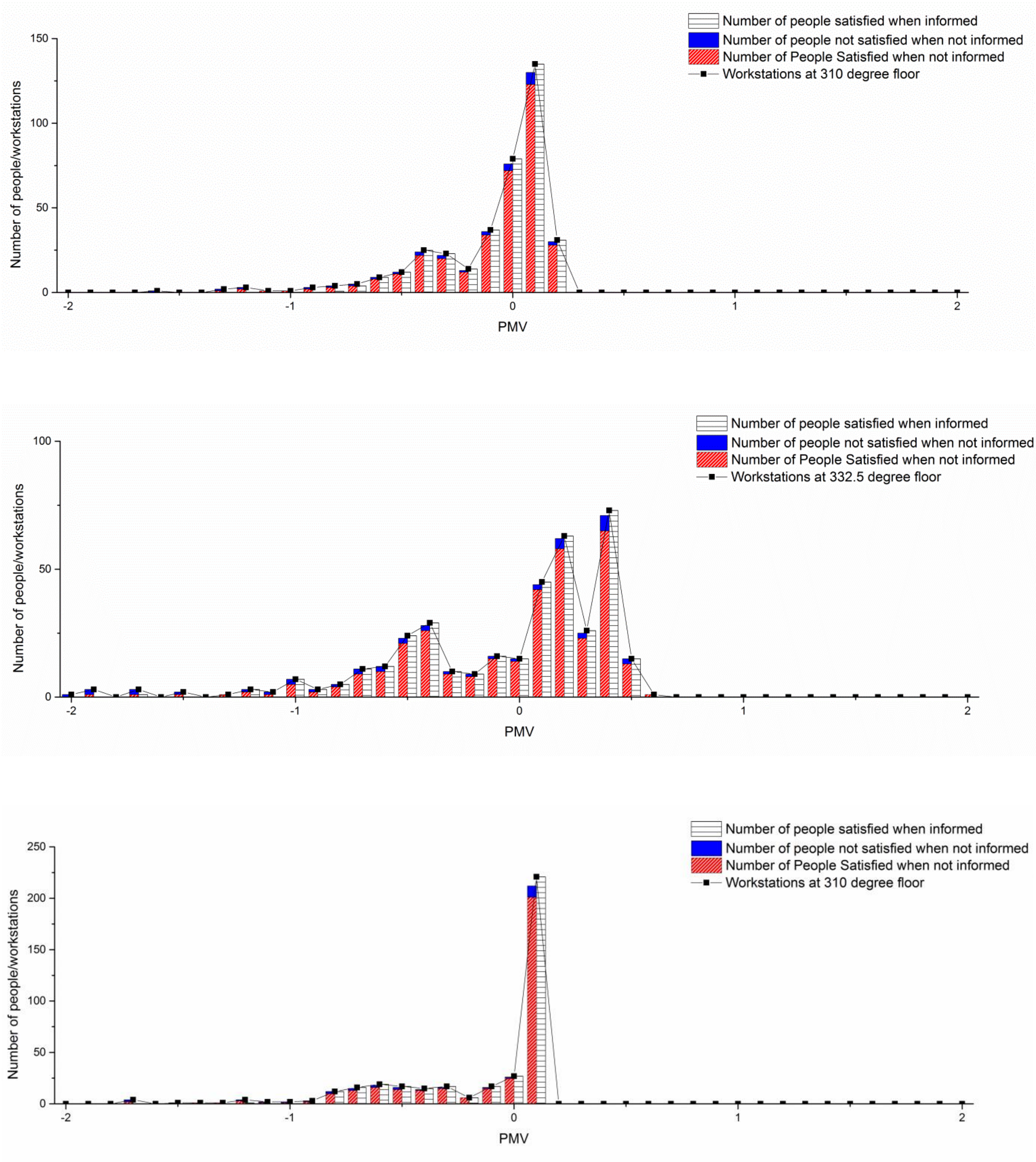
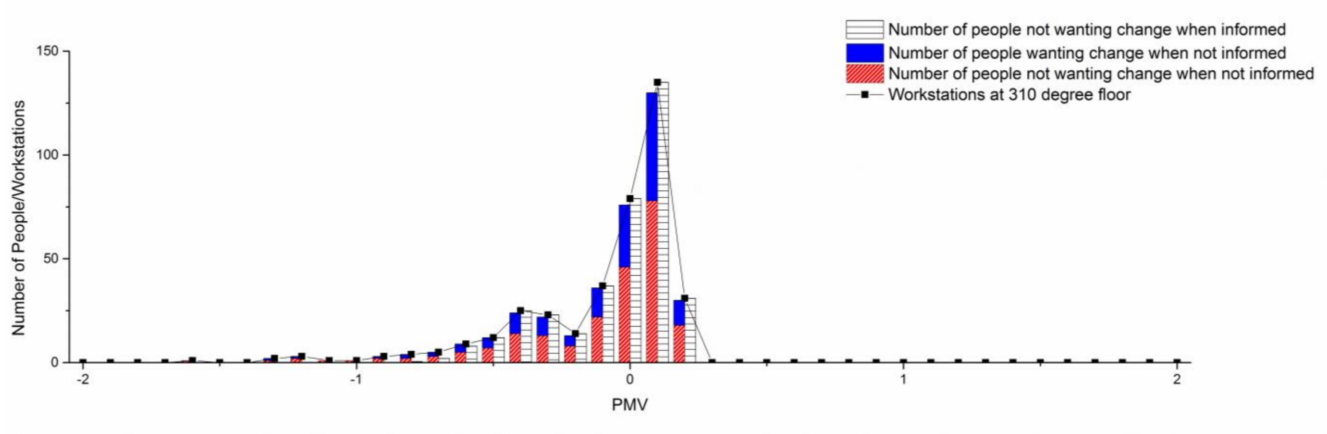
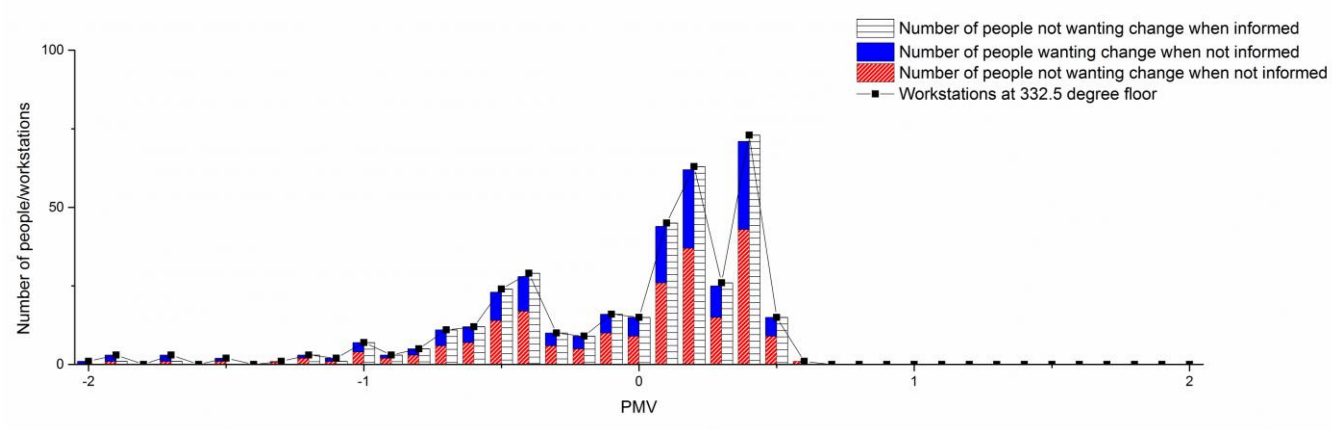


FIGURE 7-12 - HIGH CAPACITY AND OPTIMAL FLOOR TEMPERATURE COMPARISON OF UNINFORMED AND INFORMED OCCUPANT SATISFACTION RATES IN CASE 1 (TOP), 2 AND 3 (BOTTOM)

7.7 *The potential impact of informed occupants on preference levels*

Figure 7-13 demonstrates how Langevin's approach to thermal preference can also be applied using the same technique.





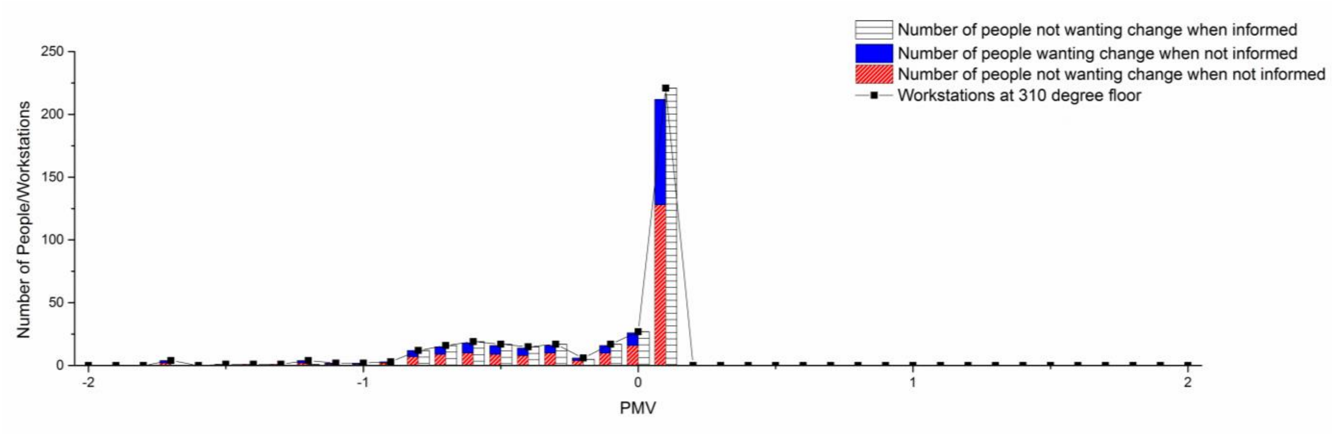


FIGURE 7-13 - - HIGH CAPACITY AND OPTIMAL FLOOR TEMPERATURE COMPARISON OF UNINFORMED AND INFORMED OCCUPANT PREFERENCE RATES IN CASE 1 (TOP), 2 AND 3 (BOTTOM)

When uninformed, a significant number of occupants would ask for a change in conditions. However, by informing people about where is comfortable for them to sit, this number can be reduced to almost zero.

