An Investigation into the Prediction of Summer Over-Heating by Dynamic Thermal Modelling - Comparisons With Three, Naturally Ventilated Case Study Office Buildings.

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By

Kelvin Vincent Jones

Welsh School of Architecture
Cardiff University, University of Wales

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ProQuest LLC
789 East Eisenhower Parkway
P.O. Box 1346
Ann Arbor, MI 48106-1346

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Abstract

The aim of this thesis is to investigate the prediction of summer over-heating in naturally ventilated office buildings by dynamic thermal modelling. Three case study buildings were modelled using the commercial, TAS dynamic thermal modelling software and their internal air temperature levels monitored.

To find the optimum level of modelling complexity that compared with the physically moniored data, dynamic thermal models were altered from an initial 'Basic' model through to a very complex modelling set-up. From the changes in internal temperature prediction, created by varying the complexity of the model set-up (allowing for variations in the modelling strategy applied and the estimates/data applied by necessity in the model e.g. weather file information, blinds usage etc.) the relative effects upon the building design of these results can be assessed. This assessment was conducted by viewing the results against current UK over-heating guidelines used in the building design industry and/or by building users. Further, where these current guidelines proved of little usability for the cross-comparison of the actual monitored summer data and the realistic modelling set-up decisions, a new overheating guideline criteria was proposed.

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1.0 Introduction.

1.1 Aims/Objectives:

The principle aim of this thesis is to attempt to find the most applicable level of complexity in dynamic thermal simulation so that a realistic level of overheating will appear in a simulation's prediction as it would in the actual building modelled (by comparison against physically monitored data). To achieve this, the computer modelling will be completed using Dynamic Thermal Modelling (DTM) and will be achieved through the use of a currently existing commercial programme - TAS. To find this most applicable level of complexity the simulations will be compared to Case Study buildings that have been monitored in use. Three Case Study buildings will be chosen that utilise natural ventilation, however each building will represent a different level of design complexity – from a simple, small speculative designed office block to a large, prestige office that also incorporates mixed mode ventilation.

A secondary aim is to assess whether a more robust/useful overheating guideline criteria can be created for DTM predictions that will also correspond well to the physically monitored data. Whilst current guidelines exist for both allowable limits of design risk in a building and the desired maximum temperature allowed to be tolerated in a working office environment, DTM predictions are reliant on inherent assumptions in its inputs. Therefore, following the completion of the first aim, the data collected should also allow for the testing of a hypothetical "DTM overheating criteria" that whilst still able to illustrate the overheating found should also highlight the correlation between the DTM predictions and the physically monitored results with a more simlistic model set-up. This simpler model will not need to make as many inherent assumptions about occupant behaviour, levels of internal gain from office equipment etc.

To achieve this, the thesis will be required to firstly assess the summer overheating in a number of naturally ventilated case study buildings (designed utilising ‘traditional’ design tools/ procedures). This assessment will be achieved by the physical monitoring of the internal air temperature in selected offices in each Case Study Building. Subsequently, a ‘matrix’ of computer simulations will be run for each Case Study which allows for an increasing level of model complexity from an initial, basic run. Each of these runs, from the computer modelling predictions and the data logged from the physically monitoring of the existing Case Study buildings must then be assessed in the same manner. To do this existing UK overheating guideline criteria will be used. A hypothetical overheating guideline will then also be assessed, using hours where the internal to external temperature difference is 3°C or higher (and where external temperatures exceed 22°C). The thesis will also attempt to show the correlation between the two sets of data, logged and DTM predicted, for this proposed guideline.

Naturally, the process of creating these increasingly complex DTM runs must also take into account associated criteria, such as the time penalties and other costs of more accurate modelling (to limit the amount of assumptions made), which will affect user demand. In practice, the time cost in creating a highly complex model will exceed that of an initial basic, model designed to give only rough, approximate predictions of likely internal environmental conditions.

1.2 Background/Reasoning to Thesis

The thesis will attempt to make use of an existing, commercial DTM programme to provide predictions of overheating. The attempt to gauge overheating with the aid of DTM simulation comes from the concept that building design is already beginning to incorporate “computer automation” in the design process - even where this is only the transfer of drawings to CAD files for existing buildings for future reference and revision. Design details, including CAD drawings, will now be required to be kept considerable amounts of time due to changes in UK law e.g. Construction, Design and Management Regulations 1995. Therefore, it is likely that this will prompt the further use of holding design details, services layouts etc. on computerised files.

Current UK legislation is also pushing the uptake of dynamic thermal modelling in building design. For example, the current Part L2 section of the Building Regulations (introduced in 2003) have introduced a method by which dynamic thermal modelling can be used to test a building for Part L2 compliance. Three methods of compliance currently exist, however the third method offers the most scope for the testing of innovative, passively ventilated designs.

- The first method, the "elemental" method merely considers the performance of each aspect of the building individually. To comply with the provisions of Part L, a minimum level of performance should be achieved in each of the elements e.g. external walls of U value 0.35 W/m^{2}K. Some flexibility is provided for trading off between different elements of the construction, and between insulation standards and heating system performance. This method does not require the use of DTM.
- The second method, the "whole building method", considers the performance of the whole building. For office buildings, the heating, ventilation, air conditioning and lighting systems should be capable of being operated such that they will emit no more carbon per square metre per annum than the benchmark based on the Energy Efficiency Office's "Energy Consumption Guide 19 – Energy Use in Offices" data. Naturally, this is designed for and most suitable for use with office accommodation, the comparative data from Guide 19 may be of lesser value when creating differing building types such as schools, libraries or other public buildings. DTM can be applied to this method if required.
- The third method, the "carbon emissions calculation method" also considers the whole building but can be applied to any building type. To comply with the provisions of Part L, the annual carbon emissions from the building should be no greater than that of a notional building that meets the criteria of the Elemental Method. Dynamic simulation therefore needs to be used to estimate the carbon emissions. In this way, if a DTM of the actual building design is seen to produce less carbon emissions from energy consumption than a 'notional' building model when all other inputs are the

same but ~~this uses~~ the given Building Regulations U-values and percentage fenestration – the building design will be compliant.

Future changes to part L2 of the Building regulations are also likely to improve the take up of dynamic thermal modelling. Proposed changes to Part L's Section 8 "Energy Performance of Buildings Directive: Calculation Methodologies which seeks to implement changes in line with the European Union's "Energy Performance of Buildings Directive" (Article 3) requires Member States to have national calculation methodologies in place by the 4th of January 2006 in order to deliver the building performance standards and certification procedures. To achieve this a detailed energy simulation method has been proposed i.e. using dynamic thermal modelling, which currently can only be met with the application of existing commercial programmes. The proposed change states that(1)

> "In order to address all building types, now and into the future, a simulation-based approach would probably be the only solution..... Because the interface developed for the national tool will be very constraining in terms of the allowable user inputs etc, it means that the package produced for Part L compliance checking would not be suitable as a general purpose design tool and therefore not compete with the established proprietary tools. **We therefore recommend that, at least in the short term, the national methodology and the Building Regulations should be able to accommodate the use of commercial software to address more sophisticated designs."**

Furthermore, a draft ISO standard that is intended for use by specialists to develop and/or validate methods for the hourly calculation of the internal temperatures of a single room is due to come into effect in the first quarter of 2005. Currently, prEN ISO 13791 "Thermal performance of buildings - Calculation of internal temperatures of a room in summer without mechanical cooling" (2) is at draft stage, however its ratification is imminent and it will be applied to:-

> "a) assessing whether a building may overheat
> b) optimizing aspects of building design (building thermal mass, solar protection, ventilation rate, etc.) to provide thermal comfort conditions;
> c) assessing whether a building requires mechanical cooling"

This internationally recognised validation standard should therefore help to promote DTM use, as an increasing user confidence would be gained in all simulation software as they would each have to meet this regulatory standard. With this increasing computerisation of the design process in mind, it would seem wise to investigate the best apllicable method of modelling when attempting to predict overheating by the use of DTM and, from this finding, whether any robust guidelines exist to gauge **exactly** what overheating can be defined as in a naturally ventilated building.

This work is of importance as it attempts to clarify the potential use of computer modelling to aid the design process, in this instance by aiding the designer avoid creating a building with uncomfortable summertime temperatures. The computer modelling itself is merely another means by which a designer can attempt to create a more energy efficient building **and comfortable conditions** for the occupants. However, in the example of a naturally ventilated building this optimisation of comfort (and energy efficiency) by the use of natural ventilation could be compromised by the potential for errors in the DTM modelling. For example, any under estimation of the amount of time deemed to be over heating (such as when using CIBSE's design risk guidance of a 2.5% of occupied hours not exceeding 27°C for the internal temperature), would lead to excessive internal temperature in a building. This could lead to an uncomfortable working environment in individual rooms that may have been easily remedied by inclusion of small, split pack air-conditioning units to these areas alone. Therefore, this thesis, by trying to identify the most suitable level of model complexity/input data, ultimately seeks to avoid the over/under-design of naturally ventilated and mixed mode office buildings.

This thesis will concentrate solely on naturally ventilated and mixed mode commercial buildings rather than the whole building sector i.e. those also employing significant mechanical ventilation or air conditioning systems. The reasoning behind this is twofold. Firstly, it is assumed that the future construction of naturally ventilated buildings will far outstrip those that will require air conditioning solutions as the industry attempts to create more energy efficient and environmentally benign buildings. The increased demand for energy efficient building means that, wherever found to be possible, energy consumption for comfort cooling (via mechanical ventilation or air conditioning) should be avoided where passive means are possible. The current L2 section of the Building

Regulations can be passed (via the "Whole Building" method) where the total consumption of a standard, naturally ventilated (type 2) office is less than 236 kWh/m^2 per annum.

Secondly, the Case Study buildings chosen for use in this thesis are examples of modern, naturally ventilated design but of three distinct levels of complexity. Initially the three Case Studies were derived from 16 buildings chosen from an EPSRC Research Project into creating "Guidelines for the Operation of Naturally Ventilated and Mixed Mode Office Buildings"(3). However, the MOD Building, Morgan Bruce and the Barnardos buildings were taken from these to highlight three varying degrees of building design in themselves. Barnardos is a simplistic, naturally ventilated building comprising only small, cellular office spaces. Morgan Bruce is a larger office building that, whist also purely naturally ventilated, uses a wider floor plan and contains larger open plan areas for use as office space as well as for conference rooms, library facilities etc. The MOD building is a very large, prestige headquarters building that is predominantly open plan, of a wide floor-plan (14m, hence using double sided, cross-ventilation) and is most distinct from the prior two buildings as it uses a mixed mode ventilation system – a mechanical displacement ventilation system providing a constant 2.75 ach to each office area.

1.3 Importance of Natural Ventilation in Building Design.

As stated above, the future construction of passive office buildings using natural ventilation is likely to exceed those utilising mechanical ventilation or full air conditioning. However, the design of naturally ventilated buildings provides a dilemma in that a healthy and comfortable environment must be provided for the occupants **without** the use of mechanical services or air conditioning solutions that will necessitate energy usage (and therefore have an environmental impact). A building will need to be ventilated for various reasons:- to remove or dilute foul air and/or toxic/ harmful gases; to maintain the internal temperature of a space at a comfortable level or to directly cool the occupants of a space.

The distinction between the latter examples is important as building cooling merely depends on the introduction of colder outside air. Occupant cooling, however, can be achieved either solely by the circulation of internal air (e.g. by a simple fan) or as cool air enters the building and cools the body through convection and evaporation as the air change rate also increases. Therefore, a need is created whereby air change rates must be sufficiently high enough to provide fresh air for occupants (typically so that CO_2 concentrations do not exceed 800-1000 ppm) and yet environmental conditions must be maintained to allow thermal comfort. However, thermal comfort is a subjective state of satisfaction that varies with the individual and circumstances (such as clothing levels) and as such thermal comfort is generally regarded as a band of acceptable environmental conditions - e.g. 40-60% relative humidity, 19-22°C air temperature and relatively low airspeeds of 0.05 to 0.2 m/s so that troublesome draughts can be prevented.

In the UK this design guidance for comfort conditions is available from numerous sources such as the Chartered Institute of Building Services Engineers (CIBSE), Building Research Establishment (BRE) and via the government through agencies such as the Energy Efficiency Office. For example, recommendations from the Building Research Establishment Energy Conservation Unit in its Report 30 "A Performance Specification for the Energy Efficient Office of the Future" (4) state that-

> "The building should be designed not to exceed a dry resultant temperature of 28°C for more than 1% of the year and not to exceed 25°C for more than 5% of the year. Air movement in a naturally ventilated building may be used to offset higher dry bulb temperatures, but the air velocity should not exceed 0.8 m/s for cooling. If the moving air is lower in temperature than the bulk air condition then an air movement limit of 0.2 m/s should be used. Within the context of these rules, vertical temperature gradients should be limited to no more than 3°C through the occupied zone. For mainly sedentary activity this will be the vertical temperature gradient measured between 0.1 m and 1.1 m but for mainly standing activity this gradient will be between 0.1 m and 1.8 m. For general office applications standard design recommendations for humidity limits would apply - ranging between 40% and 70% for air-conditioned spaces. For naturally ventilated spaces a free swing in humidity conditions is an inherent characteristic of the design."

If natural ventilation is to be utilised it must be realised that its effect will be variable as the conditions affecting ventilation rates are also variable; depending on meteorological factors such as wind speed and direction, external temperature **as well as** the design and shape of the building and its surroundings. Therefore, providing a building design that can successfully achieve both sufficient air change rates and maintain an environment suitable for human comfort is a difficult proposition. Therefore, traditional design tools generally rely on creating designs that fulfil these criteria for an optimum period of time rather than as a constant.

Given the UK's temperate climate a heating system is a necessity, the choice of how this additional heating will be provided being the nature of the problem to a building services designer. Comfort cooling, on the other hand, is rarely a necessity in UK offices unless the building in question is at risk from overheating due to its use (e.g. it has a very high internal gain via higher than average occupancy rates or use of electrical equipment) or if has been designed with a large percentage glazing and is therefore at the mercy of high solar gains to the space. In many buildings natural ventilation can be used as an alternative to mechanical ventilation or full air conditioning to provide sufficient comfort cooling. In BSRIA's Guidance Note 7/2000 "Making Natural Ventilation Work"(5) it is stated that natural ventilation is on the increase as it offers the following benefits

"· capital costs in the region of 10-15% lower than air-conditioned equivalents
- lower operating costs (energy and maintenance)
- simpler and more manageable environmental control systems due to the building envelope acting as the primary climate modifier
- reduced environmental impact through the elimination of mechanical ventilation and refrigerant air conditioning
- productivity improvements due to occupants preferences to control their own ventilation rate
- increased robustness, flexibility and adaptability."

However, a risk of the building overheating to an unacceptable degree is an interrelated concern where natural ventilation is used. To prevent this problem the design can be tested to see whether overheating is a possibility and this is a task well-suited to dynamic thermal simulation (DTM).

DTM simulation is now routinely used for this task in the UK design industry. For example. the Energy Systems Research Unit (ESRU) at the University of Strathclyde were asked to assess the need for a mechanical cooling system as part of the proposed refurbishment programme to the GTW offices in Glasgow and so a comprehensive simulation study was conducted utilising the dynamic thermal model ESP(6). Prior to the proposed alterations, the offices suffered from overheating in summer. The main alterations in terms of the simulation study were, the replacement of the south facing external wall with a new facade incorporating a low solar transmittance glazing, and insulation of the roof. Based on the results of the study, it was recommended to the client, that they need only consider installation of a mechanical cooling system, which limits the maximum indoor temperature to 27 °C during warm summer periods, for the top/uppermost storey offices. The simulation was therefore successful in greatly limiting the amount of mechanical cooling that would otherwise have been employed.

An example of the use of thermal modeling with the TAS software (as used in this thesis) for overheating/energy efficiency purposes, is from EDSL Ltd (7), where two roof glazing options were considered for a London office atrium, 'Kalwall crystal' and 'SG Planitherm' double glazing. The Kalwall glazing would reduce solar heat gains and hence reduce the risk of overheating compared with the SG Planitherm, but it would also reduce the daylight available at the bottom of the atrium. To compare the two options a 3D TAS computer model of the building was created. This model contains the thermal and lighting properties of all the materials that were used in the building. The model was able to predict internal temperatures **and** compared with models of daylight availability on an hourly basis for periods up to a full year. In order to judge the relative performance of the design options, the number of hours exceeding 25°C resultant temperature was determined for the summer months.

By the use of natural ventilation coming in via the entrance and leaving at atrium roof level, the number of hours the atrium exceeds 25°C at floor level was reduced to 200 hours with the Kalwall glazed roof and 300 hours with SG Planitherm. However, the former would give a daylight factor of 3.3% at floor level in the atrium, whilst the SG Planitherm gave a daylight factor of 6.7%. CIBSE Guide A (in its Table 1.13) recommends an average daylight factors of 2%. Therefore, the Kalwall glazed roof, would meet this criterion. However, the thermal performance was not as acceptable – the BRECSU recommendation is that for naturally ventilated offices the resultant temperature should not exceed 25°C for more than 5% of the occupied time, which is about 175 hours for a typically occupied office. As the atrium was not a working space as such, this target could be relaxed as it is a guide figure only. Therefore the thermal modelling indicated that the Kalwall roof offers sufficient daylight at atrium floor level and is more effective at controlling summer temperatures compared to the alternative option studied.

1.4 Case Study Building and DTM Software Choice.

The TAS software was chosen as it is an example of a commercial software programme used in the UK building design industry for simulating the thermal performance of buildings and has a proven track record of use. The three parts of TAS version 8.5 (3D TAS, ATAS and TAS Systems) allow for numerous applications of the program such as the assessment of environmental performance, natural ventilation analysis, prediction of energy consumption, plant sizing, analysis of energy conservation options and energy targeting. Its ability to assess environmental performance makes this programme a suitable choice for the thesis' attempt to quantify overheating in the 3 naturally ventilated, Case Study buildings. TAS offers the capability to calculate natural ventilation air flows arising from wind and stack pressures via a zonal model of air movement. This capability is of prime importance to this thesis as it is an investigation of dynamic thermal modelling of naturally ventilated buildings only. Therefore, how well the software simulates natural ventilation will be a key factor in the accuracy of its predictions.

TAS calculates natural ventilation using a zonal air movement model whereby flow equations are solved iteratively as they "ping-pong" back and forth with the thermal analysis calculations. At each time step, a set of equations is set up describing the balance of mass flow into and out of each zone (solved using a gradient-based method to yield zone pressures and flow rates in both directions through each aperture) these flows are then fed back to the TAS thermal analysis where they are used to generate updated zone temperatures. This iterative process continues until zone temperatures (both air and mean radiant) "converge to an accuracy of 0.01K and flow rates converge to an accuracy of 0.0005 kg/s".

The Case Study buildings to be monitored will be chosen from 16 buildings previously chosen to be assessed by the EPSRC Design Guide project for naturally ventilated and mixed mode buildings. The offices in this EPSRC study were chosen from those regarded to fulfil criteria for being either "innovative" or "to current building regulations". This means that the office designs studied will be those of a quality to fulfil only the needs as required by the then current UK construction law as regards ventilation efficiency (i.e. 'to current building regulations') **or** those thought to exhibit innovative design features which will aid ventilation. The case study buildings chosen will be naturally ventilated or mixed mode designs (as per the criteria for selection for the EPSRC project on "Guidelines for the Operation of Naturally Ventilated and Mixed Mode Office Buildings") with this previous project providing the raw data for the physical monitoring for use in the thesis. That is, air temperature monitoring in multiple locations in each building (at 15 minute intervals) for a minimum of the Summer months. This raw data was able to be taken and manipulated to provide data for use in the thesis, such as the comparison to the CIBSE overheating criteria for internal air temperatures found in Guide A8.

Whilst this monitoring of the physical environment could then be used as a comparative check to compare against the future computer simulations of the Case Study buildings' environmental conditions there is likely to be a small, inherent inaccuracy in the physical monitoring equipment available (e.g. a +/- 4% error on the additional/back-up 'Tinytalk' dataloggers used). Therefore, to reduce these errors all monitoring equipment was to be calibrated before use and, where appropriate, the monitored data was error-checked before being used for the later contrast against the computer simulations' predicted temperatures. It is therefore worth noting that the data collected via the EPSRC project was merely 15 minute averaged data of temperature and relative humidity values in the Case Study buildings. No error checking of the readings had taken place prior to this. Therefore for their use in the thesis, all the data provided for the Case Study buildings had to be examined so that the problem known familiarly as "Garbage In Garbage Out" did not occur. Unless checked for faults and missing data, the EPSRC project's collected information would have proved inaccurate for comparison to the TAS DTM predictions.

Naturally, the EPSRC data would then need to be converted into hour averaged data, analysed statistically and graphically output as per the same formats as the DTM predictions for comparison purposes. Therefore, it can be seen that this information supplied by the EPSRC project acted only as the raw data to the thesis, akin to the DTM prediction outputs, and thus needed the same level of analysis methodology applied.

It is hoped that the process of assessing the computer model predictions against the physically monitored data will highlight the level of the predictions accuracy. This analysis serving two main purposes:-

i.e. finding the most applicable level of complexity in dynamic thermal simulation so that a realistic level of overheating appears in the model as it would on the actual building (if any) and finding whether a robust overheating guideline criteria can be created for DTM predictions that correspond to this physically monitored data. Therefore, the accuracy of both the DTM derived data and the physically monitored data was crucial, a high level of confidence needed to be placed on the data ensuring that a significant degree of error checking and "sanity-checking" of the data occurred before it was available to be used.

However, despite the accuracy of the final computer simulation, as compared to monitored results, it will have been reliant on enforced estimates which will undoubtedly affect the final result to differing degrees. For example, when modelling a building 'blind' the computer operator may have precise construction and geometry data to create a reasonable model yet have very little data regarding incidental heat source gains in the building or a suitable weather file. These discrepancies may cause a large deviation in predicted temperatures.

The resulting design decision based on varying predictions, created by varying input data, could be great (e.g. 100% occupation rates for each working day or the assumption of some level of diversity to these gains over the course of each day). A 100% summer time occupation rate alone could make the difference to a room achieving the preferred BRECSU maximum internal (dry resultant) temperature or not i.e less 5% of the year above 25°C. It is likely that costly mechanical ventilation or air conditioning would be advised if the BRECSU criteria could not be met by passive means alone. Naturally, all levels of model complexity will contain elements of assumed input variables, such as the meteorological file used, whether at the most basic level or at the most sophisticated. However, a complex thermal model, where not only will it attempt to most closely mimic the building in use but also to make allowances for reasonable levels of internal heat gain, may be the only means to accurately predict actual overheating levels in an existing building with its dynamic profile of use.

However, despite any limitation being created by the inherent and enforced use of simplistic estimates of internal gain, hours of operation, example meteorological files etc, the dynamic nature of thermal modelling and the ease of repetition of simulation may still highlight a potential benefit of computer simulation over traditional static heat loss/gain calculations. As a basic model can become a more complex model with only limited additional time costs, e.g. as a model is more tightly re-zoned, has an alternate weather file applied, adjusted internal gains etc., this methodology will highlight one of its great advantages.

Therefore, this exercise will be timely as, if an appropriate level of modelling complexity can be found to compare to actual levels of overheating experienced by the Case Study office buildings, then other factors must be identified to account for their current lack of use in the design process. These factors may be numerous and act concurrently. For example, an Energy Design Advise Scheme study from 1995 (8) found that formula and manual calculations are still by far the most predominate design tools in use. This was due to computer simulation modelling being seen to be; the domain of certain technological experts in the field (and as such are not perceived to be of widespread use); too costly if current design tools are seen as adequate; subject to user reluctance due to a general lack of knowledge in the architecture/engineering industry about computer simulations packages' availability and abilities.

As previously mentioned, the current design ethic relies largely on designing via established precedent and by the use of design data guides. However, if computer simulation can be shown to be of value in the architecture/engineering field, despite its enforced estimation of many parameters and its relative infancy, then this research will be timely.

1.5 Future Scope for Dynamic Thermal Simulation in Design Use.

Though examples of DTMs in overheating assessment may only be limited, at the time of writing, when compared to standard, manual hand calculations, it is worth noting that future technological advances may substantially aid the utilisation of computer simulation in the future. For example, the rapid expansion of the Internet may allow such Thermal Modelling programmes (and their necessary processing requirements) to be accessed and ran 'online' from standard-specification office based personal computers. It is also within the realms of possibility that future upgrades and cost reductions will allow such simulation programmes to become as accessible as Computer Aided Design (CAD) packages have become to current architecture/engineering practices. In this light, it should be remembered that the current, seemingly ubiquitous nature of CAD packages in design practices was not the case a mere 10-15 years ago. As of July 2004, a full version of "TAS NG" - the 'next generation' of the TAS model specifically designed for the Windows operating system, could be downloaded free of charge from the Internet along with its tutorial packages and construction/ materials/weather etc. databases in a file of only 24mb. Though a full version of the software (but limited to a 2 month trial licence) and provided in conjunction with all the standard databases available in a commercial release in order to complete a simulation this download therefore immediately makes modern DTM software easily accessible to any engineering student or small practice previously not undertaking DTM studies. Whilst clearly intended as a trial of a commercially available DTM package, this internet download availability does indicate the increasing ease with which DTM programmes (plus the necessarily files/information needed to create a successful DTM simulation) are being made available to the public domain.

To illustrate this example, figure 1.1 below shows the percentage of software applications used by consultants in the Building and Construction industry during 1993 (9). (Reproduced from the CICA "Latest Industry Survey of Leading Firms"). As can be seen word processing and spreadsheet analysis is near universal with ca. 90% of respondents indicating their use. However, Computer Aided Design/Drafting also constitutes use by some 71% of consultants – clearly a large market share for such a relatively new technology. The use of computer simulated analysis via DTM (or CFD or lighting simulation) has not even been included in this study. This suggest that its uptake in the industry was so low that the question of its use was not even deemed relevant by the compilers of this study.

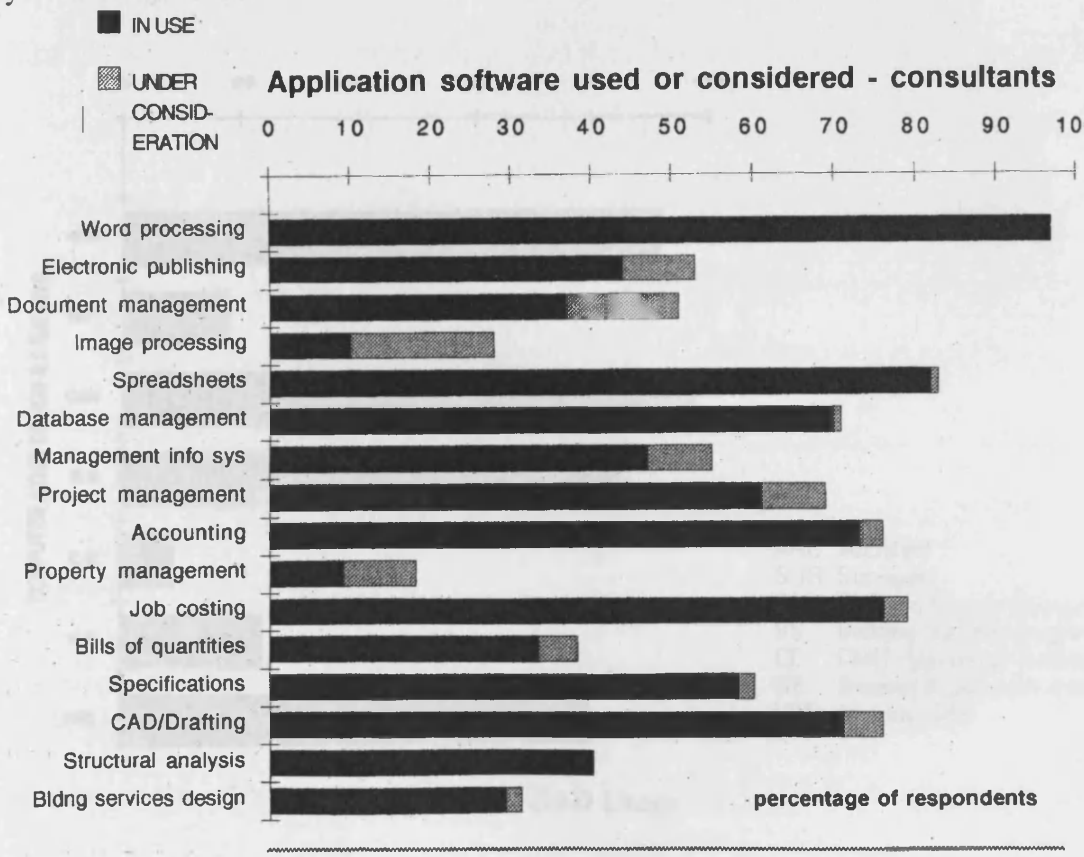

Figure1.1 – Application Software use in Construction Industry

To better indicate this, Figure 1.2, also from the CICA report, shows the use of CAD in architects and other engineer's offices. The CICA CAD Sales Survey expected further growth of CAD to the 90% level already found in the larger architects offices, however whilst a larger number of workstations in total was expected by this survey, it predicted that many of the larger CAD systems were to be replaced by smaller, desktop ones. Therefore, it seems that not only a growth was predicted for IT software uses themselves but also in the number of actual workstations available for their use. It could be expected that as Building Services engineer's and architects etc take on board CAD and other, formerly novel, computer software as part of everyday work skills they will also seek out and invest in newer technologies and applications such as computer simulation. Added to this, modern, commercially available DTM (such as TAS in this thesis) can actually convert current CAD (.dxf - drawing exchange format) drawings to their own format to rapidly speed up the process of creating their building geometries. As can be seen, most Architects and Services Engineers now operate CAD systems.

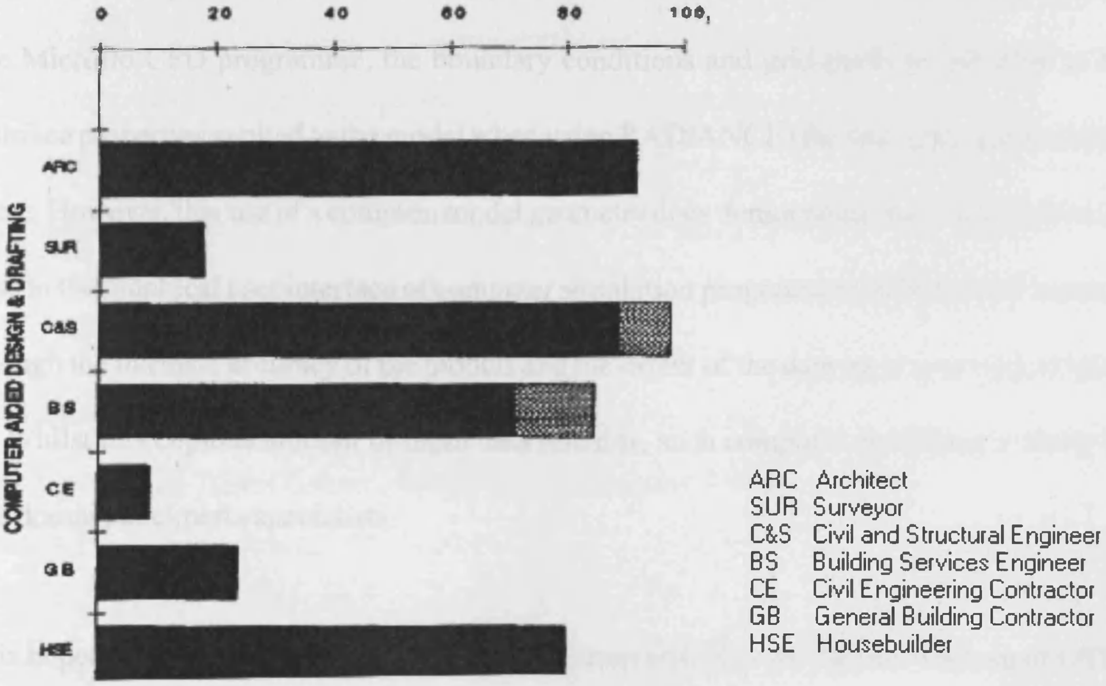

Figure 1.2 CAD Usage

There has already been some integration of existing computer simulation packages in order to minimise the repetition of creating the actual building model. Following on from a European wide "IBIDS" research programme to create an integrated data model (IDM) that could be used in conjunction with multiple modelling packages. A current example is IES Ltd.'s "ModelBuilder" software. The "ModelBuilder" software creates an IDM (with or without the aid of CAD systems) that can be used as the basis of the building model to be used by various simulation and design calculation programmes. For example, the IDM data can be used in a CFD package – MICROFLO, a Dynamic Thermal Modelling package – ESP-r, a lighting simulation programme – RADIANCE and a HVAC simulation package – APACHE HVAC.

However, whilst the repetition of creating a totally new computer model for the same building has been somewhat avoided by the use of the "ModelBuilder" software, many inputs are required dependant upon the number of simulation packages used. Whilst the bulk of creating the model has been achieved (akin to TAS's '3D-TAS' system), to use ESP the necessary climate, plant control, incidental gains, shading masks etc. have to be applied to the building. Then to use the same geometry file on the Microflo CFD programme, the boundary conditions and grid-mesh would have to be created, surface properties applied to the model when using RADIANCE (the daylighting simulation package) etc. However, this use of a common model geometry does demonstrate that there appears to be progress in the graphical user interface of computer simulation programmes (where there is much scope), though the intrinsic accuracy of the models and the extent of the data input required remains the same. Whilst this copious amount of input data remains, such computer modelling is likely to remain the domain of experts/specialists.

It is hoped that in answering its main aims this thesis will also aid the user take-up of DTM simulation as it seeks to highlight the relative accuracy of overheating predictions at varying levels of model complexity. Even as the thesis attempts to ascertain the level of modelling complexity required to achieve comparable predicted overheating rates to those experienced by 3 Case Study buildings the ease of re-modelling alternate runs will be demonstrated. Naturally ventilated buildings are the chosen building stock in the thesis, as they are seen as a growth area in UK office building design. This is due to continually lowering carbon emissions which must be achieved by a building (and hence lower energy consumption) as ever more stringent building regulations are applied.

Furthermore, given the lack of firm guidelines on what temperature or continuing conditions actually create overheating, the thesis' attempt to propose a more robust/useful guideline figure for overheating to be used by DTM predictions and building occupants will also seek to more greatly assure users/ designers that their building will not overheat (in all but extreme weather conditions) following its substantiation by computer simulation.

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2.0 Theoretical Background

This chapter will aim to establish the current levels of knowledge gained and research instituted into predicting the internal environmental conditions of commercial buildings e.g. temperature, solar gain and air change rates. In so doing, it is also wise to discuss the problems encountered in designing the modern office environment. For example, the need to maximise a buildings' energy efficiency potential without compromising a satisfactory level of environmental conditions, that will be required by the office workers within that environment. To gain a full understanding of the problems faced by a designer, which can be modelled by computer simulation programmes, it will therefore also be necessary to determine what current design tools are available to enable these problems to be overcome. Further, to these concerns is that there is no commonality within the building design industry or consensus of opinion on exactly how "overheating" is defined - i.e. the key parameter to be determined in this thesis. Therefore, a brief discussion of relevant overheating standards and 'rules of thumb' will also be reviewed.

In order to fully understand the principal elements that need to be considered when a naturally ventilated, commercial building is to be designed it would be wise to "start from the beginning" and briefly look at the methods of heat transfer, how these then relate to the built environment and their effect on a person's perception of thermal comfort.

2.1 Heat Transfer

Heat transfer in a building takes place through the following three methods; Conduction, Radiation and Convection (as enshrined in the pages of any basic physics text book). Therefore, by controlling these factors the designer hopes to control the thermal conditions within his building to create a comfortable internal environment. The basic tenet of heat transfer is that heat always flows from warmer to cooler substances - therefore with several different objects in a uniform surrounding temperature, each cool object will warm and each warm object will cool until all the objects and their surroundings equalise at a common temperature. The equalising of these temperatures is caused by the above three methods of heat transfer, that will now be briefly explained.

Conduction is the transfer of heat energy between adjacent vibrating molecules in a solid, fixed position, this transfer always occurring between the warmer (and faster vibrating) molecules and the cooler (and slower vibrating) molecules. This transfer will occur readily in all directions and **all** substances have a degree of heat energy by virtue of the fact that their molecules are in motion. This heat transfer would only stop at the point of "absolute zero" which is 0°K (or expressed on the more frequently used Celsius scale -273.15°C), this is the temperature at which all molecular activity stops.

Of course, differing substances will have differing levels of thermal conductivity (K) and mass which will alter the time it takes for these three elements to reach the same temperature. Thermal conductivity being the "heat transferred by conduction through a substance of a given thickness, in a given time, where a given temperature difference is applied to a given area"(1) - from Fuller Moore. For example, when choosing construction materials, the designer would be likely to choose those substances that have the smallest levels of conductivity (i.e. the greatest insulators) to decrease the amount of heat loss from the internal areas to the external environment (and therefore also to reduce heat gains in internal areas from the warmer outside environment). A simple example of this would by the choice of glazing for a building. A window of one single pane of 6mm glazing would clearly have a far greater level of thermal conductivity than a double glazed window whilst allowing in similar amounts of daylight. Typically, a U value for a single 6mm pane of glass would be 5.6 W/m^2 K (without frames) whilst a double glazed option (allowing for a 6mm air gap) would have a U value of 2.9 W/m^2 K. (from the ASHRAE Fundamentals Handbook [2]).

In terms of thermal comfort, clothing can be seen as 'insulation' material for the body. The intrinsic insulation of clothing is a property of the clothing itself (and not the external environment or body condition) and represents the resistance to heat transfer between the skin and clothing surface. The rate of heat transfer through the clothing is by conduction, which therefore depends on the surface area (m^2), temperature gradient (°C) between and skin and clothing service and the thermal conductivity of the clothing itself. Naturally, as we perceive thermal discomfort, by being too cold or too warm in an environment, a person will add or shed layers of this 'insulation', as appropriate, to try to compensate for these conditions.

A further method of heat transfer is via **Radiation**. Heat transfer by radiation is a result of electromagnetic waves as molecules of a substance's surface vibrate they emit radiant energy. These waves of radiant energy will travel until they hit another surface and are absorbed. This absorbed radiant energy will be converted to heat, hence raising the absorbing surfaces' temperature. The temperature of the emitting surface will not only determine the quantity of radiation emitted, but also its spectrum of wavelengths - the warmer the substance the shorter the wavelength. For example, (from Fuller Moore) the relatively hot surface of the sun emits radiation in comparatively short wavelengths (between 0.4 and 4 microns). Building surface molecules, however, vibrate more slowly, emitting longer wavelengths of between 8 and 50 microns.

Unlike conduction no medium is required, radiation occurring most readily in a vacuum. However, as all substances radiate energy in all directions as a function of their absolute temperature, a cool surface will radiate energy to a warmer surface and vice versa, although the cooler surface will receive the greater levels of energy. Therefore, the **net** energy transfer will still occur from warmer to colder surfaces. As radiation travels in a straight line, it is necessary that both the emitting and the absorbing surface are within each other's line of sight.

A simple example, as regards thermal comfort requirements in an office building, would be the sun lit area of an office's floorspace that would lie beneath a large window space. The additional heat gained by the occupant (and furnishings etc.) in this sun lit area, as a result of the sun's emittance of radiant energy may prove unhelpful, pushing occupants above the level of thermal comfort, despite the internal air temperature being within desired parameters. The simple solution of merely shading these areas at times when overheating is possible may not be realistic as the light admitted by the windows may be required for adequate lighting levels to exist.

The effects of this sun-patching on the design of an office building could be numerous. For example, it could be dealt with by specifying glass with a low total solar transmission (G value) that would still allow reasonable amount of illumination into the office. Or perhaps the problem could be dealt with by the actual design of the building as it attempts to incorporate some solar control devices, such as overhangs or side fins. This would avoid the direct sun-lighting of the office space (and therefore also its occupants) whilst still allowing enough diffuse daylighting to allow for usable amounts of illumination in the office - e.g. to meet CIBSE and the Building Regulations' recommended 2% average daylight factor for a room.

This former example of glazing choice highlights the emissivity of a particular substance. Emissivity is the measure of the ability of a surface to emit radiation at a given surface temperature. Emissivity is gauged over the 0 to 1 range, where 0 equals no emittance whilst 1 equals the maximum emissivity (a notional "black body"). Therefore, from the previous example of an occupant in the sunlit portion of an office space, the designer could choose a window material of lower emissivity than standard glazing, hence ensuring that whilst light is emitted the re-radiated heat from the glazing into the office is lessened by use of this lower emissivity glass. Therefore an attempt has been made to remove the radiant heat gain from the office whilst retaining the useful admittance of daylight. However, solar control would more effectively be achieved by shading of the office space via curtains or other blind/control device. In this instance, the direct radiative transmission of solar gains to the room are halted as they now only reach the opaque blind/curtain rather than the transparent window element, naturally though this will also remove the useful illumination of the room by direct and diffuse light. Therefore, as the latter example shows, the design choice problem posed here is to eliminate the unwanted solar gain to the occupants in Summer yet still maintain the useful light admittance to maintain a suitable amount of illumination in the office.

A third method of heat transfer is **Convection**. Convection is the transfer of heat by a moving fluid medium, such as the air or water (essentially, though, convection is a process of both radiation and conduction acting on the moving medium). To illustrate this principle imagine (once again) two objects - one cool and one warm. When the moving fluid, e.g. air, comes into contact with the warmer object it will be warmed through conduction and radiation (this heat will then diffuse through the fluid by physical mixing and conduction between its molecules). This now warmed fluid will then travel and pass over the second, colder object losing heat to it by the same process. Therefore, the significant difference in this type of heat transfer is the molecular movement as energy is transferred as the molecules physically relocate themselves as the fluid moves on. With conduction, however, molecules will not actually change location but transfer heat energy from one molecule to the next in a form of domino effect.

Convection is perhaps the most important method of heat transfer in relation to human thermal comfort. Though, our bodies may be in thermal comfort with the surrounding environment, as the heating system is maintained at a constant temperature and the effects of radiation are limited for example, we may still experience annoying cooling/heating from convection due to air movement. The skin will be cooled by convection as colder room air flows across the skin's surface, the cooler the air the greater the transfer rate will be. This rate of convective heat loss will also be affected by the speed of air movement across the body (known familiarly as the wind chill factor). Thus in a seemingly warm office (ca.21^{0}C) an individual may be in thermal discomfort if subjected to colder draughts of air movement, this therefore places limits on the permissible air speed allowed before thermal discomfort will occur.

The following advice is given in a teaching unit for ventilation by BICEPS (Building Industy Co-ordinated Education Package) (3)

> "If the air speed in a space is above 0.15 to 0.2m/s in winter, it is often perceived as a draught, especially if the occupants of the space have a sedentary activity. Draughts can be caused by air supply devices, such as supply jets, open windows or vents, or by the negative buoyancy effects of cold air induced by cold internal surfaces, for example, down-draughts from cold glazing surfaces. In summer, higher air speeds may be maintained during hot weather for comfort cooling. However air speeds greater than about 0.5m/s can cause mechanical problems of papers moving, etc."

It is therefore important for the designer, of an office space for example, to not only consider the need to provide an area that can be sufficiently ventilated but also to ensure that the ventilation strategy does not cause discomforting cold draughts or allow too great a vertical air temperature gradient to occur within a space. This concern has been sufficient for standards for temperature gradients to be issued. For example, (from Awbi[4]) ISO7730 recommends a maximum air temperature gradient of 3^{0}C between 0.1 and 1.1 metres above the floor, which corresponds to 5% persons dissatisfied, whereas ASHRAE recommend the same temperature gradient between 0.1 and 1.7 metres above the floor i.e. the average standing (not seated) height of a person.

A further method of heat transfer is via **Evaporation**, which is similar to heat transfer by convection but also requires an initial change of state from liquid to vapour at the surface and the subsequent diffusion of this vapour across the boundary layer into the ambient air. More commonly applied to thermal comfort, evaporation is used by the human sweat response to attempt to cool down the body. As the deep body temperature of a person must remain fairly constant (at 37 ^{0}C) the body must find alternate means to lose heat in a hot environment, therefore the ability to lose heat via evaporation i.e. sweating means that it becomes the dominant heat loss method in hot environments. The ability for the body to lose heat via evaporation will not only be related to the ability of the body to sweat but it will also be dependant on the velocity of the surrounding air and its relative humidity. Therefore, convection and evaporation are closely linked. Furthermore, the rate of evaporation will decrease as the air becomes more saturated, thus thermal regulation via evaporation is also linked to the relative humidity of the air. Therefore, the body will find it harder to lose heat in environments with higher relative humidities. This has led to many air conditioned buildings to have some degree of dehumidification as well as temperature control applied to the supply air for comfort purposes - typically the relative humidity of this supply will fall in the bands 40-60%.

It can therefore be seen that the thermal response of a building is via a complex interaction between various sources of heat transfer - e.g. from direct radiant sources such as the from the Sun, conductive sources from differing building materials and the outside environment, heat gain/loss from direct air exchange with outside (whether this ventilation is desired or not) etc. Having established the primary methods of heat transfer it is now important to see how these methods relate themselves to the human perception of thermal comfort, with particular regard to the office environment.

2.2 Thermal Comfort

The primary method that provides heat to the human body is by its metabolism - simply, the conversion of chemical energy i.e. food into mechanical and thermal energy i.e. our activity rate and body heat. Of course, if our rate of activity is increased the greater the metabolic rate needs to be to convert our food into work and heat. As warm blooded mammals, humans must maintain a constant **deep body** temperature (ca.37^0C/98^0F), therefore any surplus heat will need to be lost or additional heat will need to be gained to maintain this temperature. Therefore, in times of great activity more heat will be generated by the human body that will need to be released into the surrounding environment to maintain the deep body temperature as a constant. The release/gaining of this heat is achieved by a combination of convection, radiation, conduction and evaporation acting on the human body.

Just as any other object, the body will be cooled or warmed by convection as air moves across the body. The skin will lose heat to the surrounding air as cooler air flows across it, or, conversely, gain heat when the surrounding air is at a higher temperature than the body. The body may also gain or lose heat through conduction to surfaces it is in direct contact with. However, in normal day to day office life, the area of contact of the body with significantly hotter or colder surfaces is minimal and the length of contact only limited. Therefore, the effect of bodily heat loss due to conduction is likely to be only minor compared to convection. The body can also gain or lose heat to the surrounding environment via radiation as radiant energy is given off by the skin just like any other object. The earlier example of an office worker directly affected by the sun's radiated heat, in a sun patched office area, is a familiar example of how the body may gain heat by radiation. Heat gained (or lost) by radiation is independent of the surrounding air temperature, however, being affected by the surface size of the emitting object (in relation to the absorbing object) and its surface temperature. Therefore, a person subjected to direct sunlight or adjacent to a radiant heater can be at thermal comfort at lower air temperatures than would otherwise be the case, whereas a person in the same space, yet shaded, may therefore not be in thermal comfort. The body can also lose heat to the surrounding air through the process of Evaporation. As the surrounding air temperature increases or the metabolic rate increases (as a result of greater activity), the body may not be able to lose enough heat through the processes of convection, conduction and radiation alone. Therefore, perspiration will occur and the skin will be cooled by evaporation. However, the rate of evaporation will be dependant on the velocity of the surrounding air and its relative humidity (as evaporation rates decrease as the air becomes saturated).

The relative proportions of bodily heat loss attributable to each of the above methods were examined by Stein in 1986 (reviewed by Moore(5)). At 70⁰F/21⁰C (i.e. common room temperature) it was found that radiation, convection and conduction (including respiration) equalled 82% of total heat loss whilst evaporation equalled only 15% of total (a further 3% attributable to physical loss via faeces and urine). However, at higher temperatures (ca. 85⁰F/29⁰C+) evaporation becomes the dominant form of heat loss as normal body temperature and air temperature become closer to one another, thus lessening the effects of convection and conduction.

Having briefly looked at the physical process of bodily heat transfer, the perception of human thermal comfort may now be examined. Thermal comfort is, of course, a highly subjective state of satisfaction that will vary between each individual and his/her current circumstances. Therefore, providing an internal environment to satisfy each person's perfect level of thermal comfort is nigh on impossible and, as such, a band of acceptable environmental conditions is usually created within a space (i.e. the comfort zone - e.g.

19-22°C, 40-60% RH etc). The range of environmental conditions that actually form this comfort band that will satisfy most people has been the subject of much research and therefore also varying standards.

As discussed earlier, air temperature will only affect bodily heat transfer by convection but will be most significant at common room temperatures, evaporation becoming the most important at higher temperatures (e.g. 85°F/29°C), when the temperature difference between the air and skin is minimal, which reduces the effects of convection and conduction. Evaporation is greatly affected by the relative humidity of the surrounding air. Therefore, any indicator of thermal comfort must take into account both the effects of air temperature and relative humidity. From the building up of these values, ASHRAE (American Society of Heating, Refrigeration and Air Conditioning Engineers) formulated a chart to delimit the comfort zones within certain environmental parameters e.g. air temperature, relative humidity etc. the ASHRAE standard 55-1981 uses the operative temperature for evaluating different comfort levels at differing activity and clothing levels.

ASHRAE 55-1981 has become a widely accepted standard for thermal comfort and is defined as (from Awbi [6]) "the uniform temperature of a radiantly black enclosure in which an occupant would exchange the same amount of heat by radiation plus convection as in the actual non-uniform environment". The Standard is designed to be acceptable to 80% or more of the occupants of a space during sedentary activity and of normal clothing ensembles. The Standard also specifies maximum average air speeds so that heat loss by convective draughts are minimised - these are 0.15metres/second in Winter and 0.25metres/second in Summer environments.

The figure below (figure 2.1) shows the acceptable ranges of temperature and humidity for sedentary activity in Winter and Summer clothing ensembles:-
(Reproduced from Kreider [7])

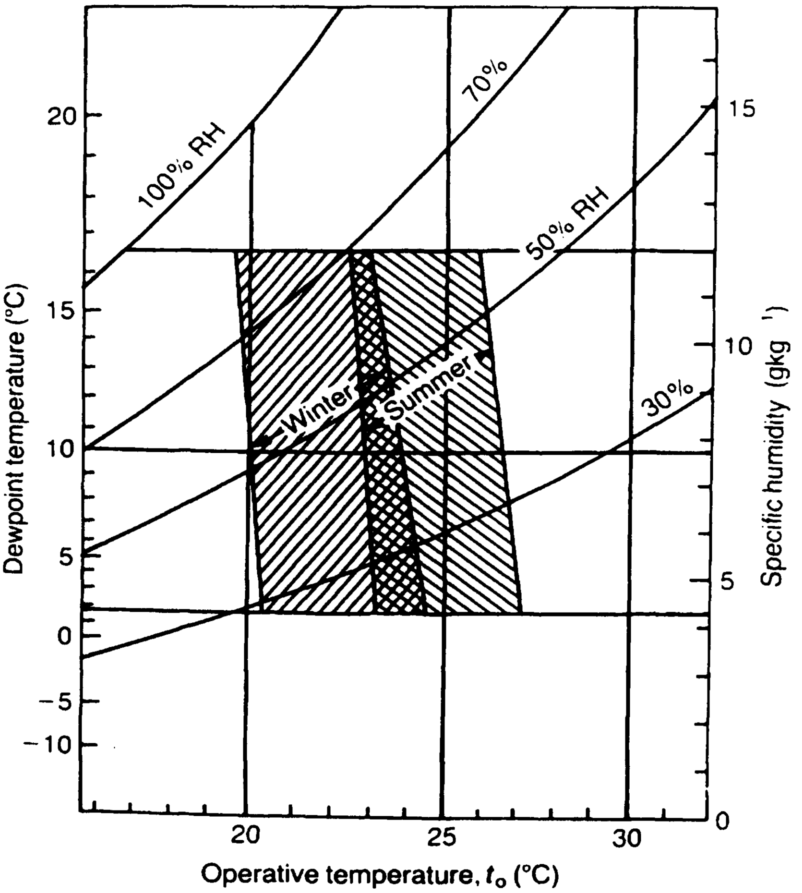


Figure 2.1: Standard 55-1981 equates to a sedentary activity level (ca 58W/m^2) and appropriate clothing insulation levels i.e. 0.5clo in Summer and 0.9 clo in Winter.

As can be seen from the ASHRAE chart the comfort zones are related to a number of other factors such as air speed, activity and clothing levels. Air velocity is important as this will affect convective heat loss from the body. The greater the air speed of cooler air, the greater the rate at which the warmer air surrounding the human body is replaced, thereby speeding up the physical relocation of the warmed air molecules. Although convective heat loss is most greatly affected by the relative differences between the body and the air's temperatures, air velocity is of sufficient importance to ensure that air temperature alone cannot be used as a measure of thermal comfort. Though the body cannot be cooled below the surrounding air temperature, the acceleration of the cooling process by increased air speeds is so perceptible as to affect thermal comfort i.e. the familiar "wind chill effect" reported by weathermen (the calm wind temperature that would produce the same heat loss from the body as to compared to the actual effects of the current air temperatures and velocities).

Air velocities can be controlled by the designer. However the ASHRAE standard still takes account of two factors that are not controllable (clothing levels of occupants and their activity) by instead assigning notional average values to them - in this instance sedentary activity and Winter/Summer clothing levels. Clothing can be seen as insulation material for the body and as such it can be quantified. Clothing levels are typically gauged between 0 and 4.0 in CLO units, where 0 equals total nudity whereas 4.0 is a practical maximum that will still allow for movement (e.g. a polar weather suit). As the Clo number increases, the insulation level increases and therefore the body can be in thermal comfort at a lower temperature. The ASHRAE standard has therefore chosen two typical office clothing levels, one for Summer ca. 0.6 CLO and one for Winter ca. 0.9 CLO. As mentioned earlier, as the activity rate of a person increases, so will his metabolic rate, thereby producing greater body heat. A person may typically only give out only 50 watts of heat for sedentary activity but 200 watts for strenuous activity such as running. Therefore, the ASHRAE standard has also had to choose a typical activity level for an office worker to create the comfort zones (which in this instance is sedentary which is relevant to office work).

Many studies have been undertaken to test the accuracy of these comfort zones. Schiller et al (8) found that Winter temperatures perceived to be of neutral satisfaction by test subjects correlate well with the ASHRAE standard, however the temperatures viewed as of neutral satisfaction in Summer were lower than that suggested by the standard. It must be noted, though, that the standard is based largely on laboratory test data. Also, the comfort zones created by the ASHRAE standard are, of course, exactly that - zones, being designed to meet the criteria for comfort for most people. Therefore, tests such as Fanger's Predicted Mean Vote (PMV) designed to illicit levels of satisfaction on a bi-polar scale (e.g. +3=hot, 0=neutral -3=cold) are somewhat flawed as the distribution of votes will show a large scatter whatever the environmental conditions, as thermal comfort is subjective to the individual. A more useful indicator is the Percentage of People Dissatisfied (PPD) - i.e. the percentage ratio of the people dissatisfied with the thermal environment as indicated by the PMV. By plotting the PMV and PPD together it was noted that an almost symmetrical pattern is created and that even under ideal conditions 5% of people will be dissatisfied, whilst approximately +/- 0.8PMV will still satisfy at least 80% of people. Therefore, PMV and PPD data can be used for room comfort analysis purposes. For example, the environmental parameters in a room of uniform temperature may be measured and this then used to calculate the PMV. Where this PMV is beyond ca. +/-0.75 (staying with the tolerance so that no more than 20% of persons are dissatisfied) the temperature level can be simply adjusted to restore the PMV and PPD to acceptable levels. Of course, rooms are rarely of a constant temperature throughout, hence a need to zone a room into areas. Those zones outside 0.75PMV only, will require their temperatures to be altered accordingly.

These conflicting levels of PMV and PPD in spaces of similar temperature may be due to factors other than pure air temperature and relative humidity calculated by the ASHRAE standard. For example, a person may be in thermal neutrality as a whole but subject to colder extremes at head or feet level as a result of a large vertical air temperature gradient in a room. Therefore, the ASHRAE standard suggests that a gradient no greater than 3°C should exist between 0.1 and 1.7 metres (the average standing height). A person may also be in thermal discomfort if subjected to cold draughts of air of differing velocities, causing undesired heat loss by convective cooling. The sum effect of the draught will be the result of the draught's air temperature and velocity (which will effect the rate of convection) and also to which area of the body it acts upon. Houghton et al in 1938 (from Awbi [9]) found that a 1.8°C fall in ankle skin temperature corresponded to 10% dissatisfied and a 2.4°C fall to 20% dissatisfied. however, they also found that the fall in ankle temperature required to produce discomfort was the same at the neck but larger air velocities were required at the head despite the same fall in temperature (1.8 and 2.4°C). The face is therefore more resilient to air velocity changes than the exposed neck. The feeling of draught will also be significantly affected by the turbulence of the air stream. Therefore, although a designer must ensure adequate temperature and humidity controls in a space to ensure thermal comfort, the ventilation strategy used might act against this as cold draughts are caused or temperature gradients are built up.

Whilst a person may be satisfied with his/her thermal conditions in a building, dissatisfaction may be caused by the ventilation strategy as air quality of a certain standard is required. For example, air may be considered to be stale and unacceptable beyond 800ppm of carbon dioxide (e.g. in BREEAM 2002) or pollutants/noxious materials may be present in the air e.g. carbon monoxide, cigarette smoke etc. Therefore, minimum air change rates (ACR) are also necessary to provide fresh air, as well as a means of providing acceptable internal temperatures. Though there is legislation to deal with the

The standard is complied with if the levels of pollutants are below those shown in the t (figure 2.2 from Kreider [10]). The standard can also be complied with provided certain m change rates are delivered e.g. 0.7 litres/sec/m^2 of fresh air for an office building allowir with an occupational density of 0.1 person/m^2.

VENTILATION

TABLE 2.1. MINIMUM VENTILATION RATES WHEN DENSITY OF OCCUPATION IS KNOWN (*IHVE Guide*, 1970)

Air space per person (m^3)	Fresh air supply per person (l s^{-1})		
	Minimum	Recommended minima	
		Smoking not permitted	Smoking permitted
3	11·3	17·0	22·6
6	7·1	10·7	14·2
9	5·2	7·8	10·4
12	4·0	6·0	8·0

Note. The statutory minimum volume per person in factories and offices is 11·5 m^3 and the corresponding minimum fresh air supply is 4·72 l s^{-1} per person.

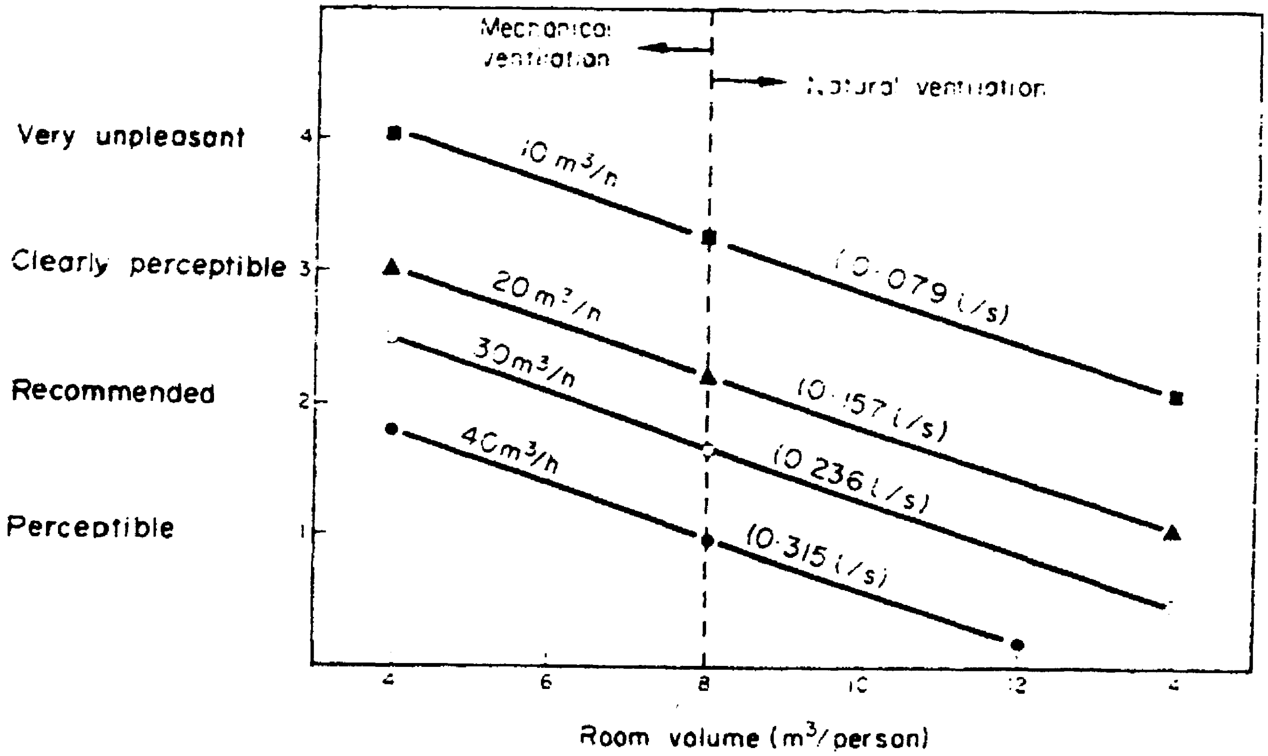


Figure 2.2: Statutory Controls on Indoor Air Quality

Though moisture control in buildings is also important in relation to comfort it is largely dealt with along with air temperature in relation to the ASHRAE comfort zones from Standard 55-1981. However, for the health of individuals, humidity levels may need to be further controlled, on occasions, so that extremes of low or high humidity are not created. Particularly low humidity levels may cause sore eyes, throats etc. whilst high levels may cause weeping eyes, sinusitis, running noses etc. In these instances, though an office may be perfectly acceptable thermally, its environment must be controlled to provide suitable humidity levels for the occupants - typically 40-60% rh. This is achieved by mechanical humidification/dehumidification as necessary. It is not unknown for air conditioning services to be provided to control humidity alone, such is its effect on occupant comfort.