In the high occupancy scenario, the more full the building becomes, the lower the chance of being able to meet the comfort preference criteria of new occupants of the building as the number of available places are reduced. However, if the occupancy levels reduce to medium capacity, then the relative number of available seats in comfortable locations increases. Therefore, the likelihood of being able to suggest a thermally comfortable workstation for the next occupant is increased, as shown in Figure 7-14 for Case 3. It can be seen that if a single person, preferring a condition of 0.1PMV, entered the building at this point, there would be approximately 40 available workstations at their preferred PMV.

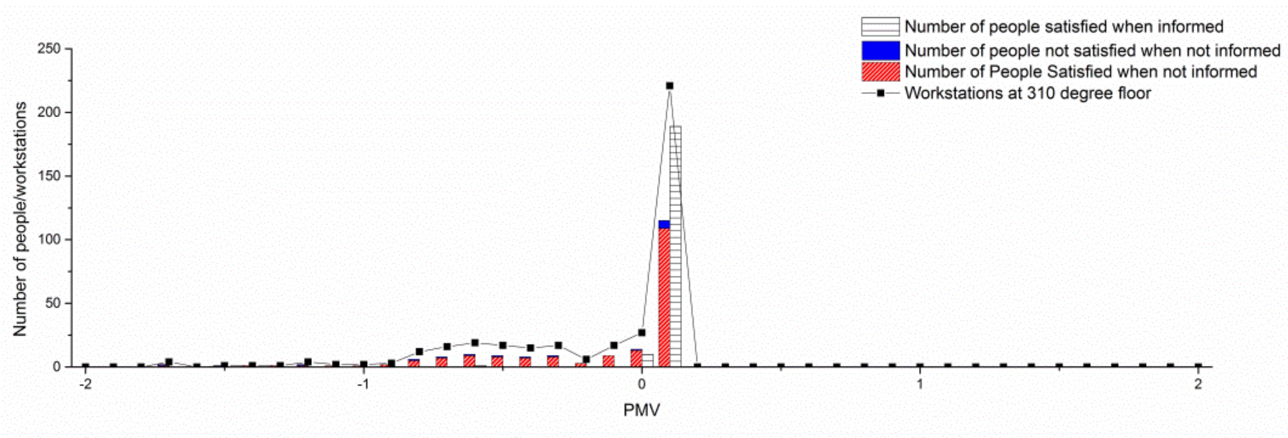
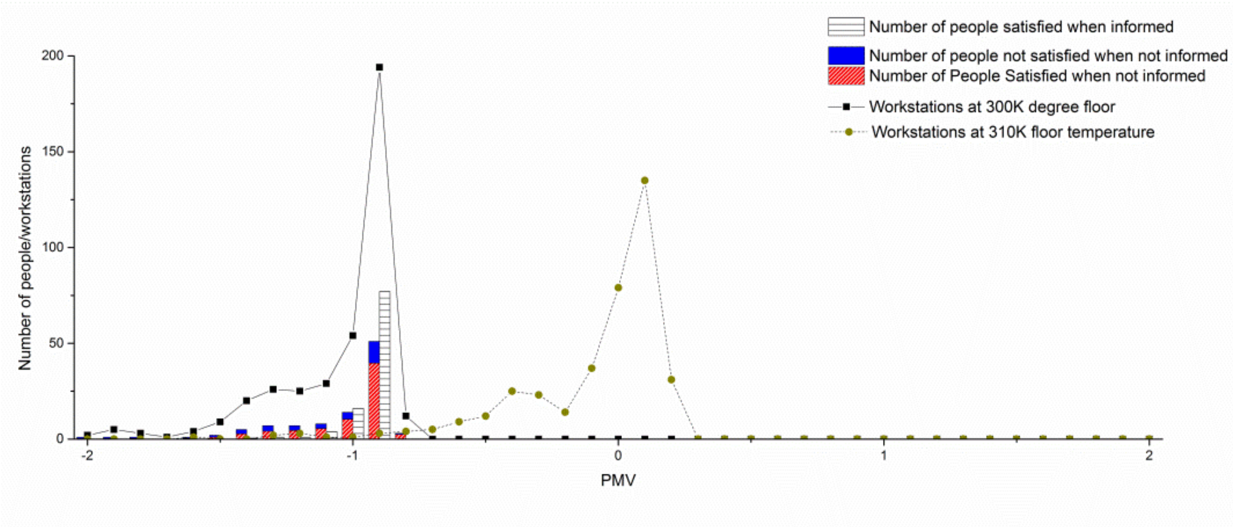


FIGURE 7-14 - CASE 3 OPTIMUM TEMPERATURE MEDIUM CAPACITY SATISFACTION RATES

7.8 *The potential impact of informed occupants on energy consumption*

At lower occupancies, it becomes easier to satisfy all occupants by informing them, whilst the same percentage of randomly seated occupants are dissatisfied. However, when the building is allowed to thermally drift by lowering the floor temperature, Figure 7-15 shows that it is possible to keep all 100 occupants satisfied when informed. If these occupants were randomly seated, 25 would be likely to be dissatisfied with the conditions, which would conventionally be unacceptable.



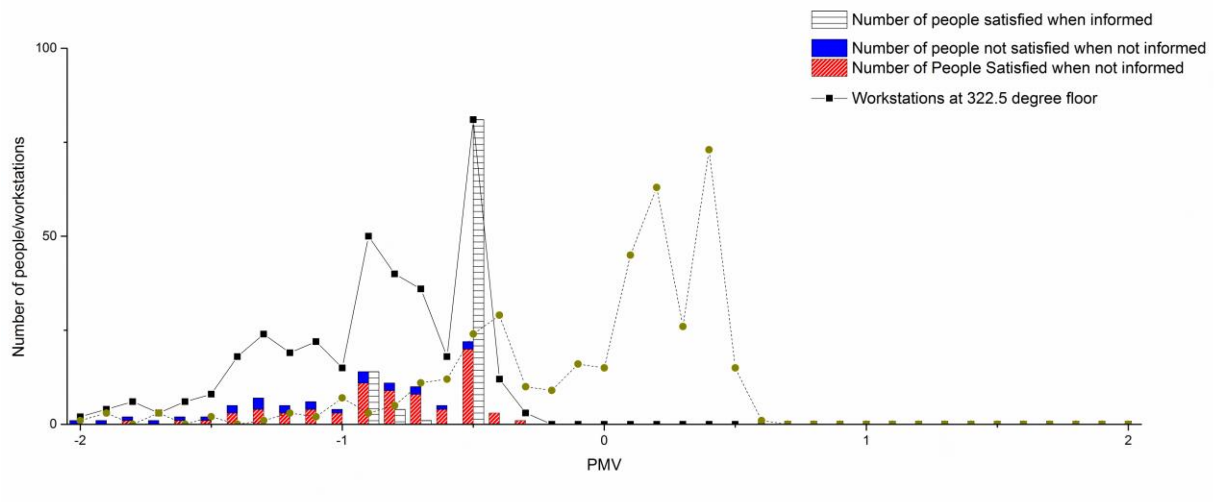


FIGURE 7-15 - LOW CAPACITY AND LOW FLOOR TEMPERATURE COMPARISON OF UNINFORMED AND INFORMED OCCUPANT SATISFACTION RATES

Table 7.6 shows the related reductions in energy inputs required by the building in these two cases, accounting for the reduction in internal people gain.

TABLE 7.6- REDUCTIONS IN ENERGY INPUT WHEN LOWERING FLOOR TEMPERATURE

Case	Original energy input (kW)	Lower energy input (kW)	Energy reduction due to lower occupancy (kW)	Reduction in space heating energy input (kW)	% reduction in space heating load
1	87.57129	42.31855	13.5	31.75274	36.26
2	306.9947	235.755	13.5	57.73963	18.8

This shows that by informing occupants of comfortable spaces to work, the energy consumption of the building can be reduced significantly without sacrificing the comfort of the occupants.

Figure 7-16 shows that at both optimal temperature, high occupancy and lower temperature, low occupancy conditions, both rates of dissatisfaction and wanting change can be reduced significantly. It can be seen that at high occupancies there are 2 occupants that would be likely to ask for a change in thermal condition, but these two occupants are still be likely to be *satisfied* with their thermal comfort.