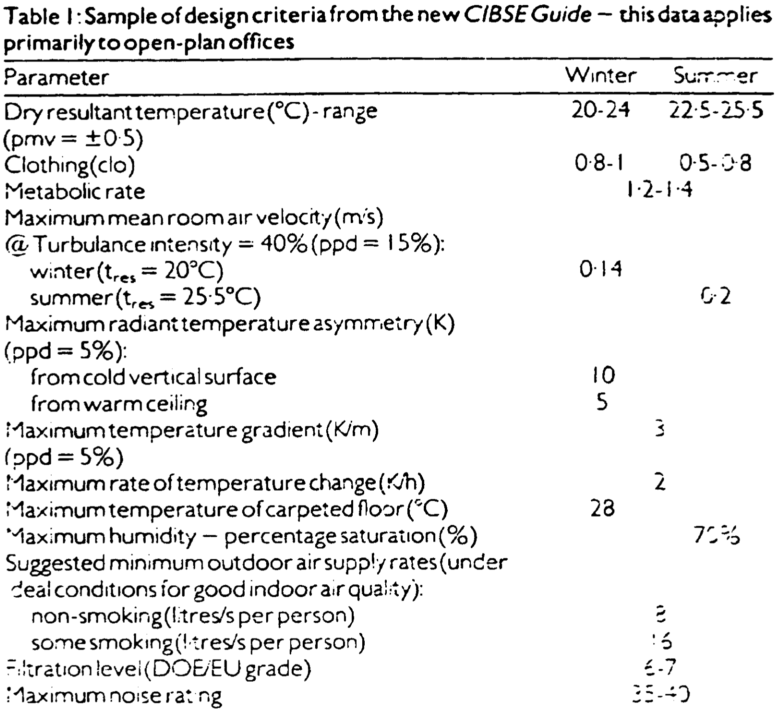


Table 1: Sample of design criteria from the new *CIBSE Guide* – this data applies primarily to open-plan offices

Parameter	Winter	Summer
Dry resultant temperature (°C) - range (pmv = ±0·5)	20-24	22·5-25·5
Clothing (clo)	0·8-1	0·5-0·8
Metabolic rate	1·2-1·4	
Maximum mean room air velocity (m/s) @ Turbulance intensity = 40% (ppd = 15%):		
winter (t_{res} = 20°C)	0·14	
summer (t_{res} = 25·5°C)		0·2
Maximum radiant temperature asymmetry (K) (ppd = 5%):		
from cold vertical surface	10	
from warm ceiling	5	
Maximum temperature gradient (K/m) (ppd = 5%)	3	
Maximum rate of temperature change (K/h)	2	
Maximum temperature of carpeted floor (°C)	28	
Maximum humidity – percentage saturation (%)		70%
Suggested minimum outdoor air supply rates (under ideal conditions for good indoor air quality):		
non-smoking (litres/s per person)	8	
some smoking (litres/s per person)	16	
Filtration level (DOE/EU grade)	6-7	
Maximum noise rating	35-40	

Figure 2.3: CIBSE Guide Vol. A1 (1991) "Environmental Criteria for Design"

Though, the examples here are from the USA, the United Kingdom has analogous standards to ASHRAE 55-1981 and 62-1989 in the Chartered Institute of Building Service Engineers (CIBSE) Guide Volume A1 (1991) "Environmental Criteria for Design" (figure 2.3). This large volume of standards was created so that the UK comfort standards could be brought into line with those published by the ISO, ASHRAE and others. Briefly, the guide's method of comfort analysis uses Fanger's Predicted Mean Vote (PMV) and Percentage Persons Dissatisfied (PPD) scales so that occupant satisfaction can be gauged (as previously discussed). CIBSE recommend a PMV of -/+0.5, which is equivalent to only a 10% level of occupant dissatisfaction. However, as also mentioned earlier, certain factors likely to cause discomfort are not calculated by this PMV method and therefore where relevant the Guide will provide dissatisfaction limits for each of these.

As can be seen from the above examples, guidelines are available to cover most variables that attribute to the perception of thermal comfort. In the UK, the CIBSE guidance for building services designers would lead to a working, office environment that is; between 20 and 22 ^{0}C, has a relative humidity between 40 and 70%, has an air speed of 0.1 m/s or less, would not allow a CO_2 concentration above 0.5% be allowed to occur and would be ventilated to a level to provide at least 8 litres/person/second. However, these are merely guidelines to be followed, rather than robust criteria to provide comfortable working conditions, as Leaman explains (11).

> "Over the years the definition of comfort has become enshrined by an ever expanding set of environmental criteria, such as 8 litres/sec/person of outdoor air, 500 lux on the working plane, relative humidity no lower than 40% and (possibly the most contentious of all) design conditions of 20 ^{0}C +/- 1.5 ^{0}C. But apart from references to Ole Fanger's thermal indices for percentage persons dissatisfied, nowhere in the CIBSE guidance is there any design data on building occupants' relationship to services........................ As a consequence, the more subtle behavioural and attitudinal aspects of building use are rarely appreciated by the building services designers, who rely heavily on laboratory derived physiological data to support their design criteria. Building designers need much more information on human interaction with buildings and their services if they are to provide systems which support comfortable, satisfied and productive people.

As can be seen from the above, definitions of thermal comfort exist and guidance regarding an acceptable quality of internal environmental conditions is given - e.g. in the UK the CIBSE standard recommending a PMV of -/+0.5 which equates to a 10% level of occupant dissatisfaction. However, no such definitive guidance exists when it comes to the quantification of overheating temperatures created in a building. Various definitions of an unacceptable level of overheating can be found from various sources. For example, unions that are concerned with employee rights have more severe but simplistic measures of overheating than the design industry - the Trade Unions Congress (TUC) stating in 2002 that air temperature conditions exceeding 30^{0}C should be a maximum for sedentary workers (12), more recently (2004) the Union of Shop, Distributive and Allied Workers (USDAW) setting this level at only 27.^{0}C(13). Whereas CIBSE in Guide A8 states manual method to calculate the maximum design risk for unacceptable conditions, here being defined as an environmental temperature over 27^{0}C for more than 2.5% of the year. Further guidelines exist; in BRECSU's Report 30 "Recommendations for the Office of the Future" (14) state that dry resultant temperatures should not exceed 28^{0}C for more than 1% of the occupied year and that 25^{0}C should not be exceeded for more than 5%, "Requirements for Office Buildings" set out in PACE(15) (Property Advisors to the Civil Estate) allow a design risk of 240 hours over 10 years for temperatures exceeding 28^{0}C. There can therefore be seen a wide variety of current guidelines, some that take into account hours of occupation and some that do not, and even within these simplified guidelines there is little commonality - e.g. a 3^{0}C difference between the TUC's demands and the more limited operating conditions created by USDAW and 5^{0}C difference to the British Safety Council which called for a maximum internal temperature of 25^{0}C for sedentary workers in UK offices.

All the above examples are guideline criteria only, definitive legislation regarding overheating limits does not currently exist in the UK. A quantifiable minimum temperature does exist, however, this is 16 ^{0}C and is set out in the "Workplace Health, Safety and Welfare Regulations"(16). Newer legislation such as Part L of the Building Regulations (Conservation of Fuel and Power) that are regularly updated concentrate on reducing the energy consumption of the buildings themselves rather than being concerned with the occupants comfort. The ever tightening laws reducing energy consumption in buildings also has a 'knock on effect' on occupant thermal comfort. As insulation levels in buildings are increased with lower, minimum fabric U Values this makes heat loss in buildings more difficult. Greater improvements in overall air tightness of the building fabric also demanded by legislation will also curb background ventilation rates in a building - these improvements aimed at energy consumption will combine to create greater instances of summer overheating in naturally ventilated building (unless the building shifted to utilising mechanical ventilation/air conditioning which, with its greater energy use, is the exact converse of what is desired).

2.3 Energy Efficient/Green Buildings

As public concern has grown over the seemingly indiscriminate and wasteful use of finite sources of energy in recent years, so have attempts to ameliorate this problem in most industries. In the case of the construction industry it is widely accepted that, on the whole, a naturally ventilated commercial building design will be less energy intensive than one which requires an air conditioning system of some description. In order to try to reduce energy consumption, more passive, energy efficient building designs are likely to become predominant in the future and as such a growth in the use of natural ventilation will be seen. It is also for these reasons that the EPSRC Research Project into creating guidelines for the "Design and Operation of Natural Ventilation in Offices" was initiated and also, therefore, partially the rationale behind the research problem to be investigated by this thesis. However, with the use of natural ventilation the internal environmental conditions will also be harder to control as they are largely determined by the temperature difference with the external air, plus predominant wind speed and directions - all of which will fluctuate greatly.

It is seldom acknowledged to how high a degree a building will affect the environment. The BRE, when considering one major promoter of the Greenhouse effect alone - Carbon dioxide – state that over half the CO_2 emissions come from buildings and the generation of electricity needed to run them (17). To further worsen matters, energy use in buildings has grown over time as comfort levels have improved (e.g. requiring greater levels of air conditioning), the population has risen (on a world-wide scale) and in particular more energy consuming devices are present in buildings (e.g. the recent I.T. explosion of modern times).

A first scant look at a building would give many people the impression the such a collection of bricks and mortar etc. would have a benign effect upon the environment. However, on closer inspection a building's effects upon the environment prove to be many; from being a major contributor to global warming and ozone depletion to an air polluter adding acid rain forming gases to the atmosphere.

Global warming is possibly the greatest of all current environmental problems and commercial buildings play a major part in this problem. Firstly, it is wise to briefly discuss the "Greenhouse Effect" itself. There is no debate as to whether global warming by the greenhouse effect actually occurs. This is a natural phenomenon and it accounts for Earth's average temperature being at 15°C rather than a possible -18°C (18). It is achieved as high levels of atmospheric ozone (O_3) in the upper atmosphere filter out high energy, ultraviolet radiation, however some of this energy reaches the Earth and is then reflected back at a lower energy level. This lower energy level of heat energy is in the infra-red spectrum, so cannot now escape the atmosphere and is instead absorbed by clouds, carbon dioxide (CO_2) etc. in the upper atmosphere - hence global warming. The largest contributor to this is natural water vapour (i.e. clouds) as well as atmospheric CO_2, however in more recent times a considerable amount of CO_2 has entered the atmosphere from anthropogenic sources as well as the contribution of other man-made "greenhouse gases". For example, CFC12 was used widely as a refrigerant and blowing agent for plastic foams. This has the potential to produce global warming 4500 times that of CO_2.

The fear of global warming is, that it is being increased to supernormal levels by emissions to the atmosphere from mankind's industrial activities. These rapid temperature increases could have disastrous effects upon the world primarily through an increasing level of the Oceans which could then lead to extensive flooding and thus the possibility of the wiping out of much coastal, arable land and low-lying towns and cities. A large contribution to the greenhouse effect has come from industrialisation which has increased the amounts of CO_2 in the atmosphere by 25% over the last 200 years (19). Observations show that the atmospheric CO_2 concentration had increased from 315ppm in 1958 to 343ppm in 1984. From these calculations the Intergovernmental Panel on Climatic Change predict an average global temperature rise of 2.5°C by 2025 resulting in a 66cm sea level rise.

CO_2 is emitted whenever a fossil fuel is burnt, therefore a building can contribute directly as gas or oil are burnt in its hot water boilers or indirectly as they use energy from power stations that burn fuel to provide electricity. Of the CO_2 emissions in the UK 50% is the result of energy use in buildings for lighting, heating etc (20).

The table below, from Baldwin et al (21) suggests the relationship between fuel use and carbon dioxide emissions.

CARBON DIOXIDE EMISSIONS THROUGH FUEL USAGE.

FUEL	**CO_2 EMISSIONS (kg/kWh delivered)**
Electricity	0.71
Solid Fuel	0.34
Fuel Oil	0.29
Gas	0.21

Obviously, these statistics are only indicators as emission rates will depend on the carbon content of the fuel. Electricity, though, is by far the highest source of emissions as when fossil fuels are converted into electricity at power stations some 60-70% of the energy is wasted. Therefore, it stands to reason that with effective controls on electricity consumption much of the CO_2 emissions could be reduced.

Unfortunately little can be done to make the primary provision of energy (i.e. the gross calorific value of the fossil fuels or equivalent) any more efficient without considerable spending on the UK's national power supply system. Courtney (22) claims that 3.73 units of primary electricity must be created before just one unit could be supplied to its user. Therefore, if the final user were able to become energy efficient every 1kW of energy saved, for instance, would translate as 3.73kW of energy that a central power station would not have to produce.

Commercial uses of energy were split up into their constituent parts by a study from the US Atomic Energy Commission(23) and they showed that space heating of buildings was by far the largest user of energy (48%), followed by air conditioning (20.1%) of which over a third was refrigeration needs whilst water heating required a mere 7.6% of the total energy demand. However, this leaves 24.3% of "Other" energy uses but this is very likely to be primarily the lighting requirement of buildings as in the UK the Energy Efficiency Office state this may be up to 20% of total office energy use (24). It is likely that as an industrialised 1st world country, the commercial energy use for the UK's building stock would follow a similar pattern to that found in the USA, though no equivalent definitive study is available, however Energy Consumtion Guide 19 does give a more minor breakdown of total energy use for office buildings - including catering electricity, fans/pumps, lighting, humidification (if present) etc..

Apart from the large energy requirement needed to provide air conditioning to a building, its use of ozone depleting chemicals for use as refrigerants will also have a major environmental impact. Briefly, the problem with ozone depletion is that it is this layer in the stratosphere and troposphere that prevents the majority of the short wavelength, ultraviolet radiation from the Sun penetrating the Earth's surface, thereby preventing excessive global warming and creating a habitable planet. Too much ultraviolet radiation can cause forms of skin cancer and have harmful effects on plants, agricultural crops and marine life.

There are many natural but also man-made gases known to cause ozone depletion. Of the man-made ozone depleters halocarbons are the worst offenders, the most well known of these being chloroflourocarbons or CFCs. CFCs have been widely used in buildings, for example they were widely used as blowing agents to create some foamed plastics used as insulation materials, such as polystyrene, polyurethane and phenolic foams. However, significantly refrigerants in chiller machines of air conditioning systems were previously almost always CFCs such as R11, R12, R500 and R502 - R12 for example has an ozone depletion potential 20 times that of the alternative refrigerant the hydrochloroflourocarbon (HCFC) R22. These HCFCs were developed and used as refrigerants as they were able to demonstrate similar properties to CFCs but with only minor effects on the ozone layer when compared to CFCs.

However, HCFCs, like CFCs before them still have, an adverse effect upon the ozone layer as well as being "greenhouse gases" exacerbating global warming. Halons, HCFCs and CFCs alike have large Global Warming Potentials (GWP). This means that as well as ozone destruction itself they also act as greenhouse gases in the same way as carbon dioxide but to a much greater degree. One part of the halon 1301, for example, is 5,800 times more effective at causing the greenhouse effect than an equal amount of carbon dioxide. Therefore, their use and production is being phased out. Through the Montreal Protocol signed by 50 countries, including the EU, in 1988, CFC production and consumption must already be cut by 20% of the 1986 level before final phase out in the year 2000. EU legislation goes further though - CFC production was phased out by 1/1/95 under Regulation 3952/92, halon production was cut out (as of 1/1/94) and HCFC production was proposed to be phased out for 1/1/2003 (currently the date is set for 1/1/2015). From Baldwin:-

THE EFFECT OF REFRIGERANT CHEMICALS UPON THE ENVIRONMENT.

SUBSTANCE	**ODP**	**GWP**	**ATMOSPHERIC LIFETIME** (years)
CFC11	1.0	1500	60
CFC12	1.0	4500	120
HCFC22	0.05	510	15
HALON1301	10.0	5800	110
HFC134a	0	420	16
AMMONIA	0	0	>1

(ODP=Ozone Depletion Potential, GWP=Global Warming Potential)

However, when all is said and done a building's effect on the environment is likely to be most greatly influenced by the actions of its occupants. For example, a building may be in possession of all the latest energy saving devices and have an efficient Combined Heat and Power system to provide its energy requirements but the impact of these measures will be greatly reduced if the building's users are content to let profligate use of energy be the norm.

The figures from the Energy Efficiency Office's :Energy Consumption Guide 19: indicates that the inclusion of even energy efficient air conditioning systems will typically add 30% to total electricity consumption for existing office buildings in its Energy use Indices (25). Therefore, utilising natural ventilation will significantly reduce electricity costs and as such reduce CO_2 emissions from these buildings. From a purely financial point of view, the latest (2000) update of the Energy Efficiency Office's Guide (26) assumes £4.05/m^2 as electricity costs in a typical naturally ventilated, open plan office structure, yet £11.70/m^2 in a typical air conditioned building. The "Basecase" examples taken from BREEAM Version 4/93 (i.e. standard building layouts and services derived from the Electricity Association's Easicheck computer programme) suggests that an open plan, naturally ventilated building will emit 92kg of CO_2/m^2/pa, yet an open plan building using fan coil air conditioning will emit 124kg of CO_2/m^2 annually.

As can be seen, energy costs and CO_2 emission savings can occur simultaneously, making them appear of particular attraction to building owners. However, it must be remembered that for commercial buildings, their energy costs are tiny when compared to the total value of the business

As can be seen above, buildings in their construction and use have a negative im environment. Aside from the embodied energy in the materials needed to create a nev harmful substances, such as ozone depleting CFCs, can be used in air conditioning syst the actual energy consumption of the buildings themselves further depletes the World's fi of fossil fuels. Therefore, it follows that, where this resource use can be minimised altogether, the greater the reduction in harm to the environment – whether this be the harmful CFCs, a greater energy efficiency by buildings or even the same equivalent energy cc but a shift to fuel supplies with lesser or zero carbon dioxide emissions (e.g. gas suppli power respectively).

2.4 DESIGN CONCEPTS

As has been shown in the above examples, the decision to naturally ventilate a building both financial and environmental benefits. However, to achieve a naturally ventilated de considerations must be taken into account so that thermal comfort levels can be provided anc acceptable air change rates can be achieved. Obviously, thermal comfort and ventilatio more easily regulated via mechanical means, however these are no longer an option, thus co the design process. **It is not the intention of this review chapter to reproduce materi in various design guides, however it is important to highlight the various factors that ventilation rates and thermal comfort that will need to be considered by the designe**

Realistically, the search for the optimal naturally ventilated design will involve the cal performance against the calculation of costs. Even assuming that costs are of no consequence tc decisions in these examples, the number of available design options are so large that guidelines are required. Of course, there is the complication with any design of the ability of the "foresee the future". For example, if a building has been constructed assuming occupancy rates of 0.1 persons/m^2 (as in the ASHRAE standard), yet the actual occupancy rate on completion is 0.2 persons/m^2, then the design may be flawed as insufficient air change rates have been allowed. The design would no doubt be different if the actual occupancy rate had been known at the time of design. As Kreider suggests (27) "It is advisable to plan for flexibility and to avoid designs that are too vulnerable to changes in occupancy or visualisation." Therefore, the actual design process should depend largely on the type and utilisation of the building to be constructed. Where heating/cooling loads dominate, much effort will need to be concentrated on the thermal performance of the building envelope (e.g. glazing ratios, element U-values), whereas a building with high internal gains would suggest that, for example, the efficiency of the lighting system be looked at and the possible need for localised cooling.

As previously mentioned, ventilation is required for numerous reasons but principally to provide fresh oxygen (a basic life requirement), to control airborne contaminants as the air will act as a dilutant (e.g. to minimise CO_2 levels) and to promote air movement as this is an environmental comfort factor. The quantity of fresh air that needs to be provided to sufficient oxygen levels is small and therefore ventilation rates tend to be based on the secondary need to dilute CO_2 levels and/or other pollutants. Further fresh air may then be introduced to secure adequate air movement, for example when internal heat gains are high and convective cooling needs to be promoted.

For naturally ventilated buildings, fresh air enters by two methods: **uncontrolled infiltration** i.e. the leakage of air through the building due to imperfections in its structure such as cracks in doors and windows, and **controlled ventilation** i.e. air entering via the designed number of openings and the size allowed for these openings. However, controlling ventilation via design alone is not an easy option. As Gordon states(28)

> "The intelligent arrow is the one that you often see on drawings, optimistically showing the air coming into a room the way the designer needs it to go. Unfortunately air follows the laws of science as defined by Newton and not wishful thinking"

If ventilation rates are to be controlled by a naturally ventilated design alone with no mechanical support, then the results are likely to be variable as they rely on varying motivating forces. These motivating forces are the wind pressure on the building and the stack effect. Although the two effects work in tandem, the former is predominantly the strongest of the governing forces in the UK. As the wind meets and moves over a building it will develop zones that are of positive or negative pressure relative to one another. It is this difference in pressure that can be used to create cross ventilation within a building - in fact, the inlets and outlets for air movement do not have to be directly opposite one another for effective ventilation as long as the air is flowing between positive and negative pressure zones. (See Figure 2.4 – from Givoni)

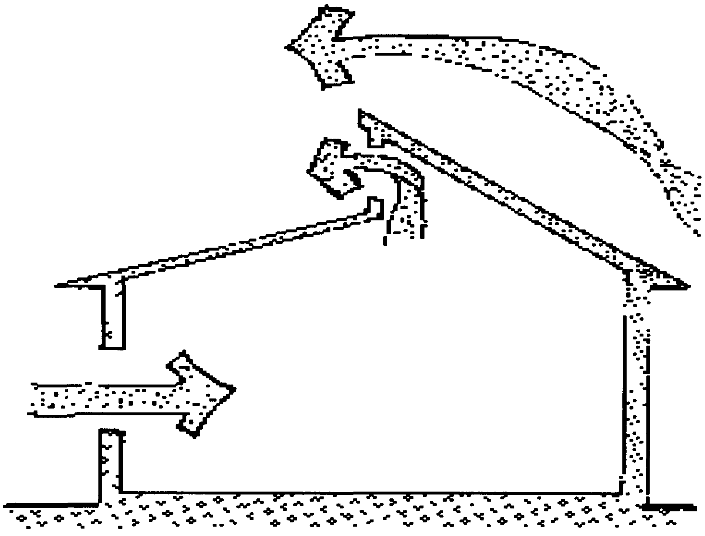
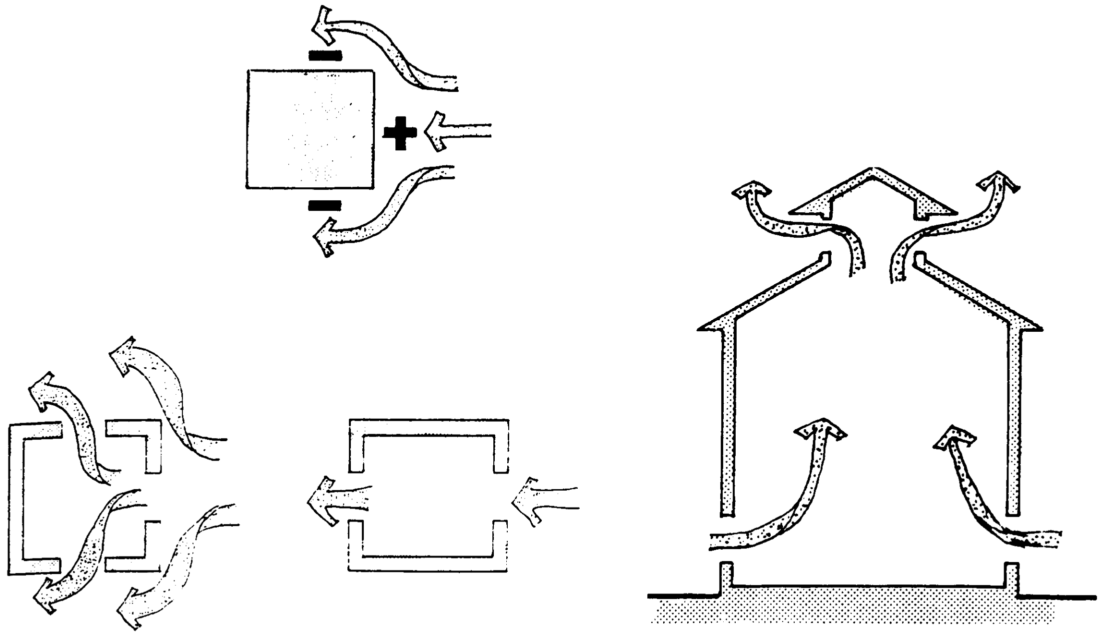


Figure 2.4: Air Flow Between Pressure Zones

The motivating force of the stack effect is the increased buoyancy of the air due to an increase in its temperature - i.e. hot air rises. Therefore, for the stack effect to be induced, the incoming air must be cooler than that of the air already present in the room. Hence, any inlet position will be lower than that of an outlet. (See Figure 2.5 from Givoni). Combining both pressure and stack induced effects may enhance ventilation rates in a building. As Gordon states (29)

> "Although there is no rule of thumb that relates to the effectiveness of ventilation to the depth of a room......under normal conditions a room having a depth of no more than 6-7 metres can be naturally ventilated by an openable window in one of its sides."


PRESSURE ZONES AND WIND MOVEMENT

THE 'STACK EFFECT'

Figure 2.5: Stack Effect

According to Givoni(30) where only one opening exists the average air velocity will be around 3.3 to 4.7% of the wind velocity, depending on the wind direction (though window size seems to have little effect). Where two opening windows are present, the average velocity rises to between 4.3 and 15.7%. However, partitions within a room can block or deflect intended patterns of air movement. Though, this problem can be overcome by the use of both high level inlets and outlet, this then renders the ventilation strategy as far less useful for the contact cooling of occupants. This convective cooling of occupants via air movement is usually required under Summer conditions so that thermal comfort may be achieved. Therefore, it can be seen that much attention is required to be paid to the design of a naturally ventilated building both in terms of the level and positioning of air inlets **and** the patterns of air movement within the building.

To actually calculate air infiltration four quantities must be known.

1) The wind speed and direction
2) The external and internal air temperatures
3) The position and flow characteristics of all openings
4) The pressure distribution over the building for the wind direction under consideration.

In practice it is extremely difficult to determine all these quantities accurately and as such a simplification of the problem is necessary. For example, the ASHRAE method, uses the following equation:-

$$Q = A\surd\,(a\Delta T + b\surd_r^{2})\ \mathrm{m^3\ h^{-1}}$$

Where A = the total effective leakage area of the building (cm^2)

a = stack coefficient ($m^6\ H^{-2}\ cm^{-4}\ k^{-1}$)

b = wind coefficient ($m^4\ s^2\ h^{-2} cm^{-4}$)

ΔT = average inside-outside temperature difference (K)

$\surd_r$ = mean local wind speed (ms^{-1})

As the inputs (1-4 above) are only available for all but the simplest structures such as dwellings, simplified empirical models, based on statistical fits to measured data, have been used to predict ventilation rates. However, these too have been confined to dwellings rather than to larger, non-domestic buildings. For example, the "1/20th rule" which states that the average infiltration rate for a sheltered UK dwelling is 1/20th of the air change rate of a pressurisation test performed at 50 pascals.

Despite the problems of designing for adequate ventilation rates in a naturally ventilated building, the whole ethos of energy efficiency will dictate that many other inter-related design choices will need to be made. Fortunately, general guidelines are available that present themselves for use in most designs. These can generally be broken down into the following categories: the external environment (i.e. site effects), structure/envelope, equipment/services and their control.

When considering the external environmental conditions of the site alone many implications for an intended design will become clear. For example, shading is of great importance as it will not only affect the heating (and therefore also the cooling) requirement of the building but also the amount of available daylighting that could be used. There have been many examples of a large structure being erected next to existing (and correctly functioning) buildings and hence casting much shadow or reflected radiation upon them from substantial glazing. The prevailing wind patterns of a site can greatly affect the air infiltration rate of a building and at the same time the level of convective cooling of that building, as mentioned earlier. A remedial measure such as providing an external treeline or other windbreak could reduce a building's heat loss via convective cooling and thus reduce heating costs. However, with a naturally ventilated form this may reduce the ventilation rate in Summer months that will be required to provide adequate internal temperatures and air change rates. This latter example, brings up the maxim as described by Perera (31) of " 'Build Tight Ventilate Right' as a building cannot be built too tight (i.e. effectively insulated and sealed) but it can be underventilated. The tighter and better insulated a building the less its sensitivity will be to external effects such as wind patterns. This aspect of construction becomes even more important when one considers where external wind patterns are most difficult to change with the use of windbreaks and landscaping - i.e. around other buildings, a likely site for most new buildings.

The next important design consideration is in the fabric and form of the building structure itself i.e. its "envelope". For any given floorspace, environmental driving factors can be minimised by also minimising the surface-to-volume ratio of the building. A cuboid naturally seems the best building form from this perspective - a large floorplate with a lower level of perimeter wall to lose/ gain heat through. However, in reality many other considerations tend to define the building form. One of the most important factors is the human concept of satisfaction, both for aesthetics and comfort. For example, people like windows and therefore to maximise the number of rooms with a window position, a large surface to volume ratio is gained. Other effects likely to influence the actual form of the building will tend to be site and design specific e.g. height or floorplate restrictions via legislation, orientation and depth restrictions for ventilation strategy requirements etc. The next most important factor to influence a building's form will also influence its fabric construction - its thermal behaviour.

Heat gain/loss from a building will depend greatly on its construction, therefore where financial constraints allow well insulated designs are chosen with corresponding low U-values. The lower the U value of building the lower the heating load will be (the cooling load will also be lowered, though the lower U values can only affect the external temperature related element of the cooling load). The thesis case studies were constructed to the (then current) 1995 Building Regulations Part L, where any new construction must have a fabric constructed to the following tolerances:- 0.45W/m^2/K or lower for floors and walls and 0.2 W/m^2/K or lower for roofs. These minimum U values have been gradually reduced by legislation over time to encourage energy efficiency - e.g. the wall U value was previously only 0.6 W/m^2/K or lower (1979) but was then further lowered to 0.35 W/m^2/K for the 2003 Building Regulations. The greater the level of insulation of the envelope, the lower the risk of discomfort caused by temperature effects inside the building such as cold draughts from leaky walls and windows.

Therefore, lower U values can benefit the thermal comfort performance and reduce the running costs of a building concurrently. Conversely, though, a better insulated building will have more difficulty in losing its heat gain to the external environment - therefore this would be problematic in Summer conditions when an enhanced air exchange rate with cooler, external conditions overnight would be beneficial. Here the greater the air change rate between the cooler external and warmer internal, room air (perhaps created by a deliberate night time purge of internal air) will aid in reducing the following day's internal temperature as the room should now start the day at a similar temperature to its external environment.

As previously mentioned, a minimum supply of fresh outdoor air is required for comfort and health purposes. Uncontrolled infiltration through the fabric is unlikely to supply the minimum air change rate necessary and as such only a controlled ventilation strategy will succeed. However, this designed air change rate greatly affects the heating and cooling load of the building. It is therefore important that any design fully integrates the requirements for both minimum air change rates and the reduction of heating/cooling loads. However, in climates where extreme heating/cooling loads are necessary, mechanical ventilation techniques when combined with near-airtight constructions may prove more energy efficient, though this is unlikely to be the case in the UK.

Of the entire building fabric, window sizing and construction will require the greatest attention as it is through these that environmental factors, such as solar heat gains and conductive heat gains, will be the most strongly significant. From Kreider(32) "With conventional construction, heat transfer and solar heat gains are an order of magnitude larger per unit area than through opaque walls. Windows can make the difference between efficiency and waste." Solar heat gains through windows can be beneficial in reducing Winter heat loads but, of course, conversely they can be a definite cost in Summer months as they may raise the cooling load required and/or push occupants into thermal discomfort. This Summer penalty is increased when one considers that to shade the windows would eliminate useful daylight from entering the building and thus now require the use of energy consuming, artificial light.

Traditionally, architectural considerations and the human desire for window space has overridden the thermal performance requirement of windows. However, a modern integrated design could make use of windows with low heat loss coefficients as a result of utilising low-emissivity coatings and a cavity construction e.g. double glazing. When combined with good control of solar transmissions through the window, e.g. with finely controllable shading devices, much of the previous problems with windows, such as having high U values, can be avoided.

The final major strategy to consider in the construction of a naturally ventilated building is its internal services and their controls that will be required to meet the building's heating load. Of course, heating a building is a must in the UK climate and therefore this decision is of an either/or variety. In general, these decisions may be left to a building services engineer who will endeavour to install equipment of the correct size and highest efficiency versus lowest cost to meet the heating demand. However, by virtue of the previous design choices mentioned (for example a well insulated building with a low percentage glazing that is in a sheltered location) this heating load could be only 79 compared to 151 kWh/m^2 of treated floor area -i.e. the Best Practice and Typical levels for naturally ventilated offices as given in the Energy Efficiency Office's Best Practice Guide 19(33).

It can therefore be seen that the designer's job is a complicated one in that if he/she is to provide an energy efficient yet also thermally 'comfortable' building for its occupants they must take account of the complex nature of the thermal response of a building via its various sources of heat transfer (conduction, convection and radiation). These interactions must be understood in enough detail so that the relevant, though hardly robust, guidelines currently available for creating a comfortable working environment are adhered to (e.g. fresh air to 8 l/person/sec, design conditions of 20 ^{0}C +/- 1.5 ^{0}C, 500 lux at the working plane etc). This may pose problems in that, for example creating enough window space in a naturally ventilated building to provide adequate day-lighting and to allow for ventilation may also allow for greater amounts of solar and conductive heat gains to the space – this in turn prompting overheating of the space, past levels set by relevant design guidance. Whilst keeping these competing demands from design guidance in mind, the designer must also attempt to minimise the carbon emissions of the building - as it was seen that its energy consumption will further deplete the World's fossil fuels whilst also contributing carbon dioxide emissions to the atmosphere, further promoting the Greenhouse Effect.

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33) EEO (2000 update) Op cit Appendix B

3.0 Literature Review

It is apparent that the capabilities of the computer modelling systems currently available merits discussion. For example, are current thermal simulation models accurate enough to be used in the design process to examine overheating, total heating loads etc. within a given design? Or is there another limiting factor on their adoption by the design industry? The aim of this review chapter is therefore to postulate on the future of computer modelling techniques by the discussion of current and ongoing research and the applications of such current programmes. This review will also examine the potential for DTM techniques in future design work; as although the "technology" is already available it does not necessarily mean that it will automatically gain widespread user acceptance. Therefore, when looking at the future of computer modelling techniques, they must be seen in the light of user acceptability:- i.e. does current research indicate that computer modelling will become user friendly?, be seen to be of value to the design process? and/or be seen to be readily available for use?

3.1 Dynamic Thermal Models

Dynamic thermal models (DTM) are computer programs designed to simulate the thermal performance of a building. To simulate this performance many of the factors affecting thermal transport (and hence gains/losses to the modelled building) need to be determined e.g. fabric conduction, ventilation rates, insolation, heating/cooling equipment, incidental gains etc. Therefore, the need for variables to be input into the DTM program are many as well as the obvious need to correctly model the geometry of the building in question.

The development of these computer programs initially stemmed from their need to conduct building energy analyses. (From Ahmed (1))

> "The early programs were computerised versions of empirical handbook procedures, mostly based on steady state heat flow calculations. Soon after the 1973 energy crisis attention was focused on energy

efficient building design, thus it became necessary to evaluate the dynamic thermal behaviour of buildings."

To this day many programs persist ranging from the more simplified "rule of thumb" applications to the complex DTM. Of these DTM many, varied programs are in existence throughout the world, for use both in research and as a working design tool - e.g. BLAST, CLIM200, DEROB, DOE2, ESP-r, SERI-RES, TRYNSYS and HTB2. The drawback of any available DTM is that they have frequently not been fully validated by parties outside their own development teams. Validation of any model is required to establish its accuracy and reliability - a pre-requisite before any "evaluation" can take place to establish the model's usefulness and usability. It is for this reason that , in recent years, validation exercises have been carried out on existing commercial and research DTM programs - e.g. the International Energy Agency's BESTEST program. Validation, including that to the new proposed ISO standard is discussed later in this chapter.

Prior to any building simulation being undertaken, much data will be required to be input for an accurate prediction of thermal performance. Needless to say, the greater the extent of "guesstimation" the less likely that the results will be accurate. For example, for a simulation run under the Welsh School of Architecture's HTB2 programme the following information is required) (From HTB2 User Manual (2)

"Building:-

The geographical location of the building: latitude and longitude.

The spaces and zones into which the building is to be divided.

The partition elements separating the spaces.

The physical layout of these elements in terms of their connections to the surfaces.

The number and specifications of constructions used in creating the partitions.

The thermo-physical and transparency properties of the materials used in these constructions.

The external site shading of the facades.

Services:-

The number, type and control characteristics of heating systems in the building

The number, heat output , control and connections of lighting circuits

The number, type, heat output , control and connections of small power sources.

The number, heat output and locations of occupants.

The ventilation characteristics (rates, flow patterns, control strategies) of the building and its spaces.

Operation of the building:-

The time dependant operating schedule diary of the building.

The external meteorological conditions for the test.

The configuration of the simulation i.e. simulation length

The selection of data output types and intervals."

Though, this data collection seems immense, the main issue in any simulation is likely to be what is known as the "descriptive abstraction" - i.e. the level to which the simulated model parallels the real situation. This will have the greatest effect upon accuracy. As Gonclaves states(3)

> "The application of design tools to the design process and performance assessment is a technique which needs minimum background requirements of building physics, heat transfer phenomena, and a lot of common sense.......With this information and above everything else knowing quite well or exactly what is wanted as a final result, the necessary decisions can be taken regarding all the implicit simplifications which need to be done to the building in order to obtain a consistent model with the reality, in physical and heat transfer process terms."

Therefore, when assessing the objectives of the simulation, and bearing in mind the limitations of the DTM program, the extent to which precision is required in the input data can be assessed. Whilst it may be important to maximise the precision of the model in regards to its geometry (e.g. dimensions, opening areas etc.) and its construction (type of envelope walls, glazing etc.) more lax estimates may be allowed to be used for occupational affected parameters (e.g. small power outputs) if it is thought that their effects on the total thermal performance of the building is low. However, under a differing simulation scenario, perhaps evaluating the inclusion of cooled air from an air conditioning system, the nature, extent and time dependant profiles of incidental gains from occupants and small power sources may become important.

The actual "model definition" problem may also have more than one answer. For example, how many zones may realistically represent the building? This may be as large as one for the whole building or as small as to require every room to be modelled individually. Again, this will be largely dependant on the expected results but if precise constructions, orientations and occupational profiles are important (e.g. for lighting/HVAC/small power use) the latter example could easily be the case.

A user of a DTM must make further decisions as to the performing of the simulation itself - relating to the climatic data used, the period of the simulation etc. Climatic data to accurately imitate average external conditions may be a constraint on the user as it may not be available, or if so, at too gross a time period (e.g. daily temperature profiles rather than hourly data). Whilst gross figures of daily temperatures could be of use in assessing the extent of the cooling/heating season of a building (akin to degree days) this may not be appropriate when analysing overheating over the period of only one day/week - e.g. in an office where the addition of solar and incidental gains could create thermally uncomfortable conditions. How realistic is the weather file chosen for the simulation? Is it from a reasonably close location to the intended site? A major variation between the weather file and building's actual location and/or height above sea may naturally mean that there is little relationship between the meteorological conditions experienced by the intended site for the building and the weather data included in the DTM run. Even where the weather file is from a reasonably close location, a chosen example year may be from a particularly cool year, for example. In this instance would this file be suitable for the calculation of overheating conditions in Summer months? Therefore, it must also be asked whether the meteorological file is suitable for inclusion given the end product required from a particular dynamic thermal model's simulations. For example for weather files containing the three warmest summers in recent times in the UK (1976, 1990 and 2003) it would be expected that these would produce higher internal temperatures than those of other example years. Given the important nature of meteorological data in DTM simulation it is therefore important to also discuss its availability and the choice of suitable weather files in its own right.

3.2 Meteorlogical Information for Simulation Purposes

Until the recent past the main requirements of weather datasets was that they contained a representative set of hourly, or other time series, values for air temperature, humidity, solar radiation, wind speed and wind direction. The end use of the computer simulation project would determine the actual file chosen as it should be from a suitably close weather station to the building site in question and would contain, for example, a representative year for energy use assessments, extreme cold period for sizing of heating equipment and a representative warm season for summertime overheating assessments. This need for representative and end-use related weather files has led to many variant file types being created to fulfil these needs. E.g. the WYEC-2 (weather years for energy calculation) and TMY2 (typical meteorological year) types in the USA and the EWY (example weather year) and TRY (test reference year) in the UK.

In the UK, the new CIBSE "Guide J: Weather, Solar and Illuminance Data" includes design guidance for CIBSE's UK weather file types. This promotion of real, hourly weather data, can be seen to be replacing the older admittance method of a daily cyclic temperature and radiation wave as was traditionally used in manual calculated design by CIBSE. The Guide states(4)

> "Hourly simulation has been used widely to compare the predicted annual energy consumption of buildings. This needs typical or representative weather time-series covering all seasons of the year as form of overall average, but retaining realistic short term patterns and variations... Simulation is increasingly used for problems requiring non-typical weather inputs such as assessing loads for heating and cooling design, predicting comfort in naturally ventilated buildings and modelling the composite needs generated by mixed mode buildings. These applications require near extreme weather data with a return period of 2-20 years."

However, the retention of "short-term patterns and variations" may prove more troublesome. Finding a weather file for a suitable location, let alone an extreme 'hot' summer or other rare sequence may not be possible. As Guide J mentions nearly all simulation programmes require solar radiation data in addition to synoptic data (e.g. wind speed and direction, humidity and air temperature), yet only around 120 locations exist throughout the UK that measure even this latter type of information. Guide J goes on to state that with further closures of manned weather stations only around 15 locations exist where both synoptic and radiation data is measured. Naturally, this leaves much of the UK with only limited coverage as just 15 sites are available that have data for use in computer simulations. This problem is further exacerbated by missing and/or corrupt data in the data sets. Recognising the need for a single representative weather year as a basis for predicting energy use, from these main 15 sites CIBSE developed the EWY (example weather year) file type.

The EWY type was chosen with the aim of predicting and comparing energy consumption at the design stage and therefore are not chosen to reflect extreme seasons. Such an EWY may not be suitable for use in predicting overheating in a naturally ventilated building, for example, as it does not include hot enough summer conditions to assess the building's warm weather performance. CIBSE's Guide J "Weather, Solar and Illumination Data" published in 1999 takes note of this inapplicability of previous EWY files for use in overheating assessments in its Section 8.5. devoted to "Design Summer Years". Here it states that

> "Naturally ventilated buildings need to satisfy an overheating criterion, often expressed as a percentage of occupied hours during which the given internal temperature is exceeded. The number of hours when such a threshold is exceeded varies considerably from year to year and a

typical weather year selected for energy use calculations may not include sufficiently onerous warm weather conditions to assess the hot weather performance of the buildings........it is better to use a near extreme season."

To attempt to tackle this problem a near extreme summer was selected and adapted for use in 3 UK sites (Manchester, Edinburgh and London) to create CIBSE "Design Summer Years". This weather data costs (at Dec 2004 prices) £290 per city site. Whilst this begins to tackle the problem of providing weather data suitable for its end use, in this instance overheating assessments, it can be seen that having readily available data for only 3 sites/cities in the UK will be insufficient to satisfy the demands of the design industry. Even where a suitable weather file can be found for an individual UK region, at present there is no assurance that this data will be of use for assessments of severe cold or warm periods without alteration by the designer/modeller.

The method of creating these DSY files, and thus representative hot summers, relies on calculating average dry bulb temperatures for the summer months (April to September) over 20 years of meteorological data and then selecting an upper year from these ranked averages (at the mid point of the upper quartile) - e.g. the London data uses 1989 as it representative hot summer. However, 20 years worth of consistent weather files may not be available either for the location at all or to the modeller himself in a given case. Furthermore, this method is based on finding a near-extreme summer that in reality will be warmer than all but 1 in 8 years, whereas in reality the effects of weather vary from building to building. For example, in a building containing a large glazed surface area the primary weather variable affecting its level of overheating may be solar radiation. Ambient temperatures are more likely to be the dominant variable where a building has either a low percentage glazing or makes good use of solar protection. The Guide also states that "Wind effects will be important for many naturally ventilated buildings, for which a still, warm day may create higher internal temperatures than a hot, breezy day". This lack of available and useful weather data may hamper the take-up of DTM in the design process despite CIBSE's promotion of such techniques.

Previous overheating calculations were based on analysis of cyclic repeating gains for each month of the year, radiation and temperature data being given for a worst case (i.e. a south-west facing room) for a July day (found in CIBSE Guide A2). However, no information is given on co-incident wind speed which is important for any natural ventilation assessment, whilst it is also possible that highest solar gain can occur in months other than July when the sun is lower in the sky. As mentioned above, solar gain may be the key weather variable in a particular building leading to it's overheating. This banded weather data from Guide A is therefore limited as; it is collected from a weather station outside a major conurbation (hence ignores the 'heat island' effect), is only truly representative of a limited region of the UK, and is based on 1959-1968 observations - thus ignores any global warming trends (though this only only accounts for a small increase in annual average temperatures).

In its Application Manual AM10 "Natural Ventilation in Non-Domestic Buildings"(5) CIBSE state that

> "Computer-based methods can be useful in identifying the main heat gain likely to cause overheating (it may be high solar gain or an internal gain in a particular area). Careful analysis of the results can direct the designer to the key design issues that need to be addressed...For greater accuracy, an hourly dynamic simulation for all 365 days of a representative year can be carried out".

However, AM10 does also discern the problem that the common CIBSE EWY file does not necessarily contain a sequence of extremely hold of cold weather and therefore may not be representative of overheating analysis. In a report on "Simulation of Building Energy and Indoor Environment Quality - Weather Data Issues"(6) Hensen concludes that users of energy simulation programmes should avoid using single year, EWY-type weather data as no single year can represent typical long term weather patterns. When comparisons were made of simulated energy, heating and cooling costs of a prototype office building (using the DOE-2.1e programme) a range of predictions were created, yarying with the use of alternate weather file types. For example, for cooling loads a

30 year average weather-file was 9.8% of the design size, using a TMY2 file this figure was 23.6% above design size but only 0.6% above using a TRY weather-file. Hensen therefore states that:

> "For developers of future weather data sets, one of the recommendations is to create a typical weather file that has three years: typical (average), cold/cloudy, and hot/sunny. This would capture more than the average or typical conditions and provide simulation results that identify some of the uncertainty and variability inherent in weather."

Despite creating a weather-file type as Hensen would recommend, this may still not answer criticisms that also affected the older, banded weather data used in manual CIBSE calculations. The microclimate around a building is still of considerable importance as the assumed weather data is sourced from a nearby locale is therefore representative of only a location rather than being site specific to the building per se. These 'micro-climate' issues are of importance as Hensen concludes

> "A hardly researched issue concerns the differences in weather data between the area immediately surrounding a building and the weather data measurement site, usually at a considerable distance from the building. These differences are most pronounced in terms of temperature and wind speed and direction; i.e. the main driving potential variables for the heat and mass transfer processes in buildings."

The additional air temperature found in an urban area is known as the 'heat island' effect. As cities tend to be up to 10°C warmer than the surrounding rural areas this poses a problem as meteorological stations are typically sited in these rural areas (such as airports), so the heat island effect will not have been taken into account. For instance, studies have found that, under clear skies and light winds, temperatures in central London during the spring reached a minimum of 11 °C, whereas in the suburbs they dropped to 5 °C (7). Similarly, the wind speed reduction on a building in an urban area is unaccounted for as the reduction between the building site's wind speed and that of the weather station has not been catered for.

Despite these failings an appropriate meteorological file must first be sourced for use in a DTM simulation. As Hensen points out "for many locations worldwide there is no weather data readily available for use in buildings simulation". However, several tools for weather data generation do present themselves. Firstly, the main source of UK weather information would be CIBSE, with

EWY files available for 15 sites. Similarly, weather files in a similar format can be found for other countries e.g. TMY2 files for 239 locations and WYEC-2 files for 76 locations in the USA, from ASHRAE. Further data is also available on the World Wide Web as it becomes an increasingly important resource for locating meteorological data. (e.g. at the American website for the Energyplus DTM programme at *www.EERE.Energygov/buildings/energyplus/CFM/weatherdata/ weather_request_search.CFM* [8]). Where no weather data is readily available for use in building simulation, long-term (i.e. monthly) averages for most major weather variables may be available. This meteorological data can be used to generate synthetic hourly weather data. For example, the commercial, public domain software Meteonorm not only contains the weather files for 7,400 sites worldwide but is also able to generate hourly weather data files for 2,400 sites additional sites via interpolation. As the description of the Meteonorm (version 5.0) states(9)

> "For many regions of the world, measured data may only be applied within a radius of 50 km from weather stations. This makes it necessary to interpolate parameters between stations. Interpolation models for solar radiation, temperature and additional parameters, allowing application at any site in the world, are included in the software."

To conclude this review of meteorological information sources, it can be seen that the references point to the fact that, for a successful DTM exercise, weather data must be generated for a suitably close location (perhaps involving the use of "artificially" generated data e.g. as from Meteonorm), if possible some account must be taken of micro-climate issues affecting the building and the file used be of the correct type - i.e. a DSY for overheating predictions rather than an example/reference year (which was created to gain predictions of the annual energy consumption of the building). As Hensen states (10)

> "The major problem is that each reference year is designed with a certain purpose in mind; say, to accurately predict the annual energy consumption of an "average" building. The validity of the reference year will deteriorate as soon as we want to do something else; e.g. establish peak loads, or predict the performance of a "non-average" building, etc".

3.3 Quantification of Over-Heating in Office Buildings

As briefly discussed in the Theoretical Background section of the thesis, several guidelines will present themselves for use in the UK. For example, design guidance for office buildings offered in BRECSU's Report 30 "Office of the Future" is that 25 °C dry resultant is not exceeded for more than 5% of occupied hours, whereas for school buildings' the UK Department of Education produced "Building Bulletin 87 – 2004" has a maximum internal air temperature of 28°C that should not to be exceeded for more than 80 hours. As these guidelines are created for design use they are not developed with the monitoring of actual buildings in mind. Therefore, staff-led concerns have created more simplisticly monitored guidelines for the measurement of maximum internal temperatures e.g. 30 °C demanded by the TUC (Trades Union Congress) (11) and 27°C by USDAW (Union of Shop, Distributive and Allied Workers) (12). Whether designed for application when the building is being designed or in actual use, however, these guidelines are not supported by legislation as no overheating law exists. To date in the UK only a minimum air temperature of 16 °C has been set out (in the "Workplace Health, Safety and Welfare Regulations").

Whilst it was previously shown that people's perception of thermally uncomfortable conditions can be quantified e.g. by Fanger's predicted mean vote and percentage persons dissatisfied this does not answer the question of "what is unacceptable overheating"? Whilst this previous research has identified the average neutral temperature that will be preferred by occupants in closely controlled building environments these guidelines would be very difficult to apply to non-air conditioned buildings that are allowed to be " free-running" in summer i.e. their internal temperature being closely linked to that of the external temperature (plus an internal gain allowance). Even though occupants may be tolerant of a wide swing of internal temperatures over a working day at some point a level of dissatisfaction will occur when the temperature becomes too great. How can this point be quantified and how can it be assessed in design and during occupation has yet to be universally agreed.

International Standards also tend to be aimed at thermal comfort rather than a quantification of what defines overheating in a building. As previously discussed in reference to thermal comfort the ISO 7730 standards adopts the criterion that a PPD of 10% is an acceptable working maximum whilst the USA's ASHRAE Standard 55-92 recommends a similar 10% PPD (based on 26^{0}C, 50% rh and an air speed of 0.15 m/s for sedentary activity). However, unlike the UK, the potential problems of the fall in office worker productivity, through thermal discomfort, has led other European countries to create legislative controls. Cohen et al (13) reveals that " the Dutch already have criteria for maximum summertime temperature incorporated into their Building Services Regulations". These state a maximum allowable internal air temperature of 25 °C in the case of high ambient temperatures. However, this is not an absolute level as 5% of annual working time is allowed to exceed this 25 °C level and 1-2% to exceed 28 °C if caused by extreme ambient conditions. Switzerland's laws are defined at the Canton level with the Zurich Canton applying criteria to allow the use of air conditioning equipment. Where it can be proved that the "indoor temperature exceeds 28 °C for at least 30 Kelvin hours/year" the use of air conditioning is permitted, however this criteria ignores periods when ambient temperatures exceed 30 °C.

With many varying guidelines it is unsurprising that design advice aimed at the UK building industry itself has no set level of overheating. As previously mentioned CIBSE in Guide A8 allow for a 2.5% design risk over 27^{0}C. The BRE Environmental Design Manual states that summertime resultant temperatures should be seen as the minimum acceptable if they have an average of 25^{0}C with a maximum swing of +/- 4^{0}C (thus a 29^{0}C maximum). In a review of guidance by Cohen(14), BRECSU Good Practice Guide 71 states that "even in the warmest parts of the UK, outdoor temperatures exceed 28^{0}C for only 10 hours and 25^{0}C for only 40 hours in a typical year" and therefore comfort cooling is only deemed necessary if it is unacceptable for internal conditions to reach these levels. Whilst all these guidelines avoid the problem of verifying a performance guarantee against a criterion as difficult to quantify as PPD (due to it being made up of several values e.g. clothing level, activity level etc) they serve to highlight the different views of overheating as perceived by employee-concerns based groups and the design industry.

The problem is therefore to assess overheating at the design stage and make it a verifiable quantity to be measured for the building in use. The more simplistic the criterion the easy to measure in use but also more limited in its scope as it provides a simplistic pass/fail for this test. Given the nature of dynamic thermal modelling which is based on many estimated inputs of gain such as from occupants and equipment and predicted decisions of the building in use (e.g. blinds to limit solar gain) such simplistic pass/fail criteria could be met or missed with alterations to one or two simple input estimates. Most notably of these input estimates is the weather data used. The design advice from BRECSU highlights the prime importance of the use (and view of) weather data when predicting possible overheating in a building design. In its assessment it views a likelihood of 28^{0}C external temperature only occuring for 10 hours - as a yearly average this may be true but offers little in the way of assessing a building during more extreme summertime conditions.

In the CIBSE guidelines published under its Application Manual AM10 for "Natural Ventilation in Non-Domestic Buildings" (15) it states that " Computer based methods can be useful in identifying the main heat gain likely to cause overheating (it may be high solar gain or an internal gain in a particular area). Careful analysis of the results can direct the designer to the key design issues that need to be addressed". Furthermore, it raises concerns with the traditional manual calculation of overheating, promoted by CIBSE and goes to on state that

> "the methods based around the procedures described in CIBSE guide A2 are based on analysis of a cyclic repeating day for each month of the year. Radiation and temperature data are given for a July day and what is assumed to be the worst case but no information is given on coincident wind speed which is important in ventilation analysis. Also, solar gain can occur in months other than July when the sun is lower in the sky, thus shading devices that work well in July can be less effective in September when the sun angle is lower."

Therefore, whilst CIBSE has provided a figure that measures overheating (i.e. 2.5% of hours above 27^{0}C) its choice of weather data seems flawed for this use. Furthermore, it states that the banded weather data used is limited as; it is based on the Kew region of London which can only be representative of a limited part of the UK as a whole, this data is from a non-urban area and is not influenced by the heat island effect which keeps cities and towns warmer than their surrounding rural areas and that this is from historic data and will not take account of increases in the annual average air temperature. For these reasons dynamic thermal models tend to use weather files containing hourly records of the primary weather parameters (relative humidity, air temperature, direct and diffuse solar radiation, wind speed and direction) which are based on real year's e.g. Kew from 1967 or a representation of a 'typical' year - in the UK these are represented by CIBSE's EWYs (Example Weather Years). As stated previously, these EWYs are representative of 'average' conditions over a 20 year period however this means that **they do not necessarily contain sequences of very hot or very cold conditions that will affect that region/**

town. For this reason they may be less suited for use in overheating analysis. An example of this problem is found with Kew data - the most commonly available EWY was from 1964/65 which had a relatively cool summer. Therefore, for overheating analysis it would be wise to change weather years used to perhaps the warmer summer found in 1967 or even the extremely warm summer found in 1976. The CIBSE AM10 states that "it is important to check that the weather year being used contains an appropriately hot sequence", however whilst this may be possible in the above example of Kew, London this does not necessarily mean that many alternative weather years will be available for all towns and regions across the UK.

Therefore, as can be seen from the above examples there is no European union wide or UK-national agreement on an exact figure to constitute overheating. A suitable definition of overheating must be created by the design team or taken from one of the above guidance figures during the design of a modern office building. Though not backed by legislation this 'pass/fail' level of overheating should be enough to ensure a client that overheating will not occur. Guideline figures such as "below 5% of occupied time below 25°C dry resultant" are taken from assessments of full summer/year predictions of the building and therefore they set up no maximum level of temperature. Yet it is exactly this 'maximum internal temperature' level used to gauge overheating that is being demanded by Trades Unions etc who act on behalf of the staff themselves e.g. the maximum 27°C internal working temperature wished for sedentary office workers demanded by USDAW.

3.4 Previous and Current DTM Use in Design Practice

As previously discussed DTM has a number of appropriate uses such as predicting maximum cooling or heating loads or in the 'thermostatic' mode as it predicts energy consumption over the year. Dynamic thermal models have also been used to investigate overheating in naturally ventilated and mixed mode buildings. For example, a project was conducted by Wright et al(16) to compare summertime comfort and energy use of naturally ventilated and mixed mode UK buildings - therefore having a strong link to this thesis. This research was conducted as it was deemed that the need for providing comfortable conditions in winter is relatively easy with good basic design, for modern offices the main comfort problems are likely to appear in summer due to overheating. Therefore the project attempted to find the limitations of natural ventilation in the UK. To achieve this a representative warm summer was created, as previously discussed, from the upper quartile of ranked daily mean temperatures for summer months, so that 1989 was the weather chosen in this instance from the 20 previous year's available data. The BRECSU comfort criterion was also taken i.e. 5% of occupied time was not to exceed 25°C dry resultant - i.e. "Buildings with fewer than 5% of hours were deemed to 'pass',while those with more were deemed to 'fail' ". Using this comfort criterion it was found that where the "<5% above 25°C" comfort criterion was met the further BRECSU criterion of "1% of occasions should not exceed 28°C" was also met. The building model set up was based on:

> "The office model chosen for simulation was based on the CIBSE rectangular office room described in the 1986 CIBSE Guide7, but with insulation upgraded to current UK building regulation standards. It was 6m deep from the external wall, considered sufficiently narrow for natural ventilation, 35m long, and 3m high. For the simulations it was oriented to face north, east, south and west, so that each simulation corresponded to an office room on one facade of a larger building."

The major findings of this research were that glazing areas and ventilation rates would determined to be the key parameters. Notably for glazing percentages it was found that increasing glazing on the north façade still increased the level of overheating. This suggests that the heat gain through this glazing by increased diffuse solar sources is greater than the increased amount of heat loss through the larger window area in conditions close to the comfort limit. Although it was also found that the north façade had the greatest likelihood of passing the comfort criterion due to it low solar gains in all situations whereas "The 'pass' region for other facades is limited to a small design region of low glazing area and high ventilation rates; the south facade only just passes, with minimal glazing, at an air change rate of at least 15 ach". Therefore, to achieve the comfort criterion on all facades a minimum of 15 ach was required, though it was seen that this could be lowered with stronger control of solar gains. Where good solar control is evident glazing areas of 40% could be accommodated with the ventilation rates as low as 6 ach, whilst still passing the comfort criterion. The project was able to demonstrate that for a hot summer in the south east of England discomfort is likely to the greatest on the east facade, then west, south and north respectively. Though designed for the south-east of England it was deemed that a similar computer simulation exercise could be conducted full any temperate region where air conditioning could be replaced by a mixed mode or naturally ventilated solution.

A building specific DTM exercise to find summer overheating conditions was carried out by the Energy Design Advice Scheme (EDAS, Scotland) for the Scottish Office building at Victoria Quay, Edinburgh(17). EDAS, though regionally based, is a UK-wide independent design advice scheme sponsored by the UK's Department of Trade and Industry to improve communication between design teams and experts in low energy technology. The Victoria Quay project was supported by EDAS design advice using the application of thermal simulation so that the effect of changes to building form, fabric and glazing distributions could be predicted. The main design emphasis was to discover whether natural ventilation could be used to provide fresh air requirements and prevent overheating alone or would some additional mechanical ventilation be required. To achieve this the simulation process was phased over 2 years and was required to compare the thermal and ventilation performance of the building's 3 design variants of the central atrium. It was assessed against performance targets set by the design team itself. To do this the entire 35,000m^2 building did not need to be replicated, instead a 22 zone, 5,300m^2 sub-division of the building could be used to assess each facade. The strategy for zoning this representative section was "almost self defined by the physical barriers between office spaces" i.e. forming a zone per office. The initial phase of the project discovered that natural ventilation could work, however it was only possible to stay within the desired maximum level of 26°C (resultant) if night purging was also operated.

On a later refinement of the design, that introduced cellular offices around the periphery of the building, it was not possible to predict with certainty the natural cross flow ventilation in the building. This shifted the building design to a mixed mode solution providing a constant 4 air changes per hour mechanical ventilation to offices which retained their opening windows. The shift in design was also taken as the original design was tested against worst case scenario conditions in summer during later model refinements. The final design chosen was predicted to perform satisfactorily, no area being predicted to exceed 26°C for more than 52 hours per annum in occupied offices, thus remaining with the set design risk of 5% of the working day per annum.

This latter example highlights the benefit of the long-term, phased approach to computer simulation. The building design benefiting from repeated input from simulation over the course of the design process including later refinements, such as cellularisation of office space. However, this model also makes reference to an absolute value of overheating chosen by the design team to determine whether the design passed or failed. In this instance, a resultant temperature of 26°C was not be exceeded. Unfortunately, this particular measure of overheating can only be seen as a reasonable guideline criterion rather than an industry standard as no such standard exists.

Overheating may be a particular cause concern to office based industry due to its effect of lowering worker performance. However, Oseland in CIBSE Technical Memoranda 24(18) "Environment Factors Affecting Office Worker Performance – A Review of Evidence" states that there is a "striking absence of literature on the measurement of knowledge-based work activities" for the field of overheating effects. Previous office-based worker research focused on laboratory studies which cannot easily be applied to the actual office environment. On-site investigations have also been undertaken into the effects of air conditioning/thermal comfort, however mostly these have concentrated on light industry e.g. Schweisheimer's use of a plant, producing nylon stockings, concluded that on average performance of workers drops by 10% at temperatures above 29°C and 38% at 35°C. However, this example covers a manufacturing process containing physical work and as such use cannot be readily applied for sedentary office workers. Therefore, TM 24 reports a dearth of research material that lends itself to direct comparison of office based workers' productivity against their environmental temperature. However, CIBSE TM 24 concludes that:

> "There is a general consensus that uncomfortably high or low temperatures result in poorer physical performance... However it is stressed that the optimum temperature depens on the subject's activity, clothing and adaptation. There is less agreement on the effect of mental performance... Nevertheless most studies show a decrement in mental performance at temperatures above 33 °C."

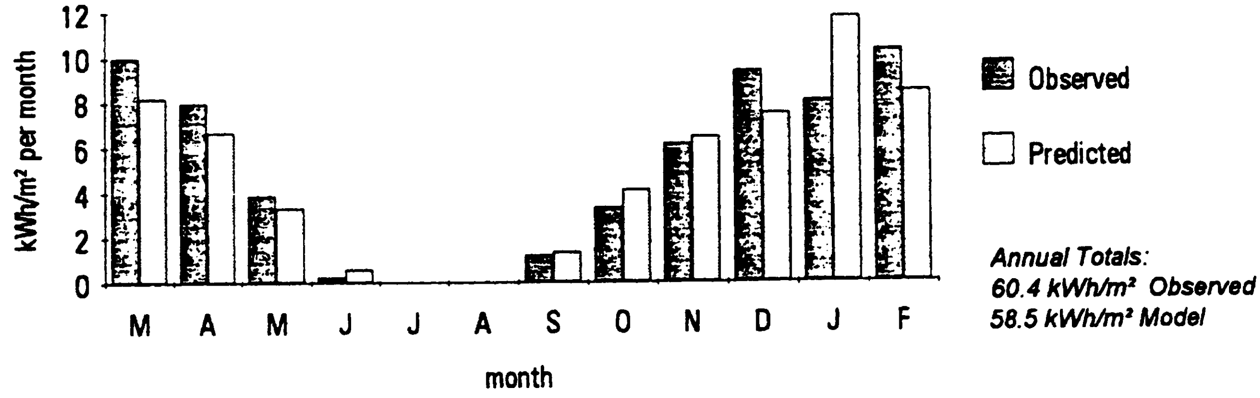
As discussed above, the majority of DTM exercises are for new designs and are therefore not available for comparison against recorded data from the building in use. However, a good example of the comparison of DTM predictions against recorded fuel consumptions was conducted by the Energy Technology Support Unit's (ETSU)(19). Under ETSU's Solar Energy Programme 60 domestic and 30 non-domestic building designs were studied in order to explore the potential of passive designs and in turn to develop design methods. In each of these studies, computer simulations were used to assess the final design's energy/environmental performance. The non-domestic design assessments were made using the DTM SERI-RES.

However, inaccuracies can occur in DTM simulations in four main ways:-

- the computer program embodies deliberate/unrecognised physical and numerical approximations (e.g. that building services exactly meet demand or that occupants behave in simple ways)
- the building descriptions, weather and/or occupancy data is imperfect (not all precise details can be known at the time of the simulation or data may simply be unavailable).
- the user makes imperfect decisions to approximate the real situation (in order to overcome the limitations of the program and/or data).
- mistakes occur in the program design, coding and use.

To ameliorate the third and fourth errors listed, SERI-RES was used which "has been shown to contain no significant coding errors and the approximations it embodies have been generally acceptable for the purpose of the design studies" according to ETSU(20). The use of formal Quality Assurance procedures ensured that mistakes made in the course of the assessment were minimised. However, as previously described many estimates for particular inputs were required and as such the model can only be seen as an approximation of the real building. The case studies in this example are Cornbrook House and Hempstead House, two commercial office blocks of ca. 2,500 - 3,000 m^2. Comparisons of actual recorded fuel bills were made against the predictions from the SERI-RES models of these buildings.

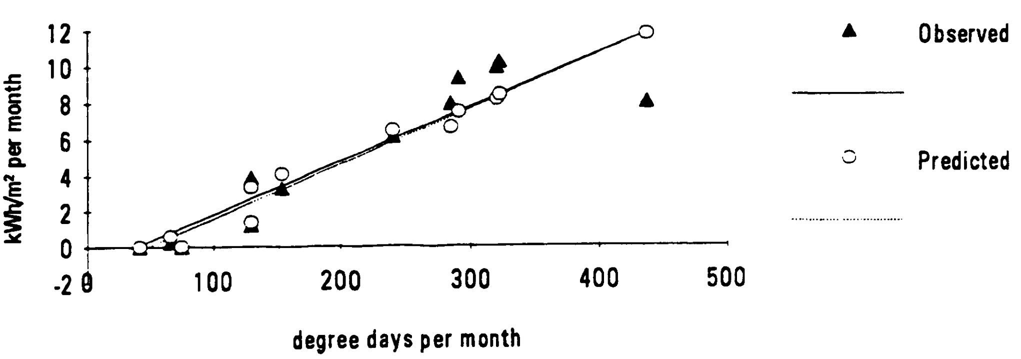
FIG 3.1 : (Reproduced from ETSU Report) Observed and predicted heating Demand at Cornbrook House 1986/87



Observed monthly heating demands at Cornbrook House, Manchester were taken in 1986/87. These results were then placed against a "best guess" SERI-RES simulation that used, wherever possible, case specific data (in this instance including measured electricity consumption as the basis of heat gains from lighting and small power sources). As can be seen from figure 3.1the annual total heating demand has been predicted to within 3% - i.e. 60.4 kWh/m^2 observed against 58.5 kWh/m^2 modelled. The month-to-month predictions also appear accurate with the exception of a large over-estimation of demand in January. Wm Bordass Associates (the contractor carrying out the physical measurements) suggest that [21] "the low actual consumption recorded in January probably arose because the end-December gas meter reading was taken before Christmas and the whole unusually cold spell coincided with a two week office closure (when heating demand reduced) and fell within the January metering period: thus depressing the demand observed in the January period."

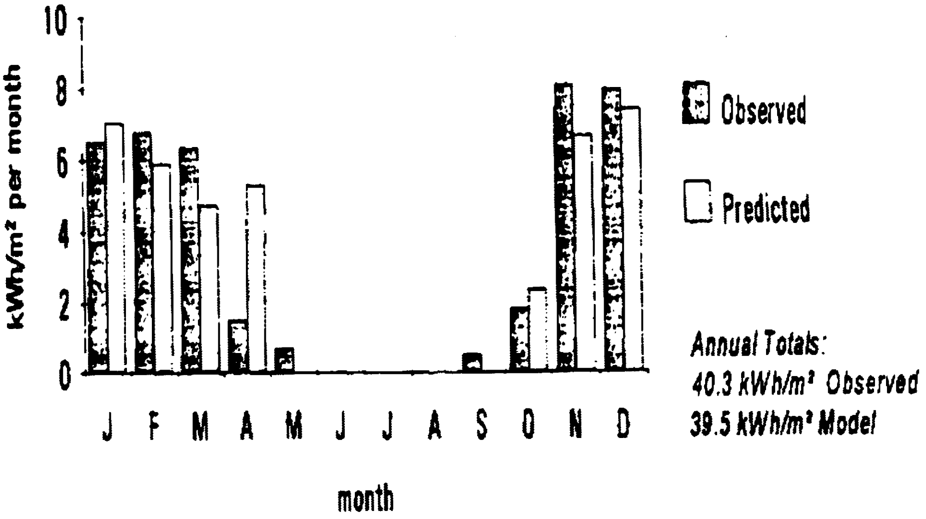
However, due to the slight over estimation of previous months calculations by SERI-RES, the January over-estimation seems to have cancelled out its affects on the annual total heating demand. Therefore, had the DTM accounted for the holiday closure the predicted annual demand would have been around 10% less than observed rather than the current 3% under-estimation - though this still represents good agreement. An internal trade-off between errors in the SERI-RES model could have also produced these closely matched results. For example, an error in the heating setpoint used by SERI-RES may have easily been offset by an error in calculating the heat loss via the fabric thus cancelling one another out. However, the close agreement between the month-to-month heating demand gives some assurance that this has not occurred. When placed against the degree day data, the heating demand predicted seems in good agreement (see figure 3.2) as does the actual heating demand (as could be expected).

FIG 3.2 Observed and predicted heating demand vs degree days at Cornbrook House 1986/87



As the sensitivity analysis states (22) "an error in fabric loss would reduce the agreement in both the slope of the line and its intercept, while errors in assumed setpoint or casual gains would tend to reduce agreement in intercept alone. Errors in the setpoint and the casual gains could also offset each other, but the casual gains data is known to be good so this is unlikely." in order to gain full confidence in the results many of these sensitivity analyses would need to be conducted to eliminate any trade off between SERI-RES internal errors. A further case study building, Hempstead House, was also analysed by this methodology to test the consistency of the SERI-RES predictions. (see figure 3.3)

FIG 3.3 Observed and predicted heating Demand at Hempstead House 1986/87



Once again, on annual heating demand predictions alone, very good agreement is found - the model predictions being within 2% (40.3 kWh/m^2 actual against kWh/m^2 predicted). However, again a small, but consistent, under-prediction was found for the majority of the year and this is cancelled out by an aberrant gross over-estimation for one month. Actual demand in April was reported to be down as a result of equipment malfunction depressing demand. Had this been accounted for. the annual heating demand would have been under estimated by 13% (i.e. similar to the Cornbrook House example). ETSU suggest that this method has underestimated actual heating demand because the performance predictions are sensitive to assumptions about the patterns of occupancy and the efficiency of building services. The assumptions made for SERI-RES under this methodology have therefore erred on the good side of average practice. Thus highlighting a limitation of DTM predictions for actual building demands - i.e. the reliance on assumptions. For example, it was found that actual equipment gains at Cornbrook and Hempstead Houses are lower than the assumed levels in Design Guide averages, thus necessitating greater heating. Design guide assumptions of casual gains err on the high side so that less conservative estimates of overheating are gained (i.e. to avoid optimistic views of a building's Summertime performance being gained). Therefore, even when realistic average data is sought for use in DTM simulation it may not be available to high enough accuracies. As the report states (23)

> "there is anecdotal evidence that winter office temperatures are commonly set to avoid complaints from the occupants who like the highest temperatures, leaving those who prefer lower temperatures to respond by wearing lighter clothes or opening windows. On this basis, the 21°C setpoint assumed (in the Design studies) may well err on the low side, optimistic from the point of view of fuel bills."

3.5 Validation of Dynamic Thermal Models

As can be seen from the above examples, there is already usage of thermal models in the UK to aid prediction of energy bills for efficiency purposes and to gauge the liklihood of summer overheating. However, to ensure that reliable predictions are being created, some form of exercise to prove the DTM's credibility is required - this exercise is known as validation. This validation can be achieved in a number of ways; through simple analytical testing whereby the model is asked to predict parameters that are so simple that the correct solution can be calculated explicitly, through "intermodel" comparisons in which the predictions of an alternative, yet validated DTM are compared (this has the advantage of standardising "guesstimates") or through empirical validation whereby predicted results from a DTM are compared against data measured from a real building.

It is clear that this third choice, empirical validation, has an immediate appeal as the computer modelling of real buildings is, after all, the end use of the program. Though physical data may be collected relatively easily, empirical validation may still prove extremely difficult to conduct in reality due to the simplification inherent in modelling an existing building. Many simplifications may be included in a thermal model for the ease of data input or to decrease solution times, naturally these simplifications should not need to be made for a validation exercise so that the truest picture of the building can be gained. However, many estimates may still need to be made out of necessity as any attempt to model the variable perfectly would be too great a task - e.g. the dynamic nature of solar and incidental gains. Even when these inherent approximations have been included and good agreement is still gained between the model and reality, it may only be as a result of internal errors cancelling each other out (as was found in the case of annual total heating demand in the ETSU case studies). Also, if agreement if found to be poor there will be no simple way of determining which of the inherent estimates has caused this or whether it is as a result of an inaccuracy of the DTM program itself. Only where a model's predictions show good agreement and it can be shown that this is not as a result of several errors cancelling each other out can any confidence be gained in a DTM.

There will also be inherent difficulties in physically monitoring all aspects of the existing building. for example, though the building fabric may be of a consistent construction flaws in its make-up may create differing U-values to be found, thus necessitating the measurement of each wall. window etc. whilst uncertainties due to extremely dynamic variables such as ground floor heat loss and infiltration will occur as constant measurement is extremely difficult. Added to this problem is the dynamic nature of the incidental gains from the occupants and their equipment. Effectively modelling all the found combinations of occupancy during a validation test run would appear unfeasibly difficult, (and , of course, this is also true for any real DTM run). However, if a pair of test rooms are heated in a 12 hour on/12 hour off schedule, in antiphase to one another (hence one room's heating operation is out of phase with the meteorological variables) analysis of the two data sets may allow the effects due to heater operation to be separated from those of climate. However, this procedure has the disadvantage that two test rooms have to be configured identically and, of course, are assumed to be perfectly homogenous in every sense - a nigh on impossible practicality. Alternatively the controlling strategy operating the test room could be randomised to ensure that it does not correlate with any external variables. Though preventing the need for identical test rooms, such random operation of the test room is clearly unrealistic. However, if any validation is to prove that the DTM can predict thermal variables over a wide range of operating conditions then this random operation of the heating system can only be seen as a very stringent test of the model regardless of it bearing no correlation with real operating conditions. A greater concern for the true validation of any DTM is that no operator bias be allowed to exist, whether deliberate or accidental . As Martin and Watson state (25)

> "The notion of 'blind' simulation runs is central to the approach to model validation. The model user who attempts to predict the performance works in ignorance of the measured values that he or she is called upon to predict......it has been demonstrated that it will almost always be possible for a modeller to adjust input parameters of the test room model to bring its predictions into line with the observations...empirical validation as a test of the model becomes useless."

Although a perfect simulation would appear to be unattainable, if designers are to utilise DTMs it is important that the programs are accurate enough for the results to come within an acceptable error band. With this reasoning the International Energy Agency (IEA) conducted the Building Energy Simulation Test (BESTEST [26]) program to gain predictions from eight programs for a range of single zoned buildings subjected to stringent weather conditions (that of Denver, Colorado). The researchers reported that BESTEST "revealed bugs, faulty algorithms, limitations and input errors in every building energy program tested including BLAST, CLIM200, DEROB, DOE2, ESP-r, SERI-RES, S3PAS, SUNCODE, TASE and TRYNSYS"(27). The BESTEST validation program also revealed a major disagreement between codes - up to 39% variation for predicted annual heating demand and up to 66% for annual cooling demand predictions. Though a seemingly large discrepancy exists between available models, such inter-model testing cannot determine which of the programs produced correct predictions and which ones do not. However, there have also been two international collaborative validation exercises to analyse DTMs using empirical validation.

The Building Research Establishment conducted an empirical validation analysis on behalf of the IEA. It aimed to create a set of predictions for a single zoned, south facing test room. This work was valuable in that it identified errors and approximations in existing DTM programs that would otherwise have remained undetected. For example, the DOE2 program, which is used to set national building energy codes in the USA, revealed a problem when calculating solar absorbivity for exterior surfaces. The bug in the algorithm responsible for this error was subsequently repaired so that now DOE2 predicts solar absorbivity results similar to other available programs. More worryingly, TRYNSYS (a US Department of Energy supported program) revealed errors in the way thermal mass effects were calculated during the IEA/BRE's validation exercise, yet this program was considered the most advanced available for the simulation of active solar systems. The error was located on inspection of the software which discovered that two sets of coefficients had simply been transposed. By rearranging the coefficients to their correct place all the discrepancies were eliminated.

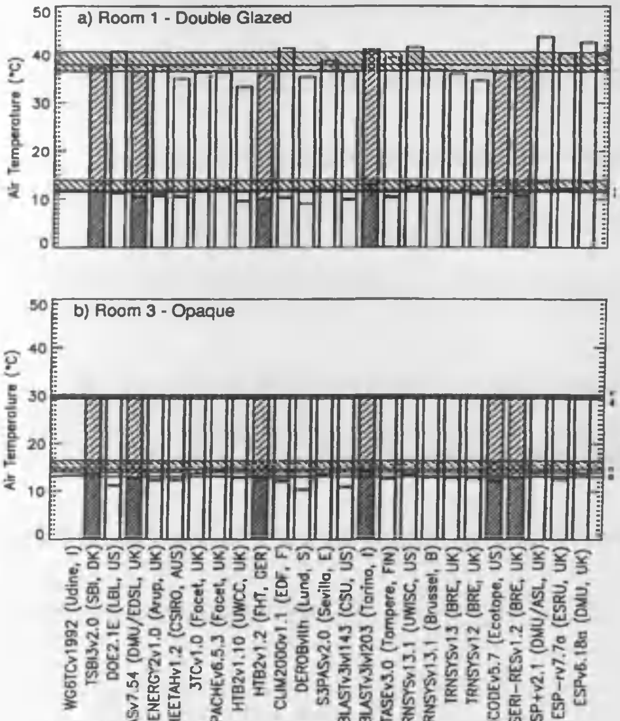
The main aim of the IEA/BRE project was to develop well tested, empirical validation benchmarks for DTM programs and to provide a snapshot of their ability to predict the performance of a simple building under conditions which could realistically exist for a true project. Therefore, some 25 DTMs were tested to fulfil these aims - i.e. 17 individual programs plus 8 alternate versions of various of these programs. The low level of detail in the test cells to be modelled would have gone some way to provide a "level playing field" for the DTMs to be measured on. However, individual DTMs have been created for individual purposes. HTB2, for example, is primarily envisioned as an "investigative research tool, rather than a simple design model....and as a test bed for future model development" as it states in its manual(28), whereas TAS is a commercially available design program. Also, the modelling itself was undertaken by the researchers/developers of the programs and as such the varying competencies in use may be expected to introduce bias as operator induced errors may have varied greatly.

The datasets against which the 25 DTMs were validated were collected from three test cell rooms located at Cranfield near Milton Keynes. These cells were described as (from Building Services January 1995) (29) of good insulation, single zone rooms, low infiltration (0.05 air changes per hour or less) and raised from the ground to prevent heat loss. However, the south facade of each cell differed in construction, two cells differed in term of glazing whilst the third was opaque. To ensure conformity matching trials were conducted on all three test room cells to guarantee that they were of the same construction, whilst post-study one room was dismantled to re-check its construction. The heat loss coefficient (U value) of this room was tested to satisfy the requirement that it was within the experimental error allowed (5%). These precise construction details were released to all the thermal modellers taking part in the validation study. guidance on how to model the rooms was also provided along with a consistent set of climatic data to be used. From this data the DTMs were primarily required to predict; the total heating energy consumption for the October heating period and the maximum and minimum internal air temperature recorded in October and May. Once this phase had been completed, the programmers were given all the measurements (and the estimated uncertainties regarding the input data) to conduct sensitivity analyses to assess the differences between the predictions and actual recorded data. Six of the programmers took this opportunity to re-run the simulations to make corrections for the previous input data's level of error. This sensitivity analysis when combined with the known level of experimental errors was combined to form an error band - thus, where the prediction lay outside this band there was a 99% chance that it was as a result of an inaccurate prediction rather than experimental error.

As can be seen from Figures 3.4 (reproduced from IEA/BRE Final Report (30)), 8 of the programs predicted total energy consumption within the error band for the opaque room and 11 for the double glazed room. One program predicted the heating energy demand, maximum and minimum temperatures to within the error bands for both the opaque and double-glazed rooms. Inter-model analysis was also conducted. This revealed an 11°C variation in predicted maximum temperatures, some 3°C to 14°C above the heating setpoint. Energy predictions also varied greatly - by 40% for the opaque room and 52% in the double glazed room. Also the predicted energy savings of a move from opaque to double glazing ranged by a factor of 3 - i.e. a 13% to 40% saving was calculated.

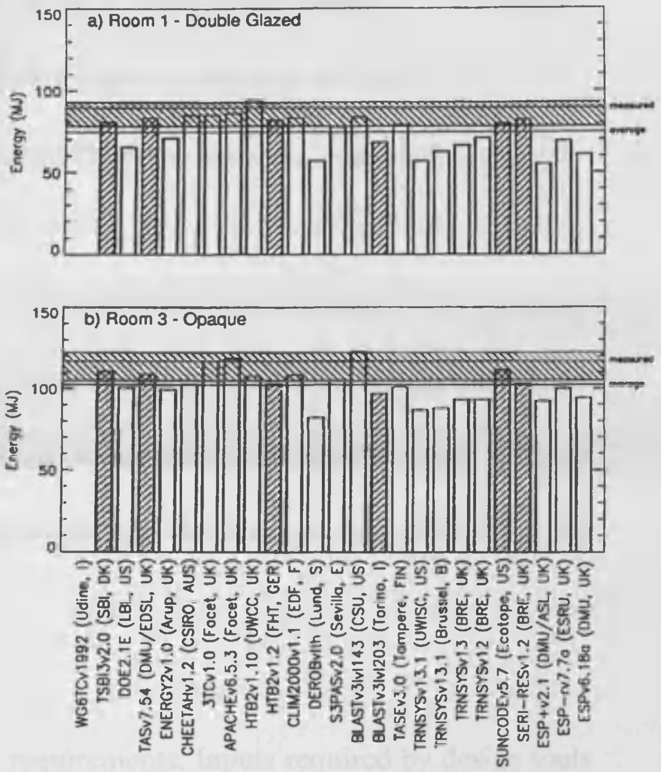
These inter-model comparisons went some way in corroborating the finding of the earlier IEA BESTEST program that the inter program differences are due to fundamental differences in the DTM programs themselves and cannot purely be explained by user effects. The second phase of the study also helped to identify differences between the features of the experiment and the necessary assumptions made by the DTM which led to the creation of errors. For example, the heat output from the test cell heater had a large radiant portion, yet many of the DTMs used had to make the assumption that this heat output was convective, thus consistent with an under prediction of heating energy demand seen in these DTMs. As these heating systems could be readily found in a real building this error (though caused by a mandatory assumption) highlights a weakness in some of the programs studied. This assumption may also help to explain the large variance in heating demand predictions between the models (i.e. up to 52%).

Figure 3.4 : IEA/BRE Dynamic ThermaL Model Validation Tests



The hatched horizontal area represents the estimated uncertainty band

Figure [illegible]
Phase 2 - Maximum and minimum temperatures during the 7-day heated (October) period



The hatched horizontal area represents the estimated uncertainty band

Figure

3.6 Dynamic Thermal Model Adoption in Design Practice

Despite the length of time that DTMs have been commercially available (i.e. giving an opportunity for potential users to be aware of their existence) and the more recent validation exercises (providing an opportunity to assess the DTM's reliability) their use within industry still lags greatly behind standard manual calculation techniques. The likelihood is that DTMs are viewed as unrobust and too detailed for everyday, standard usage. As Holm [(31)] explains, the International Congress on Building Energy Management quoted the following needs for a good design tool:-

> "The design tool should be a user friendly computer program.
>
> It should be of a general nature to facilitate "What If" alternatives readily.
>
> Calculation speeds of minutes rather than hours is a higher priority than accuracy
>
> Input formats should be user orientated – in terms of building materials rather than "Scientese" and should take less than one hour."

Whilst these all seem reasonable requests, many new questions are raised by this approach ; What is user friendliness to an architect/engineer?, How much accuracy can be sacrificed to merely speed up solution times? (and perhaps the biggest question) Then at what stage do we expect the architect/engineer to concentrate on simulations?

However, valid points are raised by Holm's requirements. Inputs required by design tools are often voluminous, of a scientific nature and generally unavailable during early design stages, thus precluding the immediate use of computer simulation tools. Also the output of many DTMs consists of bulky computer files of little significance to a designer. This is as a result of the fact that the user interface of DTMs is often neglected due to the additional funding required to produce these facets. DTMs may therefore be overlooked merely because an efficient user interface is lacking. These problems may greatly be countered by the inclusion of interactive, menu-driven pre and post-processing software – all at a cost. However, many DTMs have been primarily developed as research tools and as such few user interfaces are developed until the need arises, practical applicability is thus seen as a secondary issue. Currently only the largest of companies can afford the cost of utilising computer simulation tools as the costs plus personnel training will largely be outside of the limits of smaller design practices. Despite the inclusion of processing software the question of where in the design process a DTM would be used has still not been answered.

Of course, the greatest limit to the up-take of thermal models may be their perceived level of error. Currently some design tools are only validated by one or two experimental studies or by reference programmes. As previously discussed, until the results of many validation exercises are known, such as BESTEST, their may be little consumer confidence in DTMs. This lack of confidence may stem from the actual limitations of DTMs available. For example, as Mathews states (32)

> "Time independent thermal parameters are a prerequisite for some solution methods. The most important limitation time independancy imposes is the inability to simulate varying air change rates in a building zone. Simulating varying air change rates is essential for the investigation of natural or forced ventilation."

The key approach to encouraging the take up of DTM and other computer simulation techniques would seem to be increasing the awareness of the design community of the benefits of its active inclusion in existing projects and by providing a database of previously successful implementations of simulation. As Batty and Swann state(33):

> "Generally, the greatest barrier to the adoption of these design tools in practice is a poor understanding of their capabilities on the part of the design team, a lack of common understanding or language between the various professions regarding the design process and a poor understanding of the design process on the part of software developers. The manner in which these tools are used is an important aspect with regard to their usefulness and the development of methodologies which take account of the needs of the design process is essential."

The EDAS scheme, as discussed earlier, provides both the scope for the design industry to examine previous case studies and the opportunity to involve themselves with computer simulation. This aid should eliminate the idea that simulation is either too expensive or too complex for regular use on standard building designs. At the very least individual projects that themselves could not have justified the budget for either an in-house modelling specialist or consultancy advice will have the benefit of EDAS's free and fund-supported advice. As McElroy and Hand comment (34):

> "the integration of simulation modelling into the building design process is increasing, but is not yet standard practice. Design teams working on 'ordinary' buildings are less likely to make use of modelling software than the designers of prestige or complex buildings. The use of computers in building design tends to be restricted to CAD and steady state calculations, carried out in parallel with other design team activities."

At the time of this comment, EDAS (Scotland) reported that it had provided advice on over 1,000 projects of which 25% benefited from financial support on DTM studies(35). A commonality of design problems was noticed amongst these projects with 24% of questions posed relating to fabric measures, 19% to heating system design and 18% each to both ventilation and fenestration. With this valuable back catalogue of completed project EDAS were in a unique position to create a database from these case studies for wider dissemination. Design advice and performance information generated by EDAS was transformed into hypertext content for display on the World Wide Web. This database was designed to be project specific, however it is set up in such a way as to allow users to browse projects by building type, design issues etc. for ease of use. It is hoped that the analysis of the case study projects will also help identify a methodological approach to the use of simulation as an effective, integral part of the design process.

An in-depth investigation of the integration of buildings simulation into the design process was conducted by Morbitzer et al(36). This paper recognised the fact that "building simulation programmes are not recognised as design support tools to the same extent as CAD" and therefore attempted to analyse several key questions, such as:

- Which are key performance studies to be undertaken at the various building design stages?
- What software is best adapted to the experienceand background of the typical user at the different design stages?
- How can simulation results be displayed in a way that turns the raw data into useful quality information?

To ensure that computer simulation had an appropriate input at all design stages its involvement was looked at in terms of RIBA'S 3 main building design stages: the Outline Design, Scheme Design and Detailed design stage. The initial Outline Design stage is at a point where the design is undergoing feasibility studies, however it will be detailed enough to establish the outline proposal preferred and will give an indication of energy consumption. It is therefore important at this stage for DTM to help the designer to understand how the building shape, glazing level and construction types will affect the building. At the Scheme Design stage the building design becomes more detailed and the task of simulation is to focus on potential problems (e.g. overheating) and typical sections. The Detailed design stage is created to coordinate structural, services and other installation drawings. Therefore, at this final stage simulation will be of a more precise nature, as experts make modifications to specific details e.g. establishing control strategies, sizing aperture openings etc.

To implement this plan the same DTM programme was used throughout the design process, i.e. ESP-R, however it was to be adapted so that its interface, defaults and results analysis were more suited to the requirements of their use (and their user) at all 3 design stages. This re-interpretation of the DTM programme to suit the use/user was due to a number of reasons. Firstly, the background of a typical user of environmental design and building simulation tools varies throughout the design process. In the Outline Design stage it would be expected that the main user would be the designs architect(s), using the DTM as a tool for a quick evaluation of design concept. At the Scheme and Detailed Design stages it is more likely that a skilled DTM specialist/consultant would provide the computer simulation advice. Secondly, these various users will need different levels of information from the DTM and hence should have results geared to their needs. More detailed analysis, such as examining air exchange through individual apertures, may be needed at later stages, however an initial assessment may merely require a given air change rate to be applied to each room zone, thus in-depth results are far from necessary at this point. Finally, actual design issues will be addressed at different stages throughout the design process. For example, fine window detail or ventilation studies may only be valid at the Detailed Design stage, whereas basic orientation of the building is likely to be covered very early in the design process.

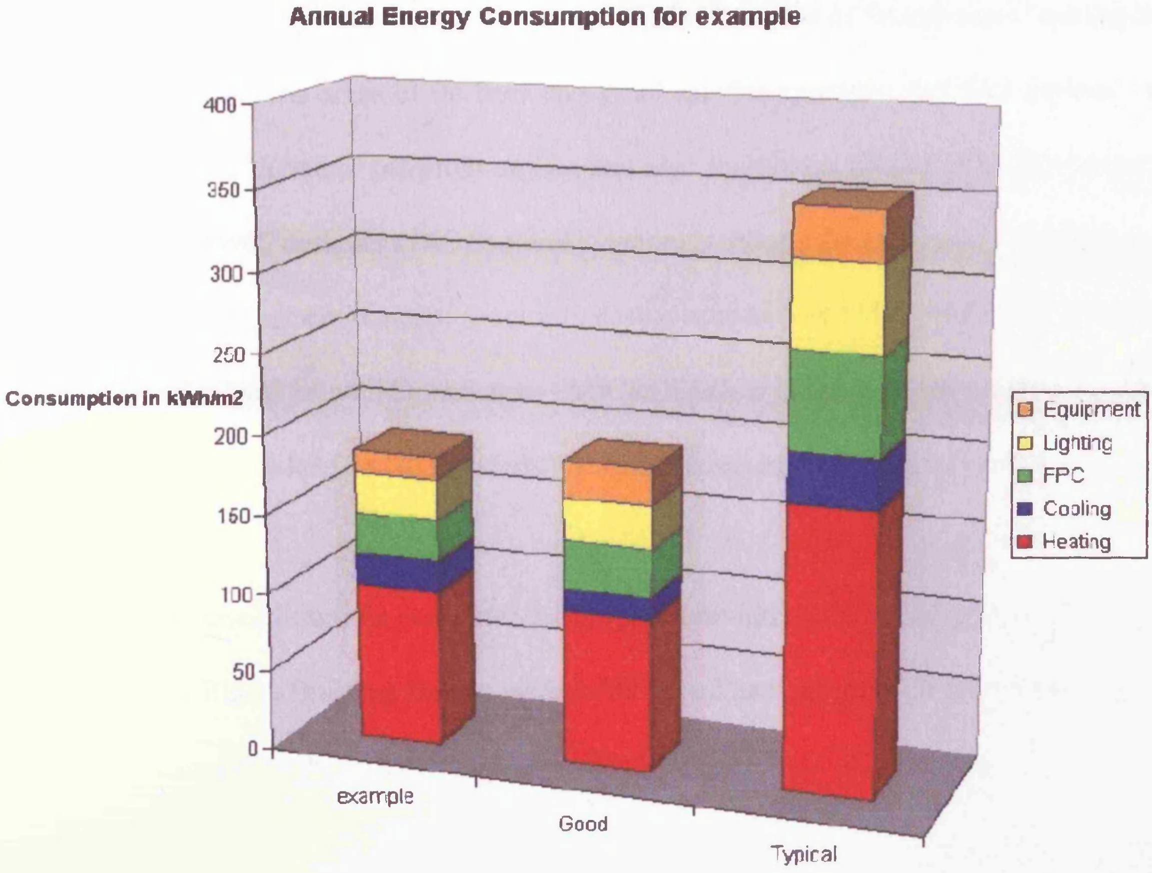
With such varying user requirements changes to the DTM were suggested for its greater applicability at the Outline Design Stage. These were; **a simplified user interface** to allow rapid, step by step data input; the importing of the building geometry via **a 3d CAD linkage** and **detailed support databases** containing relevant information for building types, typical gain profiles etc. to allow for rapid model set-up.

The CAD link will be a valuable addition as it exports a pre-defined building geometry into the DTM model for use, saving much-needed time in the Outline Design Stage which suffers from tight time restrictions. For example, the basic building geometry in TAS can be imported from Autocad .dwg or .dxf files as a 2D floor layer – the other floors then copied or built up on top of this to form a 3D model. The simplified GUI (graphical user interface) will be of great aid to a novice or unskilled user as it will allow the rapid input of the building geometry and its related information - e.g. the construction materials, window sizes and room functions (such as internal heat gains, heating or cooling loads etc). The supporting databases were "developed and extensively populated using guidelines and tables that were well accepted in the construction industry". Therefore, a step by step attribution of heat gains, ventilation rates, cooling loads etc. could be applied to each zone to create a working thermal model in a short amount of time. Finally, the output information had to be presented in a quickly analysed and useful way. To do this a coarse level of information was created that had the possibility of being presented in more defined detail should the need arise at a later stage. This information was provided to allow for; the ranking of results against Benchmark data (to view the design against instances of typical and good practice); the identification of poor performance in particular rooms/areas; the identification of the causes of this poor performance, where found. For example, during the summer months thermal comfort is the key performance criterion, therefore the model should be able to quickly interrogate zones to gauge hours of overheating. Whereas the total annual energy consumption is useful in its own right, its relative strength can best be examined when placed next to Benchmarks of energy use for similar buildings.

The paper concludes that "effective presentation is a key element of the use of building simulation (software)". This lesson has been taken on-board by EDSL Ltd, the developers of TAS, the DTM programme used in this thesis. TAS (version 8.5) allows a CAD file import of the building geometry and a GUI system to apply room/zone functions such as internal gains and inter-zone air movement as previously discussed. TAS (version 8.5) fulfills all the needs (as previously outlined by Holm) in that it has calculation times of "minutes rather than hours" which are allowed due to the Windows-based graphical user interface allowing simple imputing of data. This is combined with in-built training notes in both printed and and video formats. The training videos allow a novice user to expressly see TAS in operation and its input procedures. The graphical user interface is simplistic to navigate around so that a user can be comfortable in its operation in only a short amount of time. TAS also comes equipped with databases of modern constructions and materials (including glazing) so that basic, 'Building Regulations' buildings using standard materials can be modelled immediately.

Recent additions have allowed the programme to use pre-defined 'report generators' to output the often voluminous prediction data created by a DTM run into a more useable format. For example, to analyse overheating a zone's cumulative frequency of temperature can be graphed – the hours and days from which this data is culled can be defined by the user - e.g. hours exceeding 25°C for all working weekdays between 9am and 5pm. Annual energy consumptions for a design can be output next to the Energy Efficiency Office's Energy Consumption Guide 19's 'Best Practice' and 'Typical' levels. Resulting carbon emissions from these energy consumptions can also be output against Benchmark figures (see figure 3.5below) – in this way TAS could be used to demonstrate compliance to Part L2 of the Building Regulations under the "Whole Building Method". Therefore, as stated in the Theoretical Background, as a modern, commercial programme used by clients in the UK's design industry, TAS is a logical choice to use as the DTM programme in this thesis.

Figure 3.5: Annual Energy Consumption Prediction Comparison To ECON 19 Guidelines



3.7 Future DTM Software Developments

Whilst DTMs can provide a dynamic time profile for a building they may not accurately be able to as accurately simulate the air exchanges over this period as a full computational fluid dynamics simulation (though these cannot be run dynamically for a week/month/year as per a DTM analysis). Therefore their potential may be limited for the designer. The “answer” appears to be a fully integrated modelling package allowing both CFD for air flow solutions within dynamic thermal modelling of a building.

To date, no combined computer modelling system is available to the engineer\architect that will run both a thermal model or complete a prediction via computational fluid dynamics techniques. The closest available integration within the current market is a suite of "stand-alone" packages that has commonality in some areas of its files and graphics. For example, the TAS thermal model programme is sold in a 'suite' of programmes that also includes a limited 2D CFD programme (Ambiens) and a HVAC designer (TAS Systems). Amongst others, the University of Dublin use the IES VE (Virtual Environment) suite of programmes that uses a central "ModelBuilder" programme which can then be used in a CFD package – MICROFLO, a DTM package – ESP-r, a lighting simulation programme – RADIANCE and a HVAC simulation package – APACHE HVAC.

However, the proposed future for computer modelling in design to aid architects and engineers is the Integrated Intelligent Building Design system (IIBDS). The concept of the IIBDS has evolved from the need to improve the energy efficiency of buildings by:-

1. Providing an integrated software environment which allows design professionals to communicate freely from the earliest stages of a project. As, according to Kennington and Monaghan (37)
   > "The design of energy efficient buildings is a complex task involving many different design disciplines and....there is usually little communication between professionals involved in the different design domains especially in the early stages of a project when decisions have the greatest impact on future energy usage."

2. Integrating software tools into building design systems. These software tools (DTMs, CAD etc.) will provide information in a useable form to aid in the building design **and** will help identify areas in the design process where energy savings might be made.

The two largest projects attempting to develop these IIBDS are the U.S.A.'s AEDOT (Advanced Energy Design and Operations Technology) project and the E.U.'s Combine project. The Combine project aims to provide a conceptual base for a future IIBDS by creating a prototype building product model – the Integrated Data Model (IDM). This IDM will allow different design professionals to exchange their information about building design and thus from this prototype integrated design tools can be created.

Kennington and Monaghan go on to state that it is difficult to incorporate existing computerised design tools into the building design process because: the programmes are difficult to learn, the data input (particularly the building geometry) is time consuming whilst the outputs may be over or under detailed <u>and</u> the program itself only allows a limited number of design options or simply cannot translate the design-orientated request into simulation outputs. Presently some companies involved in the development of HVAC/energy design software also produce CAD software files that can be used in conjunction. For example, as discussed earlier an Autocad .dwg file can be used to define the building's geometry under the TAS DTM programme. However, the building geometry would still need to be redefined for use with a CFD package. Therefore, the Design Tool Prototypes (DTP) being created under Combine will require cross-compliance with the other assorted models to create the whole IIBDS.

There are 6 DTPs under construction for the IIBDS underway in Combine. These are:

1. "Construction design of external building elements" – University of Newcastle + BRE
2. "HVAC design" – University College Galway +CSTIC, France
3. "Dimensions and functional organisation of inner spaces – University de Liege, Belgium
4. "Input generation for thermal simulation in the latter design stage" – Danish Building Research Institute.

5. “LT method in the early design stage” - University of Ulster + University of Edinburgh, UK
6. “energy-economic design” – VTT + PI Consulting, Finland

However, the Combine I project merely wishes to allow different design professionals to exchange design information through the model’s software prototypes. The design prototypes themselves are unlikely to evolve until secondary Combine style projects are undergone and, perhaps more importantly, the notion of IIBDSs are taken on board by commercial design model producers/ companies.

User reluctance in the UK may also be attributed, in part, to the fact that to date a UK validation standard for dynamic themal modelling programmes is not in practice - although an Applications Manual CIBSE AM11 “Building Energy and Environmental Modelling” is available for guidance. Its pro-forma in Appendix B can be used to demonstrate that a programme, such as TAS, is suitable for use in the Whole Building calculation method to satisfy Part L2 of the Building Regulations. However, the American ANSI/ASHRAE Standard 140-2001 “Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs” exists(38). This Standard defines a series of tests for building energy simulation programmes and is based on the IEA “BESTEST” diagnostic tests referred to previously. The standard method of simulation requires that simulations are made of a number of variants of a test building and aims to identify and diagnose differences in predictions that may be caused by software errors. These variants range from a simple building shell without glazing, infiltration or internal gains to a comparatively realistic building. The simulation results can be compared against the predictions from other building energy programmes to the example results provided in the Standard’s Annex B8 and <u>also</u> to other results that were generated using the ‘SMOT’ - standard method of test.

For example, the ApacheSim DTM programme provided by IES Ltd is tested in accordance with ANSI/ASHRAE 140-2001 (39). As the IES validation documentation states.

> "While the text of the Standard emphasises that all building models are simplifications of reality, and full validation cannot be achieved by a single series of tests, the ASHRAE 140 tests provide a valuable benchmark by which the predictions of a simulation program may be compared with those of its peers, as means to establishing a degree of confidence in the correctness of its algorithms and their implementation."

With this testing IES Ltd. concluded that the ApacheSim programme produced results which were in good agreement with those from other reference programmes as "Out of 326 tests. ApacheSim predicted a value outside the range set by the other programs in only 13....In most of these the difference can be accounted for in terms of modelling refinements incorporated in ApacheSim's algorithms. The tests did not reveal any bugs in the software."

A greater effect on the future of DTM may be had by the use of legaslative controls leading to the harmonisation/uniformity of not only the DTM programmes themselves but also their application to building design. For example, a major effect may be had if the proposed European and ISO standard prEN ISO 13791 comes into effect. This standard currently at draft stage covers the calculation and validation procedures for naturally ventilated building simulation. This proposed standard, titled "Thermal performance of buildings - Calculation of internal temperatures of a room in summer without mechanical cooling - General criteria and validation procedures" is scheduled for ratification in the first quarter of 2005. By this time all models should confirming compliance with all aspects of prEN ISO13791. This standard is intended for use by specialists to develop and/ or validate methods for the hourly calculation of the internal temperatures of a single room. The examples of the application of this method include: assessing whether a building may overheat/ assessing whether a building requires mechanical cooling, optimising aspects of building design and to provide thermal comfort conditions. Therefore, it directly links to the application of dynamic thermal models. The standard describes its scope as(40):

> "specifying the assumptions, boundary conditions and validation tests for a calculation procedure, under transient hourly conditions, of the internal temperatures (air and operative) during the warm period, of a single room without any cooling/heating equipment. No specific numerical techniques are imposed by this standard."

This scope would mean that although "no specific numerical technique" is required to be used in order to be seen as compliant to this standard its results should conform with the results produced by the prEN ISO 13791 method. In the standard's attached 'annexes' procedures for the calculation of the different parameters necessary for determining the internal temperature, according to the assumptions included in the standard, are proposed. Therefore, any dynamic thermal model that is used for the prediction of internal temperatures in naturally ventilated rooms will be bound by this legislation to conform to this standard and must be validated accordingly. The draft standard states (41)

> "Any existing or new numerical solution which claims conform with this standard shall be validated with the tests in section 7.1 (Validation procedures) and to be in agreement with the procedures and assumptions. The results provided by any numerical solution model shall be within the range indicated for each test. The check of existing or new solution models shall be made by the producers of the numerical solution models as well as the producers of computer programs. The validation procedures refer both to each relevant heat transfer process and to the whole solution model."

The application of this standard can therefore be seen to create uniformity within the range of DTM programmes available as, on ratification of the standard, they must be seen to reproduce the same results for the prediction of the operative temperature under cyclic conditions for several cases. Under this 'Whole model validation' a DTM must calculate the daily maximum value, daily average value and the daily minimum value of the operative temperature. In all cases these predicted results must give "a difference of less than 0.5 K"

With this legislative control in place, it appears that the future of DTM application will not be as diverse as seen in its recent history with each DTM forced into using uniform assumptions as detailed in Section 4.1 of the standard - e.g. the air temperature is uniform throughout the room, the mean radiant temperature is calculated by weighting the various internal surface temperatures according to the relevant areas, the operative temperature is the average between the internal air temperature and the mean surface temperature etc. The compliance to prEN ISO 13791 has already been considered by EDSL Ltd, the developers responsible for updating the commercial programme TAS (as used in this thesis). Conduction algorithms in TAS have been enhanced to include higher order time analysis to ensure compliance with the temperature error limits laid down in prEN ISO 13791. TAS users are able to select four 'validation' models which enable the user to run each test and confirm compliance. With the other available commercial DTM programmes also achieving this common level of validation, all DTM's may now be seen to share a great deal of commonality by the design industry - their validation approved by a ISO standard, an individual programme's use (or lack of use) may shift to other considerations such as cost, ease of use for the end-user and availability of trained modelling staff.

3.8 Study Area for Development

As dynamic thermal modelling has many available uses, as noted above, the prediction of overheating being just one subset of its applicability to the design industry. Therefore, given the findings of above review it highlights the dearth of dynamic thermal modelling used in the quantification of overheating in office buildings. Where this exercise has been completed, for example in the design of the Scottish OIffice building at Victoria Quay by EDAS (Scotland), it has been for the design of a new building - it is therefore unknown to what extent the DTM overheating predictions were matched by the conditions post-occupancy over the following years. Though satisfactory results may have been gained by the DTM exercise to reassure the designers that overheating would not occur, over and above their own a designated guidelines, this may have been a large over or under prediction of actual conditions experienced by the building in use. To attempt to tackle this problem the thesis will therefore compare both DTM predictions and physically monitored data.

The above example of the Scottish Office design also indicates another gap in knowledge - i.e. What are appropriate criteria for overheating in office buildings? The EDAS design designated that the temperature of 26°C (dry resultant) was not to be exceeded for more than 5% of annual working hours (which equated to 105 hours) in the Scottish Office, however this was a guideline chosen by the design team rather than a strict, legislative criterion to be met for a building. The review has shown that many guidelines exist over the UK and EU-wide, covering a range temperatures (e.g. a 30°C pass/fail point from the TUC and 27°C from CIBSE), that both air and resultant temperatures are used and guidelines exist that do and do not take into account actual hours of operation of the building. The thesis will attempt to find an appropriate criteria for overheating that can be applied to the physically monitored data of temperature conditions in existing case study buildings and the DTM predictions. Given the inherent estimates needed by the DTM modelling procedure, it is possible that the guideline levels may vary between the DTM predictions and the physically monitored data - for example, an internal temperature of no more than 27 °C could be specified for DTM results to ensure that the actual building will not exceed 30°C in use.

Given the multitude of available modelling options an 'appropriate' level of modelling must also be found. For example, a quickly built but simplistic model using a weather file for an example/ reference year on the most simplistic of zoning systems may compare well with the physically monitored data. The converse may of course be true, as only the overheating predictions from a highly complex model which more accurately mimicks the dynamic application of internal gains and natural ventilation levels may bear any relation to the overheating found in reality. For example, intuitively it may be considered that as these case studies are naturally ventilated buildings additional modelling emphasis may need to be placed on the mimicking of window opening. Therefore the thesis will test this hypothesis by creating DTM runs of increasing complexity to allow for the influence of the localised weather files, accurate zoning, realistic window opening and lighting use, solar shading and a reduction of internal sources of gain. As mentioned above TAS is a commercial DTM programme and therefore benefits from the at the application of CAD based geometry inputs, a user friendly graphical user interface etc., plus it is validated to a current (draft) ISO standard It is also well-suited to the application of the matrix of varying modelling complexities described above, as additional algorithms are added and the inputs manipulated to create more sophisticated models - from more complex zooming of the model to the mimicking of window opening and artificial lighting use by occupants. It is for these reasons that TAS can be seen to be an appropriate choice for use in this thesis, as it filfills the requirements for a modern DTM programme as highlighted in this review section.

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4.0 Methodology

4.1 Introduction

As described in the previous Theoretical Background and Literature Review chapters it can be seen that overheating is a problem encountered by naturally ventilated buildings due to their nature - i.e. they lack a way to artificially cool the heat build-up in a building. However, as was also noted, it is possible to use dynamic thermal models (DTM) to predict this possible level of overheating, though this is not without its pitfalls. For example, the meteorological file used may differ widely from conditions experienced by a building in any one year, the assumed occupancy rate (or other internal heat gain) may be higher or lower in use than anticipated at the design stage and even the zoning of the model may affect results as some areas that are designated as offices en-bloc, are in reality conference rooms, storage/filing rooms etc. In conjunction, these differences could lead to a building which in use is far different to that envisioned in the basic DTM.

Of course, the overheating predictions created by the DTM are created in order to inform the designers of potential problems. Therefore, any overheating prediction created by a DTM will have a consequential effect upon the building design. Where the DTM predictions are erroneous this could lead to future problems for the building in use. Any prediction of major overheating that does not appear in reality will lead to the unwarranted re-design of the building such as the installation of a larger openable window area or external shading for example, or perhaps even the introduction of artificial cooling that is not justified. Conversely, artificial cooling/air conditioning may be necessary in the building yet this will be omitted as, at the design stage, the DTM modelling may predict no possibility of overheating. In "Environmental Criteria for Naturally Ventilated Buildings" (1) Cohen states that

> "In the UK CIBSE provides a calculation method but only limited guidance as to what limits should be set for acceptable thermal conditions. Calculations can be done by hand or computer models....It must be recognised that no calculation method can predict exactly what will happen in a building under actual operating conditions. All methods involve assumptions and none can give 100% accurate results."

Therefore, given the inherent assumptions in a DTM model, any modelling options taken will affect the overheating predictions, and this in turn will impact upon the building design. The aim of the thesis is therefore to investigate the sensitivity of these modelling assumptions on the prediction of overheating. To achieve this the temperature levels (and therefore any overheating found) will be measured in three Case Study buildings. These results will be compared against DTM simulations of the Case Study buildings. These DTM simulations will increase in complexity from a "basic" model using easily obtained but non-local weather files, simplistic zoning etc. to more "complex" models which more closely attempt to mimic the office building in use and use site specific weather data and more defined zoning. Where no distinct level of fit is found to exist between the physically monitored data and a level of modelling complexity, across the 3 Case Study buildings, it will be examined as to which modelling stage most closely replicates the physically monitored results in each instance.

The thesis will therefore test the validity of the following assumptions:

- Poorly designed buildings which are prone to overheating will be detected relatively easily during the earliest stages of modelling stages made with simplistic assumptions.

- There will be a level of model detail where the modelling results match the results found in reality.

- Well designed buildings will be prone to overheating when using simplistic modelling assumptions.

These questions are further complicated by the simplistic nature of current overheating guidelines. No rigid, legislative figure for overheating exists, the current criteria for assessing which conditions exactly qualify as overheating are not yet uniform across the design industry in the U.K. As Cohen states (2)

> "Do clients want to know the level of temperatures in an average year or the hottest in 40 years for a 2.5% level of design risk?....Any assessment of overheating risk needs to be understandable by clients, which means presenting the results in a meaningful format. Additionally it is important that the client understands the level of design risk involved: how often is the building or parts of the building going to be at nominally unacceptable conditions. Despite the difficulties and uncertainties a standardised calculation method and overheating criterion applicable to buildings in the UK would be useful in order to compare design options and indicate the level of performance that can be expected from a building."

Several helpful guidelines are available from organisations such as CIBSE (from the design industry) in its Guide A (3) and the TUC (acting upon the interests of office staff) though these tend to vary from one another and are simplistic in nature – e.g. the TUC demand that a 30°C air temperature be seen as a maximum allowable working condition(4). Perhaps a more stringent temperature threshold needs to be applied e.g. a 28°C modelling maximum to meet the TUC's 30°C maximum threshold, as it should always be remembered that DTM computer simulation is still only an approximation of conditions likely in a building and is taken from the use of reasonable estimates/inputs. In this study, given the complexity of mimicking occupant controlled natural ventilation accurately, even the most sophisticated modelling approach will, quite likely be viewed as an inadequate approximation to the actual situation by the design industry – therefore an extra "level of confidence" in the results would be required, such as by applying a more severe overheating criteria.

Therefore, the next hypothesis to be examined by the thesis is:-

- A differing set of overheating guidelines are needed for DTM predictions, as opposed to those created for field studies/surveys, in order to take account of limitations in DTM modelling.

4.2 Problem of Modelling Overheating.

The proposed matrix of alternate runs leading to a refining of the DTM models goes to the core of the problem as referred to in the Introduction - i.e. the real use of the building may be little akin to the dogmatic on/off nature of the variables as applied by the thermal models. Given the dynamic nature of the real building in use it is probable that at a point over the refining of the DTM runs from "Basic" to "Simple" to "Complex" to "Sophisticated" that the closest approximation of the building will be reflected. However, at what point this lies or whether it is at one extreme or another of this list is unknown. **Therefore, the overheating of the three case study buildings as found in reality will be examined by analysis of physically monitored results from each building.** Furthermore, the three case study buildings themselves were taken to reflect increasing complexity in design of naturally ventilated buildings.

For example, the most simplified building is the small office block of the Barnardos building. A far larger building comprising significant amounts of open plan office area is shown by the Morgan Bruce building. The increasing building complexity is seen with the third and final case study building, the MOD building, Bristol. This building is predominantly open plan and relies on mixed mode ventilation, the natural ventilation of the building being seen as additional ventilation and cooling over and above the 2.75 air changes per hour supplied to all offices via a displacement ventilation system. These buildings could be seen in light of the Energy Efficiency Office's "Energy Consumption Guide 19 – Energy Use in Offices"(5). Here, Type A "Naturally Ventilated Cellular" is represented by the Barnardos building as it closely fits the description i.e. it is "A simple building and relatively small. Typical size ranges from 100 m2 to 3000 m2." The larger, Morgan Bruce building, which make significant use of both open plan and cellular offices, plus gives considerable space over to conference facilities, is more akin to the Guide's Type B classification "Naturally Ventilated Open Plan" i.e."Largely open-plan but with some cellular offices and special areas.

Typical size ranges from 500 m2 to 4000 m2." The largest building, the Ministry of Defence (MOD) Procurement Services "Walnut" building is part of a very large site that houses 6,000 workers in purpose built office facilities. Rather than employ full air conditioning throughout the building, the open plan office spaces are serviced via a mixed mode system comprising of natural ventilation that assists a mechanical displacement ventilation system. With the exception of the servicing method of the building, as the MOD utilises an innovative mixed mode design, it therefore is appears more akin to the Guide's Type D classification "Air Conditioned, Prestige" i.e "A national or regional head office or administrative centre. Typical size ranges from 4000 m2 to 20000 m2." The comaprison to ECON 19 is provided in more detail in Section 4.4

This variation in building design may also lead to a variance regarding the comparability of different levels of modelling sophistication between the simulations of the Case Study buildings. For example, the Basic and Simple models may form a truer picture of the two purely naturally ventilated buildings whilst further refining of the model is the most comparable to the MOD building as it servicing strategy is more complex. Therefore, by the comparison of physically monitored results to DTM predictions the thesis will test the assumption:-

- that the additional effort of a very complex modelling strategy is unwarranted with more simplistic buildings.

All three case study buildings may concur on the most appropriate complexity of modelling to be applied to the building - whether all at the most complex stage, most basic or some other point in-between. If the Basic modelling stage is seen as the closest approximation of the building and correlates well with the physical monitoring of the 3 case study buildings then it will be concluded that the additional time and cost model in refinements is unwarranted. A perfectly acceptable level of confidence could be gained in the model without the need to apply fine control mechanisms such as window or lighting control algorithms.

Furthermore, the more refined modelling may make a poor building at the initial modelling stages and in use, appear more favourably as the use of internal blinds is optimised and internal heat gains are lowered etc. These refinements would then be counterproductive as an overheating building could be seen to be acceptable with fine tuning to the DTM. Artificial cooling may be demanded in reality which at the design stage did not reveal itself due to the over-complicated DTM runs allowing too lax allowances for the building's heat gains and optimised window opening. However, were the models to correlate with the physical monitoring of the building at only the Complex or Sophisticated stage, then the additional time and effort for this refinement would be warranted. The subsequent costs of creating the complex DTM runs would be worthwhile as any lower order of modelling may make a naturally ventilated office building with perfectly acceptable conditions appear to overheat. Naturally, the consequence of this "under-modelling" would be to the design of the building, perhaps needlessly adding full air conditioning or mechanical ventilation systems to areas that do not require them. Were the models, ideally, to concur on a level of modelling for all three case studies an optimum level of model in complexity could be seen to exist.

4.3 Quantifing Overheating

As mentioned in the Literature Review, to quantify overheating of the building the temperature levels found by both the physical monitoring and DTM predictions must be assessed against some very simplistic measurements. For example, no hours above 30°C, 5% of working occasions when the dry resultant temperature should be below 25°C etc. Furthermore, none of these measurements are enforced by law and are, at present, only guidelines to be adhered to.