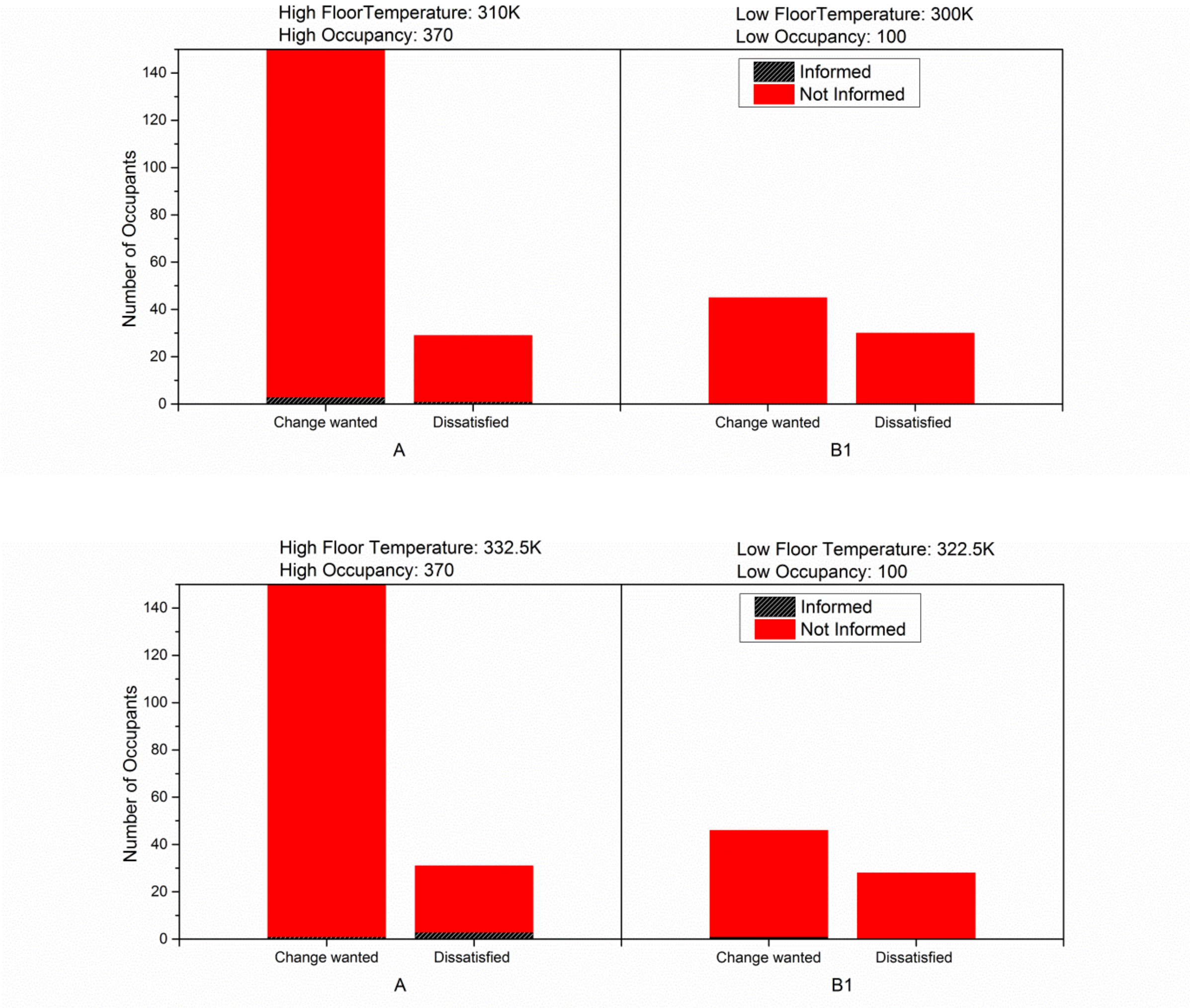


FIGURE 7-16 - NUMBER OF PEOPLE DISSATISFIED OR WANTING CHANGE AT OPTIMUM AND LOW FLOOR TEMPERATURES, FOR HIGH AND LOW OCCUPANCIES, IN CASES 1 (TOP) AND 2

7.9 *Discussion of The Diamond Results*

The two principle investigations that have been undertaken are the impact of influencing workstation choice on comfort levels, and the impact of influencing workstation choice on energy input levels at low occupancies. The results from this case study have shown steady state variations in thermal comfort conditions within the building in three different sets of external environmental conditions. At both high and low occupancies it is demonstrated that there is potential for both increases in energy efficiency and comfort rates, accounting for Langevin's no-change metric and Fanger's satisfaction method.

The importance of these results is two-fold. The first relates to engagement of occupants within a building. As discussed in the Chapter 2, adaptive comfort has been shown to impact comfort in a number of different occupant-building dynamics; whether it is the external to internal variation in conditions, or the opportunity to modify the immediate internal environment. Recent research proposing that comfort improvements can be made through the provision of 'adaptive opportunities', whereby occupants are given the opportunity to achieve their own comfort, is aligned with this work[85, 191]. This research has demonstrated the impact that a different form of adaptive comfort could have; enabling occupants to achieve their own comfort conditions using informed choices.

Acknowledging that there will be trends in variation of comfort conditions within a building, it could be suggested that regular occupants of a building will know where the most comfortable places are based upon habit. Although this is by no means guaranteed, and in theory informed choices will still be more able to match actual thermal conditions to preference, this is an area that could be researched further; the benefit of informed choices over habitual learning of regular occupants in a functionally flexible working environment.

However, increased levels of comfort during high occupancy periods are arguably not the most important result of this research. It has been shown in this work that by informing occupants of comfortable space, the internal environment no longer needs to be made homogenous throughout the entire space. Energy input can be reduced to a level that will keep only the required spaces comfortable. As long as the locations of these spaces are known, the ability to inform choices will enable energy consumption to vary with occupancy. This will not only allow the heating input to be lowered, but would remove the need for extra heating to account for a reduction in heat gain supplied by the occupants themselves and the computers that they may be using. Although a relatively small contribution in the coldest months, the proportion of total input attributed to internal gains in the warmer months becomes more significant.

Importantly, this concept is implementable given the relevant information is available to the building and the occupants. It would reasonable to assume that within peak time usage the entire building is assumed to be at capacity. However, with a similar occupancy profile to The IC, which is only a couple of hundred metres away and serves a similar function during out of work hours, it would be reasonable to introduce thermal drift during low occupancy hours. Unlike conventional buildings whereby comfort provision is hidden from occupant view, a concept like this needs to be known to the occupants. They would need to know that this thermal drift happens at low occupancy hours and would need to understand why it is used. Thermal drift happens slowly in such a large building, but as long as occupants are made aware of what will be happening in the near future, they will be able to prepare for it, by choosing to stay in an area that is acknowledged to be cooler than usual. These psychological processes and interactions with the building would be interesting to research further as if occupants are found to be open to interacting with the buildings they inhabit, a wide range of smart concepts could be implementable.

8 Overall Discussion of all Results

The results of the research are discussed in the context of the wider research field. Themes are drawn between the three main research topics carried out in the work and are discussed in light of how they can be extended. Finally, the limitations of the research are acknowledged and discussed.

8.1 *Smart Buildings*

The three distinct phases of work (the definition of a Smart Building and the two case studies) within this thesis are intrinsically linked through the definition of a Smart Building developed within Chapter 3. The definition formed was:

Smart Buildings are buildings which integrate and account for intelligence, enterprise, control, and materials and construction as an entire building system, with adaptability, not reactivity, at the core, in order to meet the drivers for building progression: energy and efficiency, longevity, and comfort and satisfaction. The increased amount of information available from this wider range of sources will allow these systems to become adaptable, and enable a Smart Building to prepare itself for context and change over all timescales.

This definition is intentionally pitched as a high level definition: avoiding specific requirements and tick-box processes in favour of a purpose and method through which this can be achieved so that it is flexible to the context of the building's function and design requirements. It is based upon thematic links throughout literature to develop a purpose for with Smart Buildings should be designed. This enables a larger amount of flexibility in terms of how it can be practically achieved, allowing it to be moulded to different categories of building. The counter argument to this approach would be that it can be too subjective making it more difficult to create standards around which industry can innovate.

Alternatively, low level definitions focus upon individual sub-systems that are required to be present in order to achieve some form of Smart Building "status". These objective metrics help contractors and provide realistic constraints to designers. However, such low level definitions have a tendency to result in inappropriate elements being incorporated into a building, such as when using sustainability metrics BREEAM and LEED. It is envisaged that this definition of a Smart Building is more suited to being represented in a similar way to that of the SPeAR assessment tool used by Arup, as shown in Figure 8-1 and Figure 8-2.

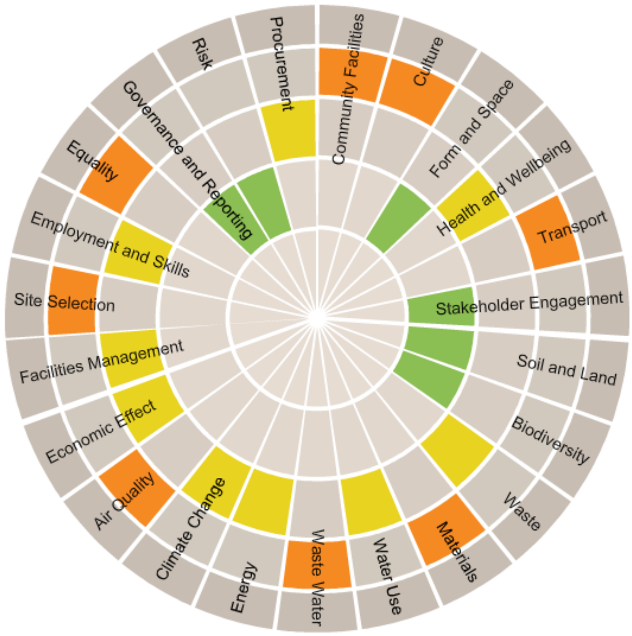


FIGURE 8-1 - SUSTAINABLE PROJECT APPRAISAL ROUTINE EXAMPLE IMAGE [192]

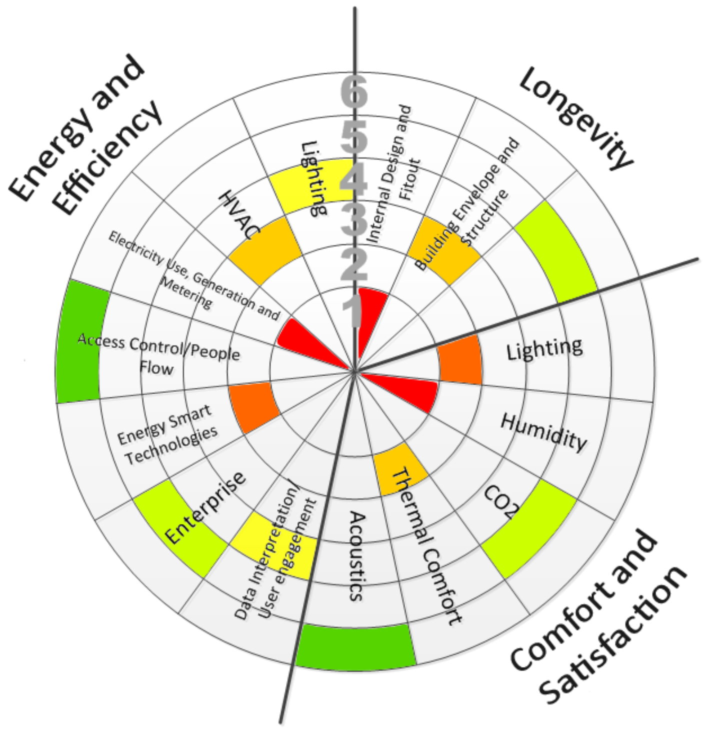


FIGURE 8-2 - SMART BUILDING ASSESSMENT METHOD EXAMPLE

The colours assigned to each segment are defined by a justified value given to the approach taken to that area. Furthermore, it is recognised that there are virtuous cycles through which one improvement impacts upon other areas. Within Smart Buildings, this could be exemplified by a high level of user engagement and data interpretation translating into higher levels of thermal comfort by acknowledging the existence of adaptive comfort and enabling and assisting occupants to achieve their own comfort conditions.