Therefore, the thesis could look at only one of these non-statutory guidelines to satisfy the quantification of overheating. However each guideline has different sensitivities, the BRECSU "A Performance Specification for the Energy Efficient Office of the Future" method(6) uses dry resultant temperatures whereas the Trades Union Congress (TUC) and the Union of of Shop, Distributive and Allied Workers (USDAW) guidelines use air temperature. The TUC(7) and USDAW(8) guidelines are insensitive to the hours of use of the building and have no element of design risk. The CIBSE guidelines in Section A8 (9), however, could allow for doubling of actual hours past 27°C compared to another building if it was in operation for double the length of time per year, as it requires that a design risk of 2.5% of occupied time is not exceeded. It is therefore important to look at more than one guideline. In addition the modelling scenarios may be highly sensitive to one change in its input variables that will create a pass or fail dependant upon the guidelines used. For example, additional internal shading may have little effect on the percentage time a building passes 25°C dry resultant though may be effective enough to remove several instances of post 30°C temperatures as the direct solar gain is reduced. In this instance, little variation may be seen against the BRECSU guidelines but the building may now pass the simplistic TUC criterion after previously just failing.

Therefore, a further aim is to assess if **there is a more robust method of quantifying overheating that can be applied to dynamic thermal modelling**. Or does this mean the inheritance of existing guidelines with an additional design risk allowance to allow for uncertainty in the modelling involved?

A simplistic "no conditions past 30°C" may not be as applicable to DTM predictions as it is for measuring actual buildings in use, for which was designed. Given no major reassessment of other variables (e.g. running the model with weather data containing extremely hot summers) can a more useful and robust guideline be created for DTM predictions? For example, to ensure 30°C is not exceeded in reality, do results show that a more harsh or relaxed guideline criteria would need to be placed on the DTM results such as simple shift to 28°C or 32°C as a maximum internal temperature? Alternatively, are these example 30°C temperatures predicted overly affected by modelling choices such as weather file choice. Therefore, a guideline linked more to the relative temperature control of the building (for example assessing the building's ability to minimise internal heat gain above ambient conditions) will be created, rather than one aimed at keeping below a target maximum temperature.

It is likely that an extra level of confidence would need to be placed on the predictions if they are to match the physical monitoring of the initial "Basic" or "Simple" modelling stages. A comparable result between the "Basic" model predictions and the physical monitoring may only be as a result of input variables that are cancelling each other out. Whilst an overly harsh effect is had on the model where 100% levels of occupant, artificial lighting and equipment heat gain are applied, this may be countered by an overstated scheduling of window opening. Therefore, whilst any alterations to the guideline temperature limits for the DTM should bring about results more closely comparable to the physically monitored results (and be seen across the 3 case study buildings) they should also be more impervious to purely modelling-method alterations e.g. the window opening or lighting algorithm being applied. Further modelling refinements, for example lowering the occupant or equipment gains as demonstrated in the final "Sophisticated" modelling stage, would also, no doubt, have an effect upon predicted overheating but these are changes in the **actual** input data and would be at the discretion of the modeller.

To attempt to create a more suitable guideline, the proposed guideline method will includes the following provisos:- It will use a design risk allowance rather than the simplistic pass/ fail system; it will have an operational requirement i.e. be based upon percentage time occupied; it will use the dry bulb air temperature, due to its its simplicity and ease of measurement; it will be linked to external temperature conditions.In this thesis the physical monitoring season was reduced to only portions of July, all of August and September due to equipment limitations and due to the fact that the monitoring methodology was designed for the EPSRC "Guidelines for the Design of Natural Ventilation and Mixed Mode Buildings" project. Naturally such a reduced season will not compare with a full summer that was envisioned when the CIBSE, TUC etc. overheating guidelines were created (e.g. the extreme "Design Summer" datasets of London, Edinburgh and Manchester created by CIBSE contain 6 months work of data, April to September).

Therefore, by necessity the analysis of the overheating conditions has been confined to the periods for which there is physical monitoring data. This will allow the comparison between the TAS predicted data and actual buildings. This can be used to assess both the datalogged information and predictions against the overheating guidelines used **and** can be used to cross compare the cumulative frequencies of temperatures created by the predictions and the dataloggers to find a more suitable guideline temperature for application to DTM results. For the existing guidelines a cross-comparison between the DTM variations against the current BRECSU guidelines will be made. This additional design guidance will be used as it makes use of dry resultant temperature which is a better indicator of thermal comfort as it comprises both MRT and pure air temperature - this guideline also uses the lowest/severest overheating threshold temperature of 25°C. However, a lesser number of datalogging points of globe temperature can be compared to the similar dry resultant temperature data predicted by the DTM simulations. This was due to a lack of availble monitoring equipment in the EPSRC study for which the physical monitoring was conducted. Despite this, another advantage of using this guideline is that it allows the "percentage time" of overheating to be compared for a building's actual hours of operation, thus it is expressly intended as a design stage guideline and forms the most up to date standard of guidance.

Comparisons between the physical monitoring and DTM runs should reveal a realistic level of modelling refinement for a naturally ventilated building, where the models can most clearly be seen to concur with the actual buildings. However, as stated previously, not only could these modelling stages vary between the 3 case study building, but also, even at a comparable modelling stage is it possible that the building could pass some of more simplistic overheating guidelines yet fail others? Here the step-wise refinement process of the modelling in the thesis will be of use as it should reveal which changes have the greatest effect upon the DTM's prediction. For example, allowing for additional diversity of occupant and equipment gain may be of little value as compared to the effects of mimicking natural ventilation via the use of the window opening algorithm.

4.4 Case Study Building Selection

Three Case Study Buildings were chosen from the 8 buildings that underwent physical monitoring as part of the EPSRC Research Project into creating "Guidelines for the Operation of Naturally Ventilated and Mixed Mode Office Buildings" (10) monitored by the Welsh School of Architecture (WSA) and De Montford University, Leicester. The 8 buildings that made up the EPSRC study were chosen as the research team applied the following general criteria :-

- **New buildings**: because of their complexity or because of communication difficulties the services in buildings can take some time to settle into their normal operating pattern. Therefore, to limit the effect of commissioning problems, operator inexperience or company relocation, buildings were only considered that had been occupied by the current occupant for at least 12 months.
- **Problem buildings and problem services**: buildings (or building services) with a known problem in their design or operation were excluded from the investigation, on the grounds that further work on something that was already known would be an inappropriate use of the project's resources.
- **Organisational conflict** : as an occupant comfort questionnaire analysis formed a large part of the project, buildings occupied by organisations that were in dispute with their workforce were not considered.
- **Innovative ventilation**: within the project buildings were selected according to two basic types. Buildings of the first type were chosen as being representative of simple, yet effective, narrow plan naturally ventilated offices. These were designated *building regulations* buildings, as the main constraint under which they were designed would have been the then-current building regulations. The Barnardos and Morgan Bruce buildings fall into this category. The second type, designated *innovative* buildings were selected as being at the forefront of current thinking on how naturally ventilated and mixed mode buildings could be designed to optimise their ventilation and general environmental performance. The MOD building is part of this second category.

From the 8 buildings for which the year-long physical monitoring was conducted by the Welsh School of Architecture, **three were chosen for use as Case Studies in the thesis as they**

represented three distinct and increasing levels of design sophistication. Firstly, the Barnardos building is typical of a small, cellular office block that is naturally ventilated. The Morgan Bruce building is more sophisticated in that although still a purely naturally ventilated building it comprises a significant degree of open plan office space and also allows a large area for other uses such as conference rooms, computer rooms. libraries and kitchen facilities. Finally, the MOD Procurement building represents a prestige building equivalent to a company's national headquarters building. It was built specifically for the client, is primarily open plan, allows considerable space for additional services e.g. catering for the many thousands of staff on site as a whole and is placed on a site with dedicated parking and rail links. These 3 buildings could be seen in light of the Type A, B and D buildings from the "Energy Consumption Guide 19" (11) with the exception to the case that the office space in the MOD building is serviced by mixed mode ventilation rather than fully air conditioned. - i.e.

Barnardos = TYPE A "A simple building and relatively small.Typical size ranges from 100 m^2 to 3000 m^2. The domestic approach, with individual windows, lower illuminance levels, local light switches and heating controls helps to match the operation with the needs of occupants and tends to reduce electricity consumption in particular. There also tend to be few common facilities. Catering often consists of the odd sink, refrigerator and kettle."

Morgan Bruce = TYPE B "Largely open-plan but with some cellular offices and special areas. Typical size ranges from 500 m^2 to 4000 m^2. This type is often purpose built, sometimes in converted industrial space. Illuminance levels, lighting power densities and hours of use are often higher than in cellular offices. There is more office equipment, vending machines etc, and more routine use of this equipment. Lights and shared equipment tend to be switched in larger groups, and to stay on for longer because it is more difficult to match supply to demand"

MOD = TYPE D "A national or regional head office, or technical or administrative centre. Typical size ranges from 4000 m^2 to 20,000 m^2. This type is purpose-built or refurbished to high standards. Plant running hours are often longer to suit the diverse occupancy. These buildings include catering kitchens (serving hot lunches for about half the staff); air-conditioned rooms for mainframe computers and communications equipment; and sometimes extensive storage, parking and leisure facilities."

There were other, more minor factors that made the the choice of the Barnardos offices in Cardiff, Morgan Bruce offices also in Cardiff and the Ministry of Defence's Procurement Offices (MOD) in Bristol look advantageous as compared to other similar buildings in monitored as part of the EPSRC Project. Naturally, purely logistical and cost considerations had to be taken into consideration. Should any building require a significant number of additional data gathering visits to its site these would have proved more difficult and costly where the site was the farthest afield, leading to the advantage of buildings in South Wales and the South West of England. A further minor consideration was the availability of meteorological data for the area for later use in the thermal modelling exercise. It was known that an EWY (Example Weather Year) file was available for Bristol and that meteorological data was available for Cardiff from the Welsh School of Architecture's own meteorolical monitoring site.

4.5 Physical Monitoring.

In order to analyse the predictions created by the dynamic thermal model, TAS, physical monitoring of certain environmental parameters within the case study buildings was necessary. The physical monitoring, for the EPSRC project for which it was designed, was required to at least be conducted through the peak extremes of external conditions (i.e. summer and winter periods) and where possible for a full year so that all seasonal and inter-seasonal differences could be analysed. The enormity of the task, time-wise, required that the extent of the physical monitoring within the building be limited to include only the major factors affecting thermal comfort – i.e. air temperature, mean radiant temperature and relative humidity. Thus no long-term account was taken of air velocities, for example, within the case study buildings as this would have proved impractical. The choice of Case Study building came from two over-riding factors: that they are fully naturally ventilated or mixed-mode, non-domestic buildings (as this is the portion of the building stock of interest – offices); and that they were constructed or thoroughly refurbished to meet the then current Building Regulations (i.e. post 1989). Thus it can be assumed that any case study building was built to a level to satisfy current legislation, though this does not necessarily imply best practice.

At this point it is worth re-iterating that the physical monitoring was conducted as part of an EPSRC project rather than being designed specifically to serve the thesis' aims. The data from this physical monitoring alone has been taken for use. This resulted in the environmental parameters that could be monitored were limited by the length of the monitoring period. Thus only air and globe temperature data could be collected in sufficient detail and in enough spaces per building to be of worth for comparison against predictions from varying TAS zones from the DTM modelling. The EPSRC project methodology ensured that pure air temperature measurements were taken at three heights per logger position – 0.3, 1.1 and 1.7 metres. This is because, as previously described, gradients of differing temperatures can occur within a space causing localised discomfort. However, only the air temperature value at 1.1m was used in this thesis as it had a far greater logger coverage in each building. A “globe” temperature measurement is also taken at the same point as the 1.1 metre air temperature on some logging positions. Briefly, this measurement is a combination of both the mean radiant temperature (MRT) and the air temperature and can be taken as the resultant temperature at low air velocities. Thus, knowing the air temperature at the same point, the MRT can be simply calculated (typically “globe” temp =50% air temp. + 50% MRT). TAS will also predict MRT as a result of radiant gains to a space and hence by the calculation of MRT (from the monitored globe and air temperatures) the accuracy of the predicted MRT could have also be assessed. However, only direct comparison of ‘globe’ and air temperatures to TAS predicted air and resultant temperatures will be made in this thesis. As this data will be used to give an overview of environmental conditions within the buildings and is specifically aimed at helping deduce the level of overheating found, it has been pared so that only the working hours of the building remain, this means that only working, weekday hours from 9am to 5pm have been compiled. However, the dates of the monitoring varied in each instance, for example the MOD building was physically monitored for 18 more days than than the Barnardo’s building due to restrictions on logging equipment available. The recorded data was collected over the following dates - Barnardos = 12/08 to 30/09, Morgan Bruce = 01/08 to 30/09, MOD = 24/08 to 30/09 inclusive.

Unfortunately, only enough sets of monitoring equipment that contained both air and globe temperatures to do a sample set of rooms in ease case study building. Therefore, for comparison against the DTM zones, which are room specific, in the majority of instances only the air temperature could be used as only this had reasonable coverage by the physical monitoring across the Case Study buildings. Comparisons between globe temperature and predicted resultant air temperature were restrained by the lack of logger coverage, typically only one globe temperature logger was available per floor/wing of a building. An external site monitoring both temperature and relative humidity levels was also used but was not available for the creation of realistic external variables to create a meteorological file of the Case Study locations as it only provided measurements for only two variables. Whilst site-specific weather data would have been a useful addition to gauge the effects on DTM predictions caused by the microclimate (as the typical local weather files were compared against site based measurements) they could not aid in creating a weather file - the external logging positions were set up to gain external air temperature and relative humidity readings only.

4.5.1 Physical Monitoring - Logging Position Equipment and Set-Up.

The primary sensor used to measure the air temperature was a device utilising a 2k thermistor bead (for use with a Campbell Scientific CR10X or Grant Ltd "Squirrel" series datalogger). A thermistor is a generic name derived from "thermally sensitive resistor" and operates similarly to a resistance thermometer i.e. the electrical resistance of its material changes in a reproducible manner with temperature. A thermistor can be formed into rods, beads or small discs, however the small bead shape provides the fastest response. The bead used will give a typical response time of 4 seconds and be accurate to within 0.2 °C. The sensor worked within a tolerance of -40 °C to +75 °C and was therefore more than adequate to be used for the measurement of internal temperatures. The "globe" temperature sensor also made use of the same 2k thermistor bead. The globe temperature sensor comprised a 2k thermistor encapsulated in a 40 mm, thin walled sphere coloured black to increase its absorbivity. This is a very common device for measuring the combined MRT and air temperature of a space. The instrument is suspended within an enclosure and will reach an equilibrium temperature between convective and radiant heat transfer from the surface of the sphere – the globe temperature will then lie between the MRT of the enclosure/space tested and the temperature of the air surrounding the globe.

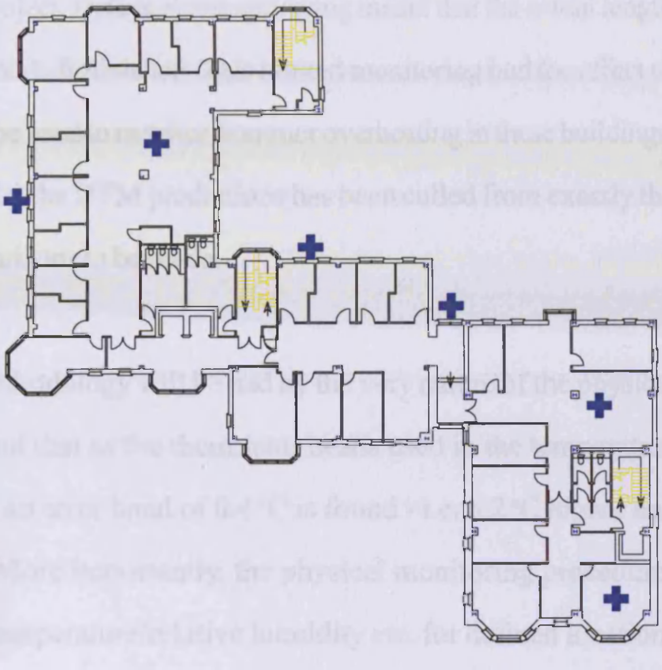
The temperature measurements also made some very minor use of the Tinytalk II series of dataloggers. From Gemini Dataloggers Inc., the "Tinytalk II" is a stand-alone, battery powered sensor integrated into a datalogger that is contained within a 35mm film type canister. The problem of a limited memory capacity (1800 readings) applied to these temperature loggers, however, though the 35mm cased device provided an extremely useful sensor to position in most cases, easily outweighing this consideration. The Tinytalk II sensor utilises a 10k thermistor and will operate in the range of –40 to +75°C with a typical accuracy of -/+0.2°C in the 0-70°C range. As the thermistor is mounted internally in the datalogger it has response time of 5 minutes (in the sealed canister), however as the primary purpose of the device was to gain 15-minute average temperatures this was well within acceptable limits for their use. These devices were used solely in cellular offices to act in addition to the main logging positions, thereby giving a floor wing the coverage of one open plan area plus 2-3 cellular offices rather than only one which would have otherwise been the case.

The primary dataloggers used for the physical monitoring were the Grant Ltd Squirrel 1200 series and 8-bit model. The 8-bit model allows up to 4 channels to be used for temperature sensors and has an 8000 byte memory capacity – thus 21 days capacity for 4 temperature sensors set at a logging interval of 15 minutes. The 8-bit model is unable to take a capacitative probe of the nature of the Vaisala RH sensor used and therefore the 1200 series logger was also required. The 1200 series is a far more versatile datalogger as it has channels that will readily accept a volt reading, standard 1.5mm jack or Din plug and has 42, 315 bytes of available memory, some 5 times that of the 8-bit model. Therefore, 1 single 1200 series logger is capable of receiving all the inputs for one logger position in the study – i.e. 4 temperature and 1 RH sensor. The only drawback of the separate logger and sensor system is that the actual file type downloaded is a .dat data file and as such requires conversion, by specialist software from the manufacturers-Grant Ltd, into a usable format e.g. a .txt, .prn format. This proved only a minor additional step of processing the physically monitored data, however, as it had to be turned from 15-minute to 1 hour averaged data for comparison with the DTM predictions. However, in the case of the peak temperature value gained by the physical monitoring, its peak value was used rather than that from the hour-averaged data set, in order to prevent its lowering by the averaging process. Naturally, this data averaging came after standard checks of the physically monitored data for results that were clearly corrupt or contained other errors.

Naturally, some element of equipment failure was expected during the physical monitoring process. During several instances individual air temperature sensors and/or the data-logging devices failed so that, that period's air temperatures were not recorded. These failures were removed from the data-sets of recorded temperatures. These failures and other erroneous data could be clearly seen against the other logging positions recorded temperatures from the same point in time and theerfore proved of only minor concern. However, in one instance a data-logger failure proved more serious as it provided no data at all for a specific monitoring point. On the 3rd Floor of the Barnardos building, over several of the Summer months, one of the Campbell Scientific datalogger used failed on repeated occasions. This left no air temperature data for this floor, for comparison against DTM results, for the Summer season for this area.

An example of a standard logging pole set-up and logging locations on a sample floor (in this instance on the First Floor of Morgan Bruce) can be seen below. The full, floor-by-floor depiction of logging positions for each Case Study building can be found in the Appendices.

On-Site Logger Pole monitoring set up



Example Monitoring Locations: Morgan Bruce 1st floor

4.5.2 Physical Monitoring: Effects on Comparison Methodology

The initial problem found by the physical monitoring methodology created for the EPSRC project was that of limited coverage in the buildings due to equipment limitations (i.e. limited numbers of dataloggers). However, wherever possible a full logging pole system was given over to each floor (or large open plan zone) that was in turn supported by several positions containing air temperature sensors only. This, at least that each floor/zone would provide at least 1 logging position that could provide information for comparison against the predicted data from TAS zones. Even with this limitation, this level of monitoring provides for a minimum of 7 locations for comparison in each Case Study Building.

Secondly, the original monitoring procedure had allowed a timescale that would involve monitoring equipment being left in-situ in the Case Study buildings for 1 whole year. However, the 3 Case Study buildings in this thesis were merely 3 of the 16 buildings in total monitored for the EPSRC "Guidelines for the Operation of Naturally Ventilated and Mixed Mode Buildings" project.

All eight of these buildings monitored by the Weslh Scool of Architecture had to share monitoring equipment, in addition, due to the nature of the project, the physical monitoring of each building could not commence until after an occupant survey for the EPSRC project. Delays in this surveying meant that the actual length of monitoring in each building became much more diminished. This limited monitoring had the effect of reducing the available season's data that could be used to monitor Summer overheating in these buildings. To overcome this problem, the data provided by the DTM predictions has been culled from exactly the same time periods to allow like-for-like comparisons to be made.

A further effect on the comparison methodology will be had by the very nature of the physical monitoring system. It should be borne in mind that as the thermistor beads used in the temperature sensors have up to a +/-0.2 °C possible error, an error band of 0.4 °C is found - i.e. 0.2 °C higher and lower than the physically monitored result. More importantly, the physical monitoring procedures provide point-specific measurements of air temperature/relative humidity etc. for defined locations in an office building. However, the zoning method created by DTM models uses 'zone averaged' air temperatures. This means that whatever the extent of the defined zone in the DTM, the air temperature is assumed to be constant throughout that space at all points and also assumes that no vertical temperature gradient is created in the space over its height. For the vertical temperature gradient to be created a DTM zone would effectively have to be split by false planes along its height i.e. doubling of trebling the number of zones created dependant upon the number of temperatures at height "X" wanted (e.g. from 0-1, 1-2 and 2-3m of the room height). Similarly, to create a smaller room zone that sub-divides a room into a number of individual zone section (e.g 4 for north south, east and west) this would also entail massively increasing the number of zones used and the imposing of false walls/apertures on the model to create the smaller zones. In the DTM programme used in this thesis, TAS, it has a maximum 60-zone limit, which serves to allow each Case Study building to be broken down into a "zone per room" though leaves little leeway for more finite zoning. To achieve this more finite modelling of smaller zones (e.g. a room of 12 quadrants - 3 heights by 4 sub-sections) would demand each floor of the building be modelled individually to allow TAS to remain within its 60 zone limit. This re-modelling would therefore quadruple the effort to model 1 DTM run on a 4-storey building for example. However, even these small zones would still assume a 'zone average' temperature - therefore such point-specific temperature predictions can only be gained by computational fluid dynamics, though this cannot produce dynamic, hourly predictions of temperatures demanded by the comparison methodology.

There is no clear evidence for how far a radius around a point-measurement of air temperature will be representative of that value - in closely controlled air conditioned buildings this will be further than in a free running, naturally ventilated building. Ideally, therefore, temperature measurements would need be taken at each workstation. However as the methodology cannot, due to the DTM's zone averaged temperatures, exactly compare like-with-like it was deemed that they can only be applied as per a standard modelling methodology. Zoning the model by discrete room/areas is a logical basis for a model. Where these zones represent small, cellular offices it would be expected that they will be a closer match to the temperatures found on the point-specific logging equipment compared to those in larger open plan spaces. However, even this zoning procedure may be time consuming, whereas a basic DTM model may have need of only "ballpark" information regarding temperature conditions and suffice with a simplistic but quickly defined zoning strategy e.g. a zone per floor or wing of the building. Further zoning refinements can be created on subsequent modelling runs. The thesis applies this technique of basic zoning with a further level of complexity as a zone per distinct room/area is added later. This method would be typical of working practice as a DTM model is refined over time, however no amount of refinement can remove the DTM's zone average temperature values and therefore, strictly speaking, an exact comparison cannot be made to the spot measurements taken from a thermistor bead. As previously stated this exact comparison could only be made with a point-specific prediction from a (non-dynamic) CFD model, therefore this limitation must be borne in mind when comparing the prediction and monitoring results.

4.6 Modelling Strategy

Each building will be modelled with four levels of sophistication of input data, requiring the creation of 11 simulations per building. These modelling stages will lead the model for each Case Study building through an increasingly sophisticated modelling approach, the stages designated as the "Basic", "Simplistic", "Complex" and "Sophisticated" levels.

4.6.1 Modelling Level 1: BASIC

It is likely that people would intuitively assume that gaining an initial, working dynamic thermal model of a building can be done relatively quickly and effectively using basic 'rules of thumb' information regarding its internal loads and the weather file of a reasonable approximation for the area in question where a weather file from close proximity to the building is not readily available. A simplistic method of zoning the DTM model could also be used, taking out all the most obvious corridor and storage areas from definite, working (i.e. office) zones. Whilst it is intended that an overview of the building should be gained in this way, this is not a particularly defined method - it is also possible that this method would reveal some areas of the building to overheat that may not be seen in more refined model runs (or vice versa). However, such initial runs could be viewed as useful in giving a "ballpark" estimate of likely environmental conditions within a building and therefore would be considered to perform a valuable task.

Several of these potential pitfalls created by such a simplistic modelling methodology could be eliminated, however, with variations in the DTM input. At the simplest level, if occupancy rates are a worry several alternative levels of occupation could be applied over varying DTM runs - a constant 100% of the design load would be highly uncommon. Further alterations could be made for the building model to more accurately mimic the natural ventilation strategy applied by the building in use, for example an alternate simulation run could be made using a window opening algorithm to make all aperture openings temperatures sensitive rather than just on a simplistic time-based schedule (i.e. using the same criteria which prompts the actual staff to open/close window).

A model defining only simplistic premises will be created as the **"Basic"** model in this thesis. In this initial, Basic model Kew, London data will be used for the case study buildings in this thesis, though they are in Cardiff and Bristol and zoning will be applied per floor/wing of each building. This initial model also assumes that:-

The full lighting load is applied during all office hours (i.e. weekdays 9am-5pm) for each room

The windows are allowed to open to their maximum given percentage area for every occupied office hours

There is no use of blinds or other internal shading devices on any window for any facade.

Occupant gains are applied at 100% levels for all working hours i.e. continuous maximum occupancy is assumed.

Equipment gains are applied at 100% levels for all working hours i.e. no allowance is made for diversity as equipment is powered down or switched off over the day.

4.6.2 Modelling Level 2: SIMPLISTIC

To allow for a more realistic model, however, the model should at least be zoned at a reasonable limit to remove corridor or other non-working areas from the actual office-use areas (and ideally to define cellular and open plan areas separately as their heat gain per square metre are likely to differ). Furthermore, to gain a realistic picture of the building in use, a local weather file should be used that will experience the same climatic conditions – ideally this will be from a locale near the intended site, as external conditions have a large influence on the models predictions (though this cannot account for microclimate differences).

In the thesis, these changes will be made, firstly to apply a 'zone per room' allowance for all office areas and secondly to apply a local Example Weather Year for the cities in question (Cardiff and Bristol). These changes will be made individually to assess their relative effect as compared to the Basic model. Ideally, if the meteorological data existed this could have been contrasted with a weather file for a Design Summer Year or other extreme hot sequence), however this was not available for the locations studied. These two changes (zoning alterations and local meteorological file) can then be combined to form a more representative picture of the building's in use - this will be taken as the **"Simple"** model in the thesis.

4.6.3 Modelling Level 3: COMPLEX

In the case study buildings chosen, the natural ventilation strategy will be the key component in reducing the level of summer overheating as this is the only method with which naturally ventilated buildings can cool (in the case of the mixed mode building, it is the only additional cooling, over and above the basic, low level of air supply created by a displacement system). The "Basic" and "Simple" studies merely assume that 100% of available window opening will be applied at all times scheduled in the summer i.e. a constant given percentage window opening area, dependant upon window type. The likelihood that all windows will be opened for the majority of hours which correspond neatly to working hours is extremely unlikely and thus a better approximation of window opening by the occupants should be used. A further change to mimic reality should also be made given the occupants use of artificial lighting.

It would be assumed that when natural day-lighting provides a great enough internal lighting level (e.g. 400 lux) that the artificial lighting would be turned off as most modern luminaires are fitted with automatic dimming features to make use of this natural daylight, automatically reducing their output (and hence power consumption and heat-emittance to the room) as natural daylight is available. Occupant action is also ignored when it comes to the use of internal blinds. It would naturally be expected that some form of internal shading would be applied when external lighting levels are very high. In part this would be due to undesired glare in the office, however the restriction of direct sunlight entering the room would be, in large, as a response to the direct heat gain on the occupants and space from these solar sources.

In the TAS programme a suitable method to mimick window opening is available by the simple application of a window opening algorithm. To mimic occupant-controlled natural ventilation a window remains on the same opening schedule (e.g. 9.00 AM-5.00 PM) but is allowed to open/close between certain criteria defined by internal temperature. For example, where the algorithm "zdwon,1,22,24,30,5" is entered in TAS, the following strategy for aperture opening will occur. As the dry bulb temperature in zone 1 rises above 22°C the aperture will start to open. The aperture will be fully open at 24°C. As the temperature rises above the 24°C cut-off temperature, the aperture will start to close and be fully closed at 30°C. The aperture will also close if, at any time, the outside temperature is greater than the inside temperature. This proposed alternate run, whilst still only an approximation of occupant-controlled window opening, at least offers a thermally responsive window opening pattern and is therefore more akin to reality than the simplistic on/off percentage window opening schedule that will be used in the less defined "Basic" and "Simple" runs.

The improved control of artificial lighting can also be readily applied in TAS with an algorithm that controls the artificial lighting output forming another alternate run. A room is prescribed a daylight factor, this is assumed to be 2% as demanded by the current Building Regulations, and the algorithm then controls down from the maximum lighting load available (e.g. 16 w/m^2 in the MOD building) to meet a certain internal the lighting demand e.g. 400 lux. As in the case of the window opening algorithm, this method may be an exaggerated or overly-complex method of applying lighting gains, being more precise than simple occupant actions. However it still represents a more realistic assumption than the "Basic/Simple" models which assume that artificial lighting is on 100% of the time. This lighting algorithm, which can be easily applied, should be seen as more akin to mimicking modern auto-dimming luminaires that are widely used.

The blind schedule will be applied irrespective of the external conditions (e.g. blinds in use 10.00 AM-3.00 PM on all summer weekdays) in the cases of the Basic and Simple runs. However, a simplistic on/off pattern or even the omittance of internal shading altogether could be seen as an over simplification. Therefore, a further alternate run which will allow blinds to be scheduled and linked to external conditions will be conducted (solar gains of >20w/m^2 on a given window inducing blinds use). Once again, the application of this algorithm to the model is readily made in TAS, though it again could again be argued that this is over-sophistication as compared to simple occupant actions. However, as the alternate choice is complete omission or a simple on/off time scheduled application of blinds, this provides the best method of mimicking the office building in use.

Whilst also modelled separately, all three of these algorithms will be applied in conjunction with one another to form the **"Complex"** model. This Complex model will represent a building with more realistic patterns of use than the initial Basic and Simple models. However, in all 3 instances of these algorithms being applied no additional input data will be required. All changes made form part of the TAS modelling package's method of application of this pre-existing data. The maximum lighting load, the window opening areas or their actual schedules are not to be altered in themselves, merely the way these variables are to be applied. In so doing, a modeller would hope that a more realistic run will be given by the DTM of an actual building in use than would have been expected from the initial Basic and Simple models.

4.6.4 Modelling Level 4: SOPHISTICATED

Whilst initial models can be built upon the assumption of 100% occupant and equipment gains throughout the building, this is likely to be far from realistic. Though the maximum numbers of persons and equipment supplied to each room may be known at the design stage, this does not allow for any level of **diversity** of these loads as they are applied in reality. Much research has been undertaken to quantify actual occupancy rates in offices, e.g. to determine floor space per occupant by letting agents or for the use of occupancy sensors as lighting controls in individual offices - such as a study in the offices of the US National Center for Atmospheric Research(12) which found that office occupancy patterns show that, for the facility investigated, individual offices are typically occupied only 50% of the workweek (defined as between 8 am and 5 pm from Monday to Friday). In investigation into actual office occupancy rates Veldhoen and Piepers(13) suggest that there is a downeard trend of occupancy for the office environment, reporting that "Staff occupancy rates in offices fell dramatically from two-thirds to barely half between 1960 and 1995 when sickness, weekends and holidays were taken into account". The results of this ongoing research into office occupancy patterns shows that, individual offices are typically occupied ara rate closer to 50% than 100% of maximum over the workweek. Allowing for absenteeism, staff holidays and vacant positions a 100% occupancy rate is highly uncommon for an office in reality. Naturally, this lower occupancy rate would also indicate that equipment loads too, whether personal pc.s or shared items such as printers and copiers, would be expected to be powered down for a significant portion of the day also, hence lowering their heat gain than to the room. In reality levels as low as only 30% occupancy would be expected over a normal working day in a UK Office building (as described in guidance given in Appendix C of CIBSE's AM11 "Building Energy and Environmental Modelling"14).

A "working day" pattern of gains can be applied in TAS i.e. a changing, hourly profile of levels of internal gain over a day type, though this cannot be randomised as such between a predicted maximum and minimum equipment and occupant levels. No definitive profile exists for the diversity found in levels of equipment use, CIBSE AM 11 stating that "Given the lumped nature of the (internal) gains, it is inappropriate here to provide profiles for individual heat gain sources" but that "on average, occupant presence is reasonably well correlated to equipment and lighting usage". However, rules of thumb for calculating expected annual energy consumptions from equipment use are available and heat loads found per square metre by personal pcs, printers etc in use can also be gained. Therefore, given that no reliable basis can be found for applying hourly diversity levels to these loads (plus the option is not available in the TAS programme), a more simplistic approach will need to be taken. For example, in this thesis the hourly applied load for occupant and equipment gains will be halved to account for the 'diversity factor' (as occupation levels may only reach 50% on average and thus their personal equipment use would fall also). Naturally, across an average day internal equipment and/or occupant gains would fluctuate to levels far higher and lower than this average value. Therefore, a simplistic but suitable average value is the best approach to be taken, given that truly dynamic alterations cannot readily be applied to heat gains for every hour run in the model. Whilst not an ideal method of approximating realistic internal loads from occupants and equipment, this is unlikely to be the gross over estimation of taking 100% of gains at all hours. If time permitted, ideally a series of runs would be produced, from the worst case scenario of 100% gains at all times down to more realistic average levels of e.g. 30%, 50%, 70% of maximum etc. With the given time restraints, two alternate runs are proposed; one halving the applied levels of occupant gain and the other halving the applied equipment gain - from the difference between these runs the internal source of gain that has the largest effect on overheating will be revealed.

When combined these alterations to the internal load inputs will form the **"Sophisticated"** model (or the best case scenario for the overheating analysis). All possible methods of making the building mimic a naturally ventilated building in use will have been included and minor adjustments made to the internal gains to make them a more realistic reflection of heat gain in a real building. Naturally with lower heat gains applied (and all other things being equal) the 'Sophisticated' model stage should reveal lesser overheating than the 'Complex' stage, given that a direct effort was made to make them more realistic by lessening occupant and equipment gains. However, it would also be expected that a 'Complex stage' modelled building would show a significantly lower degree of overheating than the more basic stages, however it is not known if this added complexity will bring the modelling predictions closer in line with, or further away from, the results found by the physical monitoring of the case study buildings. A graphical representation of the modelling stages and the changes to their model set-up is shown below.

	MODELLING STAGE										
Model Stage	**Basic***			**Simple**				**Complex**			**Sophisticated**
Model Alteration	-	1	2	3	4	5	6	7	8	9	10
Cardiff/Bristol Weather file	×	✓	×	✓	✓	✓	✓	✓	✓	✓	✓
Room Zoning	×	×	✓	✓	✓	✓	✓	✓	✓	✓	✓
Lighting Algorithm	×	×	×	×	✓	×	×	✓	✓	✓	✓
Window Opening Algorithm	×	×	×	×	×	✓	×	✓	✓	✓	✓
Internal Blinds	×	×	×	×	×	×	✓	✓	✓	✓	✓
Reduced Occ. Gain	×	×	×	×	×	×	×	×	✓	×	✓
Reduced Equip Gain	×	×	×	×	×	×	×	×	×	✓	✓

*	Uses Kew (London) Weather Data & Zoned per Floor/Wing
✓	Model Alteration Included
×	Model Alteration Not Included

4.7 Computer Simulation Programme

4.7.1 Dynamic Thermal Model Programme Choice

The choice of EDSL Ltd's TAS (Thermal Analysis Software) dynamic thermal modelling programme was made as it is a programme much utilised within the UK design industry since 1989 and adequately deals with the requirements of the alternate runs demanded by the above 'matrix'. The ability to achieve the above stated modelling alternatives pre-determined that only a modern, commercial programme such as TAS would have been suitable, rather than a programme chiefly created for research purposes such as the Welsh School of Architecture's HTB2 programme. Whilst available for use HTB2 would not have been able to manipulate the artificial lighting gain to a room for a given daylight factor, for example. TAS is an example of a currently available, commercial DTM programmes in use within the UK along with other programmes such as ESP-r (integrated into a suite of "Virtual Environment" software applications by IES Ltd as ESP) and Apache and foreign alternatives such as EnergyPlus from the USA.

As previously stated, TAS is able to benefit from a high level of support ensuring that the programme is updated on a regular basis and can remain validated to any future mandatory standard. For example, TAS Version 8.5, used in this thesis (released in April 2004), is compliant to the draft standard ISO 13791 due to come into effect in the first quarted of 2005. Pre-empting the introduction of the ISO standard 13791, conduction algorithms in TAS have been enhanced to include 'higher order time analysis to ensure compliance with the temperature error limits laid down in prEN ISO 13791'. Version 8.5 of TAS(15) allows users to select four, pre-defined 'validation' models to confirm compliance to the results expected by prEN ISO 13791. Also as previously discussed in the Literature Review section, TAS was the subject of a test cell validation exercise conducted by the Building Research Establishment on behalf of the IEA (16). In addition this programme was chosen as, as well as its proven track record of use, as a commercial software release TAS also benefits from the inclusion of standard libraries of input materials. The programme contains all 16 UK Example Weather Years as well as pre-defined libraries of common opaque and transparent building materials such as clear and low emissivity glazing, brick and blockwork, internal blinds etc.

4.7.2 TAS Overview

The main applications of the TAS programme are the assessment of environmental performance, prediction of energy consumption, plant sizing, analysis of energy conservation options and energy targeting(17). In this thesis only the assessment of environmental performance is of interest of the many possible DTM applications as the reasoning behind the modelling exercise is to predict the level of overheating in the three Case Study buildings.

The fundamental approach adopted by A-Tas is dynamic simulation. This technique traces the thermal state of the building through a series of hourly snapshots, providing the user with a detailed picture of the way the building will perform throughout a typical year. This approach allows the influences of the numerous thermal processes occurring in the building, their timing, location and interaction, to be properly accounted for. These processes are:-

- **Conduction** in the fabric of the building is treated dynamically using a method derived from the ASHRAE "response factor" technique. This efficient computational procedure calculates conductive heat flows at the surfaces of walls and other building elements as functions of the temperature histories at those surfaces.

- **Convection** at building surfaces is treated using a combination of empirical and theoretical relationships relating convective heat flow to temperature difference, surface orientation, and, in the case of external convection, wind speed.

- **Long-wave radiation** exchange is modelled using the Stefan-Boltzmann law, using surface emissivities from the materials database. Long-wave radiation from the sky and the ground is treated using empirical relationships.

- **Solar radiation** absorbed, reflected and transmitted by each element of the building is computed from solar data on the weather file. The calculation entails resolving the radiation into direct and diffuse components and calculating the incident fluxes using a knowledge of sun position and empirical models of sky radiation. External shading and the tracking of sun patches around room surfaces may be included at the user's option.

- **Internal heat gains**, which include room gains from lights, equipment and occupants are grouped together in profiles with infiltration rates and plant operation specifications (i.e. additional heating and cooling) which are applied to the various zones of the TAS model. Gains are modelled by resolving them into radiant and convective portions, the convective portion is injected into the zone air, whilst the radiant gains are distributed amongst the zone's surfaces. Infiltration, ventilation and air movement between the various zones of the building causes a transfer of heat between the appropriate air masses which is represented by terms involving the mass flow, the temperature difference and the heat capacity of air.

- Tas provides an option to specify a **mechanical ventilation** rate for a zone in addition to the infiltration. The purpose of this is to allow estimates to be made of air conditioning loads in simple cases. The ventilation air is assumed to be drawn into the zone direct from the external environment.

- Air moving between zones in a building carries with it sensible heat and water vapour and this too may be specified in TAS via **inter-zone air movement** as a scheduled input parameter for up to 12 source zones feeding air into each zone. Air movement from the outside may also be specified in this way.

4.7.3 TAS Natural Ventilation Simulation

TAS also allows the user to specify apertures in the building fabric through which air may flow. Each aperture, which may be a window, a door or a portion of a floor, has an area, a mean altitude, an orientation and a plan hydraulic diameter derived from the 3D-Tas geometric model. TAS calculates the air flow through these openings and thus takes into account the effect of natural ventilation upon the building. This method also allows a time-varying "aperture factor ". This means that each distinct window/door aperture can be opened to a given percentage free area (i.e as a fraction of the area of the surface it is associated with) over a time schedule prescribed by the modeller.

The actual air flows across the apertures are calculated by TAS using a model which takes account of the pressure-flow characteristics of the apertures, wind and stack pressures, and any prescribed air flows (which are given by the modeller in the set for zonal air movement). However,the method which is applied in TAS for the modelling of flow through vertical apertures differs for horizontal and sloping apertures (refinements are applied to the basic theory to allow for effects relating to the behaviour of the air flow as it approaches and leaves the aperture). The modifications take different forms depending on whether the air above the aperture is warmer or cooler than that below it.

Furthermore, the theory and calculation method applied by TAS is strictly designed for sharp-edged orifice apertures which are small in relation to the spaces they connect to. This method is not ideal in cases where the apertures are shaped to reduce turbulence at entry or exit, or where they have an area comparable with the cross-sectional areas of the adjacent spaces. Another restriction on this method should be where a re-circulating flow is found (i.e. air exchange between spaces connected by large apertures) as this is considerably more difficult to analyse. The accurate prediction of such flow where large apertures are concerned is beyond the scope of the zonal model adopted by TAS, and requires instead an approach based on computational fluid dynamics (CFD).

Fortunately, the building designs of the 3 Case Study buildings in this thesis do not rely on any large atria or complex patterns of air movement. The Barnardos and Morgan Bruce buildings are simplistic naturally ventilated designs based on single sided and cross ventilation. The MOD building is primarily ventilated by a displacement ventilation system which is supported by double sided ventilation via window openings, although these openings only make up a small portion of the façade on both sides of the building.

4.7.4 Wind Pressure Simulation in TAS

The wind pressure on a building facade depends in a complicated way on the speed and direction of the wind, the geometry of the building and any nearby obstructions, and the nature of the terrain in the building's vicinity.

TAS bases its analysis on the concept of a wind pressure coefficients. On the windward side of the building the wind pressure coefficients are usually positive and their values tend to increase with height. On the leeward side they are usually negative and roughly constant with height. Negative wind pressure coefficients also tend to apply where the wind blows parallel to the building surface. There are three possible approaches to the problem of estimating these wind pressures:

1. 3-dimensional computational fluid dynamics (CFD) modelling.
2. use of specific experimental data (from the building itself or a wind tunnel model of it)
3. use of generic correlations based on wind tunnel measurements.

The first two approaches are catered for in TAS by the option of specifying a 'Wind Pressure Coefficient' file which has calculated or measured wind pressure coefficients for each aperture. However, with no such data available for the majority of new building designs, including the 3 Case Study buildings, TAS also offers a third approach. TAS is able to use correlations based on wind pressure coefficients derived from wind tunnel experiments.

Where no Wind Pressure Coefficient File is specified, TAS estimates the wind pressure coefficients using correlations based on wind tunnel experiments carried out at the National Research Council Canada(18). These tests were performed on a 1:400 scale model of a tall building with a flat roof, located in a rectangular array of flat-roof low rise buildings (the building had actual dimensions 0.11m x 0.076m x 0.23m thus its height was 91m to scale). Results from the tests are in the form of pressure coefficients for an array of rectangles on the building facade, and for several wind directions. For the TAS correlations, these coefficients are averaged across the building facade at each level, and coefficients from different facades are averaged to produce coefficients dependent only on altitude (relative to the building reference height) and the angle of attack of the wind. The resulting pressure coefficients can be found in the Appendices section. It is only this later method that is appropriate to the modelling in this thesis as no wind pressure co-efficicient data was available for any of the three Case Study buildings. The shielding effect of surrounding buildings and other nearby objects may be also taken into account by setting a "mean height of surroundings" parameter for the model as a whole. An option is also provided in TAS to designate all apertures of a given type as "sheltered", which has the effect of treating the apertures as though they were on the leeward side of the building e.g. this feature may be used to treat apertures which face into an enclosed courtyard and so are not subject to the wind pressures experienced by the exposed façade's apertures. However, this is also not appropriate to be used for the three Case Study buildings used in the thesis. Finally, the "stack effect" (i.e. the pressure differences arising from gravity forces) is modelled on the assumption that within each TAS zone, and for the outside air, the air temperature is uniform.

4.7.5 Solution of Air Flow and Thermal Equations in TAS

TAS solves the sensible heat balance for a zone by setting up equations representing the individual energy balances for the air and each of the surrounding surfaces. These equations are then combined with further equations representing the energy balances at the external surfaces, and the whole equation set is solved simultaneously to generate air temperatures, surface temperatures and room loads. This procedure is repeated for each hour of the simulation

The flow equations are solved iteratively. At each time step, wind pressures and wind pressure gradients are calculated for all exposed apertures. Then at each iteration step, air densities in all zones are calculated from the zone temperatures, and these are used (together with the wind pressures if appropriate) to calculate stack pressures and stack pressure gradients for both sides of each aperture. A set of equations is then set up describing the balance of mass flow into and out of each zone. This balance takes into account any air flows prescribed in the "Air Movement" facility. However, infiltration and simple ventilation flows, specified under the Internal Conditions dialogue, play no part in these equations, however, since they are assumed to be take the form of balanced inflows and outflows. The equations are solved using a gradient-based method to yield zone pressures and flow rates in both directions through each aperture. These flows are then fed back to the TAS thermal analysis where they are used to generate updated zone temperatures. The iterative process continues until zone temperatures (both air and mean radiant) converge to an accuracy of 0.01K and flow rates converge to an accuracy of 0.0005 kg/s.

4.8 Conclusion and Methodology Plan

To conclude this section will summarise the aims of the thesis and the proposed strategy to fulfill these aims. The problem defined by the thesis is a lack of information regarding the accuracy of overheating predictions by dynamic thermal models for existing, naturally ventilated office buildings. Where such DTM simulation have previously been carried out, few post-occupancy reviews existing to compare/contrast against the accuracy of the overheating predictions made.

To conclude, the thesis' main aims are to:-

I) attempt to find the best apllicable level of complexity in dynamic thermal simulation (via comparison against physically monitored data) so that a realistic level of overheating appears in the model as it would on the actual building (if any).

II) assess whether a more robust and useful overheating guideline criteria can be created for DTM predictions that corresponds to the physically monitored data with a simple model set-up.

To achieve this naturally the thesis will need to:-

A) Analyse physically monitored data from three chosen Case Study buildings, subsequently conduct DTM simulations of these three buildings. The Case Study buildings will represent 3 distinct levels of design of naturally ventilated buildings from the most basic design through to a mixed mode option. These Case Studies will be physically monitored for a summer to gain actual data regarding its temperature conditions. The thesis must also therefore prepare DTM simulations for comparison against these findings.

B) In order to answer the first stated aim multiple simulations must be conducted on each Case Study building to find the best level of fit to the physically monitored data. Simulation will begin at the most 'basic level of complexity and advance through to a sophisticated model. In so doing account will be taken of; local meteorological files, improved zoning, improved window opening simulation, improvements in artificial lighting attribution, improvement in blind/shade attribution and the alteration of assumed levels of internal gain to achieve more realistic working levels. The simulations will form a "matrix" of modelling options as tabulated previously. To achieve this task, TAS will be used to model the 3 chosen Case Studies as it is capable of creating the simulations of increasing complexity required by the methodology.

C) To assess the overheating criteria must be chosen to define not only what is overheating but also to what extent it has occurred. To do this 4 initial Guideline figures for air temperature will be used by the thesis (as discussed in section 3.3). These are:

TUC (Trades Union Congress) - No occassions of +30°C temperatures.
USDAW (Union of of Shop, Distributive and Allied Workers) - No occassions of +27°C temperatures.
PACE (Property Advisers to the Civil Estate) "Requirements of Office Buildings" (19) - Maximum of 240 Hours per 10 years (thus 24 hours per year) to exceed 28°C..
CIBSE Guide A8 - Design risk of 2.5% or below of occupied time to exceed 27°C.

Furthermore to aid completion of the first aim, the additional criteria of overheating assessed by the dry resultant temperature can be examined. However, fewer logging positions thus comparable area will be available to compare against alternate DTM simulation results as globe (resultant) temperature data collection was more limited during the physical monitoring exercise. This additional guideline from BRECSU refers to limits to the percentage of occupied time 25°C and 28°C dry resultant temperatures can be exceeded (5% and 1% respectively). Given the multitude of overheating guidelines no definitive standard exists for DTM predictions. Therefore, to meet the second, subsidiary aim, a proposed overheating guideline will also be assessed by its comparisons for the physically monitored data and the DTM simulations.

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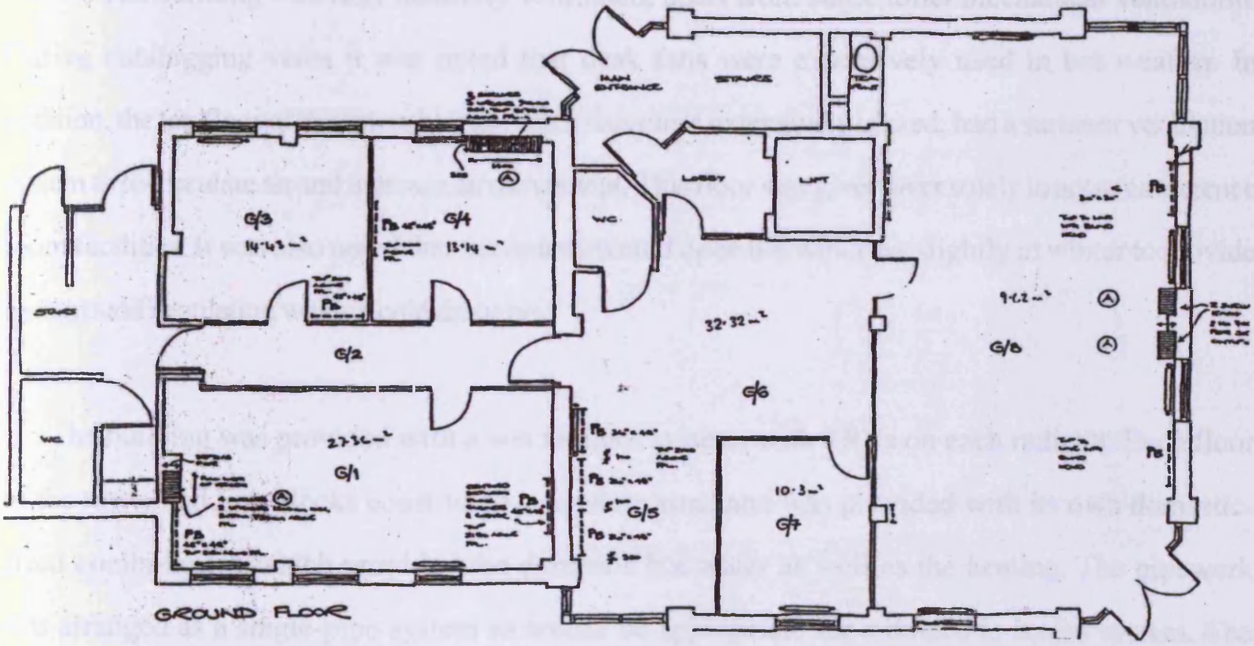
5.0 Case Study Buildings

5.1 Case Study Buildings: Overview

5.1.1 Barnardos Headquarters, Cardiff

Front View of Building

Rear View of Building



Example Floor Plan: Ground

The Barnardos' offices were part of a recent low-rise speculative office development of 985m_2. The offices were arranged around a courtyard, with car parking in the centre. The corners of the courtyard were marked by five-storey square "tower blocks", which connected to three-storey "link blocks". Barnardos occupied one tower block and a small section of a link block, having recently knocked through to connect the two previously unconnected parts of the building.

The walls were generally of cavity/brick/block construction. The corners of the tower blocks, mostly used as stairwells had vertical glazing, however, there were insulated panels under the windows, covering the ends of the floor slabs as well as the lower parts of the wall. The building is double glazed throughout, with sliding vertical louvre-drapes providing internal shading. The windows were of the "tilt and turn" type. The "tilt" provides natural ventilation, and the "turn" allows access for cleaning.

The building was designed to be open plan, but post occupation Barnardos had extensively partitioned the interior of the building. In addition a suspended ceiling had been added. Unfortunately, in some cases this fouled the tops of the windows, meaning they could only be opened slightly. There was also a suspended floor. The building, therefore, was likely to respond to heat gains as a lightweight structure, as all heavyweight structural elements had been insulated from the internal environment.

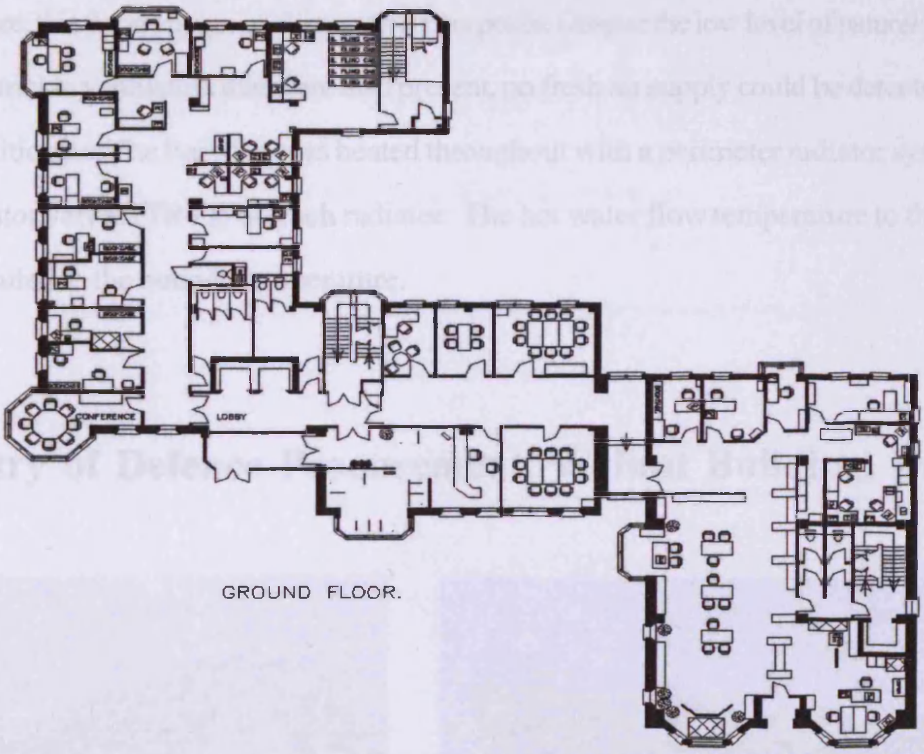
The building was fully naturally ventilated, apart from some toilet mechanical ventilation. During datalogging visits it was noted that desk fans were extensively used in hot weather. In addition, the top floor of the tower block, which was more extensively glazed, had a summer ventilation system to re-circulate air and increase air movement. This floor was given over solely to act as conference room facilities. It was also noted that occupants would open the windows slightly in winter to provide background ventilation without cold draughts.

The building was provided with a wet radiator system, with TRVs on each radiator. Each floor of the tower and link blocks constituted a separate zone and was provided with its own domestic-sized combi-boiler, which provided the domestic hot water as well as the heating. The pipework was arranged as a single-pipe system as would be appropriate for a domestic-scaled system. The boiler settings controlled the radiator flow temperature, however these were not scheduled to out-door conditions. The radiator TRVs controlling heat output to the individual rooms.

5.1.2 Morgan Bruce, Cardiff

Front View of Building

Rear View of Building



Example Floor Plan: Ground

The five storey building of approximately 3,900 m$_2$ was made up of two parts: an older section, probably dating from the 1920s or 30s, of which only the facades remain, and a newer section completed in the late 1980s. The latter consisted of a half-basement, or lower ground floor, ground floor and three upper floors. It was constructed of brick with concrete floor slabs. It was assumed that the old facades were solid brickwork whilst the new section, was known to be of a modern brick/cavity/block construction.

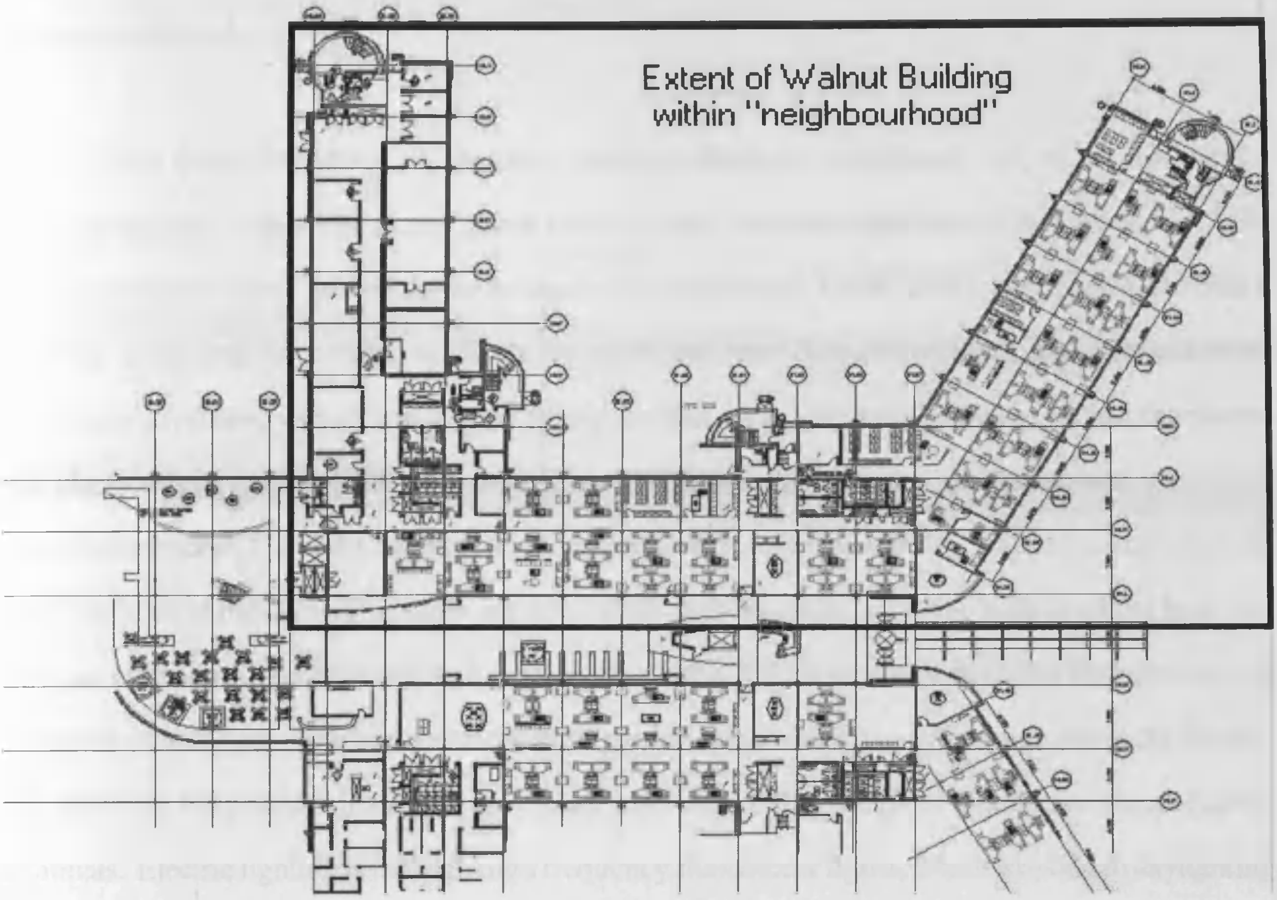
In the old block, where the original windows were retained, there was single glazing. This part had a suspended ceiling. In the new section the windows were tinted and double-glazed with internal vertical louvre drapes for shading, this area also utilising a suspended ceiling. Most of the building was naturally ventilated by means of openable windows which enabled single sided or cross ventilation in many areas. The building was generally of narrow plan, with an average distance across the floor plan of 8.2 metres. There was some mechanical ventilation to the toilet areas, though this was ignored for computer modelling purposes.

On the top floor, there were two cassette type air conditioning units, needed to control overheating in summer. Therefore, this floor was ignored for analysis purposes. Despite the low level of natural ventilation provided by some trickle ventilators that were also present, no fresh air supply could be detected to these packaged air conditioners. The building was heated throughout with a perimeter radiator system, with thermostatic radiator valves (TRVs) on each radiator. The hot water flow temperature to the radiator system was scheduled to the outside temperature.

5.1.3 Ministry of Defence Procurement, Walnut Building, Bristol

North/North East Facing Wing Section

South/South West Facing Wing Section



Example Floor Plan: Ground

The MOD building was one of Britain's most advanced green office buildings at the time of completion (1997). The building is located within the Ministry of Defence (MOD) Procurement Executive's (PE) Abbey Wood site in north Bristol. Originally conceived to fulfil the client's wish for a naturally ventilated building the final design became a hybrid solution when computer simulation indicated that excessive overheating would occur if natural ventilation alone were adopted. Whilst the displacement ventilation system eventually incorporated in the building chills or warms the air entering the offices via the floor plenum to 19°C occupants retain the freedom to temper their own environment by opening windows.

Walnut (approximately 13,100m_2), the particular building investigated, forms part of one of the "neighbourhoods" on the Abbey Wood site, and housed some 600 of the total working population of almost 6,000 people. Studying this single building was felt to be justified on the grounds that, it represented the standard office template repeated across the site and that it had been occupied the longest but most importantly that it was the most that could feasibly be achieved within the monitoring resources allowed.

Each office building on the site, such as Walnut, comprised four storeys of office accommodation, with a top storey given over to plant, services distribution and storage. A full-height atrium or "street" joined the individual office buildings. The building was constructed with a concrete frame and floor slabs, with, on the south and west facades, concrete and Portland stone cladding with relatively small windows and deep reveals, and on the north and east facades, aluminium and glass curtain walling with larger windows. There are suspended floors throughout, providing space for services. The slabs are directly exposed for 40% of their area, but air has access indirectly to all surfaces of the slab. The walls are of a "tight" construction, avoiding high levels of heat loss from air infiltration, and have insulation levels better than the then current Building Regulations. All windows are of triple-pane construction, with openable elements every 3 metres along the facade, and contain a fully adjustable inter-pane blind, providing solar and glare control for visual display terminals. Electric lighting is through high frequency fluorescent lights, which respond to daylighting levels, and can be programmed by users to meet individual requirements through remote controls.

Ceiling panels designed to improve office acoustics by reducing reverberation time are also contained in the luminaires, other services, and extract ductwork. High level services (such as cabling for electric lighting, fire alarms and the sound system) and extract ductwork are fed to the ceiling panels through the floor slab from the floor void above. While supply ventilation and desk-top services, such as communications cabling, are fed directly from the floor void of the floor served.

Initially conceived as a naturally ventilated building, Walnut was ultimately designed around a mixed mode concept following computer simulations that showed that the client's specification in terms of overheating could not be achieved by natural ventilation alone. The displacement ventilation system tempers the incoming air to 19°C, with air entering the offices via the floor plenum and leaving through a bespoke ceiling. The system could incorporate heat recovery and night time purging if required. The fenestration, which varies with orientation, is designed to limit solar gains and the consequent need for more cooling. Heating to off-set the small perimeter heat loss in winter consists of linear natural convectors, recessed into the floor void and covered by a flush floor-mounted grille under the windows.

Displacement-type ventilation is provided through floor grilles to the office areas. Cool fresh air spills from the grilles and spreads evenly over the office floor up to a maximum rate of 3.5 air changes per hour. However, the design rate stands at 2.75 air changes per hour, equivalent to 12 litres per person per second. Heat from occupants and desk-mounted electrical equipment is picked up, along with pollutants and odours, as the ventilation air warms and rises to the extract ductwork behind the ceiling panels. As the air is extracted it carries away heat from lights, reducing heat gain to the occupied space below. When the building begins to overheat the fresh air can be mechanically cooled to the 19 °C design level, effectively providing air conditioning or comfort cooling, but with the important difference that occupants can still open windows. The displacement ventilation system also provides tempered background ventilation to the office areas in winter, meaning that it should be unnecessary for occupants to open windows at these times, though this option is naturally still available. A representation showing the intended servicing strategy in the MOD building can be seen in figure 5.1 below.

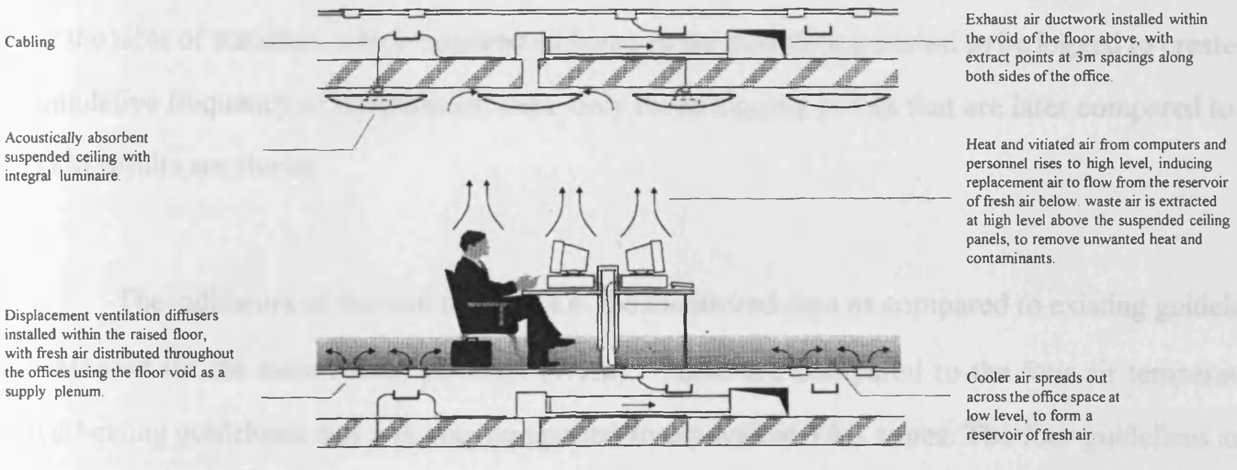


FIGURE 5.1 MOD BUILDING: PATTERN OF AIR MOVEMENT INTENDED BY THE DESIGNERS.

5.2 Physical Monitoring - Results Overview

The following results were gained from the summer logging of environmental conditions in the Case Study Buildings. As detailed in the Methodology (Section 4.5) the dates of the monitoring varied in each instance, for example the MOD building was monitored for 6 more days than the Morgan Bruce building and 18 more days than the Barnardo's building. Indeed within buildings some floors data-logging began at an earlier stage (1-3 days) than others due to restrictions on logging equipment. The Summary Tables below represent the core variables and statistics from each logging point and in so doing aim to indicate their overall environmental conditions - i.e. their rates of overheating and underheating (if any). The tables show the air temperatures (recorded at varying heights) and the 'Globe' (Resultant) temperature. For each variable, the minimum, mean and maximum values attained are shown plus the standard deviation. Some additional logger points are included on the Summary Table that are not used in the later comparison to the DTM results, this was due to the lower number of recordings found at these points due to significant logger/sensor failures i.e. logging points were removed as this lowered amount of data gathered would adversely affect the comparison agaimst operational time used as a criterion in two of the overheating guidelines. However, for the table of statistics, which required all hours in the monitoring period to be logged to create the cumulative frequency of temperature data, only those logging points that are later compared to the DTM results are shown.

The indicators of thermal comfort i.e. the monitored data as compared to existing guidelines is denoted for the main sensor position (1.1m). These are compared to the four air temperature overheating guidelines that will also be applied to equivalent TAS zones. The four guidelines are:

TUC (Trades Union Congress) - No occassions of +30°C temperatures.

USDAW (Union of Shop, Distributive and Allied Workers) - No occassions of +27°C temperatures.

PACE (Property Advisers to the Civil Estate) "Requirements of Office Buildings" - Maximum of 240 Hours per 10 years (thus 24 hours per year) to exceed 28°C.

CIBSE Guide A8 - Design risk of 2.5% or below of occupied time to exceed 27°C.

5.2.1 Physical Monitoring - Summary Tables

A) Barnardos

Summer		Logger						
	Log. ID NO.	*1*	*2*	*7*	*3*	*4*	*5*	*6*
	Floor	Ground	1st	1st (cell)	2nd	2nd (cell)	3rd	4th
Air Temperature 0.3 metres	Min	16.9	20.7		23.6			
	Mean	22.8	24.5		24.18			
	Max	29.0	31.9		24.6			
	St. Dev.	2.72	2.17		0.26			
Air Temperature 1.1 metres	Min	18.8	21.0	20.4	20.2	19.0		17.6
	Mean	23.6	25.3	24.7	25.1	24.4		24.2
	Max	31.3	33.6	28.8	30.8	32.0		32.4
	St. Dev.	2.88	2.59	1.92	2.36	2.51		3.11
Air Temperature 2.0 metres	Min	19.8	21.0					
	Mean	24.5	24.8					
	Max	32.8	33.9					
	St. Dev.	2.75	2.57					
Globe 1.1 metres	Min	18.8	21.2		20.4			
	Mean	23.8	24.9		24.7			
	Max	31.4	34.5		30.8			
	St. Dev.	2.88	2.54		2.24			

B) Morgan Bruce

Summer		Logger								
	Floor	basement	basement	ground	ground	1st	1st	2nd	2nd	3rd
	Log. ID	cell.	open	cell.	open	cell.	open	cell.	open	cell.
Air Temperature 0.3 metres	Min		18.6		20.0		20.8		22.2	
	Mean		22.4		24.6		24.4		25.8	
	Max		26.8		29.2		27.6		29.6	
	St. Dev.		1.57		1.72		1.23		1.18	
Air Temperature 1.1 metres	Min	19.0	17.8	20.0	20.6	19.6	21.6	19.4	22.6	19.8
	Mean	23.4	22.7	24.8	25.3	24.3	24.9	23.5	25.1	24.7
	Max	26.8	27.4	28.0	29.6	30.0	28.8	28.8	30.0	29.4
	St. Dev.	1.56	1.83	1.46	1.58	1.93	1.15	1.76	1.15	1.90
Air Temperature 2.0 metres	Min									
	Mean									
	Max									
	St. Dev.									
Globe 1.1 metres	Min		19.0		20.8		22.6		23.2	
	Mean		23.7		25.5		25.2		25.9	
	Max		27.2		30.0		28.8		28.4	
	St. Dev.		1.50		1.59		1.07		0.94	

C) MOD

Summer		Logger														
	Floor	Grnd	Grnd	Grnd	Grnd	1st	1st	1st	1st	2nd	2nd	2nd	2nd	2nd	3rd	3rd
	Log. ID No.	4	3	10	11	5	6	12	13	1	2	8	15	19	7	18
Air Temperature 0.3 metres	Min	17.8	18.8			19.6	18.8			19.4	18.2	19.8			20.6	
	Mean	20.7	21.1			22.1	21.8			22.9	22.3	21.6			23.0	
	Max	27.6	23.4			25.0	25.2			26.0	26.4	25.0			27.2	
	St. Dev.	1.49	0.93			0.89	1.07			1.23	1.19	1.11			1.29	
Air Temperature 1.1 metres	Min	17.8	19.2	19.6	17.4	19.8	18.8	18.0	19.0	19.4	19.4	20.0	20.2	18.8	20.8	20.6
	Mean	22.6	22.1	22.6	20.0	22.4	22.3	21.9	22.2	23.7	23.1	22.0	23.2	22.1	23.1	23.9
	Max	30.2	25.0	27.6	23.6	25.8	26.6	25.8	26.0	27.2	27.0	25.4	27.0	25.4	27.4	27.4
	St. Dev.	2.06	1.09	1.22	1.23	0.98	1.21	1.33	1.55	1.30	1.25	0.82	1.43	1.18	1.28	1.51
Air Temperature 2.0 metres	Min	18.2	19.4			19.4	18.6			19.8	19.8				20.9	
	Mean	21.9	22.2			22.4	22.4			22.9	22.8				23.2	
	Max	28.8	25.0			26.0	26.6			27.0	27.0				27.4	
	St. Dev.	1.74	1.03			0.99	1.22			1.21	1.31				1.26	
Globe 1.1 metres	Min	17.8	19.4			19.8	18.6			19.4	19.6	20.0			20.8	
	Mean	22.3	22.0			22.4	22.5			23.8	23.0	22.4			23.1	
	Max	27.8	24.6			25.8	26.8			27.2	27.2	25.8			27.2	
	St. Dev.	1.74	1.02			0.97	1.33			1.33	1.23	1.03			1.26	

D) Comparison to Existing Overheating Guidelines for Air Temperature

These tables relate to the findings of the physical monitoring of selected logging positions in the 3 Case Study buildings. The logging positions have been placed against their room number and indicate the number of hours/percentage time exceeding a given overheating guideline. Therefore their rates of overheating can be assessed against existing multiple guidelines and an indication of the environmental conditions can be gained. The floorplans (and comparative TAS zones) for each building can be found in the Appendices.

Barnardo's:

TUC No Hours >30C	**PACE** Max. of 24 Hours >28C	**USDAW** No Hours >27C	**CIBSE** **Not to Exceed** 2.5% at 27C	Room No.
3	21	35	11.11%	G8
9	26	47	14.92%	1/2
0	16	57	18.10%	1/12
5	32	55	17.46%	2/7
4	42	64	20.32%	2/11

Morgan Bruce:

TUC No Hours >30C	**PACE** Max. of 24 Hours >28C	**USDAW** No Hours >27C	**CIBSE** **Not to Exceed** 2.5% at 27C	Room No.
0	0	0	0.00%	B5
0	0	19	4.91%	G30
0	0	3	0.78%	G23
0	0	2	0.52%	F24
0	2	7	1.81%	F36
0	2	29	7.49%	S46
0	0	0	0.00%	S50

MOD:

TUC No Hours >30C	**PACE** Max. of 24 Hours >28C	**USDAW** No Hours >27C	**CIBSE** **Not to Exceed** 2.5% at 27C	*Room No.*
0	3	6	1.39%	J42c
0	0	0	0.00%	J38
0	0	0	0.00%	J31c
0	0	0	0.00%	B26f
0	0	0	0.00%	J30c
0	0	0	0.00%	H41
0	0	0	0.00%	E26f
0	0	0	0.00%	J43
0	0	0	0.00%	G26a
0	0	1	0.23%	J39a
0	0	0	0.00%	H40

The above Summary and Overheating Guidelines Tables indicate: -

A) Barnardos

Barnardos appears to suffer overheating as the Summary Table reveals that over the 7 logging positions (at desk height 1.1m) maximum temperatures were found ranging from 28.8°C to 33.6 °C. These are very high temperatures and concur with the Globe temperatures found which showed 30.8-34.5 °C being created. Therefore, high internal temperatures are allowed to exist during the working day. Such high maxima are not the only concern as mean temperatures up to 25.3°C are also seen to exist at Barnardos. The standard deviation of these temperatures from the mean is also high, for example up to 3.11 on the 4th floor. Therefore, a large swing in temperature levels can be expected during working hours - from as little as a 17.6°C minimum up to a peak of 32.4°C on the 4th floor example. The vertical temperature gradient may also prove troublesome in Barnardos as seen by the air temperatures taken at varying room heights. When looking at maximum temperatures it can be seen that a large vertical temperature gradient is formed. For example, on the Ground and 1st floor logger positions a 1.3°C and 1.7°C rise between 0.3m and 1.1m in room height is found respectively, these figures rise to 2.6°C and 2.0°C between 0.3m and 2.0m . However, whilst a large gradient this figure is still below the 3°C maximum recommended by CIBSE over a 1m rise in room height.

When assessed against current guidelines for overheating the Barnardos building's results concur with their findings from the previous summary table. Barnardos is shown to overheat by all the guideline criteria given. With all but one exception the logging points chosen exceed the 30 °C maximum demanded by the TUC. The PACE (Property Advisers to the Civil Estate) guidelines "ROB - Requirements for Office Buildings" allow a maximum of 24 hours to exceed 28°C yet 3 zones also fail this criterion. Finally, both the USDAW and CIBSE standards used 27 °C as their criteria. The USDAW guideline does not allow a room to exceed this temperature level thus every logging position is seen to fail this criteria. However, once converted to a percentage time of occupation, the CIBSE design risk allowance means that the building must not exceed 2.5% at 27°C

- here again Barnardos fails on all logging positions with a maximum of 20% of occupied time above this temperature found for logger 4 (equivalent to TAS zone 28). Therefore the Barnardos building clearly overheats to an uncomfortable level. A scant inspection of these tables would therefore indicate that the building does overheat and creates uncomfortable working conditions.

B) Morgan Bruce

Morgan Bruce appears to suffer from only mild instances of overheating as maximum temperatures of 26.8°C to 30.0°C are created across the logging positions. These maxima closely resemble those found for the Globe (resultant) temperatures found which ranged between 27.2°C and 30.0 °C. Such maxima do indicate some uncomfortable overheating in the Morgan Bruce building, though to a lesser extent than was found in Barnardos. A reasonable mean temperature is found ranging between 22.7°C and 25.3 °C. The lesser deviation from the mean as compared to Barnardos can be seen as the standard deviation in Morgan Bruce ranges between just 1.15 and 1.93. The vertical temperature rise seen between 0.3m and 1.1m is also lower than seen in the case of Barnardos. When looking at mean temperatures, rates of 0.3°C, 0.7°C, 0.5°C and -0.7°C are found. This does not suggest that too great a vertical temperature increase will be formed between the ankle height (0.3m) and desk height (1.1m) positions. These low levels are also seen when looking at maximum temperature levels created as 0.4-0.8°C increases are found between 0.3m and 1.1m, which is well below the maximum of 3.0°C specified by CIBSE in Guide A (and in ISO 7730).

That the Morgan Bruce building is more successful at limiting excessive temperatures is also seen on the Overheating Guidelines Table. No instances of over 30°C are found whereas only 2 loggers produced temperatures over 28°C. This temperature level is allowed to exist for 24 hours in the PACE - ROB guideline - no logger fails here either. Only two logging points manage to stay within the USDAW limit of 27°C. However, the short physical monitoring season spent in the building this would not adequately compare with a 'design summer' of a full 6 months (from April to September inclusive). therefore the percentage of occupied time will be a better indication of overheating. Here the CIBSE guideline indicates that just two logger positions fail this criteria as 4.9% and 7.5% of occupied hours exceed 27°C. Despite these latter failings the Morgan Bruce building shows only minor signs of overheating and no extreme (above 30.0°C) temperatures are allowed to build up. The Summary and Overheating Guideline Tables therefore indicates a reasonable environment in this naturally ventilated building, though uncomfortable air temperatures (above 27 °C) can and do occur, as seen previously in Barnardos, these are not as prevalent.

C) MOD

The maximum temperatures found by the data logging positions (at 1.1m desk-height) do not reveal any extreme overheating as maxima of only 25-27.4°C are found, though for one ground floor logging position a peak temperature of 30.2°C is created. Furthermore, low mean temperatures of 22-23.9°C are created throughout the building with the lowest standard deviation from this mean found in the three Case Study buildings. Standard deviations of only 0.98 to 1.55 are found for all but one exception (2.06 on the ground floor). It could therefore be assumed that this building does not regularly suffer from uncomfortably high temperature levels. The vertical temperature gradient in the MOD building is also the lowest found over the three Case Studies. When looking at mean temperatures these are only seen to rise by 0.1-0.8°C between 0.3m and 1.1m for all floors with the exception again being the ground floor (the ground floor shows a slightly higher rise of 1.0°C and on one of its loggers). These results are found to be very similar where the peak temperatures are used - rises between 0.2°C and 1.4°C can be seen over the full 0.3m to 2.0m heights measured for all floors except the ground. However, more noticably it can be seen that there is no discernable rise in peak temperatures between 1.1m and 2.0m (one instanc of 0.2°C is seen). These findings suggest that no uncomfortable vertical temperature gradient would be created, the levels found being well below the 3°C allowed over a 1m rise in height by guidance given in CIBSE Guide A.

The MOD building can also not be found to overheat on the Overheating Guideline Table. No instances of temperatures above 30°C or 28°C are discovered on any logging position and thus the TUC and Pace - ROB guidelines are easily passed. Only 2 logging points show any temperature above 27°C- one for 1 sole hour and the other for only 6 hours, therefore both would narrowly fail the rigid USDAW limit. However,as these durations equate to a very low 1.3% and 0.2% of occupied hours the MOD building can easily satisfy the CIBSE guideline. It can be concluded from this physically monitored data that the MOD building does not overheat to an uncomfortable degree, with some minor failings it can be seen that the MOD building provides a comfortable environment.

The conclusion that can be drawn from the comparison to the existing overheating guidelines is that one building performs very poorly, one building shows only a modest level of overheating and one building performs well. This increasing performance is in line with more complexs levels of design. Barnardos is an example of a simple, naturally ventilated building wirth poor design features as a large degree of overheating is seen. Morgan Bruce is a more detailed design for a naturally ventilated building (e.g. incorporating larger, open plan areas) and shows a modest level of overheating. The MOD building is an innovative design using mixed mode ventilation and has acceptable conditions as little overheating is seen. The proposed DTM modelling should therefore be able to detect these differences.

6.0 Results: Comparison of Physical Monitoring and Thermal Model Prediction Results

6.1 Overview of Table Data: DTM Simulation and Physically Monitored Data.

The following results were gained from the summer logging of environmental conditions in the Case Study Buildings. These results found are placed against the dynamic thermal model predictions made for each of the 10 alternate runs made after the "Basic" model was created i.e. changes made to create the Simplistic, Complex and Sophisticted models plus their own variations. As this data will be used to give an overview of environmental conditions within the buildings and is specifically aimed at helping deduce the level of overheating found, it has been pared so that only the working hours of the building remain. As detailed in the Methodology (Section 5.4) only working, weekday hours from 9am to 5pm have been compiled, however, the dates of the monitoring varied in each Case Study Building. The recorded data was collected over the following dates - Barnardos = 12/08 to 30/09, Morgan Bruce = 01/08 to 30/09, MOD = 24/08 to 30/09 inclusive.

The tables below represent the main variables recorded for each logging point which is to be used for comparison against the DTM predicted results - i.e.the **air** temperature recorded at a 1.1m (desk level) height. The dry resultant temperatures and comparisons to physically monitored Globe temperatures are presented in separate tables. The air temperature tables attempt to relate the core elements of the physical monitoring of the 3 Case Study buildings as compared to the DTM predictions i.e. for each logger and its comparable TAS zone for each model run, the mean and maximum values attained are shown plus the standard deviation. However, these values alone will only give an indication as to the overall environmental conditions in each building. Therefore the tables also show the results of the physically monitored logging points against their comparative TAS zone for 4 existing overheating guidelines figures. The DTM simulated results are from all the alternate runs, increasing in complexity from left to right. The four guideline figures chosen represent values taken for pure air temperature, the criteria most easily gained from a building in use. Of these guidelines, three were created with actual operating conditions in mind plus a CIBSE derived guideline (from Guide A8) that was developed for intended use during the design stage. The existing guidelines range from highly simplistic figures of no occurrences to be allowed past "X °C" (30°C for the TUC and 27°C for USDAW), to those guidelines allowing an element of design risk (e.g. the Property Advisers to the Civil estate allow 24 hours per annum to exceed 28°C) and finally to the CIBSE guideline that also incorporates an assessment of the operational hours of the building rather than merely giving a rigid design risk figure (2.5% of occupied hours allowed to exceed 27°C). Floorplans detailing the equivalent TAS zones and data-logging positions can be found in the Appendices (in Sections A1.1 - A1.3)

Ground Floor - TAS ZONE 4

Summer	TAS RUN	Logger	Basic	Cardiff Weatherfile	Zone Per Room	Simplistic	Lighting Algorithm	Window Op. Algorithm	Blinds Used	Complex	Reduced Occ. Gain	Reduced Equip Gain	Sophisticated
Air Temperature 1.1 metres	Max	30.8	29.2	26.9	29.2	27.1	25.5	27.5	27.1	26.0	25.8	25.3	25.0
	Mean	18.9	21.2	20.6	21.3	20.7	20.1	23.1	20.6	22.9	22.7	20.0	21.9
	St. Dev. σ	2.80	2.61	1.71	2.65	1.79	1.50	1.13	1.76	0.85	0.86	1.43	0.88
TUC	0 Hrs >30°c	3	0	0	0	0	0	0	0	0	0	0	0
PACE	<24 Hrs >28°c	21	0	0	8	0	0	0	0	0	0	0	0
USDAW	0 Hrs >27°c	35	14	0	17	1	0	4	1	0	0	0	0
CIBSE (A8)	<2.5% Time >27°c	11.11%	4.44%	0.00%	5.40%	0.32%	0.00%	1.27%	0.32%	0.00%	0.00%	0.00%	0.00%

First Floor - TAS ZONE 17

Summer	TAS RUN	Logger	Basic	Cardiff Weatherfile	Zone Per Room	Simplistic	Lighting Algorithm	Window Op. Algorithm	Blinds Used	Complex	Reduced Occ. Gain	Reduced Equip Gain	Sophisticated
Air Temperature 1.1 metres	Max	33.1	29.1	26.2	28.0	26.7	25.5	27.4	26.4	25.9	25.8	25.3	24.5
	Mean	21.1	21.1	20.5	20.8	20.3	20.0	22.0	20.3	22.2	22.1	19.9	21.7
	St. Dev. σ	2.42	2.61	1.68	2.48	1.67	1.46	1.12	1.63	0.77	0.79	1.42	0.69
TUC	0 Hrs >30°c	9	0	0	0	0	0	0	0	0	0	0	0
PACE	<24 Hrs >28°c	26	14	0	1	0	0	0	0	0	0	0	0
USDAW	0 Hrs >27°c	47	16	0	11	0	0	1	0	0	0	0	0
CIBSE (A8)	<2.5% Time >27°c	14.92%	5.08%	0.00%	3.49%	0.00%	0.00%	0.32%	0.00%	0.00%	0.00%	0.00%	0.00%

First Floor - TAS ZONE 8

Summer	TAS RUN	Logger	Basic	Cardiff Weatherfile	Zone Per Room	Simplistic	Lighting Algorithm	Window Op. Algorithm	Blinds Used	Complex	Reduced Occ. Gain	Reduced Equip Gain	Sophisticated
Air Temperature 1.1 metres	Max	28.8	27.8	25.1	28.6	27.2	25.4	29.1	27.1	25.9	25.7	24.7	25.0
	Mean	20.8	20.4	20.1	23.0	22.0	20.8	24.8	22.0	23.5	23.2	20.5	22.2
	St. Dev. σ	1.89	2.20	1.47	2.18	1.76	1.42	1.24	1.76	1.03	1.05	1.31	1.09
TUC	0 Hrs >30°c	0	0	0	0	0	0	0	0	0	0	0	0
PACE	<24 Hrs >28°c	16	0	0	6	0	0	1	0	0	0	0	0
USDAW	0 Hrs >27°c	57	3	0	17	1	0	10	1	0	0	0	0
CIBSE (A8)	<2.5% Time >27°c	18.10%	0.95%	0.00%	5.40%	0.32%	0.00%	3.17%	0.32%	0.00%	0.00%	0.00%	0.00%

Second Floor - TAS ZONE 19

Summer Air Temperature	TAS RUN	Logger	Basic	Cardiff Weatherfile	Zone Per Room	Simplistic	Lighting Algorithm	Window Op. Algorithm	Blinds Used	Complex	Reduced Occ. Gain	Reduced Equip Gain	Sophisticated
1.1 metres	Max	32.0	27.8	24.9	29.6	28.0	26.5	28.7	28.0	27.1	26.8	25.9	26.0
	Mean	20.0	20.4	20.0	23.1	22.2	21.2	25.4	22.2	24.5	24.1	20.8	23.0
	St. Dev. σ	2.46	2.20	1.47	2.47	1.94	1.66	1.36	1.94	1.16	1.17	1.54	1.25
TUC	0 Hrs >30°c	5	0	0	0	0	0	0	0	0	0	0	0
PACE	<24 Hrs >28°c	32	0	0	12	0	0	6	0	0	0	0	0
USDAW	0 Hrs >27°c	55	19	0	29	3	0	30	3	2	0	0	0
CIBSE (A8)	<2.5% Time >27°c	17.46%	0.95%	0.00%	9.21%	0.95%	0.00%	9.52%	0.95%	0.63%	0.00%	0.00%	0.00%

Second Floor - TAS ZONE 28

Summer Air Temperature	TAS RUN	Logger	Basic	Cardiff Weatherfile	Zone Per Room	Simplistic	Lighting Algorithm	Window Op. Algorithm	Blinds Used	Complex	Reduced Occ. Gain	Reduced Equip Gain	Sophisticated
1.1 metres	Max	30.0	29.4	26.2	30.3	28.9	25.7	30.9	28.9	26.9	26.4	24.9	25.3
	Mean	17.8	21.2	20.5	24.4	23.5	21.8	26.5	23.5	24.4	24.1	21.3	23.0
	St. Dev. σ	2.43	2.65	1.69	2.20	2.18	1.75	1.59	2.16	1.40	1.41	1.57	1.44
TUC	0 Hrs >30°c	4	0	0	2	0	0	3	0	0	0	0	0
PACE	<24 Hrs >28°c	42	0	0	23	3	0	31	2	0	0	0	0
USDAW	0 Hrs >27°c	64	3	0	46	12	0	62	10	0	0	0	0
CIBSE (A8)	<2.5% Time >27°c	20.32%	6.03%	0.00%	14.60%	3.81%	0.00%	19.68%	3.17%	0.00%	0.00%	0.00%	0.00%

Ground Floor - TAS ZONE 4

Summer Air Temperature 1.1 metres	TAS RUN	**Logger**	**Basic**	Cardiff Weatherfile	Zone Per Room	**Simplistic**	Lighting Algorithm	Window Op. Algorithm	Blinds Used	**Complex**	Reduced Occ. Gain	Reduced Equip Gain	**Sophisticated**
	Max	30.8	29.2	26.9	29.2	27.1	25.5	27.5	27.1	26.0	25.8	25.3	25.0
	Mean	18.9	21.2	20.6	21.3	20.7	20.1	23.1	20.6	22.9	22.7	20.0	21.9
	St. Dev. σ	2.80	2.61	1.71	2.65	1.79	1.50	1.13	1.76	0.85	0.86	1.43	0.88
TUC	0 Hrs >30°c	3	0	0	0	0	0	0	0	0	0	0	0
PACE	<24Hrs >28°c	21	0	0	8	0	0	0	0	0	0	0	0
USDAW	0 Hrs >27°c	35	14	0	17	1	0	4	1	0	0	0	0
CIBSE (A8)	<2.5% Time >27°c	11.11%	4.44%	0.00%	5.40%	0.32%	0.00%	1.27%	0.32%	0.00%	0.00%	0.00%	0.00%

First Floor - TAS ZONE 17

Summer Air Temperature 1.1 metres	TAS RUN	**Logger**	**Basic**	Cardiff Weatherfile	Zone Per Room	**Simplistic**	Lighting Algorithm	Window Op. Algorithm	Blinds Used	**Complex**	Reduced Occ. Gain	Reduced Equip Gain	**Sophisticated**
	Max	33.1	29.1	26.2	28.0	26.7	25.5	27.4	26.4	25.9	25.8	25.3	24.5
	Mean	21.1	21.1	20.5	20.8	20.3	20.0	22.0	20.3	22.2	22.1	19.9	21.7
	St. Dev. σ	2.42	2.61	1.68	2.48	1.67	1.46	1.12	1.63	0.77	0.79	1.42	0.69
TUC	0 Hrs >30°c	9	0	0	0	0	0	0	0	0	0	0	0
PACE	<24Hrs >28°c	26	14	0	1	0	0	0	0	0	0	0	0
USDAW	0 Hrs >27°c	47	16	0	11	0	0	1	0	0	0	0	0
CIBSE (A8)	<2.5% Time >27°c	14.92%	5.08%	0.00%	3.49%	0.00%	0.00%	0.32%	0.00%	0.00%	0.00%	0.00%	0.00%

First Floor - TAS ZONE 8

Summer Air Temperature 1.1 metres	TAS RUN	**Logger**	**Basic**	Cardiff Weatherfile	Zone Per Room	**Simplistic**	Lighting Algorithm	Window Op. Algorithm	Blinds Used	**Complex**	Reduced Occ. Gain	Reduced Equip Gain	**Sophisticated**
	Max	28.8	27.8	25.1	28.6	27.2	25.4	29.1	27.1	25.9	25.7	24.7	25.0
	Mean	20.8	20.4	20.1	23.0	22.0	20.8	24.8	22.0	23.5	23.2	20.5	22.2
	St. Dev. σ	1.89	2.20	1.47	2.18	1.76	1.42	1.24	1.76	1.03	1.05	1.31	1.09
TUC	0 Hrs >30°c	0	0	0	0	0	0	0	0	0	0	0	0
PACE	<24Hrs >28°c	16	0	0	6	0	0	1	0	0	0	0	0
USDAW	0 Hrs >27°c	57	3	0	17	1	0	10	1	0	0	0	0
CIBSE (A8)	<2.5% Time >27°c	18.10%	0.95%	0.00%	5.40%	0.32%	0.00%	3.17%	0.32%	0.00%	0.00%	0.00%	0.00%

Summer	First Floor - TAS ZONE 24												
Air Temperature	TAS RUN	**Logger**	**Basic**	Cardiff Weatherfile	Zone Per Room	**Simplistic**	Lighting Algorithm	Window Op. Algorithm	Blinds Used	**Complex**	Reduced Occ. Gain	Reduced Equip Gain	**Sophisticated**
1.1 metres	Max	27.0	28.6	25.9	29.4	27.6	26.0	28.8	27.0	26.2	25.8	25.7	25.2
	Mean	23.9	21.2	20.5	24.0	22.8	21.7	23.3	22.5	22.6	22.4	22.4	22.2
	St. Dev. σ	1.18	2.45	1.54	2.48	1.81	1.57	1.58	1.74	1.23	1.13	1.08	0.93
TUC	0 Hrs >30°c	0	0	0	0	0	0	0	0	0	0	0	0
PACE	<24 Hrs >28°c	0	3	0	37	0	0	2	0	0	0	0	0
USDAW	0 Hrs >27°c	2	11	0	61	5	0	7	0	0	0	0	0
CIBSE (A8)	<2.5% Time >27°c	0.52%	2.84%	0.00%	15.76%	1.29%	0.00%	1.81%	0.00%	0.00%	0.00%	0.00%	0.00%

Summer	First Floor - TAS ZONE 36												
Air Temperature	TAS RUN	**Logger**	**Basic**	Cardiff Weatherfile	Zone Per Room	**Simplistic**	Lighting Algorithm	Window Op. Algorithm	Blinds Used	**Complex**	Reduced Occ. Gain	Reduced Equip Gain	**Sophisticated**
1.1 metres	Max	28.3	28.4	25.5	27.5	25.7	25.1	28.9	25.5	26.1	25.3	24.9	24.7
	Mean	22.8	21.1	20.4	20.8	19.9	19.7	20.0	19.8	19.8	19.8	19.9	19.9
	St. Dev. σ	2.25	2.36	1.59	2.38	1.57	1.49	1.69	1.53	1.52	1.47	1.45	1.38
TUC	0 Hrs >30°c	0	0	0	0	0	0	0	0	0	0	0	0
PACE	<24 Hrs >28°c	2	3	0	0	0	0	1	0	0	0	0	0
USDAW	0 Hrs >27°c	7	11	0	3	0	0	2	0	0	0	0	0
CIBSE (A8)	<2.5% Time >27°c	1.81%	2.84%	0.00%	0.78%	0.00%	0.00%	0.52%	0.00%	0.00%	0.00%	0.00%	0.00%

Second Floor - TAS ZONE 46

Summer	TAS RUN	**Logger**	**Basic**	Cardiff Weatherfile	Zone Per Room	**Simplistic**	Lighting Algorithm	Window Op. Algorithm	Blinds Used	**Complex**	Reduced Occ. Gain	Reduced Equip Gain	**Sophisticated**
Air Temperature 1.1 metres	Max	28.2	28.4	25.5	31.2	29.0	26.9	31.1	28.6	27.3	26.6	26.3	25.7
	Mean	25.5	21.1	20.4	24.3	22.4	21.2	23.0	22.3	22.1	22.0	21.9	21.7
	St. Dev. σ	1.01	2.36	1.59	2.89	2.37	1.90	2.00	2.32	1.33	1.15	1.07	0.88
TUC	0 Hrs >30°c	0	0	0	17	0	0	1	0	0	0	0	0
PACE	<24 Hrs >28°c	2	2	0	51	6	0	9	5	0	0	0	0
USDAW	0 Hrs >27°c	29	6	0	78	10	0	13	9	2	0	0	0
CIBSE (A8)	<2.5% Time >27°c	7.49%	1.55%	0.00%	20.16%	2.58%	0.00%	3.36%	2.33%	0.52%	0.00%	0.00%	0.00%

Second Floor - TAS ZONE 50

Summer	TAS RUN	**Logger**	**Basic**	Cardiff Weatherfile	Zone Per Room	**Simplistic**	Lighting Algorithm	Window Op. Algorithm	Blinds Used	**Complex**	Reduced Occ. Gain	Reduced Equip Gain	**Sophisticated**
Air Temperature 1.1 metres	Max	26.5	28.4	25.5	30.2	28.7	26.1	29.3	27.8	26.7	25.9	25.6	25.1
	Mean	22.9	21.1	20.4	24.4	23.1	21.8	23.6	22.9	22.8	22.6	22.5	22.2
	St. Dev. σ	1.39	2.36	1.59	2.39	1.93	1.63	1.73	1.87	1.35	1.23	1.17	1.00
TUC	0 Hrs >30°c	0	0	0	2	0	0	0	0	0	0	0	0
PACE	<24 Hrs >28°c	0	2	0	42	2	0	4	0	0	0	0	0
USDAW	0 Hrs >27°c	0	6	0	65	9	0	12	6	0	0	0	0
CIBSE (A8)	<2.5% Time >27°c	0.00%	1.55%	0.00%	16.80%	2.33%	0.00%	3.10%	1.55%	0.00%	0.00%	0.00%	0.00%

Summer	Ground Floor - TAS ZONE 4											
Air Temperature	TAS RUN	Logger	Basic	Bristol Weatherfile	Zone Per Room	Simplistic	Lighting Algorithm	Window Op. Algorithm	Blinds Used	Complex	Reduced Occ. Gain	Reduced Equip Gain	Sophisticated
1.1 metres	Max	29.4	30.4	30.0	29.5	30.1	30.1	30.2	29.4	27.5	25.4	24.5	23.6
	Mean	22.6	22.9	21.3	23.0	21.6	21.6	23.0	21.5	22.3	20.4	20.2	19.8
	St. Dev. σ	2.09	2.73	2.69	2.52	2.73	2.72	2.02	2.64	1.55	1.59	1.45	1.33
TUC	0 Hrs >30°c	0	2	1	0	1	1	1	0	0	0	0	0
PACE	<24 Hrs >28°c	3	21	3	14	4	4	6	3	0	0	0	0
USDAW	0 Hrs >27°c	6	38	11	31	22	21	37	14	3	0	0	0
CIBSE (A8)	<2.5% Time >27°c	1.39%	8.80%	2.55%	7.18%	5.09%	4.86%	8.56%	3.24%	0.69%	0.00%	0.00%	0.00%

Summer	Ground Floor - TAS ZONE 12											
Air Temperature	TAS RUN	Logger	Basic	Bristol Weatherfile	Zone Per Room	Simplistic	Lighting Algorithm	Window Op. Algorithm	Blinds Used	Complex	Reduced Occ. Gain	Reduced Equip Gain	Sophisticated
1.1 metres	Max	25.5	30.4	30.0	26.8	26.2	26.2	26.5	25.3	24.5	24.1	24.0	23.5
	Mean	22.0	22.9	21.3	21.4	21.2	21.2	22.4	20.6	20.9	20.8	20.6	20.3
	St. Dev. σ	0.96	2.73	2.69	1.93	1.54	1.54	1.32	1.36	1.07	1.03	0.94	0.90
TUC	0 Hrs >30°c	0	2	1	0	0	0	0	0	0	0	0	0
PACE	<24 Hrs >28°c	0	21	3	0	0	0	0	0	0	0	0	0
USDAW	0 Hrs >27°c	0	38	11	0	0	0	0	0	0	0	0	0
CIBSE (A8)	<2.5% Time >27°c	0.00%	8.80%	2.55%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

Summer	Ground Floor - TAS ZONE 16											
Air Temperature	TAS RUN	Logger	Basic	Bristol Weatherfile	Zone Per Room	Simplistic	Lighting Algorithm	Window Op. Algorithm	Blinds Used	Complex	Reduced Occ. Gain	Reduced Equip Gain	Sophisticated
1.1 metres	Max	25.0	29.4	28.9	29.1	28.1	28.0	28.3	27.8	26.5	25.5	24.5	23.3
	Mean	22.1	25.1	23.2	23.9	23.1	23.0	23.8	22.8	21.6	21.1	20.5	19.9
	St. Dev. σ	1.07	2.03	2.26	2.69	2.66	2.69	2.71	2.73	2.39	2.14	1.82	1.56
TUC	0 Hrs >30°c	0	0	0	0	0	0	0	0	0	0	0	0
PACE	<24 Hrs >28°c	0	31	5	27	1	1	8	0	0	0	0	0
USDAW	0 Hrs >27°c	0	86	15	62	29	28	71	22	0	0	0	0
CIBSE (A8)	<2.5% Time >27°c	0.00%	19.91%	3.47%	14.35%	6.71%	6.48%	16.44%	5.09%	0.00%	0.00%	0.00%	0.00%

Summer	**First Floor - TAS ZONE 25**												
Air Temperature 1.1 metres	TAS RUN	**Logger**	**Basic**	Bristol Weatherfile	Zone Per Room	**Simplistic**	Lighting Algorithm	Window Op. Algorithm	Blinds Used	**Complex**	Reduced Occ. Gain	Reduced Equip Gain	**Sophisticated**
	Max	25.6	31.2	30.5	29.7	28.6	28.6	29.2	28.0	26.7	25.8	24.9	23.8
	Mean	22.5	22.9	21.2	22.9	22.2	22.2	23.7	21.8	21.9	21.5	21.2	20.6
	St. Dev. σ	1.09	2.85	2.78	2.09	1.94	1.94	1.48	1.88	1.41	1.31	1.15	1.01
TUC	0 Hrs >30°c	0	3	1	0	0	0	0	0	0	0	0	0
PACE	<24 Hrs >28°c	0	24	6	4	3	3	8	0	0	0	0	0
USDAW	0 Hrs >27°c	0	39	17	13	11	11	26	5	0	0	0	0
CIBSE (A8)	<2.5% Time >27°c	0.00%	9.03%	3.94%	3.01%	2.55%	2.55%	6.02%	1.16%	0.00%	0.00%	0.00%	0.00%

Summer	**First Floor - TAS ZONE 17**												
Air Temperature 1.1 metres	TAS RUN	**Logger**	**Basic**	Bristol Weatherfile	Zone Per Room	**Simplistic**	Lighting Algorithm	Window Op. Algorithm	Blinds Used	**Complex**	Reduced Occ. Gain	Reduced Equip Gain	**Sophisticated**
	Max	25.5	30.2	30.1	29.2	28.8	28.7	29.0	28.0	26.8	25.9	25.0	24.0
	Mean	22.4	23.1	21.5	22.2	21.7	21.6	22.8	21.2	21.4	21.1	20.8	20.3
	St. Dev. σ	0.97	2.80	2.81	2.03	2.03	2.01	1.69	1.90	1.49	1.39	1.26	1.12
TUC	0 Hrs >30°c	0	2	1	0	0	0	0	0	0	0	0	0
PACE	<24 Hrs >28°c	0	26	7	4	3	3	7	1	0	0	0	0
USDAW	0 Hrs >27°c	0	46	21	10	8	7	17	4	0	0	0	0
CIBSE (A8)	<2.5% Time >27°c	0.00%	10.65%	4.86%	2.31%	1.85%	1.62%	3.94%	0.93%	0.00%	0.00%	0.00%	0.00%

Summer	**First Floor - TAS ZONE 5**												
Air Temperature 1.1 metres	TAS RUN	**Logger**	**Basic**	Bristol Weatherfile	Zone Per Room	**Simplistic**	Lighting Algorithm	Window Op. Algorithm	Blinds Used	**Complex**	Reduced Occ. Gain	Reduced Equip Gain	**Sophisticated**
	Max	25.8	31.1	30.6	29.4	28.6	28.6	29.0	28.0	26.9	26.0	25.1	24.0
	Mean	22.9	23.2	21.5	22.2	21.9	21.8	23.2	21.3	21.7	21.5	21.2	20.7
	St. Dev. σ	1.32	2.86	2.81	2.11	2.01	2.00	1.49	1.90	1.35	1.25	1.11	0.96
TUC	0 Hrs >30°c	0	6	1	0	0	0		0	0	0	0	0
PACE	<24 Hrs >28°c	0	30	7	4	3	3	8	0	0	0	0	0
USDAW	0 Hrs >27°c	0	51	22	10	10	10	19	4	0	0	0	0
CIBSE (A8)	<2.5% Time >27°c	0.00%	11.81%	5.09%	2.31%	2.31%	2.31%	4.40%	0.93%	0.00%	0.00%	0.00%	0.00%

First Floor - TAS ZONE 33

Summer Air Temperature 1.1 metres	TAS RUN	Logger	Basic	Bristol Weatherfile	Zone Per Room	Simplistic	Lighting Algorithm	Window Op. Algorithm	Blinds Used	Complex	Reduced Occ. Gain	Reduced Equip Gain	Sophisticated
	Max	26.1	31.2	30.5	31.5	30.8	30.8	31.7	28.5	27.6	27.4	27.1	25.8
	Mean	22.3	22.9	21.2	22.3	22.7	22.7	24.1	21.7	22.1	22.0	21.7	21.4
	St. Dev. σ	1.16	2.85	2.78	2.44	2.15	2.15	1.95	1.76	1.39	1.31	1.20	1.09
TUC	0 Hrs >30°c	0	3	1	3	2	2	5	0	0	0	0	0
PACE	<24 Hrs >28°c	0	24	6	10	6	6	14	2	0	0	0	0
USDAW	0 Hrs >27°c	0	39	17	16	14	14	32	5	3	1	1	0
CIBSE (A8)	<2.5% Time >27°c	0.00%	9.03%	3.94%	3.70%	3.24%	3.24%	7.41%	1.16%	0.69%	0.23%	0.23%	0.00%

Second Floor - TAS ZONE 6

Summer Air Temperature 1.1 metres	TAS RUN	Logger	Basic	Bristol Weatherfile	Zone Per Room	Simplistic	Lighting Algorithm	Window Op. Algorithm	Blinds Used	Complex	Reduced Occ. Gain	Reduced Equip Gain	Sophisticated
	Max	26.7	31.2	30.6	29.6	28.7	28.7	29.1	28.1	27.0	26.1	25.2	24.1
	Mean	23.2	23.3	21.6	22.5	22.1	22.1	23.5	21.6	22.0	21.7	21.5	21.0
	St. Dev. σ	1.26	2.86	2.80	2.14	2.04	2.03	1.47	1.91	1.30	1.19	1.05	0.90
TUC	0 Hrs >30°c	0	6	1	0	0	0	0	0	0	0	0	0
PACE	<24 Hrs >28°c	0	30	7	6	3	3	9	2	0	0	0	0
USDAW	0 Hrs >27°c	0	52	23	12	10	10	20	6	0	0	0	0
CIBSE (A8)	<2.5% Time >27°c	0.00%	12.04%	5.32%	2.78%	2.31%	2.31%	4.63%	1.39%	0.00%	0.00%	0.00%	0.00%

Second Floor - TAS ZONE 34

Summer Air Temperature 1.1 metres	TAS RUN	Logger	Basic	Bristol Weatherfile	Zone Per Room	Simplistic	Lighting Algorithm	Window Op. Algorithm	Blinds Used	Complex	Reduced Occ. Gain	Reduced Equip Gain	Sophisticated
	Max	26.9	31.4	30.2	32.0	30.9	30.9	31.9	28.6	27.9	27.6	27.3	25.7
	Mean	23.0	23.1	21.3	22.6	22.8	22.8	24.3	21.9	22.3	22.2	21.9	21.6
	St. Dev. σ	1.37	2.86	2.80	2.51	2.26	2.26	1.80	1.89	1.25	1.20	1.12	0.99
TUC	0 Hrs >30°c	0	6	1	3	2	2	4	0	0	0	0	0
PACE	<24 Hrs >28°c	0	26	6	15	7	7	14	2	0	0	0	0
USDAW	0 Hrs >27°c	0	45	15	24	18	18	28	5	3	2	1	0
CIBSE (A8)	<2.5% Time >27°c	0.00%	10.42%	3.47%	5.56%	4.17%	4.17%	6.48%	1.16%	0.69%	0.46%	0.23%	0.00%

Summer	Third Floor - TAS ZONE 7												
Air Temperature	TAS RUN	**Logger**	**Basic**	Bristol Weatherfile	Zone Per Room	**Simplistic**	Lighting Algorithm	Window Op. Algorithm	Blinds Used	**Complex**	Reduced Occ. Gain	Reduced Equip Gain	**Sophisticated**
1.1 metres	Max	26.2	31.2	30.4	29.5	28.6	28.5	28.9	27.9	26.8	26.0	25.1	23.9
	Mean	24.1	23.2	21.5	22.4	21.9	21.8	23.1	21.4	21.8	21.5	21.3	20.8
	St. Dev. σ	0.97	2.86	2.75	2.15	2.01	2.00	1.52	1.90	1.38	1.28	1.14	0.99
TUC	0 Hrs >30°c	0	5	1	0	0	0	0	0	0	0	0	0
PACE	<24 Hrs >28°c	0	29	6	6	3	3	6	0	0	0	0	0
USDAW	0 Hrs >27°c	0	46	20	12	9	9	20	4	0	0	0	0
CIBSE (A8)	<2.5% Time >27°c	0.00%	10.65%	4.63%	2.78%	2.08%	2.08%	4.63%	0.93%	0.00%	0.00%	0.00%	0.00%

Summer	Third Floor - TAS ZONE 11												
Air Temperature	TAS RUN	**Logger**	**Basic**	Bristol Weatherfile	Zone Per Room	**Simplistic**	Lighting Algorithm	Window Op. Algorithm	Blinds Used	**Complex**	Reduced Occ. Gain	Reduced Equip Gain	**Sophisticated**
1.1 metres	Max	27.0	31.2	30.4	27.5	26.5	26.5	27.1	26.0	24.9	23.7	24.8	23.2
	Mean	23.3	23.2	21.5	21.8	21.5	21.5	22.5	20.9	20.7	20.4	20.7	20.3
	St. Dev. σ	1.03	2.86	2.75	1.97	1.45	1.44	1.31	1.24	1.05	0.85	1.08	0.83
TUC	0 Hrs >30°c	0	5	1	0	0	0	0	0	0	0	0	0
PACE	<24 Hrs >28°c	0	29	6	0	0	0	0	0	0	0	0	0
USDAW	0 Hrs >27°c	1	46	20	2	0	0	1	0	0	0	0	0
CIBSE (A8)	<2.5% Time >27°c	0.23%	10.65%	4.63%	0.46%	0.00%	0.00%	0.23%	0.00%	0.00%	0.00%	0.00%	0.00%

6.2 Overheating Tables: DTM Simulation Results for Resultant Temperature Guideline Figures

These tables show the results of the DTM simulated results for the 3 Case Study Buildings so that it can be assessed against the BRECSU guidleine used, taken from General Report 30 "A Performance Specification for the Office of the Future". The BRECSU guideline was developed for use at the design stage and incorporates both an element of design risk and an assessment of the operational hours of the building. Furthermore, this can be seen as an improvement on the CIBSE (Section A8) guideline used previously as it employs a two-fold criteria, i.e. a percentage time of operation not be exceeded for both 25°C and 28°C dry resultant (5% and 1% respectively). Therefore, as the best available overheating guideline in the UK, it will beneficial in analysing the DTM predicted results, given that these would be available at the design stage, for which the BRECSU guideline was developed. Once again, the DTM simulated results are from all the alternate runs, increasing in complexity from left to right.

This guideline uses the dry resultant air temperature. The thermal comfort index, or dry resultant temperature, is a standard index used to show the level of comfort within the occupied space and is a function of air temperature, air velocity and mean radiant temperature. The formula for dry resultant temperature is defined in Volume A of the CIBSE Guide as:

Tres = (Trad + Tair * (10*vel) ** 0.5) /(1+ (10* vel) ** 0.5)

Where 'Tres' is the resultant temperature; 'Trad' is the mean radiant temperature; 'Tair' the air temperature and 'vel' the air velocity.

This dry resultant will be compared against the globe temperature data recorded by the physical monitoring, however due to the limited nature of the physical modelling this has meant that fewer data-logging positions had globe temperatures available for analysis than had pure air temperature. The Globe temperature is a suitable comparison to be gauged against the DTM predicted resultant temperatures as for still, indoor air (from Parsons[1]) CIBSE state "The recommended values (for environmental comfort) are given in terms of resultant temperature which is the temperature recorded by a thermometer at the centre of a blackened globe 100mm in diameter". Although it must be assumed that the air velocities in the Case Study buildings are still, as these have not been recorded, the recorded globe temperatures are therefore able to be compared to the DTM predicted resultant temperatures.