8.2 *The role of information in Smart Buildings*

One feature of Smart Buildings is the ability to collect data from a wide range of sources previously underutilised within a buildings operation and adapt to it. This enables more continuous exchange of information between occupants and building and innovative approaches to comfort provision and energy efficiency: exemplified by the two case studies in this research.

8.2.1 Case Study 1 – The Information Commons

The first case study used an existing building, proposing that if real time and predicted data were assimilated and used to adapt a building, the energy efficiency of that building could be increased. This work was not simply demonstrating the adage that “turning your lights off saves energy” but was looking at how data that we already have access to can be utilised to create a building within that can reduce energy use without impacting upon occupant satisfaction. One of the important aspects of this study was the availability of data: the access gates at the entrance to the building were installed to prevent equipment and books from being removed from the library by those not involved with the university. However, the data that they produce on occupancy was the basis upon which this method of energy saving was based. The author is not suggesting that every building have access gates, but that the plethora of research into occupancy sensors such as that Naghiyev et al. [193] has potential benefits beyond those currently sighted: currently, occupancy data is thought to enable tighter control of an environment, whereas this work is demonstrating that it can be used to facilitate the control of physical space.

Another source of information used within this study is satisfaction data. Feedback within buildings is important, as recognised by the vast amount of work, both industrial and academic, into post occupancy evaluations. However, using feedback in a building enables occupants to become more a more central part of its operation. Although this research was unable to use real time feedback data during the pilot study, the method of data collection utilised could be extended for continuous use in order to ensure that changes to the building were not affecting occupant satisfaction rates.

8.2.2 Case Study 2 – The Diamond

The second study proposed that the Smart Buildings have the ability to analyse thermal comfort data from both building and occupants alongside to facilitate informed choices of comfort conditions in a flexible space. The ability to assimilate real time data enables the possibility of occupants becoming active participants in the performance of a building without impacting upon the environment itself. The alternative approaches would be either to have occupants being passive recipients of a buildings environment, which is widely regarded as an ineffective approach, or allow occupants to have responsibility to change their environment, which results in unpredictable and potentially wasteful energy use.

This approach to building conditioning accepts and embraces the variations in conditions throughout a space rather than attempting to homogenise the environment. Not only does this allow for occupants to achieve their own comfort, it also allows for more predictable energy consumption; rather than adapting the building to slight variations in external conditions, the occupants are able to adapt to the conditions. This ability to relax the coupling between the building services and set points within the building based upon occupancy facilitates a step reduction in energy reduction.

8.2.3 Smart Approaches

The two case studies in this research look to demonstrate concepts that could be used within Smart Buildings within the definition developed in Chapter 3. They meet the definition for the following reasons:

- Data used is from a wide range of sources: energy meters, occupancy predictions, occupant thermal preferences, and detailed thermal variation data.
- The building occupant relationship adapts to this information. In the Information Commons the capacity is changed with occupancy predictions. In the Diamond the occupants adapt to the thermal environment in the building upon choosing their position.
- Both methods have the purpose of reducing energy and either maintaining or increasing comfort rates.

8.3 *Methods of information acquisition and communication*

This research has assumed that all information required is available. This assumption is based upon real advances in the techniques available to building designers and operators. This section discusses a number of realistically possible methods of collection for each of the categories of information assumed available in this research.

The ability to reconcile human and automated control is fundamental in the design of Smart Buildings and is an increasingly researched area of building operation, such as the work carried out by Cole [132]. Information use within Smart Buildings is a two way flow. The effective transfer of information between occupants and the building allows the building to adapt. However, giving the occupants information about how the building is being run allows them to adapt their behaviour to the building. Therefore, it is important not only to address how data is collected by the building but also the means through which it can be conveyed to its occupants.

8.3.1 Environmental variations

Traditionally, environmental conditions have been monitored using a low number of sensors. These do not give enough detail to develop accurate models of thermal comfort variation on their own. By combining a high number of static and radiant temperature sensors with airflow sensors at the openings, it would be possible to develop a good representation of the variations of conditions throughout a space. However, this will be of limited accuracy and would be expensive.

One more realistic method through which the variations can be predicted is through the development of a real-time CFD model. Real time CFD models already exist and would work in a similar way to automated one-step coupling between building simulation and CFD. The input variables into the CFD model would be flow velocities, floor temperature set-point, external air temperature and solar radiation.

A final method through which the environmental variables could be through the validating of a CFD model by comparing it against a comparatively low number of sensors located throughout the building. By then running the CFD model under a large number of external and internal conditions, it would be possible to build up a set of data that could predict the variations throughout a space based upon previously run CFD simulation.

8.3.2 Thermal comfort preferences

There are two varieties of method through which thermal comfort preference could be utilised to influence occupants' decisions about where they choose to sit within a building. The first would be to present normalised environmental data in an understandable format to the occupants such as through a dashboard. Occupants can then use their previous experiences and knowledge of their own personal preference for that time to choose a location they wish to sit in.

The second method would be to learn individual occupant preferences through feedback mechanisms such as a mobile phone app and use these previous experiences to inform predictions for the type of thermal condition that an occupant is likely to prefer. This can then be fed back to the occupant through a mobile device, or other feedback methods.

8.3.3 Occupancy levels

Existing methods of varying accuracy are currently available to track occupancy. Infrared sensors, entry gate systems, footfall sensors and PIR sensors are some of these. However, recent technologies such as the domestically designed Apple iBeacon are able to sense occupancy through the presence of a smart phone. It can be envisaged that it would be possible not only to track presence in the building but location within the building. It is also possible to track occupancy and movement through wireless camera networks [194].

A reasonable method through which occupancy data can be predicted is through integration of enterprise systems within the building. These will vary between cases, gathering relevant information about the buildings predicted occupancy through timetabling, human resources system integration and room bookings, for example. With the development of middleware platforms and open standards such as LonWorks, XML and BACnet, the ability to integrate a wider range of information sources such as these enterprise systems within the energy strategy is becoming more feasible.

8.3.4 Satisfaction

Within the IC experiment, satisfaction ratings were recorded through interactive screens placed by the exit gates of the building. Although it was not possible within this building to capture more granular and detailed data, it would be feasibly possible to deliver questions of satisfaction through mobile devices which would time and location stamp the response. This would enable the building to adapt future changes in operation to maintain good levels of satisfaction.

8.4 ***Applicability of demonstrated thermal management concepts to other buildings***

This research has demonstrated two examples of smart systems within two university buildings with different characteristics. It would be desirable for the concepts demonstrated to be applicable to further building types. There are a number of similarities between the two buildings used, but for the cross-applicability of these concepts, flexibility is crucial. In the IC, functional flexibility allowed for non-required spaces to be closed, and in the Diamond the space is essentially hot-desking whereby the workstations are different only in location.

Flexible working styles of organisations lend themselves to this required functional flexibility; where there is an existing choice of available places to work such as hot-desking, activity based working and flexible working. Traditionally, non-flexible offices have been so due to the reliance upon paper. It could be argued that with the increasing digitalisation of work, the attachment to a single location is reduced and flexibility of environment choice is increased.

Furthermore, the benefits of the concepts proposed in this research are maximised in buildings in which there is a large variation in occupancies. The time-scale of this variation would be reflected in the complexity of their communication and implementation. For example, a diurnal occupancy swing would require more frequent closing of areas within The IC than closing zones over a summer period.

8.4.1 Comfort conditioning type

The two case studies each had a different form of comfort conditioning. The IC was cooling load dominated and used HVAC units within each zone of the building. The Diamond was naturally ventilated and underfloor heated. However, both research approaches were investigating novel methods through which energy consumption can be tailored to occupancy levels and therefore reduce the energy consumed per occupant hour. The IC physically varied capacity, whereas the Diamond study proposes that occupants can be informed of comfortable places to work.

Therefore, provided flexible functionality and by combining it with further required information sources, occupancy data can be used reduce energy consumption in both mechanically and naturally ventilated buildings.

Furthermore, the process of informing occupants demonstrated in the Diamond study could feasibly apply to mechanically ventilated buildings by recognising a natural tendency for variation of conditions within the building due to natural and built variables: the energy input into conditioning can be minimised to allow for a reasonable variation in conditions.

8.4.2 Building category

The requirement for functional flexibility within a building to enable the concepts proposed in this research naturally limits its application; for example hospitals and industrial buildings have both high utilisation rates and a high proportion of unique purpose specific space. However the benefits of these concepts could be recognised by a number of different building categories.

Classroom and work based educational buildings are suitable because value is seen to be added to the students by opening for longer occupancy hours, even when occupancy drops significantly. Therefore, by using these methods, the economic and environmental cost of that added value reduces.

There are over 200 million square meters of office in the UK. Many of these offices are open plan and have the potential to be flexible working spaces, indeed if they are not already. Occupancy will vary significantly due to different working styles, different schedules and vacancies. It is not uncommon to have the lighting in offices to be linked to occupancy sensors, but occupancy-driven conditioning is a newer concept: the latest research modifies HVAC energy use with occupancy levels. However, the spatial relationship between occupancy and comfort provision has so far been ignored. By turning off zones and making occupants aware of comfortable spaces, flexible working styles can be accommodated while minimising increased cost per occupant hour.

The value provided by hotels is a comfortable space and would be a hard value to compromise on. However, each room has its own individual environmental characteristics imposed upon it by its external environment, whether that be through exposure to direct sunlight, its vertical position in the building or exposure to prevailing winds. The approaches of both case studies in this work could be utilised: either ask tenants whether they prefer cool or warm rooms and correlate the natural conditions within the hotel as such, or become aware of the rooms which would statistically need less conditioning to bring them to a comfortable condition and assign these rooms first.

This research has primarily discussed non-domestic buildings; the smart building definition proposed is largely specific to these. However, the concept of aligning occupant comfort preference with environmental conditions within the residential sector has been addressed by Xu et al. [195] in the period during which this research has been carried out. By simulating the alignment of thermal comfort preferences with a naturally suitable apartment in the case study of 1084 homes, an energy saving between 2.1% and 42% was shown. This study shows the influence of thermal comfort preference on energy consumption and how a similar process as that used in the Diamond study can be used in the residential sector.

8.4.3 Multi-building premises

The top two floors of the Diamond building, including both atrium space and mechanically ventilated space, serve as an extension of the IC's functionality due to the high demand for the IC at peak times. Both buildings are within 300m of each other. This raises both a concern and an opportunity: at the lowest occupancy periods, will the energy use per occupant hour to fulfil a function within the university increase significantly with increased capacity. If, as suspected, it does, then the method used within the IC study could be extended to include the top two floors of the IC. At the lowest occupancy hours, it could be that only the Diamond is comfort conditioned, whilst the IC is predominantly closed.

8.4.4 *Transferring the Method*

The method through which a concept to be used within a Smart Building can be developed into an evidence based concept will vary from building to building based on function and purpose. However, the two investigated in this research share similarities in their approach that can be transferred to future buildings. The process below suggests that there are methods through which both new build and retrofit smart concepts can be identified, evidenced and implemented.

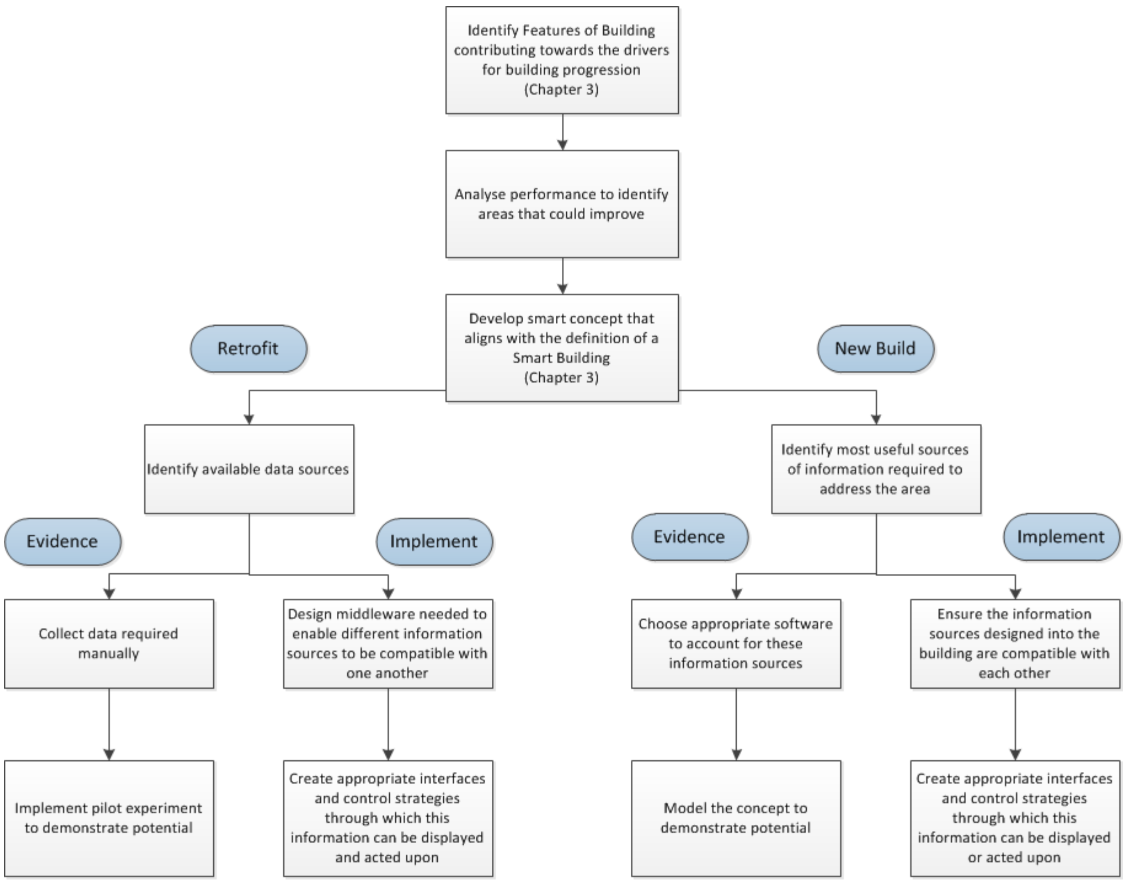


FIGURE 8-3 - PROCESS TO IMPLEMENT SMART BUILDING CONCEPTS

This research has aimed to provide evidence on both existing and new build buildings for two different concepts. The process recognises that the purpose of the smart concepts could be any of the drivers for building progression introduced in Section 3: Longevity, Comfort and Satisfaction and Energy and Efficiency. This process would be transferrable to all building sectors with little modification.

8.5 ***Recognised Limitations***

Both studies carried out in this research have been carried out to demonstrate potential uses of available data within Smart Buildings. However, in order to keep the research at a level manageable in terms of time and effort, a number of concessions needed to be made. In order to acknowledge the context to which this research can be applied, these concessions are discussed below.

8.5.1 The IC

8.5.1.1 Impact of pilot on satisfaction levels

The satisfaction levels within the IC were intended to be collected during the two week pilot study in order to compare against the original readings that were taken during regular periods of operation. The screen stands, and therefore screens, were hard installed into the floor or the IC, requiring the floor to be taken up by building services. However, the cables disconnected during installation, resulting in the screen running out of battery. The resulting conclusions have suggested that satisfaction is related to the percentage free occupancy space in the building, but it would have been useful to confirm that there was no specific attachment from the occupants to the zones turned off in the pilot.

8.5.1.1.1 The reasons for satisfaction

As described within the work, the question asked during the study was chosen in an attempt to disassociate satisfaction with the services provided by the IC from personal working, personal or University issues whilst still keeping the question short enough to be easily read and replied to within the exiting of the building. Ideally, we would like to know exactly what caused the satisfaction or dissatisfaction with the IC, but for this to be useful, hundreds of occupants would need to engage in surveys run at different occupancy periods. Methods to achieve this were discussed but it was important to the building managers that students were largely uninterrupted during their work in the building.

The ability to identify the extent of which the closure of zones affects an individual's satisfaction with their experience of a building with absolute certainty would require an extensive rollout of experiments and surveys distributed spatially and temporally throughout the pilot study. However, if this had been done and resulted in the closures having an impact, other identified questions would then increase in importance, such as the role of expectation based on prior experience, and the value that the building owner places on energy efficiency when compared to occupant satisfaction.

8.5.1.1.2 Dynamic opening and closing

This project aimed to demonstrate the potential and ability for a building to vary occupiable space with capacity, therefore reducing variations in energy use per occupant hour. However, it was only possible to carry out this work on two selected zones over a continuously under occupied two week period. This was due to resistance from the building managers for fear of impacting upon student experiences, an issue that was recurring throughout the project. This meant that it was not possible to see the potential of more temporally flexible closing on both energy saving and occupant satisfaction. Within this study, a number of assumptions needed to be made to demonstrate the potential of dynamic opening on energy consumption that could therefore be questioned without implementing a further study.

Smart Buildings have significant potential to make use of dashboards and screens to clearly communicate and implement changes in use. This would help avoid disruption to occupants of the building but without this, it is likely that there would be some disruption and confusion.

It would have been beneficial to implement a basic form of dynamic closing of spaces to see how students would respond given different warning time periods.

8.5.1.2 Occupancy within specific rooms

Footfall monitors were installed in one of the zones that were used within the pilot study. However, the accuracy of the device was poor. It was intended to demonstrate that low occupancy within the building was equally represented within the two zones in question. Although not vital for this static study, the ability to monitor occupancy on a more granular level than occupancy gates would allow for a better representation about which zones are more likely to be underutilised within certain time periods, thus allowing for less disruption to occupants. The impact of not knowing the occupancy distribution throughout the building was that the requirements for different functionality, such as silent study computing, and preference, when occupancy is weighted towards a single area, was not known. These variations could impact upon the energy use per occupant hour per zone, as well as the potential for dynamic closure of different zones, since these would need to be aligned with demand for the specific functions within these zones.

8.5.2 The Diamond

8.5.2.1 Lack of validation

In the majority of research carried out using CFD, the accuracy of the results is paramount to the usefulness of the work. This is because the work will be attempting to validate the utilisation of a technique or calculation method for a given application. Throughout this research, a number of these studies have been referenced, especially those carried out on atria by Oosthuizen and Hussain [105, 169, 170]. These studies have repeatedly demonstrated effective CFD techniques that can be used within different parameters.

In this study, CFD was used as a tool through which the variation of conditions within a space could be represented. Acknowledging the limitations and complexity presented in the building to be modelled, the methods of validation are very limited. Since the building had not yet been built, experimental validation was not possible. Cook and Linden have both used salt baths to validate their CFD models, which is very useful when modelling relatively simple scenarios such as single inlet, single outlet buoyancy driven flow to determine accuracy of specific techniques. In order to validate a model including multiple inlets, natural and forced convection, multiple outlets and internal obstructions, the validation process would be extremely difficult to achieve. With the necessity for this project debateable, it was decided that credibility of solution would be created through the following methods:

- A well performing building simulation model would be used to supply initial boundary conditions.
- Utilising meshing and numerical methods and techniques previously validated by existing research in similar field where possible.
- Examining the resultant model to see if the building is performing as expected.

However, the lack of exact model performance validation may mean that some aspects of the model may not perform as they would in reality. For example, it has been shown that buoyancy and heat transfer has occurred in the model, but whether these would correspond to the same floor temperatures in reality has not been shown. The impact on the result would be a likely consistent shift to one side of the results shown here, which is why it is important to understand that the results are relative to each other, and that it is the concept being demonstrated as opposed to the realistic modelling of a large atrium.