BRECSU Rep. 30 "Office of Future - Performance Specification" Allowance = Maximum of 5% HOURS ABOVE 25°C DRY RESULTANT

TAS	Logger	Basic	Basic	Basic	Simplistic	Simplistic	Simplistic	Simplistic	Complex	Complex	Complex	Sophisticated
ZONE			Cardiff	Zone per Room		Lighting Alg.	Window Op. Alg.	Blinds Used		Less Occ. Gain	Less Equip Gain	
4	22.22%	12.38%	1.27%	14.92%	2.54%	0.95%	12.38%	1.59%	1.59%	1.27%	0.63%	0.32%
17	34.60%	13.02%	1.27%	13.02%	2.22%	0.32%	4.13%	1.59%	0.95%	0.95%	0.00%	0.00%
28	33.33%	5.40%	0.00%	33.33%	32.70%	0.00%	69.84%	28.25%	20.00%	9.84%	0.00%	0.00%

BRECSU Rep. 30 "Office of Future - Performance Specification" **Allowance = Maximum of 1% HOURS ABOVE 28°C DRY RESULTANT**

TAS	Logger	Basic	Basic	Basic	Simplistic	Simplistic	Simplistic	Simplistic	Complex	Complex	Complex	Sophisticated
ZONE			Cardiff	Zone per Room		Lighting Alg.	Window Op. Alg.	Blinds Used		Less Occ. Gain	Less Equip Gain	
4	5.40%	4.13%	0.00%	6.98%	0.63%	0.00%	1.27%	0.32%	0.00%	0.00%	0.00%	0.00%
17	9.84%	4.44%	0.00%	4.44%	0.00%	0.00%	0.63%	0.00%	0.00%	0.00%	0.00%	0.00%
28	12.38%	0.00%	0.00%	13.33%	1.59%	0.00%	30.48%	0.63%	0.00%	0.00%	0.00%	0.00%

6.2.2 Morgan Bruce: BRECSU Overheating Table

BRECSU Rep. 30 "Office of Future - Performance Specification" **Allowance = Maximum of 5% HOURS ABOVE 25°C DRY RESULTANT**

TAS	Logger	Basic	Basic	Basic	Simplistic	Simplistic	Simplistic	Simplistic	Complex	Complex	Complex	Sophisticated
ZONE			Cardiff	Zone per Room		Lighting Alg.	Window Op. Alg.	Blinds Used		Less Occ. Gain	Less Equip Gain	
5	4.91%	12.14%	0.78%	15.25%	1.03%	0.00%	1.55%	0.00%	0.00%	0.00%	0.00%	0.00%
30	17.83%	16.02%	1.29%	26.61%	5.68%	0.00%	7.49%	1.55%	0.00%	0.00%	0.00%	0.00%
24	6.72%	14.47%	0.78%	31.27%	4.39%	0.00%	5.68%	1.29%	0.00%	0.00%	0.00%	0.00%
46	27.65%	15.25%	1.03%	39.28%	14.99%	1.29%	17.05%	6.98%	1.55%	0.78%	0.52%	0.00%

BRECSU Rep. 30 "Office of Future - Performance Specification" **Allowance = Maximum of 1% HOURS ABOVE 28°C DRY RESULTANT**

TAS	Logger	Basic	Basic	Basic	Simplistic	Simplistic	Simplistic	Simplistic	Complex	Complex	Complex	Sophisticated
ZONE			Cardiff	Zone per Room		Lighting Alg.	Window Op. Alg.	Blinds Used		Less Occ. Gain	Less Equip Gain	
5	0.00%	2.07%	0.00%	2.07%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
30	0.26%	4.39%	0.00%	7.49%	0.00%	0.00%	0.26%	0.00%	0.00%	0.00%	0.00%	0.00%
24	0.00%	3.36%	0.00%	11.11%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
46	0.52%	4.65%	0.00%	17.31%	1.55%	0.00%	1.81%	0.00%	0.00%	0.00%	0.00%	0.00%

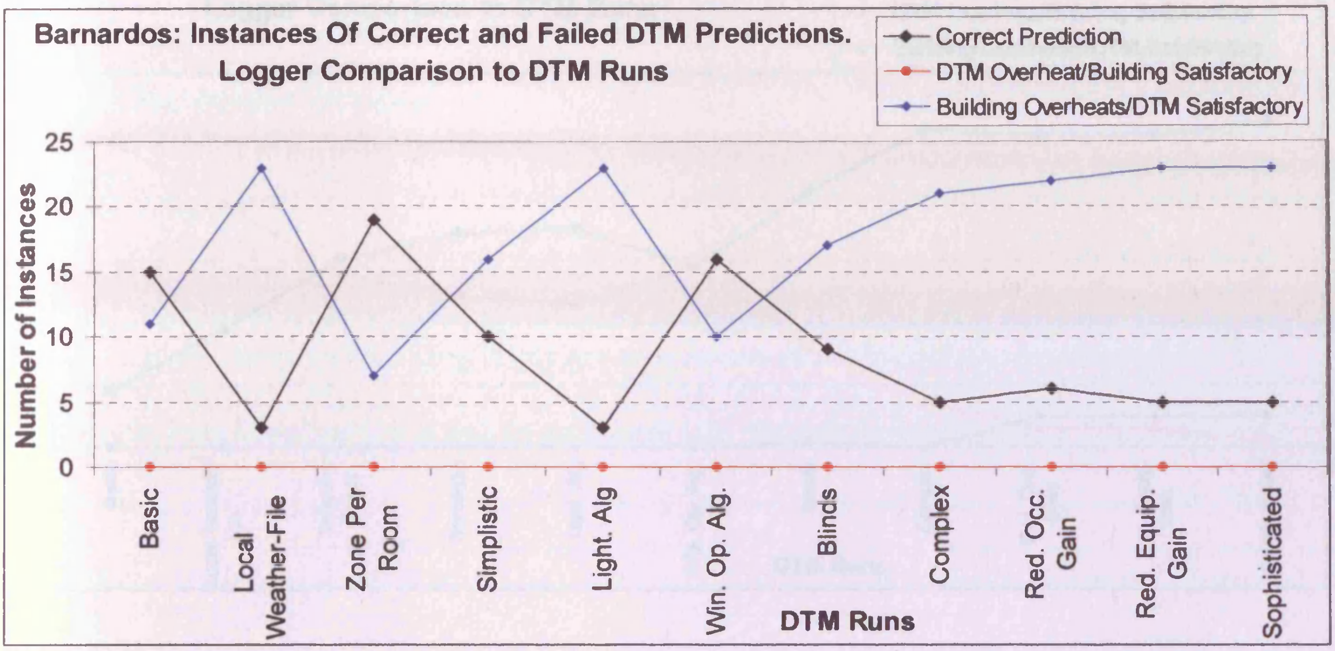
BRECSU Rep. 30 "Office of Future - Performance Specification" Allowance = Maximum of 5% HOURS ABOVE 25°C DRY RESULTANT

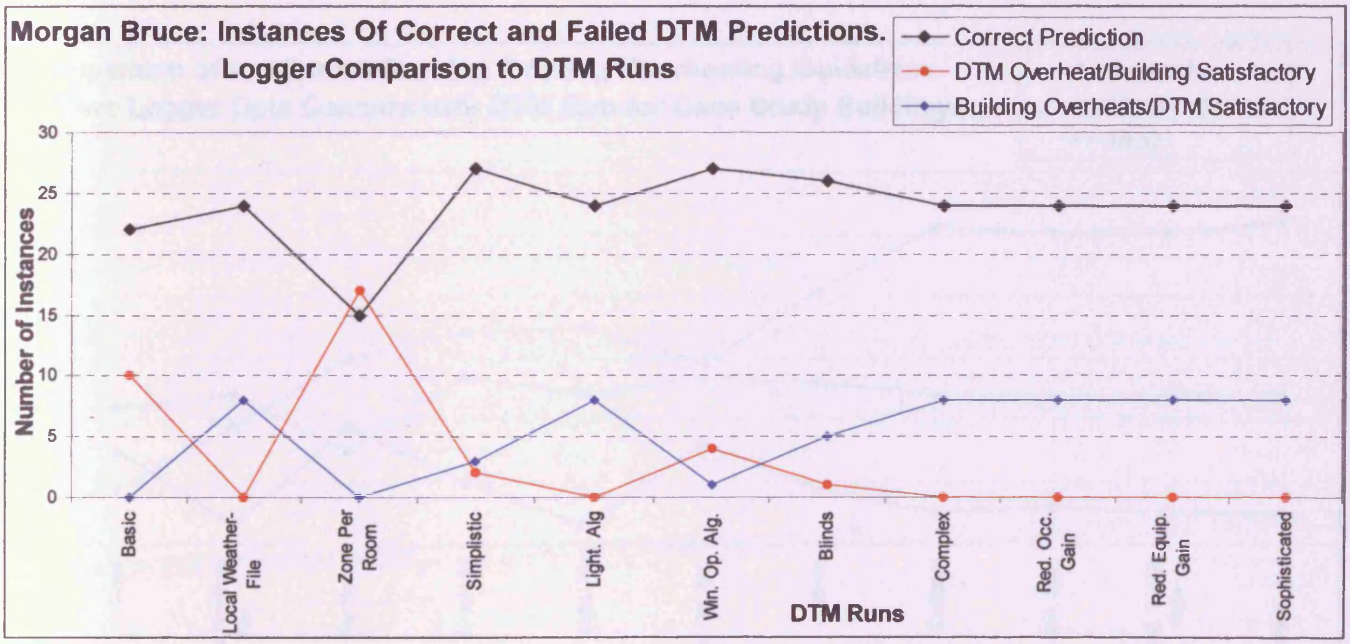
TAS	Logger	Basic	Basic	Basic	Simplistic	Simplistic	Simplistic	Simplistic	Complex	Complex	Complex	Sophisticated
ZONE			Bristol	Zone per Room		Lighting Alg.	Window Op. Alg.	Blinds Used		Less Occ. Gain	Less Equip Gain	
4	5.01%	34.92%	10.88%	17.23%	12.93%	12.93%	17.91%	5.90%	1.36%	0.68%	0.00%	0.00%
16	0.00%	36.73%	8.16%	64.63%	33.56%	30.39%	70.98%	22.45%	0.00%	0.00%	0.00%	0.00%
17	0.91%	35.15%	14.97%	29.48%	22.00%	19.73%	29.93%	12.02%	3.63%	2.04%	0.91%	0.00%
33	6.61%	33.11%	13.61%	32.43%	36.05%	35.83%	60.54%	14.74%	11.56%	9.75%	7.26%	5.22%
6	11.62%	45.58%	16.33%	33.33%	22.22%	22.00%	31.97%	15.87%	4.54%	2.49%	1.59%	0.00%
11	9.79%	43.08%	15.42%	13.15%	7.48%	7.26%	15.87%	1.81%	0.91%	0.23%	0.45%	0.00%
7	15.95%	43.08%	15.42%	32.43%	19.95%	19.50%	26.76%	13.38%	3.63%	1.81%	1.59%	0.00%

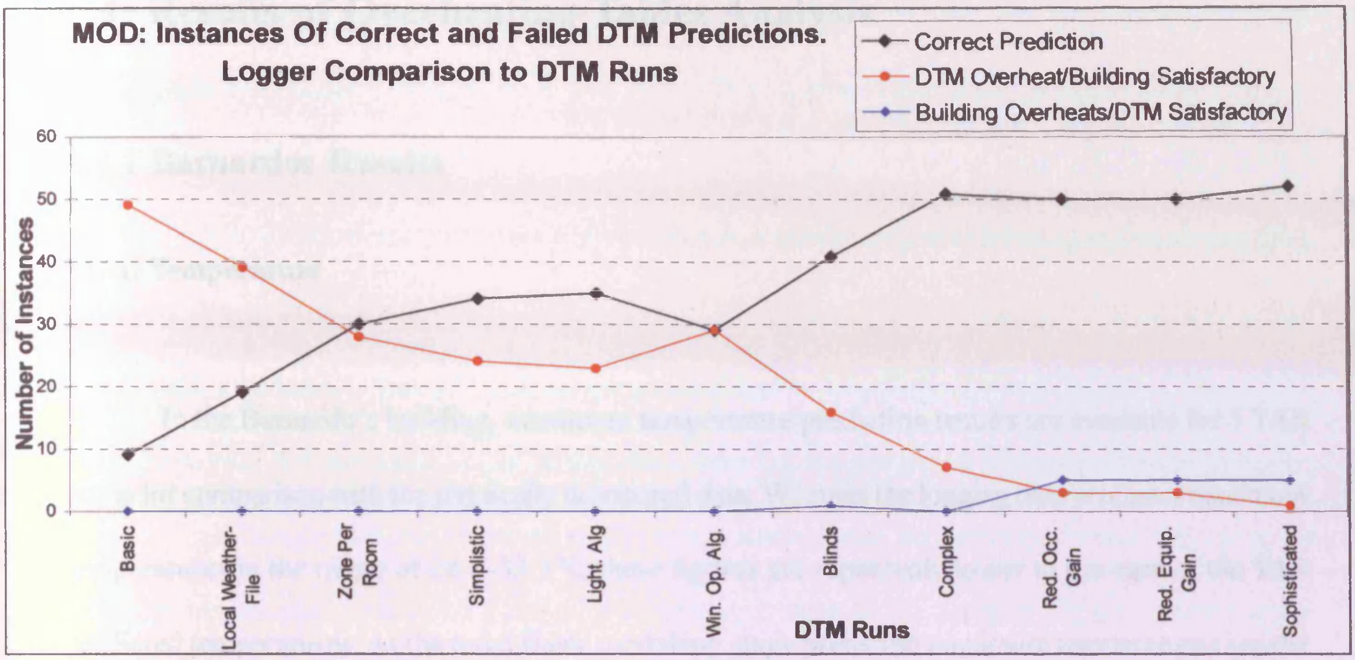
BRECSU Rep. 30 "Office of Future - Performance Specification" Allowance = Maximum of 1% HOURS ABOVE 28°C DRY RESULTANT

TAS	Logger	Basic	Basic	Basic	Simplistic	Simplistic	Simplistic	Simplistic	Complex	Complex	Complex	Sophisticated
ZONE			Bristol	Zone per Room		Lighting Alg.	Window Op. Alg.	Blinds Used		Less Occ. Gain	Less Equip Gain	
4	0.00%	9.98%	2.27%	1.59%	2.27%	2.27%	2.72%	0.68%	0.00%	0.00%	0.00%	0.00%
16	0.00%	4.31%	0.45%	9.30%	1.13%	0.91%	1.81%	0.23%	0.00%	0.00%	0.00%	0.00%
17	0.00%	11.11%	2.72%	6.58%	4.99%	4.76%	7.48%	1.81%	0.00%	0.00%	0.00%	0.00%
33	0.00%	13.83%	3.17%	11.34%	14.74%	14.74%	30.39%	3.85%	2.49%	1.81%	0.91%	0.23%
6	0.00%	18.82%	3.85%	9.07%	5.67%	5.44%	10.88%	1.59%	0.00%	0.00%	0.00%	0.00%
11	0.00%	17.91%	3.63%	1.59%	1.81%	1.81%	2.49%	0.45%	0.00%	0.00%	0.00%	0.00%
7	0.00%	17.91%	3.63%	8.62%	4.31%	4.08%	8.16%	1.59%	0.00%	0.00%	0.00%	0.00%

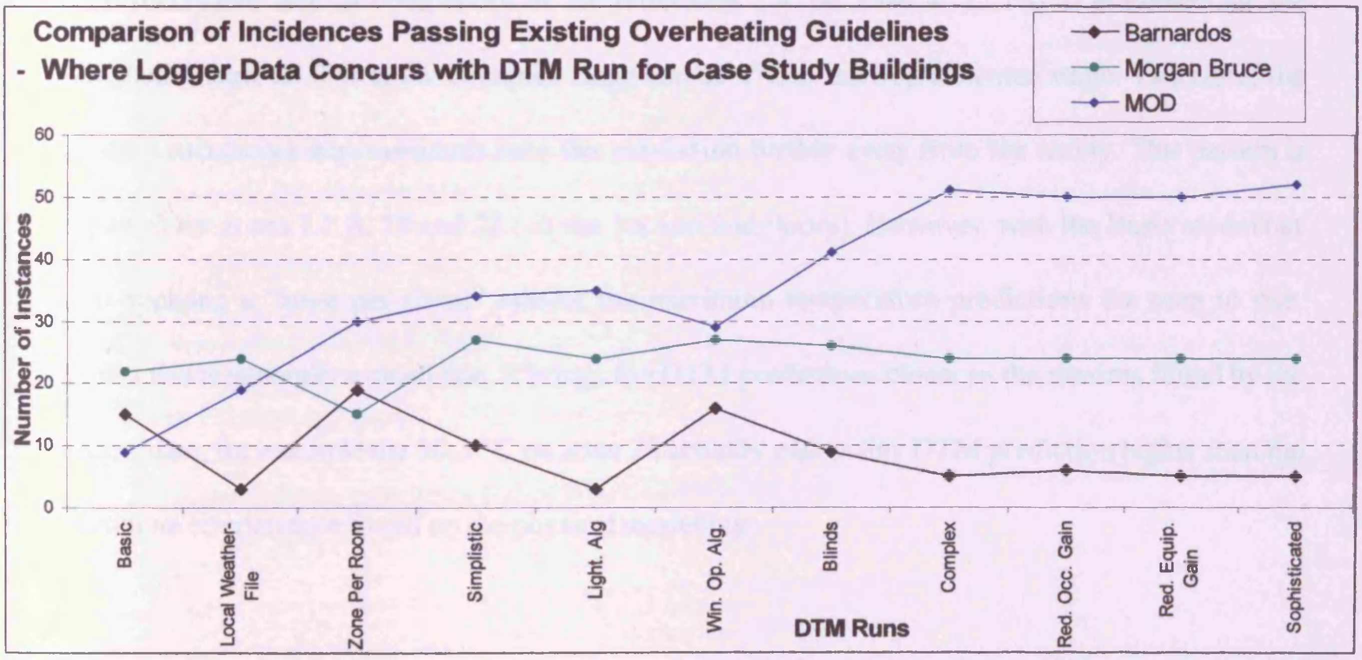
6.3 Overheating Guidelines: Graphical Representations of Passing/Failing Predictions by DTM Simulation Compared to Physically Monitored Results







6.3.1 Overheating Guidelines: Number of Passing DTM Predictions Compared to Physically Monitored Results



6.4 Results of Overheating Tables Analysis

6.4.1 Barnardos Results

a) Air Temperature

In the Barnardo's building, maximum temperature prediction results are available for 5 TAS zones for comparison with the physically monitored data. Whereas the logging data produces maximum temperatures in the range of 28.8-33.1°C these figures are repeatedly lower in the case of the TAS predicted temperatures. At the most Basic modelling stage predicted maximum temperatures are the highest - ranging between 27.8 and 29.4 °C. Therefore, cooler temperatures and a shorter range are found, even at this initial modelling stage. It is also evident that the maximum temperature falls with each successive step of complexity of the modelling e.g. on zone 4, 27.1°C is predicted for the Simplistic stage, 26.0°C at the Complex stage and 25.0°C at the Sophisticated stage. Therefore, the model's successive improvements take this prediction further away from the reality. This pattern is repeated for zones 17, 8, 19 and 28 (on the 1st and 2nd floors). However, with the Basic model but also applying a "zone per room" system the maximum temperature predictions are seen to rise. Whilst this is generally a small rise, it brings the DTM predictions closer to the maxima found by the logger data, for example the 30.3 °C on zone 28 actually makes this DTM prediction higher than the maximum temperature found on the physical modelling.

Another noticeable change to this pattern of falling predictions with increasing model complexity is found as the Simplistic model stage has a window opening algorithm applied. Here the window opening allowance is reduced to keep within set temperature parameters, though retains the same hourly pattern of opening/closing times (i.e. weekdays 9.00AM to 5.00PM). In all instances this change creates an increase in maximum temperatures predicted. This rise can be seen to be both a very small and a large change - i.e. 0.4 °C and 2.0°C on zone 4 and zone 28 respectively.

The mean temperature created by the physical monitoring of the Barnardo's building falls into a narrow band of temperatures ranging from 23.7°C - 25.5 °C. The initial DTM simulation, the Basic case, also creates a small band of mean temperature levels for the comparable 5 zones (i.e. from 20.4-21.2 °C), however as can be seen this latter band is some 3-4 °C below that found by the physical monitoring. Unlike the peak/maximum temperatures, however, a further fall in mean temperature was not predicted on the models as they became more complex. Whilst a lower mean was found for 2 zones on the Simplistic case, for all the remaining zones and the change to the Complex and Sophisticated stages a higher average temperature is predicted. The Complex modelling stage creates the highest predicted mean temperature, in the band 22.2°C -24.5 °C and is therefore the closest to levels found by the physical monitoring for all 5 logging positions. However, the prediction of mean temperatures does show some commonality to the maximum temperatures as two noticeable rises in prediction are seen on the 'sub-level' changes i.e. where a zone per room is applied to the Basic cases and the window opening algorithm is applied to the Simplistic cases. In the former instance, a rise in prediction is seen on 4 of the zones examined and range from a mere 0.1 °C difference through to a 3.3 °C rise. Where the window opening algorithm has been applied a significant rise in predicted mean temperatures is seen on all zones peaking at 3.2 °C for zone 19 on the 2nd floor.

The standard deviation, defined as a measure of how widely values are dispersed from the average, was also assessed for the logged and DTM predicted data. In the Barnardo's building these figures are seemingly large, ranging from 1.89 to 2.80. This compares to a range on the comparable TAS zones of 2.20 to 2.68 on the most Basic runs. With these levels of standard deviation the Basic model shows a close comparison to the logged data for 4 of the 5 zones - under and over predicting logger figures by up to a 0.25 difference (in 1 instance the Simplistic figure is the closest, just under valuing the real standard deviation by 0.12). The magnitude of the standard deviation is also seen to fall with increased model complexity e.g. going down to only 0.88 for the Sophisticated stage for zone 4. This clearly shows that whilst the highest rates of standard deviation are found on the earliest modelling stages they are also the closest comparison to the physically monitored data.

The TUC guidelines require that no instance of air temperature above 30°C is created by the building. The physical monitoring data reveals that 4 of the 5 data loggers picked up on very minor instances of temperatures above this level - the maximum number of hours exceeding being just 9. However, on only 2 occasions does the DTM modelling create temperatures above 30°C - on zone 29 where the Basic stage zoning was changed to include a 'zone per room' allowance and the Simplistic stage where a window opening algorithm was applied (the increases in prediction for these two minor modelling stages were also noted on the Summary Table). The main modelling stages all revealed no instances of temperatures above 30°C at any stage, from the most Basic to the Sophisticated. Therefore, even given the very low amount of overheating present on the table for comparison to the modelling stages, due to this guideline using a very high temperature criteria, as not one instance of +30°C conditions are found it is unable to help gauge any improvement/worsening in the DTM predictions as the model complexity increases.

The USDAW criteria guideline figure from 2004 uses an equally Simplistic pass/fail criteria that does not allow air temperatures to exceed 27°C. Therefore, this lower temperature level should be able to reveal more instances of overheating on both the logged and DTM predicted data. Each of the 5 logger positions shows a considerable number of occasions when temperatures exceeded 27 °C - ranging between 35 and 64 hours. At the Basic model stage, overheating occurrences can also be seen at each comparable TAS zone, though to a lower degree, occurrences ranging between 3 and 19 hours. As seen on the maximum temperature predictions, the overheating prediction falls with the consecutive increase in modelling complexity with two notable exceptions. Where a 'zone per room' allowance is added to the Basic case an increasing overheating predictions is seen (up to 46 hours on zone 28) thus making the prediction closer to the actual levels found. The addition of the window opening algorithm had a varied effect but also led the zones to raise their predictions (e.g. to 62 hours on zone 28). However, when looking at the main modelling stages, from Basic to the Sophisticated stage, a distinct pattern of falling rates of overprediction can be seen.

The Simplistic stage using both Cardiff meteorological data and a room based zoning system shows a minor fall in recorded levels creating slightly lower predictions of hours post-27°C – e.g. zone 4 has just one hour over (down from 14 hours). This falls further by the Complex stage (now also including the lighting control and window opening algorithms plus blinds usage) - only 2 instances of conditions past 27 °C were predicted for zone 19 alone. Naturally, with a reduction in incidental gains to reach the Sophisticated stage of modelling even the overheating predicted for zone 19 will not occur at this point. Therefore, the increasingly complex modelling can be seen to provide ever decreasing levels of overheating as could be expected. However, these decreasing incidences of post-27°C temperature mean that the DTM models are becoming further from the real conditions found. Because of this fact, though still under predicting (as did every DTM run), the Basic modelling stage shows the Barnardos building to fail at each logging point and is therefore the best comparison to the physical monitoring data of the main modelling stages. This level of fit can be marginally improved as the building is more closely zoned with a zone per room allowance which creates a rise in overheating instances on most zones.

Though at a higher temperature level, 28°C, the PACE overheating guideline is not as simplified as the above TUC and USDAW examples. A design risk of 240 hours per 10 years is allowed, thus 24 hours per year, leading to a greater leeway in the guideline's pass/fail point. The data logging points show that whilst all points passed the 28°C mark, only 3 of the 5 exceeded 24 hours thus failing the guideline's criteria. However, the most Basic model does not reveal this overheating, only one zone is seen to reach 14 hours of +28°C temperatures and therefore will also pass the guideline. As previously seen, the improved modelling complexity serves to lower the overheating predictions, therefore the model is seen to pass all the main overheating stages with no instances of +28°C found on either the Complex or Sophisticated stages. This improving performance of the DTM predictions is therefore taking them away from the 60% failure rate seen on the logger positions. As seen on the TUC and USDAW guideline criteria, the addition of a zone per room allowance will increase the level of over-prediction, though even here, at a maximum of 23 hours predicted, this will not fail the guideline criteria either. The addition of the window opening algorithm to the Simplistic modelling stage also leads to an increase in overheating on 3 zones with the only failure point found on zone 28. Due to the low or zero occurrences of overheating at the Basic, Simplistic and Complex stages any change created by the sub-stage alternate runs would not be able to be easily divined by this table as it to merely highlights the overheating guideline temperature of 28°C.

The CIBSE guideline (from Guide section A8) uses a lower temperature guideline than PACE of 27°C, however it is also more effective in that it uses not only a design risk of 2.5% but also takes into account the hours of operation of the building. Therefore a room must produce over 2.5% of its occupied time past 27 °C to fail this guideline's criteria. The logging positions show that each one will far exceed the 2.5% design risk, the maximum found by the physical monitoring being 20.3% of occupied time above 27°C for zone 28. A failure rate of only 2 of the comparable TAS zones was found on the Basic cases and the percentage levels found (at 0.9 - 6.0%,) were far lower than those seen by the physical monitoring. Continuing on from this initial under-prediction, the more complex stages also under-predicted actual percentage levels found as they decreased further at each subsequent modelling stage. Only 1 failure was noted at the Simplistic stage, none at the Complex stage (one zone producing 0.63%) whilst at the Sophisticated stage no zone was found to reach 27°C. Once again increases in prediction were seen where the Basic model had a zone per room applied, which contrasted with the falls to 0% overheating when the local weather file was applied. The window opening algorithms application again saw a rise in the predicted percentage exceeding 28°C for only 3 zones. However, as was seen on all previous guidelines used, the DTM results at all modelling stages under-predicted the actual amount of overheating present. Furthermore, this under-prediction increased as the additionally complex models further reduced the instances of hours exceeding 28°C. Thus, while still an over prediction, the initial, most Basic model proved the best comparison to the physically monitored data, though once again this correlation was slightly improved with a Basic model had a zoning system based on individual rooms.

B) Dry Resultant Temperature

The dry resultant temperatures found in the Case Study buildings this temperature value is widely used as the criteria for comfort purposes in building design. The Building Research Establishment's Energy Conservation Unit 's (BRECSU) "Office of the Future" guideline uses the dry resultant temperature at two temperature levels, 25°C and 28°C, for a design risk of 5% and 1% respectively. Furthermore, the design risk is to be calculated for the occupied time the building. Therefore, this guideline can be seen as more robust than the previous examples used.

The Barnardos building had only 3 zones for analysis as the other logger data for air temperature was too sparse (due to equipment failure) or not gathered for globe temperature. The logger positions show major overheating as all three logging points fail at both temperature level criteria. Percentages for hours above 25°C as high as 34.6% are discovered and 12.3% above 28°C These levels are significantly higher than the design risk allowances given by BRECSU. For the Basic stage model these zones also reveal that all will fail at the 25°C criteria though one zone will be able to pass at the 28°C criteria, thus making the lower temperature criteria look more onerous. This can be seen as an under-prediction given the lower percentage levels found on the 25°C criterion, some 10-28% below logged values, and given the passing of one zone at the 28°C criterion.

However, a major influence will be had with the application of the Cardiff meteorological file. This will ensure that now all zones pass the overheating criteria at both temperature levels. As was also seen on the results from the air temperature guidelines, the largest percentage time exceeding will be seen where a zone per room allowance is used - levels of 13%-33% being found. Once again this modelling stage proves the closest resemblance to the physically monitored data.

When the above two changes are combined to form the Simplistic stage this results in two zones failing (zones 28 and 4) at the lower 25 °C level but only zone 28 fails the 28°C criterion. The application of the lighting algorithm and blinds usage are also able to reduce the actual percentage values found, though the latter example is unable to stop zone 28 failing the guideline. The application of the window opening algorithm to the Simplistic modelling stage sees an increase in predicted percentage time exceeded for temperature levels. A large influence is had on zone 28 as very large percentage figures are created. Almost 70% of time is above 25°C and 30% above 28°C are formed as a result of the lowered window opening in this room (which contains only modest glazing percentages). The combined effect of these changes, forming the Complex modelling stage, is a lowering of the percentage values in each TAS zone.

With the increased complexity compared to the Simplistic stage, the Complex stage is able to ensure that no zone fails at 28°C though, as seen on the previous Simplistic modelling stage, zone 28 will continue to fail at the 25°C criteria. As can be expected, further reductions are seen when the lowered levels of incidental gains are applied. As these reductions in equipment or occupant gain are combined to form the Sophisticated stage, the lowest 'percentage time exceeding' predictions are gained - all the zones showing 0% of hours above 28°C and a negligible 0.32% of hours above 25°C. The above results show that the dry resultant temperature data can be seen to agree with that of the air temperature as decreasing predictions are found with increased model complexity and that the Basic model zoned on a room basis will form the closes resemblance to the physically monitored data.

C) Agreement with Overheating Guideline's Pass/Fail Criteria

The graph in section 6.3 aggregates the number of occasions when the DTM predictions for the Barnardos building matched the results from the physical monitoring for each modelling stage (for the 5 overheating guidelines previously used). Therefore, it can be seen that at the Basic modelling stage, that the DTM results over the full 5 overheating guidelines, correctly predicted that on 15 occasions the room would fail the guideline where it also did in reality (or where the room passed the guideline the DTM would also predict a pass). The graph reveals that also at this Basic stage, on 11 occasions the DTM would assume that the room is satisfactory and meets the overheating criteria whereas it fails in reality. At this modelling stage, on no occasion does the model predict that the building will overheat when it does not also do this in reality. In fact, at no modelling stage, up to the most complex level will the DTM predict that the building overheats when the equivalent room does not overheat.

It can be seen from the graph that the plotted lines will cross where a local weather file is used, as more incorrect predictions of the rooms passing the overheating guideline are found than correct predictions with this modelling change. However, using a zone per room on the Basic stage model produces the highest number of correct predictions, 19, and this is the best fit to the actual building. From this point onwards a decreasing number of correct predictions are found, For example 10 at the Simplistic stage and 5 at the Complex stage. Naturally, as no occurrences of a failing DTM prediction where the equivalent room passes the overheating guideline is predicted, the number of occasions when the overheating building is not also shown by the DTM will rise inversely to the correct predictions. At the Sophisticated stage the model will only correctly identify 5 zones whereas 23 would be predicted to pass the overheating guideline though would fail in reality. Thus this aggregation of passing/failing zones bears out the pattern of an initial minor, under-prediction which will increase with added model complexity - as could also be seen on the maximum temperature predictions and inferred by assessment of the number of overheating hours alone. The graph also corresponds with earlier findings as the modelling stage which most closely replicates the physically monitored data is where a Basic model is zoned on a room basis.

6.4.2 Morgan Bruce Results

A) Air Temperature

The maximum temperature levels found on the Morgan Bruce building are lower than those at Barnardo's, ranging between 25.7 and 28.9 °C over the 7 logging positions. This level of prediction ensures that the most Basic model overpredicts these temperatures on all occasions, 28.1 to 28.9 °C being predicted. However, as was also found at Barnardo's, the magnitude of these maximum temperatures falls with each step of modelling complexity. For example, on zone 30 (ground floor) a

28.9 °C Basic prediction falls to 27.7°C, 26.6°C and 24.7 °C over the Simplistic, Complex and Sophisticated runs respectively. This consecutive fall leads to one of the Simplistic cases providing the closest prediction of maximum temperatures - the Simplistic case with the addition of internal blinds providing the closest prediction to logged data on 5 occasions.

Once again, the changes to the model provides two instances of an increase in predicted maximum temperatures. Where a Basic model is altered to use a zone per room allowance a noticeable increase is found on all but 1 TAS zone's maximum temperature predictions, the predictions rising by up to 2.7 °C. Where the more realistic window opening strategy was mimicked by the application of an algorithm the Simplistic model also shows a rise in predicted maximum temperatures – e.g. up to 3.2 °C being gained from the Simplistic run (zone 36).

The 7 logging positions in the Morgan Bruce building show a band of mean temperatures ranging from 21.6°C to 25.5 °C. This is a far larger range of mean temperatures than predicted by the Basic modelling run as this only ranges very slightly between 21.1°C and 21.8 °C. As a result this initial run will form a close comparison in zone 5 at just 0.5°C below the physical monitoring mean but will be 4.4°C below that for zone 46. Despite this small range in predictions, the Basic run does reveal that all zones underpredict the actual mean. Furthermore, all the main alterations i.e. whether at the Simplistic, Complex or Sophisticated level do not predict mean temperatures as high as recorded on the logger data. In fact on only one zone, zone 50, where a window opening algorithm is applied, will the TAS run predict a higher mean than the actual recorded temperature. Furthermore, as was found in the Barnardo's building no consecutive fall in mean temperatures was also noted as modelling complexity increases, despite this previously seen pattern for all peak temperatures.

As in Barnardos, the Morgan Bruce building showed a large range in the standard deviation figures for its 7 logging points from 1.00 to 2.25. These figures were exceeded by the Basic model on its comparable zones as all standard deviations remained in a small, but higher band between 2.36 and 2.45. The magnitude of the standard deviation fell with model complexity in all instances as was found in the Barnardos building. Thus an initial 2.45 on zone 24 fell to 1.73 by the Simplistic modelling stage, 1.42 on the Complex stage and 1.14 on the Sophisticated modelling stage. Thus the decreasing levels of standard deviation become closer to the logged values as the DTM runs became more complex. However the stage of complexity that proved the closest comparison varied for each zone. The standard deviation had to fall as low as the Sophisticated level for 3 TAS zones to be the closest comparison to the logged data yet this was also found at the initial Basic modelling stage on 1 zone, the remaining 3 occasions were most comparable to the Simplistic modelling stage. It can be seen that the standard deviation of Morgan Bruce highlights a pattern also seen on the maximum temperature prediction (i.e. a consecutively falling figure with increased model complexity) but no definitive indication of which modelling level provides the closest 'level of fit' with the logged data is given over the 7 logging points by this sole measurement.

Using the simplistic TUC overheating guideline, which also incorporates the highest temperature criteria of 30°C, it can be seen that no logger position exceeds this temperature. This apparent lack of overheating is repeated on the Basic model as no comparable TAS zone exceeds 30°C. It is therefore unsurprising that with additional complexity the Simplistic, Complex and Sophisticated modelling stages also do not reveal any instance of +30°C temperatures. This would indicate that all modelling stages show good agreement with the physical monitoring. However with such a high guideline temperature criteria, the magnitude of overheating instances would be expected to be low - whilst any beneficial effect of the increasingly complex DTM runs is not seen as they begin with an initial prediction of zero hours exceeding 30°C. Though a low number of instances of

+30°C would be created when adding a 'zone per room' allowance onto the Basic modelling stage. Here 4 of the 7 comparable TAS zones fail the TUC guideline, the number hours exceeding peaking at 17.

The lower temperature criteria from the USDAW guideline reveals that 5 of the 7 logging points fail, exceeding 27 °C for up to 29 hours. Whilst the number of hours exceeding found on the Basic stage of modelling both under and over-predicts the actual levels found it shows a greater degree of overheating than in reality as all 7 zones fail. However, noticeable differences are found with a single change to the model. Where a local meteorological file is applied no occurrence of +27 °C is found, thus under predicting actual conditions - whereas the zone per room strategy increases the number of hours exceeding for 5 zones. The combination of these effects is that the Simplistic stage shows the best comparison to the physical monitoring as 5 of the 7 zones failed, however this was to a much lower extent than found on the physical monitored loggers (i.e. only 2-10 hours).

Additional changes to the Simplistic model therefore have only a slight effect as these minor number of hours exceeding 27°C are added to or are all removed - though this results in the remaining two zones failing where the window opening algorithm is applied or all passing where the lighting control algorithm is applied, thus revealing the sensitivity of the guideline due to its simple pass/fail strategy. As seen previously in Barnardos, a decreasing level of overheating is seen with increasing model complexity, thus one zone is found to have one sole hour past 27°C on the Complex stage and even this is removed at the Sophisticated modelling stage. These latter modelling stages can therefore be seen to produce an under prediction of hours exceeding 27 °C than that seen in reality.

The PACE guideline uses a higher 28 °C temperature criteria but also incorporates a design risk of 24 hours per annum. With this more intricate guideline in place, no logger position is seen to fail on the physical monitoring, though two zones produce a very minor over-heating of two hours at +28 °C. The Basic stage of modelling again over-predicts the actual level of hours exceeding 28°C as every zone produces between 1 and 4 hours. However, applying the PACE guideline's design risk criteria all zones will pass and therefore good agreement is seen with the logger data. As seen on the USDAW criteria, the application of a local meteorological file will remove even these minor, occurrences but these will increase where a room based zoning strategy has been applied. With this latter change and the increased number of hours found 5 zones failed the guideline - up to 51 hours exceeding 28°C are created, thus far over the 24 hour design risk allowed. The hours exceeding are seen to fall with increased model complexity, however as seen on the TUC guideline, thus little additional improvement can be noted from the Complex stage onwards as zero hours exceeding are seen with this relatively high temperature criteria. Using this guideline all modelling stages would be seen to concur with reality though the Simplistic case would form the closest fit to logged data as it creates only 2 zones with a very small number of hours exceeding 28°C. However, the relative 'fit' between the Basic, Simplistic, Complex and Sophisticated stages and the logged data is negligibly small as such a low incidence of +28°C temperatures are created.

The CIBSE criteria also utilises overheating past 27 °C, this appears on 5 of the logging points - as it should, given that it uses the same temperature criteria as the USDAW guideline. However, with the design risk of 2.5% of occupied time only 2 zones are seen to fail. This level is over-predicted by the Basic modelling stage as 4 comparable TAS zones will all produce a percentage of hours over 27 °C (predictions range from 1.55 to 3.36%). Once again these levels are increased with where a 'zone per room' system is added, as 5 zones fail, yet conversely all hours exceeding 27°C can be removed from each zone with the use of a local meteorological file. As these changes combine to form the Simplistic stage, a trade off is seen, which now creates 5 zones that exceed

27°C though just one will exceed the guideline's criteria of 2.5% of operating time. Therefore an under-prediction has been created over the course of the one modelling stage.

This under prediction becomes greater with additional modelling complexity as was also seen on the USDAW Table - all modelling stages and their sub-stage alterations would pass the CIBSE criteria from the Simplistic stage onwards, even where there is an increase in hours exceeding 27°C created by the addition of a window opening algorithm to the Simplistic model. These results would mean that, for the CIBSE guideline alone, no distinct modelling stage would present itself as the best fit - 4 zones fail at the Basic stage but none at the Simplistic stage, compared to two in reality. However, this ties in with the results from the other guidelines as the best fit of modelling stage cannot be easily deduced - all modelling stages could be seen to be comparable with the physically monitored data for either the TUC and PACE criteria alone as both showed no overheating past the temperature criteria or design risk allowance. However, the Simplistic stage and logging points saw 5 zones fail on the USDAW guideline which would reveal this to be the closest comparable modelling stage when looking at just this overheating guideline.

B) Dry Resultant Temperature

The four logging positions for globe temperature in the Morgan Bruce building reveal a building that will largely fail at 25°C, as 4.9%-27.6% is found ensuring that just zone 5 passes, yet all zones are able to pass at the 28°C criterion of the BRESCU guideline. Four zones are able to stay within the design risk of 1% for the higher temperature value as 0%-0.52% is discovered. However, the Basic model predicts that whilst all zones will fail at 25°C each will also fail at 28°C and is therefore an over-prediction of real conditions.

A very large influence is again seen by the application of the local weather files. All zones fail the BRECSU guideline at 25°C as 12-16% of hours as seen to exceed this temperature on the Basic stage, yet this falls to only 0.78-1.29% as the Cardiff meteorological file is used. Similarly, from each zone failing at 28°C on the Basic modelling stage, 0% frequencies of temperature are created (therefore passing the guideline criteria) with the use of the Cardiff meteorological file. Conversely, the application of a zone per room pushes the percentage time above 25°C to 15.2-39.2% and above 28°C to 2.0-17.3% which is a substantial increase.

The combination of these effects at the Simplistic stage shows some failure, though this was to a noticeably greater degree on the lower temperature criteria. Two zones exceed 5% of the time at +25°C yet only one zone will exceed +28°C for 1% of occupied time. However, like the Barnardos building, the application of the window opening algorithm had the effect of only slightly increasing the frequency of temperatures - 3 zones fail at the lower temperature whilst only zone 46 continues to fail at 28°C. A lowering of the frequency of temperatures can also be seen by the application of a lighting control algorithm and by blind/shade usage. However, the lighting control algorithm has a greater effect, for example allowing all zones to pass at both temperature levels, however the addition of blinds still enables zone 46 to fail the guideline. The resulting Complex modelling stage is therefore a trade-off as, of the 3 previous modelling changes, one introduces a rise in predicted temperatures whilst the other 2 changes reduce it. Consequently, the Complex stage predicts that no zone will fail the BRECSU guideline at both temperature levels. As expected, further minor falls in predicted frequency of temperatures exceeding 25°C and 28°C are again seen as internal gains are lowered. These combined to form the Sophisticated modelling stage which naturally produce the lowest percentage figures of overheating at both temperature levels. Whilst tiny amounts of overheating are still seen on zone 46, 1.17% and 0.52% for +25°C and +28°C respectively, they do not breach the overheating criteria.

The above findings show that the dry resultant temperature data concurs with that for the air temperature as a decreasing level of overheating is seen with increased model complexity. Also, as seen previously on the air temperature data, no modelling stage can be easily deduced to be the best fit when viewing the BRECSU guide alone. For example, at 25°C the physical monitoring reveals that only one zone will pass the BRECSU criterion - yet four zones will fail at the Basic stage though two can pass at the Simplistic modelling stage.At the 28°C criterion all four rooms are able to pass the guideline yet zone 46 will continue to fail at the Simplistic stage, all four zones only passing at the Complex stage.

C) Agreement with Overheating Guideline's Pass/Fail Criteria

The graph in section 6.3, as per that on the Barnardos, aggregates the number of instances that the DTM modelling directly concurs with the physical monitoring, whether both predict that the zone will pass or fail an overheating guideline (for the 5 guidelines used). For the Morgan Bruce building the Basic modelling stage shows that on 22 occasions the correct prediction has been made, however on 10 occasions the DTM would incorrectly predict that the zone overheats whereas the room was satisfactory and would pass the overheating guideline in reality. It can be seen that the best agreement is formed with the physical monitoring when the Simplistic modelling stages is applied. Here, the DTM correctly predicts whether a room suffered from overheating or not on 27 occasions - on 3 occasions it incorrectly assumed overheating when none existed and on 2 occasions when overheating would be found the equivalent TAS Zone did not reveal it.

From this point onwards a decreasing number of correct predictions can be found. This appears due to a rise in the number of occasions when the building would overheat yet this is not predicted by the DTM. By the Sophisticated stage, the DTM only correctly identifies 24 occasions when the room and equivalent DTM zone concur but predicts 8 occasions of a satisfactory zone that would overheat in reality. Thus when looking at the actual hours/'percentage time' overheating figures, the Simplistic stage rather than the Basic stage appears to concur more greatly with the physical monitoring findings. This was not able to be deduced when looking at each overheating guideline alone, however this aggregation of data shows this result more clearly. An initial under prediction at the Basic stage will lead to a greater agreement being revealed at the Simplistic stage, although this level of accuracy will then fall again as the model becomes more complex.

6.4.3 MOD Results

A) Air Temperature

The MOD building provided 11 logging points for monitoring. The maximum temperatures found at these points ranged between 25.0°C and 29.4°C, though were typically in the 25-27 °C band. Therefore, the Basic run, as found on the Morgan Bruce building, overpredicts these temperatures as conditions over 30°C are predicted on all but 1 instance as maxima of 29.4-31.4°C was predicted. Also as found on the previous two buildings, this level of maximum temperature predicted falls with increasing complexity of the model. Consecutive falls in maximum predicted temperatures are noted as the model is rerun for the Basic, Simplistic, Complex and finally the Sophisticated levels. For example, zone 17 on the 1st floor initially predicts a 30.2°C maximum temperature but this falls to only 28.8°C, 26.8°C and 24.0 °C through the more complex modelling stages. At the point of the Sophisticated model maximum temperatures of only 23-25 °C are created i.e. to a level now below that found by the physical monitoring. The closest figures for comparison to the physical monitoring are found on the Complex modelling stage or on one of its internal gain changes - this holds true for 9 of the 11 equivalent TAS zones.

As was found on the previous building a rise in the prediction was found when a window opening algorithm was applied. Here the maximum temperature rose as compared to its value at the Simplistic level, however the level of rise is not great, generally recorded at below 0.5°C, for example a 0.3°C rise on zone 17 was predicted. Conversely to the other Case Study buildings, the effect of the zoning after the Basic case showed no rise in the predicted maxima, instead a reasonable fall in prediction was noted (from 31.2°C to 29.6°C for zone 6).

The data-logging of the 11 positions in the MOD building provides a small range of mean temperatures from 22.0°C to 24.1°C. This range is marginally higher on the initial Basic DTM which creates means of 22.9-25.0°C. Whilst this is generally an over prediction of actual results its degree across the 11 zones/logging varies – e.g. on the ground floor zone 4 is over predicted by only 0.3°C and zones 16 by 2.9°C, whereas zone 7 on the 3rd floor is a 1.0°C under prediction. As was seen on the peak temperature examples, a fall in predicted mean can be seen with increasing modelling complexity. However this is not as definitive as was seen previously, for example zone 4's Complex model produces a higher mean than the Simplistic model.

The MOD building shows a small range of standard deviations from 0.96 to 1.37 for all but one clear exception (2.09 on zone 4) which is both small in magnitude and more tightly banded than was found for in the other 2 Case Study buildings. Except in zone 4, this low and small band of standard deviations is therefore clearly exceeded by the predicted data for the Basic runs. This stage creates standard deviations from 2.03 to 2.86 which are at least double the logger values in all instances. As was also seen on the Barnardos and Morgan Bruce buildings, these initially high standard deviations will fall with each level of model complexity from the Basic through to the Sophisticated modelling stages. This decreasing level of standard deviation ensures that the closest, comparable figures created by the DTM runs are created when the higher levels of modelling complexity are utilised - i.e. 5 at the Complex stage and 6 at the Sophisticated modelling stage. Thus the standard deviation highlights greater comparisons between the physical monitoring data and the latter, more complex modelling stages and therefore concurs with the peak temperature data which showed a similar trend.

Using the high temperature guideline of 30°C set by the TUC, this does not reveal any instances of hours exceeding and thus failures by any data logger data from the physical monitoring. This does not compare well with the predictions from the most Basic modelling stage as all but one zone (zone 16) exceeds 30°C, though for only the small range of 2-6 hours. However, this very minor overheating is seen to fall with the consecutive increases in modelling complexity. Three zones reveal hours exceeding 30°C on the Simplistic stage of modelling and this falls to zero by the Complex stage. Therefore, for this guideline alone, the Complex stage most closely resembles the findings of the logger data. Naturally, as incidental gains are reduced on the Sophisticated stage this too will predict that no zone exceeds 30°C.

The lower overheating criteria set by USDAW of 27 °C reveals only a very small degree of overheating on the physical monitoring data - 2 zones show instances of +27°C air temperatures, at just 1 and 6 hours. This overheating is greatly over-predicted at the Basic stage as all the zones revealed between 38 and 86 hours exceed 27 °C. Whilst the actual number of hours exceeding falls with the changes to the Basic model (i.e. the application of room zoning or a local weather file) a large over-prediction is still formed at the composite Simplistic modelling stage – here, all but 2 zones still exceed 27 °C. The alterations to the Simplistic stage also produce similar overheating failure rates, though with varying numbers of hours exceeding, noticeably, a rise has again been predicted by the addition of a window opening algorithm. As these changes are compiled to form the Complex modelling stage, only a moderate rate of failure can be seen, as was found on the physical monitoring data. Here, 3 logging points show hours exceeding 27 °C but only for 3 hours in each instance. Naturally, with the reduction of incidental gains a further reduction in overheating levels is seen with changes to the Complex model, so that no comparable TAS zone can be seen to fail by the Sophisticated modelling stage. This pattern of a lowering number of hours exceeding 27 °C with additional model complexity shows an initial over prediction and thus failure to the USDAW criteria becomes more comparable by the Complex stage, before then becoming a marginal under-prediction of failure rates by the Sophisticated modelling stage.

Naturally, using the higher temperature of 28°C for the its overheating criteria, the PACE guideline reveals a lower rate of overheating than on the previous USDAW example. One logger position fails by forming just 3 hours above 28 °C (zone 4). Also as seen on the USDAW example, the Basic stage modelling will over-predict this rate for all zones - each zone creating a number of hours exceeding 28°C, though due to the design risk used four zones do not fail the guideline criteria as under 24 hours exceeding are produced in each instance. Both the addition of a 'zone per room' system and a local meteorological file can reduce this over-prediction so that a closer comparison to the physically monitored data can be produced (though one instance of failure is still found in the former example). By the Simplistic modelling stage all zones are able to pass the PACE guideline as found on the physically monitored data, although 9 zones will still create a low number of hours above 28°C (1 to 7 hours being found). Even this predicted low number of hours exceeding 28°C are removed by the Complex stage. Therefore, while there are no failures on any comparable TAS zone from the Simplistic stage onwards a closer prediction can be seen on the Complex stage as this also removes the low incidence of hours exceeding 28°C found on the earlier modelling stage. The Sophisticated modelling stage will repeat this finding and also closely resemble the physically monitored data as no hours exceeding 28°C will be found for any zone.

The CIBSE guideline is passed by all logging points on the physical monitoring which is in contrast with the initial modelling stages' predictions. The Basic stage predicts that all comparable TAS zones will exceed 2.5% of hours above 27 °C. This is also true where a local meteorological file was used, however a noticeable drop in predicted percentages is found when a zone per room allocation is used, so that 4 zones are now seen to pass the CIBSE criteria. The Simplistic stage also over-predicts the logged results in 5 zones as they failed the overheating criteria. Individual changes to the Simplistic model also reveal failures to the overheating criteria, a fall in absolute percentages is found where blinds or a lighting control algorithm are used but these are seen to rise where a window opening algorithm is applied.

However, when combined to form the Complex stage model, a good comparison is now found with the physically monitored data as no TAS zones are seen to fail the CIBSE guideline. The minor overheating at the Complex stage (i.e. 3 zones showing under 1% of time exceeding 27 °C) is removed with further model complexity as the Sophisticated stage is reached. The Sophisticated stage is therefore the best fit for the TAS runs when compared to the physically monitored data when viewing the CIBSE guideline alone.

B) Dry Resultant Temperature

The MOD building's 7 logger positions show that 5 zones will fail at the 25°C temperature criterion, as levels up to 15.9% hours exceeding are formed. The less onerous 1% design risk applies at 28°C by the BRECSU guideline shows that each room is able to pass, however, as 0% is seen for each logging point. Thus between the two temperature levels used as criteria in the guideline either a largely failing building or one which passes in each room instance will be shown. These physically monitored rates are by far exceeded by the predictions of the Basic modelling stage. At the Basic modelling stage, every zone is seen to fail at both the +25°C and +28°C criteria. The magnitude of hours exceeding found was also great from 33-43% on the 25°C respectively criteria and 4.3-17.9% on the 28°C criteria.

A significant failure rate is seen where a local meteorological file is used or a 'zone per room' applied, though these create reductions in the magnitude of percentage time exceeding found, for example a large drop from 34.9% to 10.8% is found on zone 4 at 25°C. Even when the changes to the Basic cases are combined to form the Simplistic stage a high failure rate is seen - no zone passing at either the 25°C or 28°C criteria. The introduction of the lighting algorithm has a limited effect on the Simplistic modelling stage, vaguely affecting percentages but for only selected zones e.g. zone 16 created 30% of hours above 25°C rather than previously seen 33%. The window opening algorithm's application has a strong, but negative effect, increasing the magnitude of percentages found on all zones - e.g. a large 30% of hours above 28°C was found on the cellular office space modelled as zone 33. The addition of blinds was far more beneficial as it enabled zone 11 to pass the guideline at the 25°C criteria and this figure this improved to 3 passing zones at +28°C.

The compound effect of these changes at the Complex modelling stage was that 6 of the 7 TAS zones would now pass the BRECSU guideline at both temperature level criteria. On the halving of the incidental gains, all 7 zones can pass the 28°C criterion (as per the physically monitored data) at the Sophisticated modelling stage. It was these later modelling stage that first appeared as a good comparison to the physically monitored data on the four overheating guidelines previously examined. Naturally, when combined as the Sophisticated modelling stage the highest number of TAS zones are able to pass the guideline as it benefits from a reduction in both the elements of incidental heat gain, however zone 33 will continue to fail even at this most complex modelling stage at the 25°C criterion. The two overheating temperature levels used as criteria by BRECSU therefore reveal one (28°C) that concurs with the findings of the previous guidelines used and one (25°C) that does not as the actual building can be seen to largely fail this criteria.

C) Agreement with Overheating Guideline's Pass/Fail Criteria

The graph for the MOD building in section 6.3 reveals the number of instances that the DTM model correctly identified whether the room would overheat or not, to the criteria used for the 5 overheating guidelines assessed. The correct predictions are aggregated over the 5 guidelines used for each modelling stage. Also at each stage, the number of instances where the DTM model shows that over heating would occur (thus failing the guideline) but where this was not detected in the building is shown. The reverse is also shown i.e. the number of incidents where the DTM revealed no overheating though this would be experienced in reality.

It can clearly be seen that the Basic modelling stage is a major over assessment of overheating in the MOD building. - only 9 predictions concur with the physical monitoring yet, on 49 occasions the DTM predicts that a room will overheat when this does not occur in reality. This level of agreement rises with added model complexity, however, two more correct predictions (30) than incorrect predictions are seen where a zone per room is also added to the Basic model. This increase in agreement sees 34 correct predictions of the Simplistic stage which rises to 51 at the Complex modelling stage. The highest number of correct predictions is found on the Sophisticated stage, as on 52 occasions the model correctly concurs with the physical monitoring. Though this is just 1 instance higher than was found on the Complex stage it can be seen that the number of occasions when the DTM incorrectly assumes a room will overheat has fallen by this stage - only 1 instance is found on the Sophisticated stage compared to 7 at the Complex stage. This incorrect prediction is instead replaced by the first instances where the building overheats in reality but is not predicted by the

DTM model, therefore a slight under prediction has occurred. The more complex models were also seen to prove more accurate when looking at simple statistics such as the maximum temperature and the actual number of predicted hours overheating. Given that the reasoning behind modelling possible overheating is to test against set guideline criteria, the graph is suitable for the task and reveals the most complex model, the Sophisticated stage, to correctly concur with the physical monitoring on most occasions and thus will form the best comparison.

6.4.4 Cross-building Comparison

Looking at the 'best fit' between the physical monitoring data and the DTM modelling stages, the overheating tables show a pattern develop over the 3 Case Study buildings. The most simplistic building chosen, Barnardos, had an overheating level that was under-predicted across the 4 guidelines used. This leads to the most Basic case as the closest comparison to the logged data for the main modelling stages, despite being an under-prediction. However, a higher instance of overheating is created as a "zone per room" is allocated. The Morgan Bruce building produces a smaller level of overheating in reality than Barnardos leading to the slightly more complex modelling stages showing the best fit – i.e. the Simplistic stage. The most complex building design, the MOD, shows the least amount of overheating in reality and requires, at least, the Complex modelling stage be used to find the greatest comparison to the logged results. This would indicate that the more complex the building the greater the modelling complexity required. It is also not unsurprising then, that these factors reveal different modelling stages as the "best fit" to the logged data. As the Case Studies are 3 distinct building types of increasing complexity themselves, it is not unexpected that the closest modelling stage was found to vary for each building.

The maximum temperature predictions were all seen to fall with added complexity on all 3 buildings. This pattern was repeated for the prediction of standard deviation. However, the mean levels do not conform to the pattern seen by the peak temperature and standard deviation, here no definitive lowering of peak temperature can be seen with added model complexity on all 3 of the Case Studies.

The analysis of dry resultant temperatures also revealed these findings. Firstly, as was seen on the previous guidelines examined, an increasing model complexity will lead to a decrease in the level of failure to the guidelines. For example, at the Basic stage for the 25°C criteria examined all buildings' zones will fail yet by the final Sophisticated stage all zones in both Barnardos and the Morgan Bruce would pass, whilst only one will fail in the MOD building (and this will be to a very small level i.e. only 0.22% over the 5% design risk allowed). Secondly, it can be seen that these zones will pass the BRECSU guideline more readily at the higher 28°C criteria. For example, even at the most Basic modelling stage no zones are able to pass on the simple Barnardos building at the 25°C criteria whilst one will be seen to pass at the 28°C criteria.

Graph 6.3.1 reveals the incidences where the DTM predictions (at all modelling stages) correctly concur with the physical monitoring i.e. for occasions where both sources agree that a zone/room would pass or fail an overheating guideline (this is aggregated over the 5 overheating guidelines used). For example, in the MOD building on 34 occasions the DTM concurred with the finding of the physical monitoring at the Simplistic modelling stage.

This graphs serves to highlight two main facts. Firstly, the graph shows that each building will reveal a distinct level of modelling complexity that best highlights its level of overheating as hypothesised in the methodology. As was seen on the previous discussion of the graphs found in

Section 6.3, the Barnardos building's level of overheating is best replicated by the Basic modelling stage where a zone per room is also defined. The Simplistic stage of modelling will be most appropriate for the Morgan Bruce building. The most complex, i.e. the Sophisticated stage, will create the highest level of agreement for the MOD building over the aggregated results from the 5 overheating guidelines used. Given that the crux of the reason for modelling overheating is to test the results gained against set overheating standards, the aggregation of results to find the greatest number of occasions when the DTM concurs with the physical monitoring will aptly reveal this information.

Secondly, the overheating conditions in the more simplistic design of buildings, such as seen in the cases of Barnardos and Morgan Bruce, will be seen at earlier, more basic modelling stages (and thus be correctly predicted on more occasions here). The highest number of predictions correctly correlating with the physical monitoring is found with a Basic model that uses a more defined zone per room strategy for the Barnardos building. Here, there are 19 instances of the DTM correctly predicting that the equivalent room will also fail the overheating guidelines (which the physical monitored also revealed). In the Morgan Bruce building, which is a more complex design, the highest number of occasions (27) when the DTM modelling stage concurred with the physical monitoring was found on the Simplistic stage. In contrast, the complex design and mixed mode servicing strategy of the MOD building meant that the highest incidence of the DTM models concurring with the physical monitoring was found on one of the highly complex modelling stages – on 51 occasions at the Complex staged but an improved 52 at the Sophisticated stage. This finding establishes the thesis hypothesis that a poorly designed building's level of overheating would be discovered with relatively simplified dynamic thermal models.

REFERENCES

1. Parsons, KC *"Human Thermal Environments"* Taylor & Francis (1993) pp278-279

6.5 Proposed Overheating Guideline for DTM Simulation

The current guidelines, shown previously in Section 4.3, are a disparate grouping of criteria created for use both by the building design industry and unions/other organisations whose remit is worker/occupant concerns. This has led to the guidelines varying in their use between simplistic, maximum temperature criteria and an element of design risk., Additionally, only some guidelines (such as the CIBSE's A8) take into account the actual operating hours of the building. Furthermore, this lack of a common approach has also led to some guidelines using dry bulb air temperature and others the dry resultant temperature. Therefore it can be seen that there is little commonality in approach taken by the guidelines analysed thus far.

The thesis proposes a new overheating guideline, drawn from the benefits and also the problems inherent in the prior, existing overheating guideline examples used. It is proposed that the new guideline:-

- Uses a design risk allowance rather than the simplistic pass/fail system which is based on an absolute, maximum temperature value.

- Should have an operational requirement – i.e. be based upon on the hours the building/ offices is occupied. This precludes a precise, given number of hours for a design risk and instead replaces it with a 'percentage time occupied'.

- Use the dry bulb air temperature, as although it does not provide as good an indicator of thermal comfort as the operative/dry resultant temperature, its simplicity and ease of measurement will be valuable in an existing building. Thus its value can be simply measured in an existing building and it is directly comparable to external dry bulb air temperature.

- Be linked to external temperature, to allow the analysis of the internal conditions in the building to take heed of one of the major factors influencing the overheating in the building.

These criteria will be met by providing an overheating guideline which requires that: - **"For the hours of operation of the building, where the external conditions exceed 22°C (dry bulb) internal conditions shall not exceed an internal air temperature of 3°C above the outside air temperature for more than 2.5% of occupied time."** This figure was a re-interpretation of a secondary overheating criteria used which is applied to new UK schools built under the Private Finance Initiative (PFI). UK schools are only expected to maintain conditions so that air temperatures for 80 hours or less are below 28°C, enshrined in the guidance notes for design given by the Department of Education's 'Building Bulletin 87'. However, if this overheating assessment given in this guidance is deemed too lax it can be toughened by any Local Authority during its bidding to have a school built under PFI, the actual additional overheating guideline that must be worked to could therefore vary on a job by job basis. The proposed above overheating guideline was applied, after BRE consultation, to PFI school schemes in London.

Naturally, this method would still reveal that a very warm summer period e.g. on the Kew 1976 weather file would be likely to cause more overheating than that of Kew 1967's weather file as it has a higher number of hours which exceed 22°C. As the external air temperature value used could have a large influence on the resulting levels of over-heating found, two variations of the guideline have been used with altered values used for the external air temperature. The comparison of the overheating prediction tables produced should show the influence of this ambient temperature value used. Whilst still counting only hours where the internal air temperature is 3°C above the outside air temperature (for more than 2.5% of occupied time), comparable tables will be produced for occassions where:-

- **the external conditions exceeds 20°C (dry bulb)**
- **the external conditions exceeds 24°C (dry bulb)**

For each of these tables, failing zones/rooms will again be coloured red and passing zones/ rooms coloured blue for ease of visualisation.

Regardless of the findings of the above comparative exercise, by taking only those hours where internal temperature exceeds the external by 3°C or more the new, proposed guideline will aid a building that is more efficient in dampening the heat gain over the ambient conditions - internal conditions reaching a minimum of 25°C before instances are counted towards the design risk allowance on the proposed guuideline. Therefore, a definitive, maximum temperature value is not created by this guideline, as was also found on the CIBSE (A8) and BRECSU's "Office of the Future" guidelines.

Whilst the design risk allowance of 2.5% appears arbitrary, as do most design risk figures, over the course of the design summer from April to September this would equate to only 29.25 hours. This figure is formed as the standard opening pattern of an office building would see it open for 1,170 hours over a design summer/2,350 per annum (using the allowances given in the E.E.O.'s "Energy Consumption Guide 19 for Offices"). This would therefore produce only 3 uncomfortable working days per annum and this is in line with the design risk for the number of hours deemed acceptable by CIBSE in section A8. However, it would be expected that these overheating incidences would last for only a matter of hours at a time but for a far greater number of days in reality, due to prevailing external conditions.

A similar pattern of overheating would still be expected, as compared to the previous guidelines used, due to the varying complexity of the DTM simulations that were run. For example, the Complex model would be expected to create a higher level of overheating than the Sophisticated model which had had its incidental occupant and equipment gains halved. Furthermore, the varying complexity of the 3 Case Study building's designs reveals that the highest level of overheating is in the most simplistic design (Barnardos) which then falls consecutively to the most complex design (MOD).

The degree hours provided with the tables for the proposed guideline are taken from all instances where external temperature greater than 22°C. The degree hour data is also shown as, though not forming part of the proposed overheating guideline, it will enable closer scrutiny of the overheating results and in particular the more minor model changes. For example, it is very difficult to ascertain the change between two modelling levels where they both predict 0% rates of overheating, however these may still form a small number of degree hours (above 22°C) and these can be compared. In addition, the degree hour data should help to reveal the influence of the prevailing external conditions as a change to the Basic model uses local weather information – i.e. Example Weather Year files for Kew 1967 and Cardiff/Bristol (as applicable). Naturally, a weather file containing 100 hours of +22 °C temperatures has a tenfold chance of creating an instance of "3°C greater than external" for the overheating count than for a weather file with only 10 hours with hours above 22°C.

The degree hour data is suitable for use as when compared to the number of instances that each DTM run/logger experienced conditions that will also be 3°C above the external air temperature, a good correlation was formed. This correlation is shown by the graph of plotted correlation produced across the TAS runs and logged data for each zone/office monitored – i.e. the comparison of overheating hours (where external air temperatures are greater than 22°C and internal temperatures are 3°C higher than external temperatures) to the number of degree hours created (where the minimum external temperature is 22°C). The values that indicate this correlation is the R Squared vale. This is the square of the Pearson product moment correlation coefficient. The R-Squared value can be interpreted as the proportion of the variance in 'y' attributable to the variance in 'x'. This 'coefficient of determination' can have only positive values ranging from $\mathbf{r}^2=+1.0$ for a perfect correlation (positive or negative) down to $\mathbf{r}^2=0.0$ for a complete absence of correlation. However, the advantage of the coefficient of determination, $\mathbf{r}^2$, is that it provides an equal interval and ratio scale measure of the strength of the correlation. This value lacks the advantage of the correlation coefficient, "**r**", which can have either a positive or a negative sign and thus provide an indication of the positive or negative direction of the correlation, however each data set sampled had a positive number and thus the data was omitted, only the graphical interpretation of r^2 being shown.