8.5.2.2 Geometry simplifications

As with most CFD models, reasonable simplifications needed to be made to the geometry that was modelled in both Building Simulation and CFD models. In both models, the obstructions modelled were the pods. Adding more detailed obstacles such as the desks themselves, people, staircases and balustrades would be difficult within building simulation, whilst in CFD the extra detail would require a significantly increased number of elements. The increased time required to solve this model, along with stability issues associated with varying meshing quality, influenced the decision to simplify the model to include the pods as the only obstacles.

In reality, the presence of these obstructions could have a significant effect on the airflow within the space, in particular the flow across the floor of the building. The flow of incoming air would be less uniform in direction and velocity, resulting in a wider variation of heat transfer coefficients over the floor. The effect of this may be to reduce the impact of forced to natural convection, resulting in a more distributed heat source.

The impact of these objects however, is less likely to have an impact on temperature conditions than local air velocities. Physical obstructions to airflow are likely to inhibit the flow of air, and therefore result in perceptively warmer conditions. This would therefore suggest that the required heat input into the building would be higher in reality.

8.5.2.3 Underfloor heating

As discussed in Chapter 6, the transfer of heat within CFD models is highly dependent upon the quality of mesh. Therefore, distributed heat sources to represent each of the individuals, computers and walls would not be feasible within the resources available for such a large building. The assumption that all energy input is delivered through the floor is more accurate for winter conditions than for summer conditions, as shown by the ratios of energy sources in Figure 6.10.

By modelling each of the heat sources individually, it would be expected that there would be a slightly more graduate transition between cool and warm areas of the building. Theoretically, as shown by Linden [100], both vertically distributed and horizontally distributed point buoyancy sources of different strengths will cause more layers of stratification. However, the strength of individual bodies and computers is much less than that of the underfloor heating and the solar gain modelled in IES will be distributed throughout the space, since it is diffuse radiation.

8.5.2.4 Dynamic variation of local conditions

The thermal environment modelled within this research has constant internal conditions. However, within a real environment the local and general environmental conditions will vary with time.

Locally, gusts of wind and periods of direct solar radiation will impact upon thermal comfort conditions, especially in a building where windows and shading cannot be controlled. Within literature, locally dynamic conditions with short time scale changes are seen to have minimal effects on general thermal comfort.

The CFD model developed in this research uses steady state conditions, primarily for conservation of computing resources. However, in reality, a buildings' internal environment is transient with varying external conditions. There is a large body of research suggesting that either asymmetrical or dynamic internal thermal environments can have positive impacts on thermal comfort, especially within naturally ventilated spaces within warmer environments. As previously mentioned, this atrium does not strictly form a naturally ventilated space due to its automated windows and lack of manual control. However, the inherently dynamic conditions within a building conditioned by window control strategies will lead to dynamic conditions that may lead to variations in perceived comfort conditions.

This work is more concerned with the trends in environmental conditions within the space based upon external conditions than predicting the exact temperature and flow conditions. However, the recognition that dynamic conditions vary thermal comfort in some form is one example of how static CFD modelling could perhaps be deficient if specifying comfort to the individual workstation basis.

8.5.2.5 Wall modelling simplifications

As discussed in §5.2.6 a scalable wall function was applied to the floor to enable the model to transfer heat. This was necessitated through the wide variation in floor mesh sizes generated. With increased computing power it may have been possible to segment the floor to provide more consistent y* values and create a finer near surface mesh, allowing for a more proven wall function to be used. The impact of this limitation is that the near wall turbulence regimes were ignored and assumed to be in the log law layer or above, meaning that heat transfer coefficients used and therefore heat transfer values may not have been fully realistic. However, as previously explained, this impact was on the accuracy of the model itself, rather than on the proof of concept developed within this research.

8.5.2.6 Thermal comfort measurements

As discussed in other chapters, it is recognised that thermal comfort is based upon a wide range of factors. PMV, the metric of thermal comfort used in both existing standards and this research, is based upon air velocity, air temperature, mean radiant temperature, humidity, metabolic rate and temperature. However, the CFD modelling only measured the two former variables. The mean radiant temperature was accounted for as well as possible, but clothing levels, humidity and metabolic rate were assumed constant. Uniform humidity is a reasonable assumption, and metabolic rates would only vary significantly if activity levels varied a lot which is unlikely in a working environment. However, clothing levels will vary, leading to a discussion about three possible deviations in the results.

The first would be that a random distribution of clothing levels throughout the space would be likely to create less accurate suggestions of suitable spaces and lower comfort ratings. However, the opposing argument would be that most occupants can adapt to their thermal environment through layers. This basic form of adaptive comfort is recognised throughout literature as an argument for less standardisation, but in this case, it could be used as a “buffer” to the suggested comfortable spaces.

The final discussion point on the inclusion of clothing levels would be an extension of the concept that informing occupants allows for adaptation to building conditions without the need for extra energy and complexity. Hypothetically, it could be possible to communicate to those using the building that it may be a little colder or warmer than normal, allowing them to adapt their clothing accordingly where possible. This idea is potentially controversial, especially in the context of occupant expectations discussed in 8.5.4.

8.5.2.7 Comfort is not just thermal

Thermal comfort has been studied in this research. However, it is recognised that comfort is not solely based upon the thermal environment. Air quality is another factor, but perhaps more relevant to the open spaces in this research, acoustic comfort will influence overall comfort levels. This research used thermal comfort as a demonstrative tool, fully aware that when implemented in reality, comfortable conditions would need to take into account other variables. However, it is possible to model acoustic conditions using similar methodologies to the current research. Through enterprise systems, sensor networks, occupant interaction and agent based learning, it is reasonable to assume that all of this information is possible to be collected and by applying the approach used in this research, it could be possible to enable occupants to make informed decisions of their choice of location based upon a number of variables that can be developed over time.

8.5.2.8 Location choice is not just comfort driven

When entering a building, even if it is has highly distributed functionality, it is likely that thermal comfort is not the only factor upon which the decision of a work location is based. Other factors would include proximity to colleagues or friends, preferred views from a window, proximity to natural light and, as mentioned previously, acoustic qualities. However, thermal comfort was a demonstration of the potential of utilising information exchange between the occupants and building. Therefore, it is reasonable to hypothesise that additional factors would be able to contribute to the suggestions of location suitable for a person based upon information from a wider range of sources, which was discussed when developing the definition of a Smart Building in Chapter 3.

The impact of this limitation on the results of the work would be that the distribution of occupants would no longer be based upon a single dimension (thermal comfort) but upon multiple dimensions and therefore would reduce the number of exact seat matches available to each occupant. This would either have an impact on thermal comfort, or an impact on satisfaction of the occupants, depending upon which dimension was prioritised in seat selection.

8.5.3 Occupants are not robots

A significant amount of current research endeavours to change the existing standardisation of internal thermal environment. This research is both looking to reduce energy consumption and improve comfort conditions. It agrees with and embraces the research suggesting that occupants are not passive recipients of their environment, and can adapt to conditions by varying their clothing levels or, where possible, their physical local environment. However, this research also recognises that varying thermal preferences exist and that optimum comfort conditions will be achieved when occupants can be in a condition that they would not change given the chance.

The Diamond study suggests that occupants can choose a suitable location based upon information provided to them that takes into account the current environmental conditions of the atrium. However, it is pertinent to discuss the level of specificity given:

- If it is suggested that a single occupant should sit in a single seat, then it is rather opposing the idea that occupants should be able to achieve their own comfort.

- The next level would be to suggest a number of different workstations that may be suitable. This would not only allow for an occupant to choose a preferred seat, but other factors could be included in this decision such as those discussed in 8.5.2.6. However, in real buildings, the confidence in selecting comfortable single seats in a dynamic environment may be unjustified.
- The third variation could be using trends in building conditions to suggest wider locations in the building. This would allow occupants to make informed decisions about where they would prefer to sit based upon more than simply thermal comfort, whilst still enabling the building to correlate energy input with occupancy levels.
- If there is not a space that would fulfil the occupant's requirements, then they could be informed that the available seat was not optimal. They could then be more satisfied, as they were forewarned.

8.5.4 The role of expectation

Interestingly, one of the most significant inhibitors on the study on The IC was the lack of willingness by staff in charge of running the building to allow for dynamic experiments to be carried out involving a large amount of active student engagement, such as during term time; even if the end result was the potential for a significant amount of financial savings. The reasons for this were that it had the potential of causing a negative impact upon the student experience; it was thought that closing part of the building devalued the concept of a 24 hour, 365 day building that the students can use.

The user experience of a building must be considered, and it may be correct that the experience of the building is beyond the sole need to fulfil a function within a comfortable environment, but this view of the building managers develops the question of whether student expectation plays a role in their experience of a building. Firstly, if a dynamic building varied its occupiable spaces when it is first experienced by a new occupant, it could be questioned whether their overall experience would be affected to the same perceived extent as current occupants, with their developed expectations.

Similarly, the study on The Diamond requires interaction with occupants and the role of expected experience when using the building will influence the effectiveness of a method like this.

It has been shown repeatedly that frequent exposure to a given thermal condition can impact upon expected conditions and therefore comfort preferences [196], and similarly the customer satisfaction models in a variety of non-building related fields place importance on expectation. Universities are therefore good candidates for this type of experiment with a relatively high turnover of occupants in four year cycles. A further complexity however would be the role of increasing tuition fees on the expectations of service provided to students. A student may well form the opinion that “I pay enough money, they should make the whole building comfortable all the time”. This self-serving mind set would be symptomatic of potentially deeper topics in the relationships between government policy, students and universities, yet is still important to consider.

9 Conclusion

Within this chapter the conclusions of the work are presented before proposing further useful research that has arisen from this work.

Modern buildings have the ability to generate a huge amount of information that, in the opinion of the author, is underutilised. The dynamics between buildings and occupants are changing as the understanding of comfort and acceptability moves from a desire for tightly controlled environments to adaptive comfort models.

This work has utilised a small number of available information sources to demonstrate its effect on a small number of building performance variables in two educational buildings. Whilst touching upon a small area of the built environment, the impacts of the novel approaches taken can have a larger impact when applied to different contexts. It is a useful addition to work on Smart Buildings by providing the platform upon which further work can be developed as well as two example studies demonstrating the potential impact of a new approach to building-occupant interaction.

9.1 *Conclusions*

The following points form the conclusions from this research:

- The disparate nature of research into intelligent and smart buildings has been demonstrated before forming a definition of Smart Buildings based upon current literature. The upper and lower bounds of a Smart Building have been defined in order to prevent further segmentation and provide a unified vision for the purpose of Smart Buildings and a method about how to achieve it.
- It has been shown that by understanding a building and its users, it is possible to achieve higher satisfaction and energy performance than a random process. In case study 2, by understanding the variation in conditions within a large space, comfort levels can be increased when at peak occupancy whilst energy performance can be increased at lower occupancies.
- It has been shown that, as the occupancy of a building reduces, it is possible to change a buildings energy use provided that you understand the building and occupants. By knowing the future occupancy of the building and the respective capacities in which occupant

experience is not significantly affected, the usable capacity of the building can be physically altered to reduce energy demand. Whilst access gates were used in this building, other sources of occupancy data could be used, such as occupancy sensors or the utilisation of enterprise system data. By knowing who is going to be using the building, and when, it is possible to tailor the capacity of a building to meet the required functionality whilst minimising wasted energy resources.

- It has been shown that the metric of energy use per occupant hour (kWh $person^{-1}$ $hour^{-1}$) can be a more relevant indicator of energy efficiency than traditional metrics if the data required is available. It has been shown that this metric is able to account for changes in occupancy.
- It has been confirmed that building simulation modelling can complement the use of computational fluid dynamics. This can then be used to provide internal boundary conditions to the CFD model if the building is in the design or build stage.
- It has been shown that in problematic and complex computational fluid dynamics models with very large ranges of y^+ values along a heat transfer boundary and a limited amount of resources available, the scalable wall function is able to successfully model heat transfer from the wall to the fluid.
- The research indicates that in a large, wide atrium with continuous openings over each end, during normal operation, downdrafts are likely to occur and wind driven flow dominates buoyancy driven flow.
- The research indicates that within an atrium large enough to have net inflows from opposite ends of the space, with outflows from the upper vents and underfloor heating, a plume can form in a similar fashion to a point source heating load. The internal variation of thermal conditions become larger as the incoming air becomes colder.

9.2 *Further research*

This research provides a good base upon which future work can be developed, both in relation to the specific projects researched and the higher level approach to Smart Building concepts.

9.2.1 The extent to which occupants can adapt

This research agrees with the adaptive comfort approach whereby occupants can achieve their own comfort conditions through adaptation. The adaptation suggested in this work however has very little research. Therefore, it would be useful to investigate the time scales needed when informing occupants about changes to their environment, whether that be a closure of space, or the changing of comfort variables. The optimum balance whereby satisfaction is not reduced but performance is increased would be sought. This will then impact upon the extent to which a building can become dynamic. A methodology could be developed which can be transferred to different building types.

9.2.2 Expectation of buildings

Current research into expectation in buildings has predominantly focussed upon comfort, whether it is thermal, acoustic or lighting. However, in order to develop the hypothesis of adaptive occupants, it would be valuable to investigate the role that expectation has on an occupant's interaction with a building's physical space to achieve a purpose of productive work.

9.2.3 Distributed functionality

This research recommends that in order for occupants to move to suitable spaces, the limiting factors need to be minimised. One of these is unique functions only available in specific places. Therefore it would be useful to see the impact of distributed functionality on energy saving potential and how this requirement would impact upon the physical design attributes of the building itself.

9.2.4 *Inclusion of further variables*

It has been acknowledged that thermal comfort is just one factor that will influence a choice of location, and that the research into The Diamond is an initial investigation into a single variable. It would therefore be beneficial to explore the influence of further variables on choice of working location, and therefore the impact this will have on the ability to suggest suitable locations.

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10.1 *Peer Reviewed Journals*

A.H. Buckman , M. Mayfield , Stephen B.M. Beck , (2014) "What is a Smart Building?", Smart and Sustainable Built Environment, Vol. 3 Iss: 2, pp.92 – 109

10.2 *Refereed Conferences*

Buckman AH, Mayfield M, Meijer R and Beck SBM. Progressing from Intelligent to Smart Buildings. ICEBO - International Conference for Enhanced Building Operations 2013. Montreal: Energy Systems Laboratory, 2013.

Mayfield M, Buckman AH, Jubb S, and Wootton C. Optimising Building Design for Smart Grid Efficiency. ISC2 - International Conference on Smart Cities, Guadalajara, 2015.

10.3 *Non-Refereed Conferences*

Buckman AH, Mayfield M, Beck SBM. Some like it hot…. Sustainability and Buildings: Walking the tightrope to 2050, Loughborough, 2015

10.4 *Invited Guest Lectures*

Buckman, AH., What is a Smart Building?, Modern Building Design Module, MSc in Architectural Engineering: Environmental Design, University of Bath, 2015

Buckman, AH., Smart Data Applications, Modern Building Design Module, MSc in Architectural Engineering: Environmental Design, University of Bath, 2015

11 Appendix

11.1 *A1: Workstation Positions with associated script*

An example script is as follows:

Workstation number	x	y	z		; concatenate cells
1	-2.14	-11.13	1.10		(ti-menu-load-string "\nsurface/point-surface point-1 -2.14 -11.13 1.1")

This was repeated for all workstation positions with the following coordinates

2	-2.782	-11.024	1.10		194	-14.766	-8.374	10.10
3	-1.926	-9.328	1.10		195	-15.729	-8.586	10.10
4	-2.568	-9.222	1.10		196	-16.05	-7.844	10.10
5	-1.819	-8.48	1.10		197	-15.301	-7.42	10.10
6	-2.461	-8.374	1.10		198	-21.079	-8.798	10.10
7	-1.605	-6.572	1.10		199	-21.721	-8.798	10.10
8	-2.247	-6.466	1.10		200	-21.079	-7.95	10.10
9	-1.498	-5.618	1.10		201	-21.721	-7.95	10.10
10	-2.14	-5.512	1.10		202	-21.079	-6.254	10.10
11	-1.284	-3.816	1.10		203	-21.721	-6.254	10.10
12	-1.926	-3.71	1.10		204	-21.079	-5.3	10.10
13	-1.177	-2.862	1.10		205	-21.721	-5.3	10.10
14	-1.819	-2.756	1.10		206	-44.512	3.71	10.10
15	-0.963	-1.06	1.10		207	-44.512	4.452	10.10
16	-1.605	-0.954	1.10		208	-44.512	6.042	10.10
17	-3.852	-2.968	1.10		209	-44.512	6.89	10.10
18	-5.885	-2.968	1.10		210	-44.512	8.48	10.10
19	-8.132	-8.798	1.10		211	-44.512	9.222	10.10
20	-7.98539	-9.52816	1.10		212	-44.512	10.918	10.10
21	-7.56789	-10.1472	1.10		213	-44.512	11.66	10.10

22	-6.94305	-10.5608	1.10		214	-48.685	11.13	10.10
23	-6.206	-10.706	1.10		215	-49.969	11.13	10.10
24	5.46895	10.5608	1.10		216	-51.467	11.13	10.10
25	-4.84411	-10.1472	1.10		217	-52.216	11.13	10.10
26	-4.42661	-9.52816	1.10		218	-56.496	11.13	10.10
27	-4.28	-8.798	1.10		219	-57.245	11.13	10.10
28	-4.42661	-8.06784	1.10		220	-56.496	12.084	10.10
29	-4.84411	-7.44884	1.10		221	-57.245	12.084	10.10
30	-5.46895	-7.03524	1.10		222	-60.562	11.13	10.10
31	-6.206	-6.89	1.10		223	-61.311	11.13	10.10
32	-6.94305	-7.03524	1.10		224	-60.562	12.084	10.10
33	-7.56789	-7.44884	1.10		225	-61.311	12.084	10.10
34	-7.98539	-8.06784	1.10		226	-63.237	11.13	10.10
35	-26.108	-4.24	1.10		227	-63.986	11.13	10.10
36	-25.9614	-4.97016	1.10		228	-63.237	12.084	10.10
37	-25.5439	-5.58916	1.10		229	-63.986	12.084	10.10
38	-24.919	-6.00276	1.10		230	-65.591	11.13	10.10
39	-24.182	-6.148	1.10		231	-66.34	11.13	10.10
40	-23.445	-6.00276	1.10		232	-65.591	12.084	10.10
41	-22.8201	-5.58916	1.10		233	-66.34	12.084	10.10
42	-22.4026	-4.97016	1.10		234	-65.056	7.95	10.10
43	-22.256	-4.24	1.10		235	-64.2	7.95	10.10
44	-22.4026	-3.50984	1.10		236	-63.13	7.95	10.10
45	-22.8201	-2.89084	1.10		237	-61.953	7.844	10.10
46	-23.445	-2.47724	1.10		238	-61.097	7.738	10.10
47	-24.182	-2.332	1.10		239	-60.134	7.632	10.10
48	-24.919	-2.47724	1.10		240	-59.171	7.314	10.10
49	-25.5439	-2.89084	1.10		241	-58.208	6.89	10.10
50	-25.9614	-3.50984	1.10		242	-55.961	5.3	10.10