NEW GUIDELINE **Allowance = Maximum of 2.5% HOURS Where Internal is 3>External and External >22°C**

TAS	**Logger**	**Basic**	**Basic**	**Basic**	**Simplistic**	**Simplistic**	**Simplistic**	**Simplistic**	**Complex**	**Complex**	**Complex**	**Sophisticated**
ZONE			Cardiff	Zone per Room		Lighting Alg.	Window Op. Alg.	Blinds Used		Less Occ. Gain	Less Equip Gain	
4	**3.49%**	7.30%	1.27%	7.62%	1.27%	0.00%	1.27%	1.27%	0.32%	0.00%	0.00%	0.00%
17	**9.21%**	6.98%	0.00%	5.08%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
8	**7.94%**	2.54%	0.00%	8.57%	1.59%	0.00%	1.59%	1.59%	0.00%	0.00%	0.00%	0.00%
19	**10.48%**	3.17%	0.00%	9.21%	1.59%	0.32%	1.59%	1.59%	1.59%	1.27%	0.00%	0.00%
28	**9.52%**	7.30%	0.00%	9.21%	1.59%	0.00%	1.59%	1.59%	0.63%	0.00%	0.00%	0.00%

NEW GUIDELINE **Degree Hours Where Internal is External Air Temperature >22°C**

TAS	**Logger**	**Basic**	**Basic**	**Basic**	**Simplistic**	**Simplistic**	**Simplistic**	**Simplistic**	**Complex**	**Complex**	**Complex**	**Sophisticated**
ZONE			Cardiff	Zone per Room		Lighting Alg.	Window Op. Alg.	Blinds Used		Less Occ. Gain	Less Equip Gain	
4	**102.01**	108.50	15.85	111.88	16.69	9.51	18.17	16.44	11.20	10.31	7.17	7.69
17	**165.83**	107.91	11.99	87.64	9.74	5.08	11.11	9.52	6.51	6.08	4.01	4.78
8	**138.56**	63.33	7.15	111.67	17.54	8.95	20.22	17.46	12.24	11.08	6.05	7.64
19	**173.01**	62.32	6.59	127.50	20.99	13.85	23.70	20.97	17.44	16.13	10.62	12.35
28	**162.74**	112.52	11.85	156.23	23.45	11.35	27.00	22.90	15.09	13.35	7.38	8.56

NEW GUIDELINE **Allowance = Maximum of 2.5% HOURS Where Internal is 3>External and External >22°C**

TAS	**Logger**	**Basic**	**Basic**	**Basic**	**Simplistic**	**Simplistic**	**Simplistic**	**Simplistic**	**Complex**	**Complex**	**Complex**	**Sophisticated**
ZONE			Cardiff	Zone per Room		Lighting Alg.	Window Op. Alg.	Blinds Used		Less Occ. Gain	Less Equip Gain	
5	**0.26%**	1.03%	0.00%	4.13%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
30	**8.27%**	1.55%	0.00%	10.34%	1.03%	0.00%	1.03%	1.03%	0.00%	0.00%	0.00%	0.00%
23	**4.39%**	1.55%	0.00%	14.47%	1.29%	0.00%	1.29%	1.29%	0.26%	0.00%	0.00%	0.00%
24	**2.58%**	1.03%	0.00%	14.47%	1.29%	0.52%	1.29%	1.29%	0.52%	0.52%	0.00%	0.00%
36	**3.10%**	1.03%	0.00%	0.52%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
46	**9.30%**	0.52%	0.00%	14.47%	1.29%	1.29%	1.29%	1.29%	1.29%	0.78%	0.78%	0.00%
50	**1.03%**	0.52%	0.00%	14.47%	1.29%	0.26%	1.29%	1.29%	0.26%	0.00%	0.00%	0.00%

NEW GUIDELINE **Degree Hours Where Internal is External Air Temperature >22°C**

TAS	**Logger**	**Basic**	**Basic**	**Basic**	**Simplistic**	**Simplistic**	**Simplistic**	**Simplistic**	**Complex**	**Complex**	**Complex**	**Sophisticated**
ZONE			Cardiff	Zone per Room		Lighting Alg.	Window Op. Alg.	Blinds Used		Less Occ. Gain	Less Equip Gain	
5	**27.03**	26.31	0.00	127.62	11.14	6.70	11.26	9.84	6.96	5.82	5.33	4.01
30	**187.01**	33.16	0.56	237.50	19.57	10.50	20.17	17.93	11.67	9.43	8.43	5.90
23	**150.96**	33.16	0.56	300.22	20.81	10.90	21.51	18.97	12.46	10.11	9.13	6.31
24	**104.49**	27.15	0.46	281.18	22.16	13.96	22.71	18.79	15.26	13.31	12.42	10.02
36	**121.01**	27.15	0.46	102.27	10.49	7.76	10.57	9.40	7.95	7.28	6.99	6.19
46	**201.12**	23.56	0.20	305.51	28.39	17.61	28.84	26.20	18.73	15.91	14.57	11.36
50	**73.11**	23.56	0.20	296.32	21.21	12.79	21.67	19.12	13.93	11.89	10.98	8.45

NEW GUIDELINE **Allowance = Maximum of 2.5% HOURS Where Internal is 3>External and External >22°C**

TAS	Logger	Basic	Basic	Basic	Simplistic	Simplistic	Simplistic	Simplistic	Complex	Complex	Complex	Sophisticated
ZONE			Cardiff	Zone per Room		Lighting Alg.	Window Op. Alg.	Blinds Used		Less Occ. Gain	Less Equip Gain	
4	**0.69%**	3.01%	0.46%	5.32%	1.85%	1.85%	1.85%	0.93%	0.00%	0.23%	0.00%	0.00%
12	**0.00%**	3.01%	0.46%	0.23%	0.46%	0.46%	0.69%	0.23%	0.00%	0.00%	0.00%	0.00%
16	**0.00%**	6.48%	0.69%	2.55%	3.01%	3.01%	3.47%	3.01%	0.69%	0.23%	0.00%	0.00%
25	**0.23%**	3.24%	0.69%	0.46%	1.62%	1.62%	2.31%	1.62%	0.46%	0.46%	0.00%	0.00%
7	**0.46%**	3.47%	0.69%	0.23%	1.62%	1.62%	2.31%	1.39%	0.93%	0.46%	0.00%	0.00%
17	**0.00%**	3.24%	0.46%	0.00%	1.62%	1.62%	2.31%	1.62%	0.46%	0.46%	0.00%	0.00%
5	**0.69%**	3.47%	0.69%	0.23%	1.62%	1.62%	2.31%	1.62%	0.93%	0.46%	0.00%	0.00%
33	**0.23%**	3.24%	0.69%	0.00%	1.39%	1.39%	2.31%	0.69%	0.46%	0.23%	0.00%	0.00%
6	**0.69%**	3.47%	0.69%	0.23%	1.62%	1.62%	2.31%	1.62%	0.93%	0.46%	0.23%	0.00%
11	**0.23%**	3.47%	0.69%	0.23%	0.23%	0.23%	0.23%	0.23%	0.00%	0.00%	0.00%	0.00%
34	**0.69%**	3.47%	0.69%	0.46%	1.62%	1.62%	2.08%	1.16%	0.46%	0.00%	0.00%	0.00%

NEW GUIDELINE **Degree Hours Where Internal is External Air Temperature >22°C**

TAS	Logger	Basic	Basic	Basic	Simplistic	Simplistic	Simplistic	Simplistic	Complex	Complex	Complex	Sophisticated
ZONE			Cardiff	Zone per Room		Lighting Alg.	Window Op. Alg.	Blinds Used		Less Occ. Gain	Less Equip Gain	
4	**25.40**	89.34	13.13	204.09	63.63	63.38	66.17	56.49	31.37	15.93	8.39	2.28
12	**4.45**	89.34	13.13	12.92	16.63	16.60	26.31	11.58	7.64	5.36	3.03	1.11
16	**12.85**	166.96	23.63	85.71	59.49	58.43	69.13	55.99	33.52	19.69	7.37	1.80
25	**13.15**	92.72	13.75	24.75	39.91	39.83	55.37	35.40	28.58	19.58	11.04	2.41
7	**35.00**	99.53	14.26	17.39	39.68	39.41	49.23	35.60	29.64	21.97	13.76	3.34
17	**16.75**	100.88	14.95	10.76	38.31	37.72	48.33	33.81	27.18	19.59	11.44	3.17
5	**24.80**	102.09	15.43	15.51	40.09	39.82	51.01	35.63	29.89	22.18	13.94	3.46
33	**17.25**	92.72	13.75	18.85	39.77	39.68	57.70	26.51	23.00	18.29	10.16	4.47
6	**30.05**	105.16	15.92	18.52	42.44	42.06	53.82	37.27	31.53	23.67	15.36	3.78
11	**21.88**	99.53	14.26	15.33	7.65	7.61	15.76	5.39	3.44	0.70	3.73	0.57
34	**31.25**	103.52	14.59	23.09	40.68	40.62	55.30	28.09	22.96	18.56	11.05	3.48

NEW GUIDELINE **Allowance = Maximum of 2.5% HOURS Where Internal is 3>External and External >20°C** **BARNARDOS**

TAS	Logger	Basic	Basic	Basic	Simplistic	Simplistic	Simplistic	Simplistic	Complex	Complex	Complex	Sophisticated
ZONE			Cardiff	Zone per Room		Lighting Alg.	Window Op. Alg.	Blinds Used		Less Occ. Gain	Less Equip Gain	
4	13.02%	12.70%	1.59%	13.33%	2.22%	0.32%	5.40%	2.22%	3.49%	2.22%	0.32%	0.63%
17	21.59%	12.06%	0.32%	8.89%	0.32%	0.32%	1.27%	0.32%	0.32%	0.32%	0.32%	0.00%
8	23.17%	4.13%	0.32%	19.68%	8.25%	0.95%	9.84%	8.25%	7.62%	6.98%	0.00%	4.44%
19	26.03%	5.08%	0.32%	19.37%	9.21%	4.44%	9.84%	8.89%	9.84%	9.21%	1.27%	6.67%
28	21.90%	12.06%	0.32%	21.27%	9.84%	7.30%	9.84%	9.84%	8.89%	7.94%	3.81%	7.30%

NEW GUIDELINE **Allowance = Maximum of 2.5% HOURS Where Internal is 3>External and External >20°C** **MORGAN BRUCE**

TAS	Logger	Basic	Basic	Basic	Simplistic	Simplistic	Simplistic	Simplistic	Complex	Complex	Complex	Sophisticated
ZONE			Cardiff	Zone per Room		Lighting Alg.	Window Op. Alg.	Blinds Used		Less Occ. Gain	Less Equip Gain	
5	1.81%	3.36%	0.00%	7.49%	0.26%	0.00%	0.26%	0.00%	0.00%	0.00%	0.00%	0.00%
30	19.38%	4.39%	0.00%	21.19%	4.65%	1.55%	4.91%	3.88%	2.07%	0.26%	0.26%	0.00%
23	12.40%	4.39%	0.00%	28.17%	8.01%	4.39%	8.01%	8.01%	6.46%	5.17%	3.88%	1.55%
24	12.40%	3.36%	0.00%	27.65%	8.01%	6.46%	8.01%	8.01%	6.98%	6.46%	5.43%	3.36%
36	8.79%	3.36%	0.00%	2.84%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
46	21.96%	2.33%	0.00%	26.10%	5.94%	4.39%	5.94%	5.68%	4.39%	3.88%	3.36%	1.03%
50	4.91%	2.33%	0.00%	28.17%	8.01%	6.20%	8.01%	8.01%	6.72%	5.94%	5.68%	3.10%

NEW GUIDELINE **Allowance = Maximum of 2.5% HOURS Where Internal is 3>External and External >20°C** **MOD**

TAS	Logger	Basic	Basic	Basic	Simplistic	Simplistic	Simplistic	Simplistic	Complex	Complex	Complex	Sophisticated
ZONE			Cardiff	Zone per Room		Lighting Alg.	Window Op. Alg.	Blinds Used		Less Occ. Gain	Less Equip Gain	
4	3.94%	7.64%	1.16%	13.66%	7.64%	7.64%	7.87%	6.25%	1.85%	1.39%	1.16%	0.00%
12	1.16%	7.64%	1.16%	2.31%	1.85%	1.85%	2.55%	1.39%	1.16%	0.69%	0.00%	0.00%
16	0.93%	18.75%	2.08%	9.03%	5.56%	5.56%	6.02%	5.56%	2.78%	1.62%	0.69%	0.23%
25	1.62%	8.10%	1.39%	4.40%	3.24%	3.24%	4.63%	3.24%	2.08%	1.62%	1.16%	0.00%
7	6.71%	9.26%	1.62%	3.24%	3.24%	3.24%	3.94%	3.01%	2.55%	1.62%	1.16%	0.46%
17	1.39%	8.10%	1.62%	1.39%	3.24%	3.24%	4.17%	3.24%	2.08%	1.62%	1.16%	0.46%
5	4.40%	9.26%	1.62%	2.78%	3.24%	3.24%	4.40%	3.24%	2.55%	1.62%	1.16%	0.23%
33	1.85%	8.10%	1.39%	3.01%	3.70%	3.70%	6.71%	2.31%	2.08%	1.62%	1.16%	0.46%
6	5.32%	9.26%	1.62%	3.47%	3.24%	3.24%	4.40%	3.24%	2.55%	1.85%	1.39%	0.46%
11	3.70%	9.26%	1.62%	2.31%	0.93%	0.93%	1.39%	0.69%	0.23%	0.00%	0.23%	0.00%
34	4.86%	8.33%	1.62%	3.94%	3.94%	3.94%	6.25%	2.78%	2.08%	1.62%	1.16%	0.46%

B) External Air Temperature Value = 24°C

NEW GUIDELINE Allowance = Maximum of 2.5% HOURS Where Internal is 3>External and External >24°C **BARNARDOS**

TAS	Logger	Basic	Basic	Basic	Simplistic	Simplistic	Simplistic	Simplistic	Complex	Complex	Complex	Sophisticated
ZONE			Cardiff	Zone per Room		Lighting Alg.	Window Op. Alg.	Blinds Used		Less Occ. Gain	Less Equip Gain	
4	0.95%	2.22%	0.00%	1.90%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
17	2.86%	2.22%	0.00%	1.90%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
8	0.95%	0.63%	0.00%	2.22%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
19	2.86%	0.63%	0.00%	2.22%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
28	2.22%	2.22%	0.00%	2.22%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

NEW GUIDELINE Allowance = Maximum of 2.5% HOURS Where Internal is 3>External and External >24°C **MORGAN BRUCE**

TAS	Logger	Basic	Basic	Basic	Simplistic	Simplistic	Simplistic	Simplistic	Complex	Complex	Complex	Sophisticated
ZONE			Cardiff	Zone per Room		Lighting Alg.	Window Op. Alg.	Blinds Used		Less Occ. Gain	Less Equip Gain	
5	0.00%	0.00%	0.00%	1.29%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
30	0.52%	0.00%	0.00%	2.33%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
23	0.00%	0.00%	0.00%	2.33%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
24	0.00%	0.00%	0.00%	2.33%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
36	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
46	1.03%	0.00%	0.00%	2.33%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
50	0.00%	0.00%	0.00%	2.33%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

NEW GUIDELINE Allowance = Maximum of 2.5% HOURS Where Internal is 3>External and External >24°C **MOD**

TAS	Logger	Basic	Basic	Basic	Simplistic	Simplistic	Simplistic	Simplistic	Complex	Complex	Complex	Sophisticated
ZONE			Cardiff	Zone per Room		Lighting Alg.	Window Op. Alg.	Blinds Used		Less Occ. Gain	Less Equip Gain	
4	0.00%	0.23%	0.00%	1.39%	0.23%	0.23%	0.23%	0.23%	0.00%	0.00%	0.00%	0.00%
12	0.00%	0.23%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
16	0.00%	0.46%	0.00%	0.23%	0.23%	0.23%	0.23%	0.23%	0.00%	0.00%	0.00%	0.00%
25	0.00%	0.23%	0.00%	0.00%	0.00%	0.00%	0.23%	0.00%	0.00%	0.00%	0.00%	0.00%
7	0.00%	0.46%	0.00%	0.00%	0.00%	0.00%	0.23%	0.00%	0.00%	0.00%	0.00%	0.00%
17	0.00%	0.46%	0.00%	0.00%	0.00%	0.00%	0.23%	0.00%	0.00%	0.00%	0.00%	0.00%
5	0.00%	0.46%	0.00%	0.00%	0.00%	0.00%	0.23%	0.00%	0.00%	0.00%	0.00%	0.00%
33	0.00%	0.23%	0.00%	0.00%	0.00%	0.00%	0.23%	0.00%	0.00%	0.00%	0.00%	0.00%
6	0.00%	0.46%	0.00%	0.00%	0.00%	0.00%	0.23%	0.00%	0.00%	0.00%	0.00%	0.00%
11	0.00%	0.46%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
34	0.00%	0.46%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

6.6.1 Barnardos - Proposed Guideline Results

A) Effect of Model Changes

The new, proposed overheating guideline revealed that the actual conditions in the building were poor as all data logging points from the physical monitoring of the building created levels above the 2.5% design risk. Values of 3.49% to 10.48% of occupied time were gained from the logged results i.e. up to 4 times the allowed hours where internal conditions are greater than 3°C of external conditions (at 22 °C+ external air temperature). In comparison the Basic stage model also produces a picture of a poor, overheating building, percentages ranging from 2.54% to 7.3% being predicted. Therefore, the Basic stage model concurs with the logged data in that all zones will fail the overheating guideline although with marginally lower predicted percentage values. However, whilst all zones continue to fail, these values are increased for zones 8, 19 and 28 where a "zone per room" zoning system is used, so that they now become closer to the logged data found. A much more distinct effect is had where the local meteorological file for Cardiff is used. This enables all the zones to now pass the guidelines' criteria, with 4 of the 5 zones now producing no hours where the internal temperature will be greater than 3°C of the external temperature (for external air at +22°C).

Combining the effects of the room-based zoning and Cardiff weather-file as the Simplistic model leads to a greatly lowered overheating prediction as compared to the Basic modelling stage. Now, conversely, all 5 zones can be seen to pass the guideline (as 0% to 1.59% rates are predicted) and thus it is a major under prediction of true conditions within the building. Noticeably, unlike the previously used overheating guidelines, the addition of the window opening algorithm had no discernible affect on the percentage levels predicted for the 5 TAS zones -all remained static. This was also true where blinds were used in the summer months to block out additional direct solar gain. Both alterations to the Simplistic model would, however, continue to be an under-prediction of real overheating as all 5 zones pass the guideline criteria. The addition of the lighting algorithm had a greater effect, aiding 4 of the 5 TAS zones create 0% of hours where internal temperatures are under 3°C greater than external.

The combining of these three changes to the Simplistic stage model as the Complex modelling stage will therefore not produce a significant change, as previously 2 of these 3 changes had no effect. Two TAS zones at the Complex stage predict the same percentage levels (zones 17 and 19) whilst minor (sub-2%) decreases are seen on the remaining zones. However, these combined changes serve to take the DTM predictions further from the levels found in reality (3.4%-10.4%). As can be expected, the changes leading to the Sophisticated stage (where actual input data is lowered) to also reveal lower predicted percentage levels. Where the occupant gain is halved, 4 from 5 zones can now predict 0% levels for the internal to external temperature difference. Where the equipment gain is halved all 5 zones now show 0% levels. The combination of these changes as the Sophisticated stage means that the greatest under prediction is also found here, along with the latter example, as no zone shows any instance where temperatures are above 3°C greater than external levels.

However, with the use of this guideline changes to the Simplistic model (by the application of a window opening algorithm and the use of blinds) had no effect. As each modelling stage will be expected to have some effect and to aid comparison between the model stages, the actual degree hours created when external conditions were above 22°C have been shown in the second table. Therefore, this does not rely on the internal to external temperature difference also being greater than 3 °C. The correlation to the number of degree hours being formed (where external conditions are greater than 22 °C) and the percentage time where the internal conditions are also 3°C or greater than external is good – "r squared" values of 0.88 to 0.97 are created (these can be seen on the trend lines of the correlation graphs in Appendices Section A6.10).

The physically monitored data shows a large number of degree hours are formed, in the range 102-173. As seen previously on the "percentage time exceeding" table for the new guideline, the Basic modelling stage will under predict these levels (only zone 4 is a minor over prediction of just 6 degree hours). The fall to levels of only 6.5-15.8 degree hours when the Cardiff meteorological file is used is therefore a very significant result which can be attributed to this change alone. Varying changes are again seen with the introduction of a 'zone per room' as two zones show minor falls in predicted degree hours whilst three other zones show gains (ranging from more 44 to 68 degree hours). The combined effect of these changes (i.e. the Simplistic stage) reveals a degree hour prediction more in line with the large drop created by the use of the local meteorological file as a range of only 9.7 to 23.4 degree hours is created over the 5 zones.

Unlike the predictions seen on the table for the new overheating guideline, the degree hour table can show the small but definite effects of the changes to the Simplistic model. The lighting algorithm is able to slightly reduce the number of degree hours found, though the magnitude of this effect (4.66-12.10 degree hours) is very small. Similarly, the introduction of the window opening algorithm has a small but definite effect - raising degree hour predictions on each zone but only by 1.37 to 3.55 degree hours in total. The effect of the application of blinds was even lower, the fall in degree hour predicted across the 5 TAS zones was in the range of only 0.02 to 0.55, given the low percentage glazing in the building this was not unexpected. The resulting Complex modelling stage therefore had little scope for change as it combined these 3 minor changes in the predicted degree hours - the number of degree hours predicted now being in the very low range of 6.5 to 17.44.

The change created by the halving of the incidental gains can also be gauged, though from a noticeably low base figure found on the Complex stage. Degree hours fall by only 2.5 to 7.71 degree hours and 0.89 to 1.74 for the halving of the equipment gain and occupant gain respectively. The combined effect of these changes as the Sophisticated model is therefore also small. As can be expected the range of 4.78 to 12.35 produced by this final, most complex model is a very large under-prediction of the logged data found and a major fall from the levels predicted on the initial, Basic model.

B) Comparison to Existing Overheating Guideline

Clearly, the above results show a lot of commonality with the previously used overheating guidelines as a clear under-prediction is seen at all modelling stages – the Basic model with a zone per room runs providing the most comparable results as compared to the logged data. The new guideline also reveals a high degree of overheating in the actual building, as was seen on the previously used overheating guidelines. The proposed guideline will now be compared bearing in mind the results found when applying the existing overheating guidelines.

The proposed overheating guideline for Barnardos reveals that all the logging positions will fail. As shown above the building creates percentages of time up to 4 times the allowed design risk. This high level of failure was also noted where existing guidelines were used, for example all 5 zones failing when using the CIBSE guideline. The Basic modelling stage is able to match this failing prediction as all zones fail here also (levels of 2.54% to 7.30% being created). However, as seen previously a more comparable level of overheating will be seen when a zone per room system is added to this Basic stage model. Here levels of 5.08% to 9.21% are formed, which are closer to those found on the logger. It is also immediately noticeable that the Basic model which uses a local meteorological file is able to pass the guideline for every zone i.e. the reverse of the actual conditions. This was also seen on the CIBSE guideline for example and shows the great impact that the ambient conditions from the weather file will have on the model. As can be seen on the table of degree hours formed (at a 22°C base) only 6.5 to 15.8 degree hours are formed for each zone where a local meteorological file is used, however from 62.2 to 112.5 are found for the same model using the Kew 1967 data.

So far the new, proposed guideline repeats findings that were seen when using the existing overheating guidelines. Here also the level of overheating for a simplistic building design is noted quickly with a simple set-up. Also revealed is the fact that the frequency of overheating found will fall with added model complexity. As can be seen from the table, no instance of overheating can be seen from the Simplistic modelling stage onwards. This latter change is a significant difference to the findings from the previously used overheating guidelines, as the proposed guideline would under-estimate some degree of overheating compared to them. The proposed guideline predicts that each zone will fall below the design risk from the Simplistic stage on through to the Sophisticated stage, however this has not seen previously. For example, there were incorrect predictions on the Simplistic stage when amalgamating the data for the 5 guidelines used - the model only correctly concurred with logger results on 10 occasions whereas on 16 occasions it created incidences of overheating which did not occur in reality. This can be seen in more detail when looking at the CIBSE guideline alone. Taking the addition of the window opening algorithm to the Simplistic stage shows that 3 of the 5 zones used would fail the CIBSE guideline (creating 20% of time exceeding the criteria which is 8 times the design risk) yet the proposed guideline shows that each zone is able to pass.

The above result indicates that the proposed guideline is able to gauge the level of overheating for a less complex building at a less complex modelling stage than previously seen. However, this also means that the incidence of zones passing the guideline will also occur more quickly - all zones now passing at the Simplistic modelling stage.

6.6.2 Morgan Bruce - Guideline Results

A) Effect of Model Changes

The logger data shows a considerable failure to the proposed overheating guideline as 5 of the 7 TAS zones fail the 2.5% design risk. All zones report some instance of internal temperatures being at least 3°C higher than ambient temperatures, the percentages found ranging from 0.26% to 9.3%. These results contrast with the prediction from the initial Basic modelling stage. Here, each zone also predicts some level of overheating that is 3°C greater than ambient, however smaller figures are found as these predictions only range between 0.52% and 1.55%. These small percentage levels predicted are all beneath the 2.5% design risk allowed, thus this would see no zone failing the proposed guideline – a major under-prediction given that 5 zones fail in reality.

Once again the two changes to the Basic model produce two significant effects. The use of a local, Cardiff weather-file ensures that each zone now predicts zero instances of hours that are 3°C higher than ambient and therefore continue to pass the guideline. Given the initial passing of each zone at the Basic modelling stage this result seems of little consequence, however it is important as it is able to remove **all** instances of overheating so can still be seen to have a major effect. When zoning the building more precisely using a "zone per room" system, 6 of the 7 TAS zones were seen to fail the guideline. The significant rise in predicted percentages found, rising to between 4.13% and 14.47% for the 6 failing zones, is a major change in overheating produced as one modelling choice is altered – a considerable under-prediction has changed into an over-prediction of failing rooms/zones (an additional zone will now fail that was not noted in reality). Furthermore, the predicted percentage rates are higher in these 6 failing zones than on the physically monitored data, only zone 36 being an under-prediction (0.52% as compared to 3.01% in reality).

The two previous modelling changes were applied to form the Simplistic modelling stage. All zones are able to pass the proposed guideline at this modelling stage, revealing that the negative effect of the new zoning system is overcome by the application of the local weather file – the resulting predictions of 0%-1.29% found are therefore similar in magnitude to those found at the Basic stage. The three changes to the Simplistic model had a very limited effect so that all TAS zones passed on each alternate run. Both the application of internal blinds and where a window opening algorithm was applied showed no variation in prediction from the Simplistic stage model, the same low percentages being revealed for each TAS zone. A change was revealed with the appliance of a lighting control algorithm, however, as the minor 1.03-1.26% levels found were able to fall on 4 of the 7 zones. Naturally, the low level of overheating found on the Simplistic stage gives little lee-way for further falls with model complexity (as seen on the lighting algorithm run), however some discernable effect should have been seen with the introduction of both the window opening algorithm and internal blinds. This will be more easily verified and viewed by the degree hour data on the above table.

The combined modelling changes on the Simplistic stage form the Complex stage. The results at this point being particularly low, 3 TAS zones reveal no instances of overheating while the remainder produce figures of only 0.26-1.29%. With the exception of zones 4 and 50 the logged data has been greatly under-predicted. Further reductions in overheating predicted will be gained when the equipment or occupant heat gain is halved, as could be expected. Combined to form the model of the highest complexity, the Sophisticated stage, all TAS zones will create 0% of hours exceeding 3°C of higher of ambient conditions (where this is also greater than 22°C). Whilst a clear under-prediction is seen at all stages with this proposed overheating guideline, the modelling again reveals that lower predictions of overheating will be gained with greater modelling complexity.

As applied to the Barnardos building, a degree hour table has also been produced to more clearly show the effects of the DTM modelling stages. This data is culled from only hours where the external temperature is 22°C or higher and does not limit the data gathered to those hours where internal conditions are also 3°C warmer than external. Despite this variation in data there is good correlation between the two sources of data as the graphs (found in Appendices Section 6.2) illustrating the correlation and r-squared values for each TAS zone/logger position show. These reveal r-squared values to be high thus showing a good correlation, with one exception (0.66) values in the range 0.94-0.99 are created.

The physically monitored data revealed high levels of degree hours for each TAS zone, with the exception of zone 4, levels in these 6 zones being in the range 73.1-201.1. In contrast the Basic model showed only a range of degree hours of 22.5-33.1, thus a 3 to 9-fold under-prediction of those found in reality – zone 4 being the only close approximation within just 1 degree hour of logged data. Although this great disparity was seen on the table of 'percentage time exceeded' for the proposed overheating guideline these figures are more able to reveal the magnitude of the effect of the consequent (and consecutive) changes to the DTM model. The fall seen with the introduction of the Cardiff meteorological file is large, each zone falling from the 23-33 degree hours found previously to just 0.0-0.56. This is understandable given that the weather files themselves will create different numbers of degree hours at the 22°C base temperature. However, a more significant effect was seen as a "zone per room" was applied to the Basic model which previously had used a zoning pattern merely based on whole wings/floors of a building. Here degree hour predictions rose to be between 102.2 and 296.3. Contrary to the Basic modelling stage, this is now not an over-prediction as compared to the logged data as 6 of the 7 zones predict a greater number of degree hours than their comparable logger position (zone 36 being an exception).

The Simplistic stage, which encompasses the above two modelling changes will therefore be a trade off between the positive effect found by using a local weather-file and a negative effect of the new zoning method. Degree hour predictions between 11.1 and 28.3 are now seen, thus only a minor deviation from the Basic stage (i.e. -4.6 to 16.6). Whereas the proposed overheating guideline could not detect any difference between 2 of the 3 changes to the Simplistic stage, these can now be seen on the degree hour table. The lowering of the degree hours predicted is very small where a lighting algorithm is used – in the range 2.7 to 10.7. The usage of blinds in summer months also revealed a very limited effect, falls of just 1.0 to 3.3 being noted. This low level of change was also seen where a window opening algorithm is applied as predictions rise by just 0.1 to 0.7 degree hours. Naturally, these results led to very small percentage changes on the proposed guideline's results table as these negligible differences in degree hours are formed.

The consequence of the above minimal variations found on the 3 additional modelling changes to the Simplistic model (in order for it become more complex and better simulate reality) is that the Complex modelling stage reveals degree hour levels very similar to that of the Simplistic stage – a variance of just 2.54 to 9.66 being formed. From such low numbers of degree hours found it can be seen that the lowering of the incidental gains could only have a limited effect – the halving of the occupant gain reducing the Complex model's predictions by a further 0.6 to 2.3 degree hours or 0.9 to 3.3 where the equipment gain was halved. These further minor reductions produce a Sophisticated stage model that reveals just 4.0-10.0 degree hours being formed over its 7 TAS zones, thereby a massive under-prediction of reality as these figures are only 3.2% to 14.8% of the degree hours logged during the physical monitoring.

B) Comparison to Existing Overheating Guideline

The Morgan Bruce building reveals that 5 of its 7 rooms logged by the physical monitoring will fail the criteria of the proposed overheating guideline. The new guideline therefore appears more onerous than those previously used, for example just 2 zones fail the CIBSE criteria and all zones dry resultant temperatures were below the design risk at 28°C used by BRECSU. As also seen in the Barnardos building, this large failure by 5 of the actual rooms will not be detected by the addition of meteorological data to the Basic model due to the large influence of the external weather conditions. However, in contrast it can also be seen that each zone at the Basic modelling stage will also pass the guideline, thereby only correctly identifying the acceptable environment in two zones. The most accurate prediction can again be seen where the Basic model is more rigidly zoned on a "zone per room" basis. With this re-zoning 6 of the 7 zones will now fail the proposed guidelines. This failure is also at slightly higher percentage levels, 4.1% to 14.4% being predicted rather than the actual peak of 9.3% of working time.

The above finding concurs with the proposed guidelines effect on the Barnardos data, that the level of overheating for this simple building will be found with an initial, simplistic level of modelling. The Morgan Bruce building also concurs with Barnardos in that a Basic stage model that is accurately zoned will be the best level of fit to the predicted data as 6 of the 7 zones fail here compared to 5 in reality.

All other modelling stages (i.e. from the Simplistic to Sophisticated stages) reveal that each zone is able to pass the guideline. It would also be expected that added model complexity will lower predicted rates of overheating, particularly with the move to the Sophisticated stage where actual levels of incidental gain are reduced. This is better displayed by the degree hour values, for example zone 46 will create 26 degree hours at the Simplistic stage but these will fall to only 11 on the

Sophisticated stage. However, each zone can pass the guideline at an earlier stage than previously seen. This is an obvious related effect which goes hand-in-hand with the benefit that enables this guideline to reveal the overheating level for this simple building at an earlier modelling stage. Therefore, there is a greater risk of a room, that in reality will fail this overheating criteria, would be seen to pass it if a DTM model were constructed at even the Simplistic stage. Whilst all 7 zones can be seen to pass at the Simplistic stage here, this was not seen on the 5 guidelines used previously - on aggregating the number of passing or failing zones it was shown that whilst 27 proved correct at the prior best fit of the Simplistic stage, 5 did not. However, this note of caution does not detract from the fact that the proposed guideline has satisfied the stated aim in the thesis that a differing set of overheating guidelines are needed for DTM predictions in order to take account of limitations in DTM modelling. The proposed guideline is more easily able to show that the additional effort of a very complex modelling strategy is unwarranted with more simplistic buildings.

6.6.3 MOD - Guideline Data Results

A) Effect of Model Changes

As seen on the previously used overheating guidelines, the MOD building creates a very negligible amount of overheating, all zones are seen to pass the overheating guideline. Whilst 8 of the 11 zones produce a number of hours where the internal temperature was more than 3°C greater than ambient conditions this is for very low percentages of occupied hours, peaking at only 0.69%. In contrast, the Basic modelling stage predicts that each zone will fail, directory contrasting with the physically monitored data. However, the levels created are very small at 3.01% to 6.48% and only just surpass the guideline criteria. A minor change to a "zone per room" system will allow 9 of the 11 zones to pass the guideline, showing that this minor modelling decision will have a major impact. Even more pronounced is the change to the Basic model to include a local weather file for Bristol. This alteration allowed all 11 zones to pass the overheating guideline, creating a low percentage rate of just 0.46%-0.69%. This result shows the major effect of the local weather file as a distinct over-prediction can become directly comparable with the physically monitored data due to this sole alteration, with all other modelling inputs being equal.

The combination of these model changes as the Simplistic model will allow 10 zones to pass the guideline and therefore be only a mild over-prediction of the logged data. As seen on the previous guidelines examples used, the introduction of a lighting algorithm has no discernible effect on the Simplistic run as all predictions remain the same. However, the application of blinds to reduce the solar gain has a noticeable though limited effect as minor falls in predicted percentage levels are created. Such minor changes found will ensure that the pattern of 10 of the 11 zones passing the guideline will be repeated. A small change will also be created where the window opening algorithm is applied. Here minor increases in each zone are found, none greater than 0.92% and therefore this change is also not able to alter the number of zones which pass the guideline.

The combination of the three changes to the Simplistic modelling stage, to form the Complex stage, create a better comparison to the logged data as it now allowed all 11 zones to pass the guideline, a small percentage of hours exceeding being found (0.23%-0.46%). This modelling stage would therefore appear to be the "best fit" to the physically monitored data. Naturally, no improvement can be gained on the Complex stage as all zones pass the guideline, however the halving of the equipment and occupant gains can be seen to lower the small percentage time values seen. Consequently, a combination of these lowered incidental gains will produce a Sophisticated stage model where no zone is predicted to create any instances of temperature 3°C above the external temperature. At this point the DTM modelling can be seen to be overly-complex as it produces an under prediction of the actual overheating seen in the MOD building.

Again, the total number of degree hours found where external conditions exceed 22°C can be used to examine the changes between the DTM modelling. These degree hours are used as they do not reduce the result found to only those instances of hours where the internal temperature is also 3°C greater than the external. The r-squared values on the correlation graphs, found in Appendices Section 6.3, show that there is a good correlation between this data. The 11 zones r-squared results reveal values of 0.86 to 0.97 are found when showing the correlation between the degree hours found and the instances of hours when internal conditions were also 3°C greater than ambient (where external >22°C only).

The logged data shows a very low number of degree hours formed for each logger, ranging between just 4.45 and 35.0. As seen on the guideline table, the Basic model greatly over predicts this as degree hours are formed ranging between 89.3 and 105.1. These degree hour figures are more able to show the large effect of the use of the local meteorological file as degree hour predictions fall to a range between just 13.1 and 23.6 for the 11 TAS zones. With the noticeable exception of zone 4 (which sees a significant rise) similarly low levels of degree hours can also be achieved with the allocation of a zone per room. The combination of these effects as the Simplistic modelling stage will be a significant reduction in predicted degree hours e.g. from 105.1 to only 42.4 for zone 6 on the second floor, yet this will still appear as an over prediction compared to the logged data.

As expected, the degree hour data parallels the findings of the proposed overheating guideline. However, this data is useful as it is better able to show up the minor changes induced by alterations to the Simplistic model. The introduction of the lighting algorithm had a minimal effect, reductions in degree hours of just 0.03 to 1.03 being found. Slightly more significant changes in magnitude for the degree hours predicted are formed with the addition of blinds. Here, minor falls of 2.26 to 13.26 are seen. A further more significant effect than the previous examples is seen with the introduction of the window opening algorithm, though these are still very small in magnitude, degree hour predictions now rising but only by 2.54 to 17.93.

As these above changes combine to form the Complex stage the "best fit" to the logger data is seen, though on a zone by zone basis this may also be seen with the lowering of either the occupant of equipment gain. Across the Complex stage and its minor alterations the closest comparison is found for 9 of the 11 zones, the maximum difference being 5.97 degree hours. The Sophisticated stage, as seen on the guideline table, will produce an overly-complex model that under-predicts degree hours for all 11 zones, as a range of just 0.57-4.47 is found. Thus, an overly-complex model can be produced that can under-predict the levels of overheating in even this building which suffers only negligible amounts of uncomfortable temperatures according to the proposed overheating guideline.

B) Comparison to Existing Overheating Guideline

As opposed to the results in the cases of the two basic design of buildings, Barnardos and Morgan Bruce, the physical monitoring revealed no level of overheating in any of its 11 logged rooms - all being able to pass the proposed overheating guideline. The acceptable environmental conditions in the MOD building were also seen on the previously used guidelines. However, unlike the previously used guidelines satisfactory conditions will be revealed at an earlier modelling stage here also.

The Basic modelling stage is a large over-prediction of the overheating found in the MOD building, all 11 zones failing as opposed to all 11 passing in reality. This finding was also true, as seen on the previously used 5 guidelines. Aggregating the data from these show that only on 9 occasions would the DTM correctly compare to the physical monitoring whereas it predicted overheating that did not occur 49 times. As was also seen on the Barnardos and Morgan Bruce examples, the change to a local weather file is sufficient to make all 11 zones pass the guideline, once again the very large influence of the meteorological file chosen is brought to bear (13-23 degree hours being formed rather than 89-166 on the Basic stage model). However, as was also found on the previous two Case Study buildings, the simpler, Basic modelling stage will also more correctly concur with the logged passing/failing zones with the introduction of a "zone per room" alone. This re-zoning is sufficient to take the 11 incorrect predictions of the Basic stage and correctly predict 9 satisfactory zones (one of the two failing cases being just 0.05% over the design risk).

This finding concurs with the prior two buildings assessment against the proposed overheating guideline in that the correct prediction of overheating (or where this does not appear) will be found on an earlier modelling stage than was previously found. This rate of successful prediction will be improved at the Simplistic stage as 10 of the 11 zones show no overheating. However, in the case of zone 16 only the additional complexity of the Complex stage will also reveal that this zone did not overheat as found in reality (however its failure rate is just 0.5% above the design risk allowed). Even when the Complex modelling stage is taken as the best replication of the physical monitoring data this would be at an earlier level of model complexity than had to be used previously. On combining the data for the 5 guidelines used it was previously determined that the Sophisticated stage showed the greatest resemblance to the physical monitored data. For example, the DTM directly predicted the actual pass/fail conditions on 52 occasions at the Sophisticated stage, but only 51 on the Complex stage. However, a far greater improvement in the accuracy of the Basic model when it is zoned more rigidly is now seen - 9 of 11 zones will correctly identify that the equivalent logged room would pass the proposed guideline. On the previously used guidelines, on just 30 occasions were correct predictions formed from a total of 58 i.e. just 2 more correct predictions than incorrect were made. Therefore, despite a very different picture being formed in the MOD building, as a comfortable environment was monitored compared to the other Case Study buildings, the proposed guideline is still able to reveal this fact at an earlier modelling stage - ostensibly with a Basic model that is more rigidly re-zoned on a room basis.

6.7 Changes to Proposed Guideline Overheating Criteria

A) 20°C External Temperature Basis

The graphs in section 6.5.4 show the proposed overheating guideline using two alternate external temperature levels in their criteria. The first reports percentage time exceeding only when these are 3°C greater than the external temperature and the external temperature is at least 20°C. The second alternate uses 24°C as the external temperature value. The proposed guideline is formulated from a PFI design guideline, however the effect of the criteria chosen to form the guideline could be great. Whilst many possible variations could be created for the guideline, for example hours only counted where a 5°C difference is noted at 20°C external temperature or a 2°C difference at 21°C etc, only variations in the external temperature used have been conducted here for illustrative purposes. These tables will demonstrate the effect of two variations in the external temperature level for use in the proposed guideline and so stop short of leading to countless other alternate tables being formed.

Using 20°C as the external temperature basis it can be seen to have a major effect on the three Case Study buildings as compared to the initial proposed guideline. In the Barnardos building its physical monitoring data will still reveal that all 5 rooms fail the guideline. This failure at all points is also seen on the Basic stage model where this has a zone per room applied. Thus far this copies the findings of the guideline when the 22°C external temperature value is used. Additionally the Basic model repeats the pattern of all 5 of the zones still being able to pass the guideline. It was previously found that from the Simplistic stage onwards each zone was able to pass the guideline (where 22°C was used). For the alternate, lowered external temperature criteria a far more onerous guideline is created, now only 3 zones are able to pass at each of the 3 later modelling stages (Simplistic, Complex and Sophisticated). Therefore, whilst this change brings these later modelling stages closer to the real level of overheating found in the building it cannot change the result also seen on the actual proposed guideline i.e. that a simplistic building which overheats will be revealed by a basic modelling stage and this stage being provided where a Basic model is zoned on a room basis. Though its effect is major in that not even the Sophisticated modelling stage can stop some of the zones failing, the new external temperature value makes little difference to this main benefit of the proposed guideline.

On the Morgan Bruce building a small change is detected as previously 5 of the 7 logged rooms failed the proposed guideline, using a 20°C external temperature level this rises to 6 zones. The addition of one extra failing zone is repeated for the Basic model where a zone per room is used, as all 7 zones are now seen to fail. Changes to the Basic model to allow a local weather file to be used have no effect in that all 7 zones will still be seen to pass. A noticeable difference is formed at the Basic stage itself though, 5 failing zones are found whereas all zones passed the proposed guideline (where a 22°C external temperature values is used).

The additionally onerous nature of this lower external temperature value is also seen as, as found in Barnardos, all zones from the Simplistic through to the Sophisticated stage had formerly passed the guideline, now each stage revealed some level of failure in Morgan Bruce - 5, 4 zones and 3 zones at the Simplistic, Complex and Sophisticated stages respectively now fail. Therefore, though the lowered external temperature level can show falling overheating predictions would appear with increased model complexity it again creates a building which cannot remove all the overheating instances even when the most complex modelling is applied. However, as was also seen in the

Barnardos building this effect will not alter the main achievement of the proposed overheating guideline in that the failing building is most replicated by the equivalent zones of a Basic model that is re-zoned on a zone per room basis. The difference now being that the logged data and the equivalent Basic model that has been re-zoned now identify just one more failing zone/room each than was seen on with the less harsh 22°C external temperature criteria.

The MOD building shows little difference for the Basic modelling stage, when this has a local meteorological file applied, either all zones fail or pass respectively as was seen on the initial study. However, the harsher overheating criteria will ensure that 6 rooms fail from the physical monitoring whereas all had previously passed whilst an additional 6 zones failed where the Basic model is re-zoned on a zone per room basis. The effect of the more onerous criteria is felt at later modelling stages also, as found on the previous buildings. As before the overheating found decreases with model complexity. Four zones can be seen to fail at the Complex stage (though none failed previously) however the Sophisticated stage is able to withstand this harsher criterion and will not produce any failing zone, unlike the actual building.

The effect of this change is very much as revealed by Barnardos and Morgan Bruce. The harsher criteria will create higher numbers of failing zones (thus overheating conditions) to more complex modelling stages than seen before. However, its net effect is the same as the building is also revealed to be worse - as 6 failing zones are added to both the Basic modelling stage where it has been re-zoned as well as the physical monitoring data. Thus this DTM stage will still share the same level of agreement seen on the guideline where 22°C was used as the external temperature value, therefore the change induced by this alternate criteria seems of little value.

B) 24°C External Temperature Basis

Using 24°C as the external temperature value proved a less onerous overheating criteria as would have been thought, now only internal air temperatures of 27°C or more are counted and this must also be when the external temperature is at least 24°C. This had a significant effect on the Barnardos building as no modelling stage was able to discover the overheating in two of the physically monitored rooms. The actual rooms' equivalent to zones 19 and 17 are still seen to fail this guideline yet even the Basic modelling stage will not reveal this. This is also true where the Basic model has a zone per room applied. Here each zone also passes despite all 5 zones being seen to fail where a 22°C external temperature value was used. It can also be expected that this under-prediction would increase with added model complexity – though this would have no change in that the Simplistic to Sophisticated stages revealed no failing zones on the initially proposed guideline (0% of hours exceeding is found for all zones from the Simplistic stage onwards). The removal of even the Basic stage model's ability to replicate the overheating found would make this guideline criteria of little value.

A similar pattern of 0% hours exceeding is found on the Morgan Bruce building for all stages after the Simplistic stage, though these were not seen to fail on the initial guideline. However, as before, this less strict criteria removes the detection of the failing zones from the Basic model stage (and when this Basic model is re-zoned). The re-zoned Basic model had previously detected 6 from 7 zones as failing which was the best replication as compared to the 5 rooms seen to fail on the physical monitoring. However, at 24°C the new external temperature criteria also removes these 5 failing zones from the logged data. Therefore, each modelling stage could be said to form agreement, however as no overheating is found at any stage (unlike in the cases where existing guidelines were used) this criteria can be seen to be too lax for use as an overheating guideline.

The MOD the building mirrored the findings of the Morgan Bruce building. The physical monitoring revealed no failing zones, as seen before, and this was replicated by all modelling stages. This was also true of the Basic stage which had previously allowed all the 11 zones to fail, thus completely reversing its illustration of the building. It can be seen that using 24°C as the external temperature criteria is too lax a limit when creating an overheating guideline. Previously, zone 16 required that a model be built at the Complex stage before it passed the proposed guideline, however now this will even pass at the Basic modelling stage with these lax criteria. Furthermore whilst all zones and stages do concur in that each pass the guideline this is at the cost of the usefulness of the guideline to do its job – i.e. detect overheating. Even though overheating instances are very seldom seen in the MOD building they do occur. For example, two rooms fail the simplistic USDAW overheating criteria as they exceeded 27°C for a short time. Now no overheating is detected in the MOD building at all, 0% hours exceeding being predicted for each logged room, which reveals a very lax criteria of to be complied with.

Therefore, in conclusion whilst a 20°C criteria appeared too onerous with little net benefit as under-heating could still be detected with a simple model set-up, the 24°C criteria is also of little benefit as it is too lax and cannot detect any instances of overheating. For all the Case Study buildings tested against the proposed overheating criteria using the initial 22°C external temperature value, good agreement with the physically monitored data was found where a basic modelling set-up was used but re-zoned on a zone per room basis. Therefore, given that where overheating exists (or does not exist) this can be more quickly found at this earlier modelling stage using the proposed guideline and it should therefore be used for DTM predicted data - or as was stated in the methodology, a differing set of overheating guidelines are needed for DTM predictions, as opposed to those created for field studies/surveys, in order to take account of limitations in DTM modelling.

7.0 Discussion of Results

7.1 Introduction

From the previous results section, it was found that the physically monitored data was reproduced by the DTM modelling at a distinct modelling stage for each Case Study building. This modelling stage varied for each building, the simpler buildings being replicated at earlier modelling stages. It was also clearly noted that the level of overheating produced would diminish with additional modelling complexity. This chapter will now discuss the actual consequences of these findings and their possible effect on building design. Furthermore, of the 5 overheating guidelines applied some appeared very lax and did not produce evidence of an overheating zone/room that would have been seen on another of the guidelines used. Therefore, an alternate overheating guideline was proposed for DTM applications and its effects are also discussed.

7.2 Comparison of DTM Modelling Stage to Physically Monitored Data

A) Barnardos

Taken in unison, the information gathered by the overheating guidelines for the Barnardos building indicates that it is a poor building which is seen to overheat. This is revealed as such at the Basic modelling stage. However, the conditions revealed by the Barnardos building are so poor that they are under-predicted by the DTM at even this earliest modelling stage. For example, the logged data from the physical monitoring reveals maximum temperatures between 27.7°C and 29.3°C - an under prediction being found for all 5 TAS zones compared.

This under-prediction is also revealed by all the overheating guidelines used. For example, the TUC guideline, while showing the fewest incidence of overheating, due to its high 30°C maximum temperature criterion, shows that 4 of the 5 areas monitored fail in reality - a low number of +30°C occurrences are seen (up to 9 hours found). Conversely the Basic stage model would pass this criteria as no zone is predicted to create conditions over 30°C. However, the lower 27°C criterion from the USDAW guideline concurs with the physical monitoring findings as all logger points create hours exceeding this temperature, whilst a good agreement is also now formed in terms of failing zones, all 5 Tas zones are now seen to fail. On the less simplistic PACE guideline which uses a 24 hours per annum design risk the under-prediction of the Basic stage model is still evident as only 1 zone surpasses this design risk, whilst 3 of the 5 logging points fail in reality and as could therefore be expected the CIBSE guideline comparison also reveals the same fact. The logged data is greatly above the 2.5% design risk allowed for 27°C, reaching 20.3%, yet the Basic case model predicts that only three zones fail at a maximum of 6.03%. It is therefore clear that whilst, of the main modelling stages, the Basic case bears most comparison to the physical monitoring it will still not reveal as severe a picture of overheating as was found in reality. Where the predictions across all 5 overheating guidelines used (i.e. 4 for air temperature plus the BRECSU dry resultant guideline) were summed **the Basic model that was re-zoned to include a zone per room was revealed to bear the most resemblance to physically monitored data**. Here the correct prediction of a failing or passing zone compared to the equivalent logged room was made on 19 of the 26 occasions.

B) Morgan Bruce

The Morgan Bruce building revealed that some element of overheating appears in the building. For example, using the CIBSE guideline, the areas equivalent to zones 30 and 46 created hours exceeding 2.5% of occupied time. In comparison, the guidelines used reveal that no DTM modelling stage bears an exact resemblance to the monitored data, as either less or more overheating zones are revealed. However, it can be determined that the initial Basic stage model is an over-prediction, for example on 10 of 32 comparisons between the DTM and the physical monitoring, for the 5 overheating guidelines used, the DTM revealed overheating that did not occur as the zone was incorrectly predicted to fail the guideline's criteria. This over-prediction by the Basic stage can also be seen on the summary statistics as all maximum temperatures produced by the Basic models were greater than the data-logged equivalent. Therefore, the best correlation to the limited overheating found at Morgan Bruce lies in a DTM model of greater complexity than the Basic stage.

It was also noted that the Simplistic stage models created a modest under-prediction for some guidelines. The "percentage time exceeding" frequencies used by the CIBSE guideline (and a 2.5% design risk) showed that no zone at the Simplistic modelling stage would fail this guideline though two zones are found to fail in reality. Naturally, the Complex and Sophisticated modelling stages can clearly be seen to be further under-prediction due to their more complex modelling set-up as their name implies. For example, on the CIBSE overheating guideline no zone will fail at these stages unlike in the building itself. The best correlation therefore falls after the Basic stage model, though looking at individual guidelines it could not be verified that this would be the Simplistic modelling stage.

In comparison to the Barnardos building, Morgan Bruce reveals a lesser degree of overheating, though it must be remembered that the Morgan Bruce building is a more sophisticated design. This lesser degree of overheating leading to a modelling stage closer to the Simplistic stage than the initial Basic modelling stage. Intuitively this would appear correct as the increasing model complexity once again produces lower overheating rates. This fact was borne out as the number of correct predictions was aggregated over the 5 guidleines used. **This summation discovered the highest number of correct predictions was created by the DTM at the Simplistic stage** - 27 predictions were correct from a total of 32.

C) MOD

The MOD building, being the most innovative and sophisticated design reveals the least amount of overheating. Therefore, to predict this a high degree of model complexity was required to find the most appropriate modelling stage. The maximum temperature gives an indication of this as low maxima are produced by the MOD building that stay within a narrow 25-27°C band. Similarly low maximum temperature levels can be seen to lie between the Complex and Sophisticated modelling stages for 8 of the 11 DTM zones. This indicates a high degree of model complexity is needed before the falling overheating predictions approach the actual conditions found.

The overheating guidelines concur with this indication. For example, using the simplistic USDAW guideline just two instances of 1 and 6 hours post-27°C are found which most closely resembles the Complex modelling stage as 3 zones created 3 hours exceeding 27°C. This result is the same as produced by the CIBSE standard as this converts the hours exceeding into percentage time. However, this latter guideline instead allows both the physical monitoring data and Complex stage zones to pass the guideline as it applies a 2.5% design risk. Though the Complex modelling stage appears the closest resemblance to the physically monitored data this was not seen with the aggregation of the correct predictions across all 5 existing guidelines used. This method, where the zone concurs with the logged data that the zone/room will pass or fail a guideline, revealed that although 51 correct predictions were made at the Complex modelling stage, **52 of the 58 total would be correct at the Sophisticated stage**. The most sophisticated building therefore needs the most sophisticated modelling approach to most accurately gauge its level of overheating.

The above results from the three case Study buildings therefore suggest the a poorly designed building's level of over heating will be detected at an early modelling stage which uses a basic setup

- as hypothesised in the thesis methodology. This is seen as the most simplistic design of building, Barnardos, was seen to overheat greatly and this was best replicated by a basic modelling stage which was zoned on a room by room basis. The Morgan Bruce building whilst also of a simplistic design (though not as simplistic as Barnardos) showed some of overheating and this was seen at the Simplistic modelling stage. Conversely, the innovative MOD building which has a far more complex level of design (and incorporates displacement ventilation in its mixed mode servicing strategy) reveals little overheating. To adequately replicate this, the most complex modelling stage was required – i.e. the Sophisticated stage.

This result suggests that for the limited number of Case Study buildings, that overly-complex modelling strategies do not need to be applied to gain an indication of the level of over heating in simplistic, naturally ventilated office buildings. For example, the additional effort of lowering the incidental gains, so that they were a truer reflection of the building in use, being unwarranted. Furthermore, these changes could stop the DTM revealing levels of over heating that do exist in the building. In contrast to this, the most of sophisticated design of building needed the most sophisticated modelling approach. Anything less than this most sophisticated approach may reveal instances of overheating that do not occur in reality. The effect of this mismatch of modelling stage on the proposed design will now be discussed.

7.3 Effect of Too Complex or Too Simplistic a Modelling Stage on a Proposed Design

The relative effects of the mismatch between the earlier/later modelling stages and the logged data from the physical monitoring of the Case Study buildings can be seen as the effects of increasing modelling complexity are analysed.

Firstly, the evidence from the Basic stage model of the Barnardos building reveals that it would not predict as great a degree of overheating as was found in reality. Furthermore, with added model complexity it can be seen that the levels of overheating predicted would decrease, the DTM then becoming a far greater under-statement of overheating in the actual building. It would therefore be expected that a lesser attempt at ameliorating the build up of uncomfortable temperatures would be conducted than is required in reality, particularly for the more complex, later modelling stages. For example, re-running the DTM of the building again but including night cooling or a higher percentage of openable window area may be enough to get all the failing zones to now pass the CIBSE guideline but this might not have been adequate as in reality overheating levels found were up to 8 times that allowed by the CIBSE design risk.

That additional modelling complexity leads to a fall in overheating predicted is also clear on the Morgan Bruce DTM models. As the Simplistic modelling stage forms the closest agreement with the physically monitored data this effect will initially be beneficial. Some of the over-prediction of failing zones at the Basic stage being removed at the Simplistic stage. However, this ever decreasing number of hours exceeding will continue until the Sophisticated modelling stage where no zone exceeds any of the guidelines used. A reversal from the Basic stage will now hold true as the DTM will now predict 8 occasions of acceptable conditions in the building though the actual room would fail the overheating guidline. Therefore, though this step-wise reduction would at first bring the model more into line with the data-logged results from the physical monitoring, it will create a problem of a distinct under prediction by the Complex modelling stage. This will also have an effect on the proposed design. A room which failed the existing CIBSE guideline, for example, would appear to form an acceptable working environment from the Complex modelling stage onwards. Therefore, no attempt would be made to correct the design, perhaps by increasing the opeanable are of existing windows or inclusing mechanical ventilation. In a hypothetical design situation it would therefore be likely that these rooms would be designed "as is" and overheat - as occurs in reality.

The MOD building shows only small levels of overheating due to its use of a constant 19°C supply of air from a displacement ventilation system. It would therefore be assumed that overheating conditions would be limited because of this mixed mode servicing and this was borne out by the guideline data results. This low degree of overheating means that a comparable result will only be created where a more complex (and hence no longer over-predicting model) is produced at the Sophisticated modelling stage. Prior to this modelling stage, overheating levels would be suggested that warrant a change in design, such as a move to mechanical ventilation, though these conditions would not occur in reality.

Clearly, this fall in predicted over heating with modelling complexity would have a great effect on the proposed design dependant upon which modelling stage was used for each building. In the case of Barnardos on viewing the Basic stage, though under-predicting, the CIBSE guideline reveals that some zones would overheat, as happened in reality, it would therefore be expected that the design would be required to change to more greatly ameliorate this overheating. However, by the Simplistic stage just zone one fails the CIBSE guideline for example and this zone (28) is just 1.3% above the allowed design risk. Perhaps a greater window opening would be added to this room alone or mechanical ventilation/air conditioning applied rather than a change in the servicing method to the building as a whole. Therefore, a major change to the design may not be suggested even when using the Simplistic modelling stage which is as its name suggests is very simplistic and a level of complexity just one step up from a model created for 'ballpark'/indicative results. Furthermore, were the Complex or Sophisticated modelling stages taken as an accurate prediction of conditions within the Barnardos building zero overheating passed available guidelines' criteria would be noted, therefore any redesign or inclusion of additional mechanical ventilation would not be called for in any area. The original design would therefore go ahead resulting in a building which overheats, creating uncomfortable temperatures for its occupants. This is, of course, this situation as found in reality by the physical monitoring.

The Basic modelling stage would be only a minor over-prediction for the Morgan Bruce building but produce a major over-prediction of overheating levels for the MOD building. Conversely, whilst the Complex stage closely resembles the MOD building this modelling stage would vastly under estimate actual levels of overheating for the Barnardos and Morgan Bruce buildings. This situation would thus lead to the complex and innovative building designs such as the MOD building to have greater levels of overheating depicted by the Basic and Simplistic modelling stages. This scenario could lead to the possible redesign of the building that is unwarranted, for example the addition of full air conditioning leading to profligate energy use.

The result of increasing model complexity can therefore be seen to have a varied impact on building design. This process immediately takes the Barnardos building further from the actual temperature conditions created. With a minor and major increase in model complexity made respectively, the Morgan Bruce and MOD buildings could be brought more in line with the true conditions found on the physical monitoring. Therefore, the situation occurs whereby a disparity (as compared to actual conditions) is caused at both the earlier and later modelling stages and this could lead to unwarranted re-design of the building. This variance could therefore affect the final design solution greatly. In this instance the results indicate that such a simple design as the Barnardos building requires that a simple model must be used to create predictions that most resemble actual conditions found. Any greater modelling complexity will give a false impression of a correctly functioning building and lead to a building prone to overheating. Conversely, a simplistic modelling methodology would give a false impression of an overheating building that is not realistic, the adequately functioning building only being revealed when a DTM model of greater complexity is used. This incorrect prediction by the simplistic model would lead to un-demanded remedial actions being taken such as the abandoning of natural ventilation and the inclusion of air conditioning. Therefore, the application of DTM would actually hinder the attempted design of a passively ventilated building.