51	-31.886	-8.268	1.10		243	-55.105	4.664	10.10
52	-31.7394	-8.99816	1.10		244	-54.463	3.922	10.10
53	-31.3219	-9.61716	1.10		245	-54.035	3.074	10.10
54	-30.697	-10.0308	1.10		246	-53.714	2.12	10.10
55	-29.96	-10.176	1.10		247	-53.73	1.06	10.10
56	-29.223	-10.0308	1.10		248	-53.73	0.106	10.10
57	-28.5981	-9.61716	1.10		249	-53.73	-0.848	10.10
58	-28.1806	-8.99816	1.10		250	-53.607	-1.802	10.10
59	-28.034	-8.268	1.10		251	-54.035	-2.65	10.10
60	-28.1806	-7.53784	1.10		252	-54.57	-3.392	10.10
61	-28.5981	-6.91884	1.10		253	-55.105	-4.24	10.10
62	-29.223	-6.50524	1.10		254	-55.64	-5.088	10.10
63	-29.96	-6.36	1.10		255	-56.282	-5.83	10.10
64	-30.697	-6.50524	1.10		256	-60.562	-8.162	10.10
65	-31.3219	-6.91884	1.10		257	-61.418	-8.48	10.10
66	-31.7394	-7.53784	1.10		258	-62.381	-8.692	10.10
67	-39.055	-8.48	1.10		259	-63.237	-8.798	10.10
68	-41.623	-10.176	1.10		260	-64.2	-8.904	10.10
69	-43.549	-4.77	1.10		261	-65.056	-8.904	10.10
70	-43.4024	-5.50016	1.10		262	-66.019	-8.904	10.10
71	-42.9849	-6.11916	1.10		263	-66.982	-8.798	10.10
72	-42.36	-6.53276	1.10		264	-67.838	-8.586	10.10
73	-41.623	-6.678	1.10		265	-68.801	-8.268	10.10
74	-40.886	-6.53276	1.10		266	-69.55	-7.95	10.10
75	-40.2611	-6.11916	1.10		267	-70.513	-7.632	10.10
76	-39.8436	-5.50016	1.10		268	-71.369	-7.102	10.10
77	-39.697	-4.77	1.10		269	-72.011	-6.572	10.10
78	-39.8436	-4.03984	1.10		270	-72.653	-6.042	10.10
79	-40.2611	-3.42084	1.10		271	-73.509	-5.194	10.10

80	-40.886	-3.00724	1.10		272	-74.151	-4.346	10.10
81	-41.623	-2.862	1.10		273	-74.472	-3.604	10.10
82	-42.36	-3.00724	1.10		274	-74.793	-2.65	10.10
83	-42.9849	-3.42084	1.10		275	-75.114	-1.696	10.10
84	-43.4024	-4.03984	1.10		276	-75.114	-0.848	10.10
85	-48.471	0.212	1.10		277	-75.007	0.212	10.10
86	-48.471	1.272	1.10		278	-74.793	1.06	10.10
87	-50	0.212	1.10		279	-74.472	1.908	10.10
88	-49.755	1.59	1.10		280	-74.151	2.756	10.10
89	-56.068	-1.484	1.10		281	-73.509	3.604	10.10
90	-57.78	-3.18	1.10		282	-73.081	4.24	10.10
91	-54.998	1.06	1.10		283	-72.332	4.982	10.10
92	-56.282	-0.424	1.10		284	-71.476	5.512	10.10
93	-57.352	2.544	1.10		285	-70.941	6.042	10.10
94	-57.352	4.24	1.10		286	-64.521	5.406	10.10
95	-57.352	-7.844	1.10		287	-64.414	6.148	10.10
96	-57.137	-8.639	1.10		288	-63.665	5.3	10.10
97	-56.5495	-9.22098	1.10		289	-63.558	6.042	10.10
98	-55.747	-9.434	1.10		290	-62.702	5.088	10.10
99	-54.9445	-9.22098	1.10		291	-62.595	5.83	10.10
100	-54.357	-8.639	1.10		292	-61.739	4.982	10.10
101	-54.142	-7.844	1.10		293	-61.632	5.724	10.10
102	-54.357	-7.049	1.10		294	-60.883	4.77	10.10
103	-54.9445	-6.46702	1.10		295	-60.776	5.512	10.10
104	-55.747	-6.254	1.10		296	-59.92	4.664	10.10
105	-56.5495	-6.46702	1.10		297	-59.813	5.406	10.10
106	-57.137	-7.049	1.10		298	-63.023	1.484	10.10
107	-74.044	4.028	1.10		299	-63.772	1.59	10.10
108	-74.151	5.724	1.10		300	-62.916	2.332	10.10

109	-72.974	8.904	1.10		301	-63.665	2.438	10.10
110	-74.472	9.964	1.10		302	-62.809	3.18	10.10
111	-81.427	7.42	1.10		303	-63.558	3.286	10.10
112	-80.25	6.572	1.10		304	-60.562	1.06	10.10
113	-80.785	4.664	1.10		305	-59.492	1.272	10.10
114	-79.501	3.71	1.10		306	-58.101	2.438	10.10
115	-79.18	1.59	1.10		307	-57.352	1.484	10.10
116	-79.18	0	1.10		308	-56.282	1.802	10.10
117	-78.752	-3.498	1.10		309	-55.854	0	10.10
118	-77.361	-4.452	1.10		310	-55.64	-1.484	10.10
119	-77.04	-6.678	1.10		311	-57.352	-1.06	10.10
120	-77.04	-8.374	1.10		312	-58.101	-2.968	10.10
121	-75.328	-10.07	1.10		313	-57.994	-1.272	10.10
122	-75.328	-11.66	1.10		314	-61.418	-3.18	10.10
123	-76.612	-11.66	1.10		315	-62.488	-1.696	10.10
124	-24.717	-13.038	5.60		316	-62.381	-3.71	10.10
125	-25.466	-13.038	5.60		317	-62.381	-4.876	10.10
126	-28.89	-13.038	5.60		318	-61.418	-6.254	10.10
127	-29.746	-13.038	5.60		319	-62.381	-6.784	10.10
128	-31.244	-13.038	5.60		320	-64.2	-4.028	10.10
129	-31.993	-13.038	5.60		321	-65.27	-3.498	10.10
130	-33.705	-13.038	5.60		322	-65.056	-4.452	10.10
131	-34.454	-13.038	5.60		323	-65.591	-6.996	10.10
132	-40.339	-13.038	5.60		324	-66.661	-6.572	10.10
133	-41.088	-13.038	5.60		325	-68.266	-4.876	10.10
134	-42.8	-13.038	5.60		326	-69.122	-5.83	10.10
135	-43.549	-13.038	5.60		327	-69.978	-3.922	10.10
136	-46.866	-13.038	5.60		328	-72.011	-3.71	10.10
137	-47.615	-13.038	5.60		329	-71.262	-2.756	10.10

138	-49.327	-13.038	5.60		330	-71.048	-1.06	10.10
139	-50.076	-13.038	5.60		331	-73.188	-0.636	10.10
140	-51.681	-13.038	5.60		332	-72.332	0.106	10.10
141	-52.43	-13.038	5.60		333	-72.76	1.06	10.10
142	-44.405	4.77	5.60		334	-71.048	1.484	10.10
143	-44.405	5.512	5.60		335	-69.229	1.908	10.10
144	-44.405	7.208	5.60		336	-69.764	4.028	10.10
145	-44.405	7.95	5.60		337	-68.694	2.544	10.10
146	-44.405	9.646	5.60		338	-69.657	-2.12	10.10
147	-44.405	10.388	5.60		339	-67.945	-1.696	10.10
148	-48.471	11.13	5.60		340	-68.373	-0.636	10.10
149	-49.22	11.13	5.60		341	-67.624	0.212	10.10
150	-48.471	12.084	5.60		342	-67.196	1.802	10.10
151	-49.22	12.084	5.60		343	-66.554	0	10.10
152	-50.932	11.13	5.60		344	-31.565	-6.148	14.60
153	-51.681	11.13	5.60		345	-31.03	-7.06599	14.60
154	-50.932	12.084	5.60		346	-29.96	-7.06599	14.60
155	-51.681	12.084	5.60		347	-29.425	-6.148	14.60
156	-54.57	14.098	5.60		348	-29.96	-5.23001	14.60
157	-55.319	14.098	5.60		349	-31.03	-5.23001	14.60
158	-54.57	14.84	5.60		350	-33.491	-8.798	14.60
159	-55.319	14.84	5.60		351	-32.956	-9.71599	14.60
160	-57.031	14.098	5.60		352	-31.886	-9.71599	14.60
161	-57.78	14.098	5.60		353	-31.351	-8.798	14.60
162	-57.031	14.84	5.60		354	-31.886	-7.88001	14.60
163	-57.78	14.84	5.60		355	-32.956	-7.88001	14.60
164	-59.492	14.098	5.60		356	-33.598	-3.498	14.60
165	-60.241	14.098	5.60		357	-33.063	-4.41599	14.60
166	-59.492	14.84	5.60		358	-31.993	-4.41599	14.60

167	-60.241	14.84	5.60		359	-31.458	-3.498	14.60
168	-62.167	14.098	5.60		360	-31.993	-2.58001	14.60
169	-62.916	14.098	5.60		361	-33.063	-2.58001	14.60
170	-62.167	14.84	5.60		362	-35.631	-6.042	14.60
171	-62.916	14.84	5.60		363	-35.096	-6.95999	14.60
172	-60.241	11.13	5.60		364	-34.026	-6.95999	14.60
173	-60.99	11.13	5.60		365	-33.491	-6.042	14.60
174	-62.809	11.13	5.60		366	-34.026	-5.12401	14.60
175	-63.558	11.13	5.60		367	-35.096	-5.12401	14.60
176	-65.484	11.13	5.60		368	-38.734	-9.328	14.60
177	-66.233	11.13	5.60		369	-38.199	-10.246	14.60
178	-8.132	-7.95	10.10		370	-37.129	-10.246	14.60
179	-9.951	-7.844	10.10		371	-36.594	-9.328	14.60
180	-9.095	-5.936	10.10		372	-37.129	-8.41001	14.60
181	-9.951	-6.36	10.10		373	-38.199	-8.41001	14.60
182	-9.416	-5.088	10.10		374	-42.586	-7.738	14.60
183	-10.379	-5.406	10.10		375	-42.051	-8.65599	14.60
184	-11.77	-6.572	10.10		376	-40.981	-8.65599	14.60
185	-11.556	-4.452	10.10		377	-40.446	-7.738	14.60
186	-11.021	-9.116	10.10		378	-40.981	-6.82001	14.60
187	-12.84	-9.01	10.10		379	-42.051	-6.82001	14.60
188	-14.124	-7.208	10.10		380	-42.051	-4.77	14.60
189	-15.194	-5.936	10.10		381	-41.516	-5.68799	14.60
190	-17.334	-6.784	10.10		382	-40.446	-5.68799	14.60
191	-17.548	-8.904	10.10		383	-39.911	-4.77	14.60
192	-15.836	-10.176	10.10		384	-40.446	-3.85201	14.60
193	-13.91	-10.388	10.10		385	-41.516	-3.85201	14.60

11.2 *A2 Occupancy Profile*