7.4 Effect of Individual Modelling Changes

The decreasing levels of overheating found with model complexity are caused by the individual alterations to the DTM models. The relative effects of these changes will now be discussed.

7.4.1 Application Of Local Meteorological File.

The change from an initial Example Weather Year file for Kew, London to a more local weather file for Cardiff or Bristol was applied to the Basic stage model. This had a major impact as the previously discovered rates of overheating were dramatically reduced with its application. This result can be expected due to the way DTM models will respond to the different levels of frequency of ambient temperatures found on different meteorological files. For example, the analysis of Kew 1967 data to create the proposed overheating guidelines revealed that 29 hours above 22°C are produced during working hours in the monitoring period compared to only 5 hours on the Cardiff weather file.

For example, where a local meteorological file was applied to the Morgan Bruce building, the shift to the cooler weather file for Cardiff sees a large decrease in overheating predicted. For example, all zones will fail the BRECSU guideline at 28°C, creating 2.0%-4.6% of hours above this temperature, however 0% frequencies are found when the Cardiff meteorological file is added. This effect is as great on the 25°C criteria as all zones fall beneath the 5% design risk from earlier 12-16% frequencies found. Therefore, the inclusion of the local weather file is important to the prediction created for this simple building. The effect of using a local Bristol weather file on the MOD building was also important. For example, on the PACE guideline each of the 11 zones were at or above the 24 hour design risk allowance at the prior Basic modelling stage yet with the use of the Bristol weather file the resulting lowering of hours exceeding 27°C meant that each of the zones could now pass this guideline. This drop would be expected due to the cooler conditions found on the Bristol Example Weather Year file – just 26 hours above 22°C are found as compared to 76 hours on the Kew file for example (a breakdown of weather file statistics for the Kew, Cardiff and Bristol weather files can be found in Appendices Section 4.0).

Naturally, with the cooler weather file data a lesser rate of overheating will be seen. This result serves to highlight the massive effect had by the weather file, hence the modelling methodology would try to find a 'semi-extreme summer' to gain a near-worst case scenario if this were a true design exercise. However, as an attempt to correlate physical monitoring with DTM runs this is not appropriate in the thesis, however from the three Case Study buildings examined this ensures that where weather data is from a local site (Cardiff/Bristol) it will produce results by far under-predicting reality for the simplistic designed buildings and would create a far lower prediction than found on the Basic stage model initially used for all Case Studies.

7.4.2 Re-zoned Model on a Room Basis.

Changes to the Basic stage model are also able to alter results to create higher numbers of instances of overheating where a zone per room has been added. This re-zoning from the Basic stage model can create a large rise in predicted rates of overheating. For example, in the Barnardos building this change to zoning procedure produces overheating incidences on the CIBSE criteria which ensure that all 5 zones now fail the guideline rather than the previously found 3 zones. This finding is also highlighted by the BRECSU guideline as, using a 28°C criterion, a large 13.3% of hours exceeding is created whereas none previously existed where the most basic zoning was used. However, in contrast, zone 31 which had 5.7% of hours above 28°C fell to just 3.8% when the new zoning was applied. It can therefore be seen that this change did not produce a uniform increase or decrease in results over all the zones. The MOD building also reveals a very varied pattern of change to its predicted overheating rates where zoning is applied on a room by room basis. The BRECSU guideline at 25°C reveals falls in predicted temperatures as great as 30% on zone 11, negligible changes of under 1% on zones 34, 33 and 25 and conversely rises as large as 27.9% on zone 16.

A variety of results could be expected as a zone is now more greatly split into its component parts. For example, a cellular office is now defined as a strictly north, south, east, or west facing office dependant upon its orientation whereas previously it was incorporated into a larger area, perhaps encompassing all four orientations. An open plan area might expect a lesser change as it may still retain all four or at least east/west or north/south orientations. The new zone system will therefore benefit or disadvantage cellular rooms with this more precise orientation, as a lower or higher solar gain level will affect them and/or it has been moved into a more leeward or windward orientation. Where a simplistic zoning procedure is used each floor or wing zone may have had areas of its perimeter on both the predominantly leeward and windward orientations of the building. Therefore previously, the zoning may have allowed temperature differences on varying orientations to be averaged out in the Basic zoning strategy.

7.4.3 Application of an Artificial Lighting Algorithm.

The addition of the lighting algorithm had a lesser scope to affect overheating levels as could be seen on the example of the BRECSU guideline used. For example, the lighting algorithm had a smaller net effect than the weather file or zoning changes on the Morgan Bruce building, though was still found to be of importance. Previously 5 zones had failed the BRECSU guideline at the 25°C criteria yet the introduction of the lighting algorithm alone would reduce this so that no zone had a predicted frequency above 2.07% - i.e. each zone was now able to pass. The effect of the addition of the lighting algorithm was also negligible for the MOD building. The BRECSU guideline at the 28°C criteria reveals that 5 zones show no change in percentage time predicted, the other 6 show a reduction of only 0.2%. This limited effect in comparison to the modest falls noted on the other Case Study buildings is due in part to the particularly low lighting load of the MOD building and the low solar transmission of its triple glazing, thus the original prescribed lighting load would be expected to be maintained for the majority of time - the additional light admitted into the deep plan office space due to the 2% daylight factor being of little benefit.

Overall, the introduction of the lighting algorithm to take account for periods when artificial lighting is switched off and the use of auto-dimming features on modern luminaires is still of benefit in reducing overheating. However, its effects here are limited as it is applied only from the Simplistic modelling stage onwards which already benefits from the increased modelling complexity of a local weather file and zoning on a room by room basis being used. Furthermore, it can only possibly reduce the internal gain found up to the maximum heat gain attributed to the lighting load in the initial model - e.g. 14 W/m^2 in the Morgan Bruce building.

7.4.4 Application of a Window Opening Algorithm.

The application of a window opening algorithm also had a major influence as overheating instances were raised greatly from the previous Simplistic modelling stage. For example, in Barnardos the Simplistic case for Barnardos predicted that only zone 28 would fail the CIBSE guideline (at 3.81%) yet the application of the window opening algorithm made this zone overheat to 19.6% (3 zones now failed the CIBSE guideline). Therefore, in attempting to more accurately model window opening and thus to mimic occupant actions, a far greater level of overheating is created. This could be expected as the algorithm moves the model from a position of "all windows open at all times" to one where each window actively seeks to keep temperatures to a set level (22°C).

However, the application of the window opening algorithm created a more limited effect for Morgan Bruce than seen at Barnardos. Here, though a rise was noted in predicted overheating on all zones, its actual affect meant that only one additional zone failed the BRECSU guideline at the 25°C criterion for example. This effect was also more limited in the MOD building. The BRECSU guideline shows that whilst large increases in percentage time were found on zones 33 and 34 at both temperature criteria, the other zones showed limited increases - rates of increase of 0.46% to 5.44% being found on the higher 28°C criteria for example. This effect is due in part to the large, open plan nature of the MOD building (which has only a small area given over to cellular offices) but predominantly to the mixed mode servicing of the building. The percentage window area to room volume will be low in this deep plan, predominantly open plan building. The influence of the now more limited window opening and thus air change rates will also be decreased as the algorithm does not come into effect as much as found on the other buildings as the 22°C control temperature set by the algorithm is already met for a large portion of time by the displacement ventilation system.

Therefore, whilst it can be seen that the application of the window opening algorithm has a large effect on predicted levels of overheating, creating increases in all instances, it will have less effect on the more complex building that does not rely on natural ventilation alone. As the MOD gains a significant degree of cooling from the 19°C supply of air (at 2.75 air changes per hour) from its displacement ventilation system, the need for the windows to open, as applied by the algorithm is reduced - i.e. the 22°C temperature level from which point the windows are allowed to begin to open will not be as frequently found, internal tempperatures being reduced at all times by the supply of cooler air from the displacement ventilation system.

7.3.5 Application of Internal Blinds/Shading Devices.

The addition of blinds also had a limited effect over and above the low instances of overheating found on the Simplistic modelling stage. Again a positive lessening of overheating was produced by this more realistic approach to mimicking occupant behaviour, however its effect was at a smaller level than found for previous model alterations. For example, given the low percentage glazing found in the Barnardos building and thus the limited direct solar gain from windows, a similarly limited effect would have been expected. In the Morgan Bruce building this additional use of blinds was enough to create 0% frequencies at 28°C so that all zones pass the BRECSU guideline at this level and all but one zone (46) passes at 25°C. Despite the one failure at 25°C this is a greater effect as prior to this 5 zones had failed to fall below the 5% design risk at the Simplistic modelling stage. The limitation of solar gain was also noticeable on the MOD building as the low rates of overheating seen fell further. This is shown on the BRECSU guideline, for example, as 4 zones were able to pass the 28°C criteria whereas no zone was able to pass this guideline previously. Whilst the triple glazed fenestration of the MOD building has a low solar transmission already, the additional blocking out of the direct solely gain can therefore be seen to be of a modest benefit in hindering overheating occurrences.

As seen with the introduction of the lighting algorithm a minor benefit is gained by the introduction of blinds, however its effect is more limited than that created by the earlier modelling changes. Again this is partially due to the fact that this change was applied from the Simplistic modelling stage which also benefitted from previous reductions due to the model being re-zoned and having a local weather file applied. Furthermore, the degree to which the application of blinds can reduce the direct solar gain on each building will be limited by the building's percentage glazing level and the total solar transmission value (G value) of its glazing used. Therefore, a smaller level of reduction was found on the Barnardos building which has a low percentage glazing and in the MOD building which is triple glazed as standard in conjunction with its use of a low emissivity coating. This allows a far lesser amount of solar gain into the MOD building than would be found with the simpler double glazing used in the other two Case Studies.

7.4.6 Lowering of Incidental Heat Gains from Occupants and Equipment.

Naturally, a reduction in incidental gains would have the effect of reducing overheating levels, all other things being equal. In this study, these changes are applied at the Complex modelling stage where only a minor amount of overheating is noted, thus its actual effect is reduced. For example, halving the equipment gain in the Barnardos building for the CIBSE guideline showed that, whilst at the previous Complex modelling stage two zones still surpassed the 5% design risk these were now able to pass, thus its influence can still be strong. Morgan Bruce showed a similar result to Barnardos in that the scope for the halved internal gains to lower overheating rates was little. Despite this where overheating was noted on the BRECSU guideline at 25°C and 28°C these predicted frequencies fell. However with such low rates of overheating at the Complex stage this effect had no influence on the results in that all zones were able to pass the BRECSU guideline by the previous Complex stage also.

These results would be expected, however, the reduction in overheating would follow given the reduction in the actual input of heat gain. Despite the obvious nature of the effects of this change its inclusion was important to gauge the effects of more accurately attempting to mimic actual building operation to create the most sophisticated modelling stage. This discovered that whilst it will have a beneficial effect in reducing overheating found it will be the most limited change found from all the model alterations. However, as with the application of the lighting algorithm its effect has a maximum upper limit - i.e. the heat gain from half the occupants or equipment (for example a fall up to 5 W/m^2 for occupancy in the MOD building). Furthermore this alteration was applied from the Complex modelling stage which revealed low levels of overheating as it already benefitted from all the previous modelling changes.

Comparing each of the above modelling changes to one another individually is therefore unfair, given that they were applied at different points in the main modelling stages. However, it can be seen that the change to a local weather file will bring a large reduction in overheating seen with the specific weather files used in these Case Studies. Also, the re-zoning of the model had a large effect, though this was not a uniform increase or decrease in overheating predicted for each zone in a Case Study building. Finally, more accurately attempting to model occupant behaviour with use of the window opening algorithm had a lesser effect with the MOD building as it also uses mechanical displacement ventilation as part of its mixed mode servicing strategy.

However, it is also important to know the relative ease with which all the alternate runs and thus increasing the model complexity was made. The actual modelling method changes were typically made very easily, in journal entries no model alteration was noted to have taken over 2 hours. This was because in practise, merely a small amount of data input was need to be altered - at the very minimum 1 line of code was required to be changed to the other extreme where individual room based heat gains from occupants or equipment had to be changed for each zone separately. However, this minor time penalty is tiny in comparison to the time needed for the post processing of the DTM data. Whilst one alteration can be easily applied, the major time penalty is gained as the data is manipulated to become of use for the end purpose of the modelling exercise. For example, in this thesis only selective zones were required and from these air temperature for 9.00 AM to 5.00 PM omitting weekends - and then from this data cumulative frequency charts of temperature etc may be required. With such a large amount of post processing required yet relative ease of modelling changes it may be easy to create a high work load as every minor model alteration is simulated. Therefore, it is important to have the end results that are required in mind prior to beginning the process of dynamic thermal modelling and making any desired alterations to the model set-up or its input assumptions. It was due to having a firm idea of wishing to create a realistic, but basic, model through to an also realistic but sophisticated model that the thesis has reduced the number of alternate DTM runs to 10 - these ten sufficient to answer the main thesis aim - i.e. finding the best applicable level of modelling complexity.

7.5 Effect of Existing Overheating Guideline Criteria.

It is difficult to determine intuitively whether these existing overheating guidelines used are too lax or too stringent as the criteria used by them is varied. The TUC and USDAW criteria are for a simplistic maximum internal air temperature, PACE and CIBSE guidelines use an allowance for design risk thus the temperature conditions are compared for only the occupied hours of the building. The BRECSU guideline also suggests this later method it also employs the dry resultant temperature which should give a better indication of occupant comfort. This problem has been generated as the demands for a maximum working temperature are generated by workers concerns in existing buildings whilst industry guidance is needed to create a design solution deemed to work adequately on an assessment of conditions which is created for a 6 month design summer or full year. For example, this design year could be altered to cater for a range of semi-extreme weather conditions (e.g. likely to occur only 1 in every 8 years according to existing meteorological data) and/or for typical weather conditions. Furthermore, for a true, worst case scenario short extreme sequences of hot weather could also be used to determine the likely maximum internal temperature. However, in each instance relative levels of overheating would need to be gauged by an existing guideline and these revealed very different pictures of overheating for the same room or building.

Barnardos shows that the overheating guidelines employed will have a major impact on determining the level of overheating found. For example, of the 5 guidelines used, the Basic stage model is seen to easily pass the TUC criteria as it is the least severe, yet only 1 from 5 zones fail the PACE criteria at 28°C. This would be expected as the maximum temperature used has fallen by 2°C. However at the 27°C criteria all 5 zones on the Basic model fail the USDAW guideline as at least 1 hour exceeding is produced, yet this becomes only 2 zones for the CIBSE guideline using the same 27°C limit. This is due to the 2.5% design risk allowed by CIBSE, thus it is not unsurprising that the more robust but less severe CIBSE guideline reveals lower levels of overheating (in terms of areas/zones that pass/fail). However, this finding is important as it reveals that the guideline a designer uses to gauge overheating will be very influential in affecting his/her view. With no legislative or other mandatory overheating guideline in place the design team could use the TUC, USDAW criteria or even a guideline of their own that would reveal a building where either the 5 TAS zones used could all pass or all fail.

The presumed use of the CIBSE guideline, for example, would have a major design implication as it forms a less severe view of overheating than the USDAW guideline. On this above evidence the TUC criteria would deem Barnardos an acceptable building yet USDAW would not, but even where the same maximum temperature is used on an alternate guideline (CIBSE A8) a different view could be gained as just two zones/areas would be deemed to fail here. Such findings taken on face value would have a major consequence if the Barnardos building was at the design stage. Remedial actions such as the addition of mechanical ventilation would be suggested if solely the USDAW criteria was applied but a change in servicing method or other design feature is less likely if the TUC criteria alone was used.

The Morgan Bruce building does not reveal over heating to the same extent as Barnardos, however it can again be seen that the building will pass the less onerous guideline criteria. The TUC guideline at 30°C is not exceeded whereas the lowering to a 27°C criterion would see 5 zones fail on the USDAW guideline. However if a design risk was added just 2 zones would fail as seen on the CIBSE guideline. This effect can more greatly be seen on the PACE guideline as two occasions of 2 hours above 28°C have no consequence given the 24 hour design risk allowance. Therefore, building failure rates vary due to the added design risk criteria used and the range of temperature thresholds which mark the pass/fail points. This finding is also true of the DTM runs. Thus using the Simplistic stage model which appears the closest correlation to the logged data would reveal a passing building with the lax TUC guideline yet 5 from 7 zones fail on the USDAW guideline, though with such a low number of hours exceeding that the simplicity of this form of measurement is highlighted. The same temperature threshold as USDAW of 27°C sees no failures for the CIBSE guideline as it also incorporates a 2.5% design risk. This effect is also of importance as given that the Simplistic modelling stage appears the closest/most applicable level of modelling complexity, analysis of the results could vary tremendously due to the guideline used alone. Once again the lax TUC criteria would not deem a re-design of the building is in order though this is more greatly suggested when viewing the results in light of the CIBSE guideline's criteria.

The effects of the varying overheating guidelines can also be seen on the MOD building. For example, on the Simplistic stage three zones produce hours above 30°C, thus failed the TUC guideline's criteria and 9 zones produce hours above 27°C on the harsher USDAW guideline thereby failing. The CIBSE guideline also uses a 27°C temperature threshold, however this guideline decrees that only 5 zones fail at the Simplistic stage. This disparity in the 'reading' of the same temperature levels means that the CIBSE guideline concurs more accurately with the logged data.

The variety of the zones seen to pass/fail would be of great importance in the design stage. However, the great simplicity of the TUC, USDAW and PACE guidelines would be noted, a true building design more likely to use the CIBSE or BRECSU guidelines that were designed for this purpose. The design guideline used needs to be suitable for purpose. Therefore, whilst the TUC criteria makes a reasonable demand for workers that they are not subject to above 30°C internal air temperatures, such a lax temperature threshold is not suitable to gauge overheating over a full design year. In this instance, theoretically hundreds of hours at 29°C over the working time of the building could be created and would not exceed the TUC criteria yet this would be far from ideal working conditions, thus lower temperature thresholds and an element of design risk should be applied.

To ameliorate this great variation seen on the above guidelines used an alternate overheating guideline was proposed for use with DTM predictions. It sought to make an attempt to instead gauge the relative environmental control of the building rather than seeing how it performs compared to definite overheating thresholds given by a set temperature point.

7.6 Effect of Proposed Overheating Guideline Criteria.

The proposed overheating guideline only counted those hours when the external temperature was 3°C greater than the external temperature **and** the external temperature was a least 22°C. Therefore, only internal air temperatures above 25°C at a minimum would be counted by this overheating criteria. This applied to working time for the building, therefore results were produced as a percentage of working time and to this a design risk allowance was set. The design risk allowance was set at 2.5% of total hours i.e. the same figure used in the CIBSE A8 guideline, and equates to less than 30 working hours per summer in a typical office building. Naturally, if different criteria were chosen a different view would be expected from the results. To illustrate this point the proposed guideline had its external temperature value altered for two separate assessments- one 2°C lower at 20°C and one 2°C higher than the value proposed at 24°C.

The effect of the altered external temperature value was immediately evident. On the proposed guideline temperature where 20°C was used as the external temperature threshold it could be seen that a far harsher overheating criteria was created. This new criteria revealed that overheating would occur in the Barnardos, Morgan Bruce and the MOD buildings even at the Complex modelling stage. However, it did show a significant change from the proposed guideline in that good agreement for the three Case Study buildings was formed when the Basic model was properly zoned on a zone per room basis. This effect was also noted on the proposed guideline that used 22°C as its external temperature value, therefore, this change created a similar result to the proposed guideline in this regards. However, the changed external temperature value also produced overheating levels that were far higher and occurred on later modelling stages than on any previous overheating guideline used, therefore this alternate version's criteria was too severe for use. Conversely, on using 24°C the overheating criteria was so lax that this too would have proved of little value in gauging the overheating levels in DTM models of varying complexity. In the actual buildings each zone passed this guideline in both the Morgan Bruce and MOD buildings whereas only two zones failed in the Barnardos building (down from all 5 where the 22°Cwas used). More importantly alterations to the model complexity found difficulty in noting a change as all models pass the guideline criteria at an earlier stage. In fact, no zone of any of the three buildings will now fail the guideline's new criteria at any modelling stage. Therefore, like the TUC criteria (though this was designed for use in existing buildings) this criteria is far too lax to be fit for purpose.

The initially proposed overheating guideline was created for use with DTM simulation results in order to take account of its limitations due to the estimates it must use in its inputs. The overheating guideline therefore seeks to accurately replicate the physical monitoring results with a modelling set-up of more limited complexity - the guideline being more impervious to minor changes, such as altering incidental gain levels, that could shift a formerly failing zone to becoming a passing zone. The proposed guideline had some success with its overheating criteria as the three Case Study buildings' DTM showed a greater resemblance to the physical monitoring at an earlier modelling stage than found by the existing guidelines.

The Barnardos building showed the best agreement with the physical monitoring where the Basic model was zoned on a room basis. However, in this instance the change was not as great as this stage was also the best fit when using existing guidelines. However, the achievement of 19 correct predictions from of total of 26 on the existing guidelines was replaced by all 5 zones concurring with the logged data at the same stage with the proposed guideline. The effect was more noticeable on the Morgan Bruce building. Previously the Simplistic stage proved to the best replicate the physical monitoring findings however, this also shifted to the Basic stage where it is correctly zoned on a zone per room basis for the proposed guideline. Very good agreement was also formed for the MOD building at this stage as 9 of the 11 zones correctly predicted that no over heating would form. However, for complete accuracy the Complex stage of modelling was required by the DTM as this also showed that all 11 equivalent zones would pass the proposed guideline criteria. Despite this the new guideline brought about the most closely matched modelling stage at an earlier level of complexity than was previously found with the existing guidelines - i.e. the 'best fit' had shifted from the Sophisticated to the Complex stage. The proposed guideline was therefore able to most correctly concur with the physical monitoring at a less complex stage of modelling for all three Case Study buildings. However, the concomitant effect created by the proposed guideline's criteria must also be borne in mind in a DTM study. The proposed guideline will now reveal an even greater disparity from actual conditions at more complex modelling stages than was previously found, for example the Simplistic modelling stage at Morgan Bruce would now not detect 5 overheating rooms. Therefore, the proposed guideline will be less effective than existing guidelines if an overly-complex DTM model was created.

The effect of the use of the proposed overheating guideline would be important in a design study as a closer approximation of the internal conditions could be gained at a lesser level of modelling complexity than was previously used. From the limited number of case studies it was shown that as long as a Basic model set-up is zoned definitively for each actual room reasonably good agreement to the guideline criteria can be created. This would naturally save the time and effort of altering the model to try to more accurately mimic occupant behaviour such as their use of blinds, window opening practices etc as well as their associated heat gains. In the case of Morgan Bruce this shift from the Simplistic stage to the re-zoned Basic model to form the best agreement would mean that the time required to apply a window opening algorithm, artificial lighting control algorithm and make an assumed use of internal blinds would not be necessary. The effect is not as great in the more complex MOD building, however the proposed guideline indicates that effort need not be wasted on trying to more accurately assess internal gain levels from occupants and equipment as a closer replication of the physical monitoring results is now found at the Complex rather than the Sophisticated modelling stage.

8.0 Conclusions

Prior to concluding the findings of the thesis, it would be wise to also re-iterate the main aims of the thesis as outlined in the Methodology section and some of the major issues that affected the research. The principal aim was to find whether a best applicable level of modelling complexity exists in dynamic thermal simulation which will predict a similar level of overheating as would be found in the actual building. Secondly, given the current range of guidelines and rules of thumb used to gauge overheating the thesis sought to assess whether a more useful or robust overheating criteria could be created to assess the physically monitored against the DTM predictions.

8.1 Case Study Buildings

To fulfill the above aims three naturally ventilated Case Study buildings were compared against DTM predictions of the internal air temperatures. To achieve this, firstly the internal air temperatures were logged in all buildings at various locations throughout each floor and/or wing.

The first Case Study building, Barnardos, is a very simplistic building. It is a small building comprised predominantly of cellular offices. It features a low percentage glazing area and both the floor and ceilings comprised voids so that the building will not benefit from the effects of thermal mass. It is unsurprising then, that this building was found to perform poorly. The second Case Study building used was Morgan Bruce, a more sophisticated design than that of the Barnardos building, however it is still an office building that is purely naturally ventilated. It is also a far larger building than Barnardos, at 3,900 m^2, and comprises a large amount of open plan office space, though cellular offices are still predominantly found around the perimeter of the building. However, it also has poor design features as the tilt and turn windows are hampered by the position of the internal, horizontal blinds plus the building's position next to a major commuter road act as limiters to the natural ventilation strategy. The consequence of this improved level of design, though one that still contains flaws, is that the Morgan Bruce building is also seen to suffer from overheating. The third and final Case Study building, the MOD Procurement building in Bristol, is by far the most complex design studied. The wings/area of the site tested, the Walnut building, is a large (13,900 m^2) predominantly open-plan office building of 14m in depth. It is able to be ventilated by openable windows on both sides of the room though the building is primarily serviced by displacement ventilation system providing 2.75 air changes per hour at 19°C. The MOD building can be seen to be an innovative, mixed mode design where natural ventilation can be used to 'top up' the displacement system whether for additional air changes or comfort cooling. With such an innovative and complex design it is unsurprising that this building showed the lowest degree of overheating from the physical monitoring exercise. Therefore,

- **The 3 buildings chosen as case studies show a low, medium and complex level of design and are therefore a good test of computer modelling.**

However, the physical monitoring methodology was designed for a previous EPSRC research project, the thesis only sought to use the temperature data provided. This meant that the physical monitoring of the three Case study buildings was hampered as limited equipment was available leading to more limited coverage in the building than ideally desired. However, enough equipment was available to gain data for at least one office/area on each floor for each buildings . The consequence was that air temperature coverage across each building was adequate, though could have been vastly improved. The main drawback to the EPSRC project derived data was the relative shortness of its monitoring time-scale a each building had only 2-2.5 months of summer data collected. Furthermore, this monitoring of actual external temperature levels allowed the production of the proposed overheating guideline which took into account the internal-external temperature difference in its criteria.

8.2 DTM Modelling Stages

The physically monitored data was then used for comparison against predictions of internal air temperature made by dynamic thermal simulation. These dynamic simulation runs were made with consecutive increases in modelling complexity, this allowed for modelling stages of increasing complexity to be built up.

The dynamic thermal modelling methodology had no time-scale drawbacks given the 'repeatable' nature of the modelling exercise i.e. where one input/assumption can be altered with little additional effort. However, it is due to this ease of repeatability that the DTM process can become excessive. Were all minor changes to be modelled individually a vast number of DTM runs would be required. For example, for a model with just 5 alternative inputs this would require 120 runs to be conducted to gain all possible permutations (or 3,628,800 for 10 permutations). The thesis therefore used 10 variant models, however these changes are made incrementally from a basic model through to the most complex model. This incremental, step-wise raising of the level of complexity of the models was conducted to more accurately reflect the key determinants of overheating and the design methodology/thinking that would likely be conducted in practice. The modelling stages chosen were called the Basic, Simplistic, Complex and Sophisticated stages.

At the most Basic modelling stage the model formed represents the "quick and dirty" approach used to gain a quickly constructed, working model. The results gained from this modelling stage may vary widely from the later refinements as a generic weather file or a simplistic zoning process etc is used. The Basic model becomes the Simplistic stage model with the application of a more rigorous zoning method as a zone per discrete room is added and a meteorological file is used for the region/city in question. The modelling stage then becomes the Complex stage with the closer mimicking of the building's use. This is achieved by the modelling methodology rather than any change to inputs per se. Blinds are added to the model, as would be found in reality as occupants react to suffering from direct solar gain or annoying glare from strong, direct sunlight. In addition, the application of the lighting algorithm to control artificial lighting use could be seen to be a more realistic methodology than that of an all-lighting on/off system. A further refinement of the model is made as a window opening algorithm is applied (on the same time schedule) to attempt to maintain a set comfort temperature (22°C). Thus far, all the input data used (e.g. lighting levels, occupation levels etc) has not been changed per se, only the modelling methodology. To create the Sohisticated modelling stage the thesis used a 50% level of gain for both occupant gain and equipment gain. This percentage level used may be seen as a "guesstimate" that appears reasonable and was taken to negate the need to run many varying runs of 10%, 20%, 30% gain etc, as it is for use as a comparison purposes only, rather than a real design situation.

8.3 Summary of Results for DTM Comparison to Physically Monitored Data

Of the four guidelines using air temperature that were initially compared to the DTM data, the physical monitoring of the Barnardos building showed severe overheating by each measure used. This level of overheating was decreased in the Morgan Bruce building and was not at all evident in the MOD building.

- **The findings from the three Case Studies therefore indicate that the more simplistic the building design the more prone to overheating it is.**

Therefore as the incidences of overheating fell with additional model complexity the building's best replication by the DTM would be at three distinct modelling stages - Barnardos the most simplistic and MOD the most complex. However, this was better illustrated by the aggregation of data from the 5 overheating guidelines used. As shown on tables 6.1.1-6.1.3 and 6.2.1-6.2.3 in the Results section, this aggregation of data for the five guideline figures for air temperature and two for dry resultant temperature also revealed that the simpler designed buildings overheated more. In addition graph 6.3.1 revealed this level of overheating was correctly predicted by the DTM at an earlier modelling stage for the more simplistic buildings.

It can therefore be concluded that:

- **A poor building design's level of overheating is most easily detected by simple modelling methodology.**

- **An improved building design could be erroneously identified as being prone to overheating when a simplified modelling methodology is used. This mis-identification of overheating could lead to potential changes in the building design that would not be required.**

- **The more complex design of building required the more complex modelling stage was needed to best replicate the findings of the physical monitoring:-**

  The Barnardos building was shown to be best replicated by the Basic stage model.

  The Morgan Bruce building was best replicated by a modelling stage of greater complexity, the Simplistic stage.

  The MOD building was best replicated by the most complex modelling stage - the Sophisticated stage.

8.4 Proposed Overheating Guideline

After the initial attempt to compare the DTM runs against the physical monitored data, the thesis sought to provide a better method of gauging overheating for DTM simulation given its limitations due to its inherent assumptions that are required regarding the operation of the building and the external environment. The method chosen looks at one of the main indicators of building performance, the ΔT (delta T) i.e. the temperature difference in this instance for internal to external temperatures. Where a building can limit the ΔT it will more likely provide a more comfortable environment as it is hard to cool the building below ambient temperature conditions. Thus, if the building can remain within 2-3°C of external conditions this will provide a better indication of its performance, rather than that found when using an absolute value for a maximum allowable temperature (or even a design risk allowance for a maximum temperature).

With the latter examples the influence of external weather is great and will have had a key influence on predicted temperatures. For example, this problem would be noted for overheating guidance assessed by the PACE criteria as used in this thesis. The Government's own Property Advisers to the Civil Estate (PACE - thus in operation of charge of governmental buildings) have published their own internal guidance in "Requirements for Office Buildings" - a design risk of 240 hours per 10 years when an office/room is allowed to exceed 28 °C is given, thus 24 hours per annum regardless of the office location. Therefore, an office in Lerwick would have to perform to the same criteria as an office in Camborne, however it is more than likely that local weather file used for the Camborne will contain a significantly higher number of warmer hours than the Lerwick weather file (analysis of office hours alone reveals that only 1 hour reaches 17 °C for Lerwick but 325 hours are at this temperature on the Camborne EWY). A Camborne based office would therefore have great difficulty in reducing the ΔT to remain within the 24 hour design risk allowance whereas this would not be the case for the notional Lerwick office as significantly higher ΔTs could be allowed to form. This means that the Lerwick building could allow a greater build up of internal temperatures yet will still pass the PACE overheating guideline whilst the Camborne office may not. It is not difficult to see that a similar result would be found when applying the simplistic overheating guidelines (such as PACE used in the thesis) to office building designs in similarly disparate locations. However, ΔT is only one element of the proposed overheating guideline, as naturally a 5°C increase on an 18C external temperature would not create an uncomfortable internal temperature. Therefore, note is only taken of a ΔT greater than 3°C and when the external temperature is above 22°C - therefore only internal temperatures recorded above 25°C as a minimum will be recorded. Naturally, the weather file used may still have a large effect here, as a weather file with 200 hours above 22°C has twice the potential to create instances of overheating as a file with 100 hours greater than 22°C. Therefore, the proposed guideline criteria cannot overcome the effect had by the choice of meteorological file.

However, the proposed overheating guideline does not utilise absolute pass/fail temperature values as were found on the more simplistic TUC and USDAW recommendations. Instead it attempts to incorporate the improved elements of the PACE, CIBSE and BRECSU guidelines as it only takes into account operating time of the building and uses a design risk of 2.5% - typically 29 hours per annum where conditions are allowed to breach the guideline limits. This less simplistic guideline criteria should therefore not be as affected by short-lived instances of extreme internal temperatures, perhaps caused by a large increase in the external temperature or solar gain.

In the creation of these criteria the proposed overheating guideline sought to create an assessment value that would be more suitable for use with DTM simulation. This separate level of overheating assessment was sought as DTM simulation inherently requires that it must make use of assumptions in order to create the model. The proposed guideline should therefore seek to diminish the effect of these inherent estimations so that a closer DTM simulation of the building environment can be achieved at an earlier modelling stage.

8.4.1 Summary of Results for Proposed Overheating Guideline

The proposed guideline had some success in its aim as the three Case Study buildings showed a better resemblance to its physically monitored data at an earlier modelling stage. Therefore:-

- **The DTM models were brought closer to the environmental conditions found in reality via a simpler modelling set-up than previously seen with the use of existing overheating guidelines.**

  - **The Barnardos building revealed that the Basic model zoned on a room basis was the best fit.** (This was also found on the existing guidelines, however the number of rooms correctly concurring with the DTM rose.)
  - **The Basic model zoned on a room basis was also shown to be the best resemblance for the Morgan Bruce building** (a shift from the previously seen Simplistic modelling stage).
  - **The MOD building was also better replicated at an earlier modelling stage** (the Complex rather than the Sophisticated stage.)

These results indicate that to have a DTM simulation adequately replicate environmental conditions, a simple model can be applied as long as it is definitively zoned as found in the actual building and is assessed by the proposed guideline (with its emphasis on the internal to external temperature difference). Naturally, though the results clearly point to this fact this conclusion is hindered due to the small number of case studies used.

The proposed guideline was still able to point to the large effect of the chosen weather file on the models results. Despite the greater linkage of the results to the environmental control of the building rather than to an absolute temperature threshold the use of the Cardiff weather file ensures a major drop in predicted overheating in the Barnardos building. The same Cardiff meteorological file therefore has a large effect on the Morgan Bruce building also. Similarly, the use of the local (Bristol) weather data formed a large reduction in predicted percentages for the MOD building. Again this is due to the cooler conditions found on the Bristol EWY, for example 26 hours exceeding 22°C are seen on this weather file compared to 76 hours on the Kew 1967 weather file previously used.

However, another individual modelling change revealed some distinct differences where the proposed guideline was applied than was seen previously when the existing overheating guidelines were used. This was most notable where the window opening algorithm is applied. For example, in the Barnardos building no discernible change is noted as the overheating percentages found remain the same, yet this had a strong influence on the previous guidelines examined. Similarly, this change's effect was less pronounced in comparison to the effect seen previously in the MOD building - e.g. when assessing results on the CIBSE guideline a 9.73% increase in percentage time was found on zone 16 whereas this was just a 0.46% increase when the proposed guideline criteria was applied.

8.5 Future Scope for Research

Whilst the above results show definite trends, such as the greater overheating in the simpler buildings, there is also scope for this research to be improved upon if it were to be continued. Firstly, the thesis' use of the EPSRC data for the physical monitoring results was fit for purpose, however the modelling methodology would have changed greatly were the physical monitoring to have been an integral part of a similar research project. Naturally, the coverage of the data-logging positions would have been different were the physical monitoring procedure designed explicitly for the thesis. Whilst this was deemed adequate for the EPSRC project, ideally the physical monitoring of the buildings would have been more long term, perhaps a full 6 months summer from April to September, the same inclusive as this is the length of weather data deemed to represent a 'design summer'.

Ideally, a greater number of monitoring positions would also have been provided in each building so that not only every floor but also every orientation of room could be covered per floor. However, this restriction was not caused by the thesis' methodology as suitable physical monitoring data had to be found for use whilst the cost of gaining this data is great. Physical monitoring on the scale proposed and also as completed by the EPSRC project is a very large undertaking that requires many working hours to produce and requires a massive amount of data logging equipment to be used. Naturally, data logging even three buildings becomes a very expensive undertaking in time and financial terms, therefore such large scale monitoring is out of the scope of most projects with the exception of the larger, funded research projects (such as the EPSRC's project to provide guidelines for natural ventilation used here). This cost meant that it was only feasible to use the EPSRC data for the physical monitoring of the Case Study buildings rather than conduct monitoring solely for the thesis.

Ideally the number of Case Study buildings would also have been greater. Though the thesis compares three buildings, highlighting three distinct levels of design, only one building was available per 'level of design' category. The confidence in the results would therefore have been greater were two or three buildings used for each level of building design. However, the 2-3 fold increase in the number of Case Study buildings would lead to a 2-3 fold increase in the physical monitoring and DTM simulation required. Physical monitoring of 9 buildings would be an extremely costly exercise and likely to be out of the scope for a Ph.D. thesis, whilst the proposed threefold increase in the

DTM simulation required, and more importantly the later analysis of results, would also be huge rise in time costs.

As the Literature Review revealed, the use of DTM simulation in building design is likely to greatly increase due in part to its promotion for use in fulfilling the part L2 commitment of the UK Building Regulations by creating a "carbon emission method" model. Furthermore, user reluctance will decrease with time as DTM is seen to have had use in prior building projects and its benefits from these are promoted. With this likely increase in use it is important for the design industry to publish suitable guidelines for a designer/modeller so that they may best conduct a DTM simulation. Though in comparison to standard manual calculation methods DTM is still in its infancy, some guidelines are available, such as in CIBSE AM11 "Building Energy and Environmental Modelling"(1), however this does not answer all possible queries. For example, it would be helpful to have advice on creating a truly dynamic profile of occupancy to more correctly model this, as it occurs in the modern office environment. This would counter the estimation made and thus possible error for flexi-time office use for instance, where a building may have a longer working day than standard but staff maintain a 40 hour working week. Even on simpler examples such as assumed summer-time occupancy, as a larger amount of staff holiday leave is taken at these times, better guidance figures would be useful. Furthermore, the level of personal equipment gain is also tied to occupancy and therefore guidance on estimating correct occupancy levels would also lead to the application of more realistic levels of equipment use. Whilst some studies have been undertaken (and advice shown in CIBSE AM11) guidelines for creating a realistic level of occupancy across the working day taken from a number of verified field studies is needed. In the thesis, a more definitive study could have been made between what became the Complex and Sophisticated modelling stages - for instance one using 100% occupant and equipment gains as before but the latter using verified "realistic working levels".

Further guidance could also be useful in applying blinds to the DTM simulation as their use is currently linked to solar gain levels on the window in question, in reality occupant behaviour will also triggered by glare and privacy issues. However, the application of the window opening algorithm and the control algorithm for artificial lighting in the thesis are suitable methods for mimicking occupant behaviour and the use of auto-dimming features on modern luminaires. The modelling assumption that will have a major effect on DTM simulation is the application of the weather file. Whilst this has been the source of much research further weather data itself and advice in its application is needed. In the thesis the DTM attempted to simulate the Case Study building performance in a typical year thus a comparison to a semi-extreme weather file was not needed. However, these file types (Design Summer Years) are only available for 3 UK sites and only 16 Example or Test Reference Years (from CIBSE) cover the UK. Meteorological data should be available for more locations and for varied conditions (e.g DSY and average years) to aid the creation of the DTM model. For example, in the thesis Kew (London) and Bristol data was easily available in the CIBSE Example Weather Year format, however the Cardiff data had to be created using data gathered elsewhere. Ideally, the weather data would have been readily available for all locations used in the thesis, whilst this would not have countered the effects of micro-climate, the model would have been assured of using the site/city specific data that would also have been used by another DTM simulation of a building in the same location.

A bigger aid to the thesis would have been created if a clear definition of overheating existed. This will also help future design projects as studies suggest that the incidence of warm summers will become greater in the future. In the CIBSE TM34(2) "Weather Data with Climate Change Scenarios" it noted that 2830 cooling degree hours (at an 18°C base) were found for Heathrow for averaged 1970's data, this rose by 84% for predicted levels in the 2020s, 177% by the 2050s and 310% by the 2080s (thus creating 11,614 cooling degree hours). With such a significant predicted rise in temperatures, the quantification of overheating and its simulation by dynamic thermal modelling will become more important over time as designers seek to continue providing acceptable internal conditions by passively the main building. As CIBSE TM 36 "Climate Change and the Indoor Environment"states (3)

> "It is probable that future Building Regulations will require engineers and architects to demonstrate the need for mechanical cooling and air conditioning. In that case it will be essential that the industry has:
>
> - appropriate overheating risk criteria
> - a standardised calculation method so that all designers can obtain the same predictions
> - standardised climatic data"

In the UK there is no universally accepted overheating standard that can be applied for office buildings, as TM 36 points out "in the UK thermal performance targets for offices and many other building types are decided upon on a project by project basis, through discussion between the design team and the other building stakeholders." Therefore, the results of thesis simulation could only be initially applied to existing criteria from guidance notes such as the BRECSU dry resultant temperature criteria. A significant threshold overheating value will be more greatly needed in the future if the predicted climate change comes to pass. – for example, CIBSE TM36 created a DTM model of a 1960's naturally ventilated office building and predicted that it would already fail the modern day BRECSU criteria of a 1% design risk of 28°C being exceeded. Using predicted 2080 weather data the DTM predicted that nearly 25% of occupied hours would be over 28°C. Furthermore, a significant proportion of the summer's external air temperatures were predicted to exceed those desirable for comfort within the building. Therefore, with the potential changes due and given that a modern building design is intended for 25-40 years of occupation, the quantification of exactly what constitutes overheating is needed immediately plus adequate weather data to simulate varying locations and future climate trends. Only with this available data and given criteria to work to can the DTM simulation hope to aid the creation a building with a reasonable longevity of use. Were a universally agreed overheating criterion available, the thesis results would have had an easier interpretation as they would also have followed the overheating criteria to which all other DTM studies are assessed.

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Appendices

A1.0 Barnardos Offices, Cardiff - Case Study Building

A1.1 Building Images

North Facade of Building

South Facade of Building

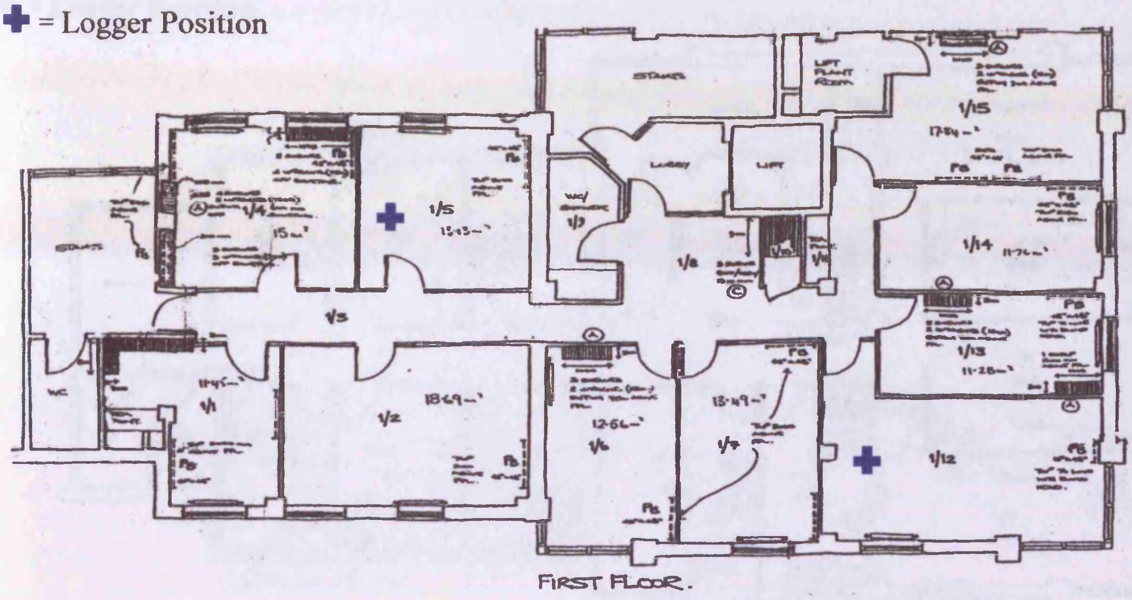
Conference Office - 4th Floor

2-3 Occupant Cellular Office

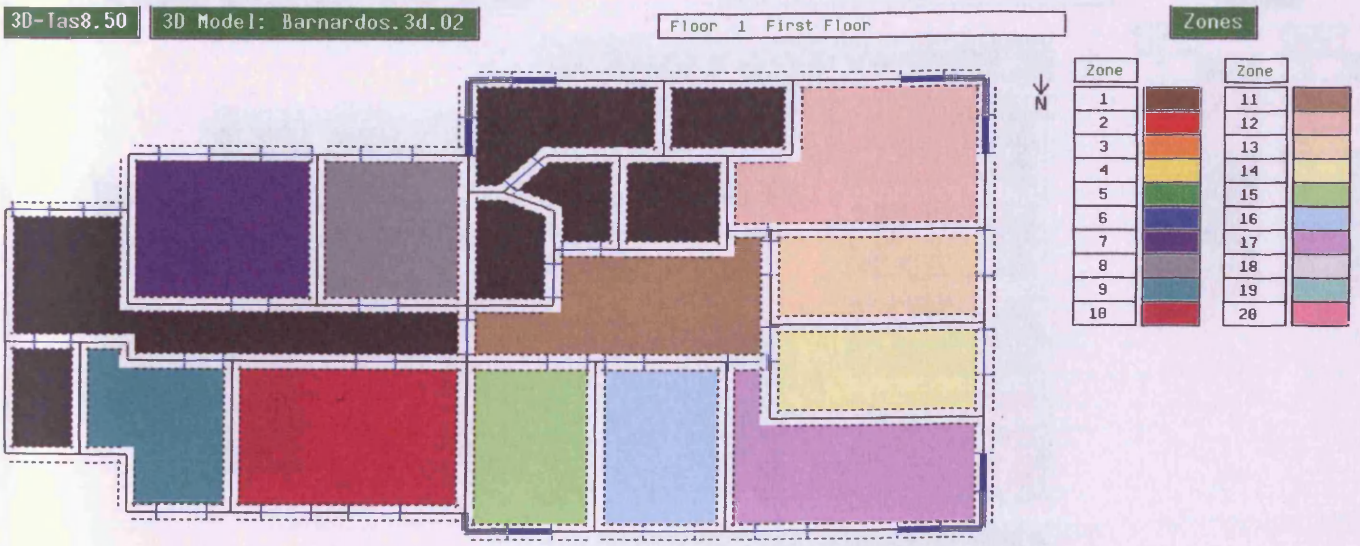
A1.3.1 Building Floorplans (not to scale) and DataLogger Positions

First Floor

✚ = Logger Position



A1.3.2 TAS Zoning - First Floor



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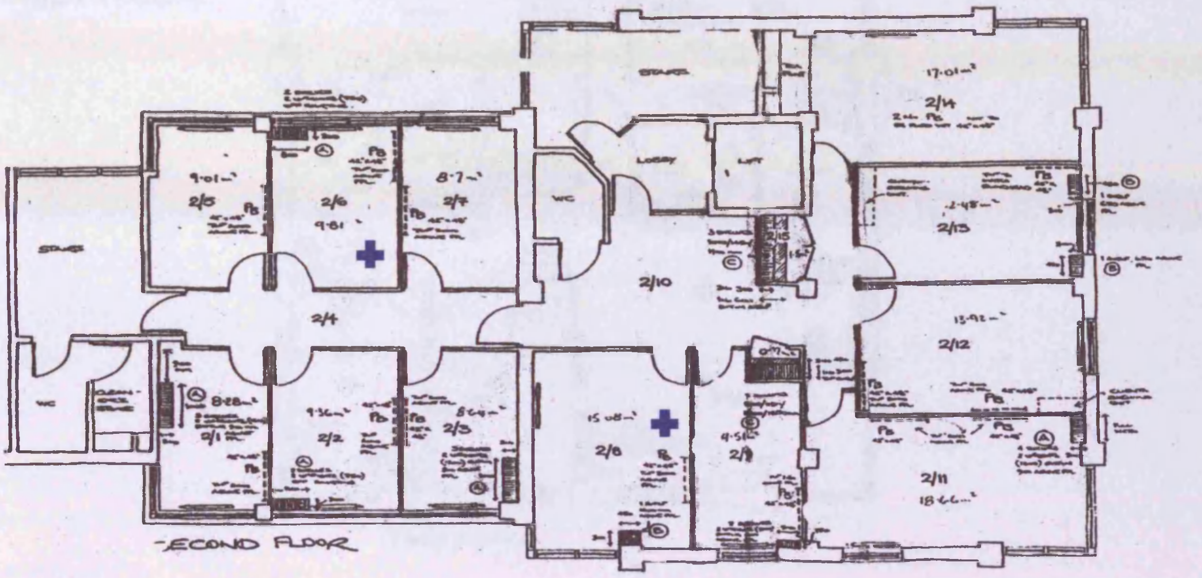
2	🟥	12	🟥
3	🟧	13	🟧
4	🟨	14	🟨
5	🟩	15	🟩
6	🟦	16	🟦
7	🟪	17	🟪
8	⬜	18	⬜
9	🟦	19	🟦
10	🟥	20	🟥

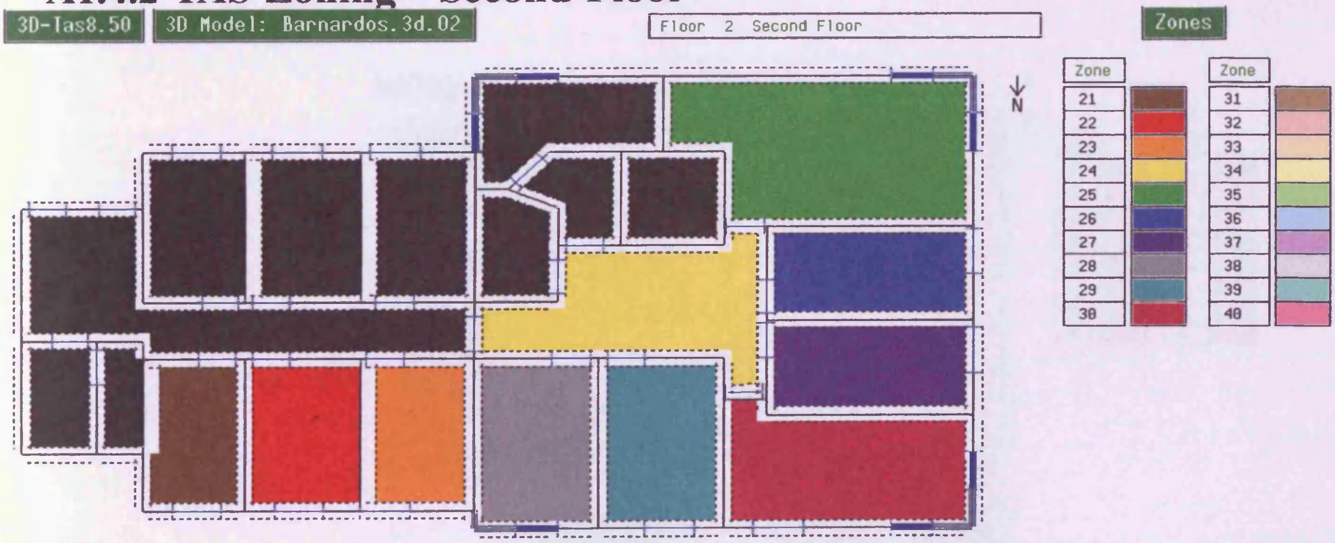
A1.4.1 Building Floorplans (not to scale) and DataLogger Positions

Second Floor

✚ = Logger Position



A1.4.2 TAS Zoning - Second Floor



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24	🟨
25	🟩
26	🟦
27	🟪
28	⬜
29	🟦
30	🟥

Zone	
31	🟫
32	🟥
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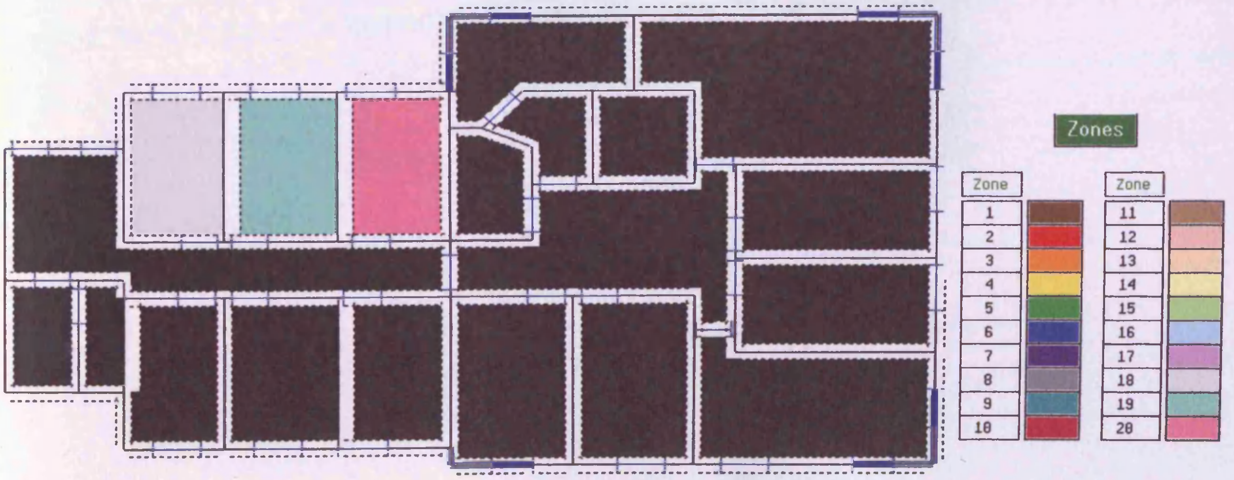
38	⬜
39	🟩
40	🟥



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7	🟪
8	⬜
9	🟦
10	🟥

Zone	
11	🟫
12	🟥
13	🟧
14	🟨
15	🟩
16	🟦
17	🟪
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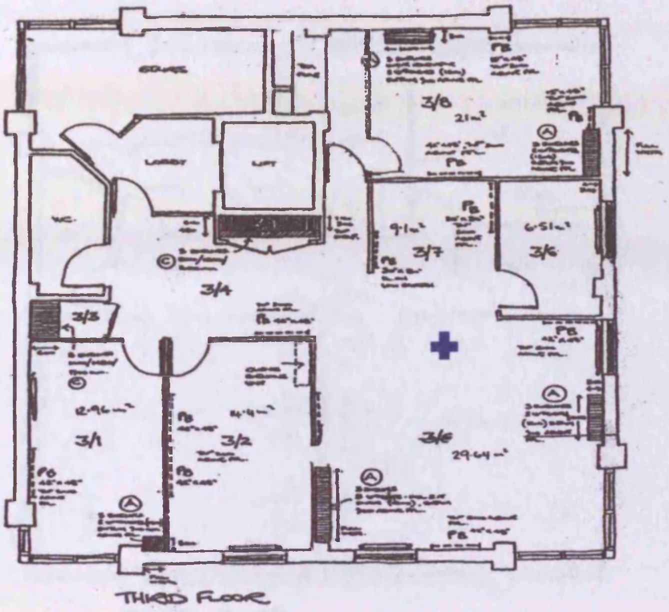
19	🟩
20	🟥

A1.5.1 Building Floorplans (not to scale) and DataLogger Positions

Third Floor

✚ = Logger Position

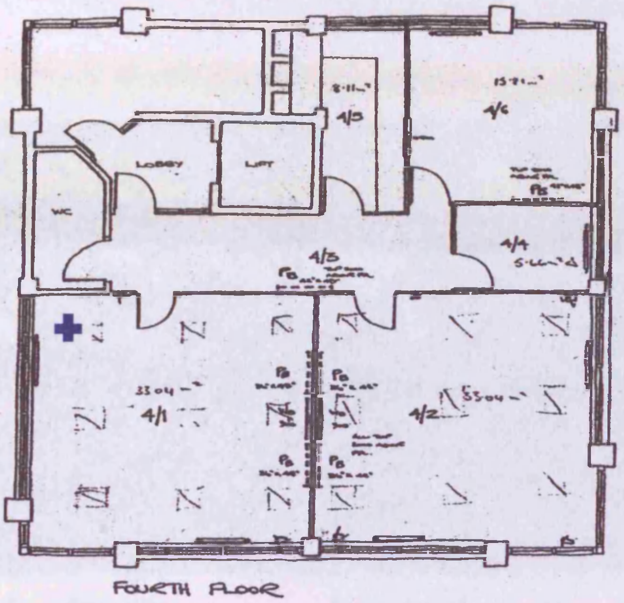


A1.5.2 TAS Zoning - Third Floor

A1.6.1 Building Floorplans (not to scale) and DataLogger Positions

Fourth Floor

✚ = Logger Position



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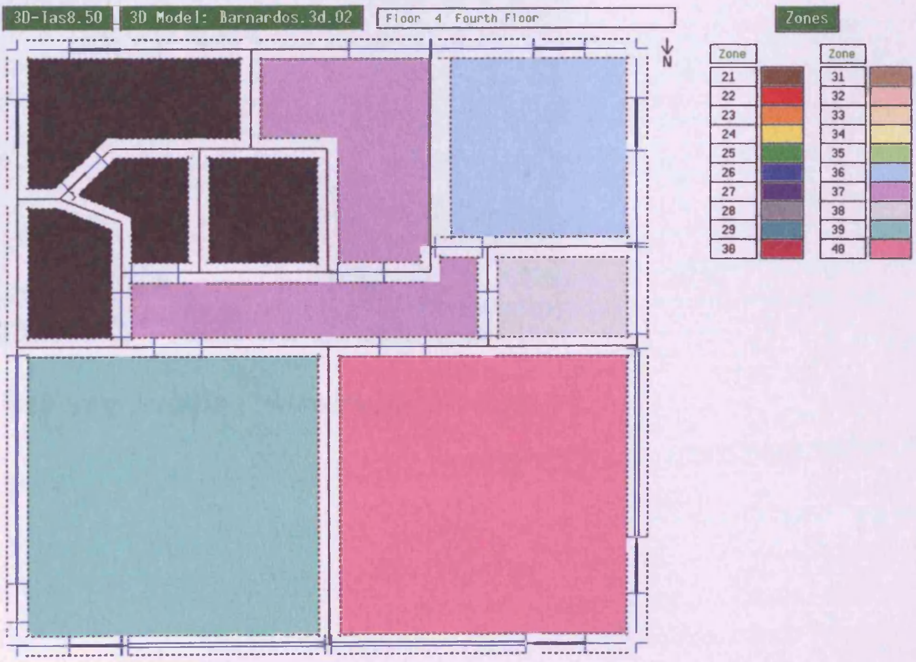


A2.0 Morgan Bruce, Cardiff - Case Study Building

A2.1 Building Images

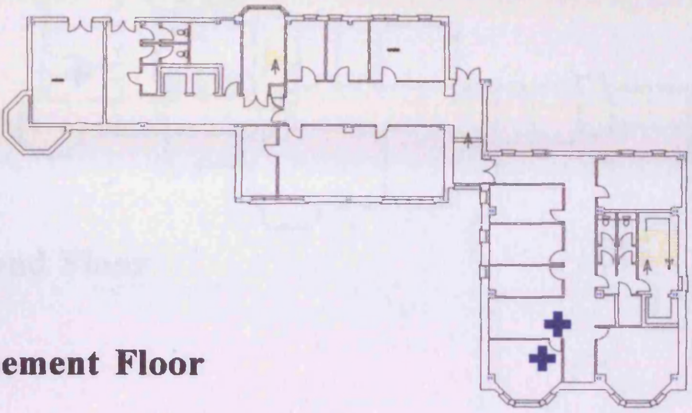
New Building - West Facade of Building

New Building - East Facade of Building

Link to Existing Building (retained, older facade)

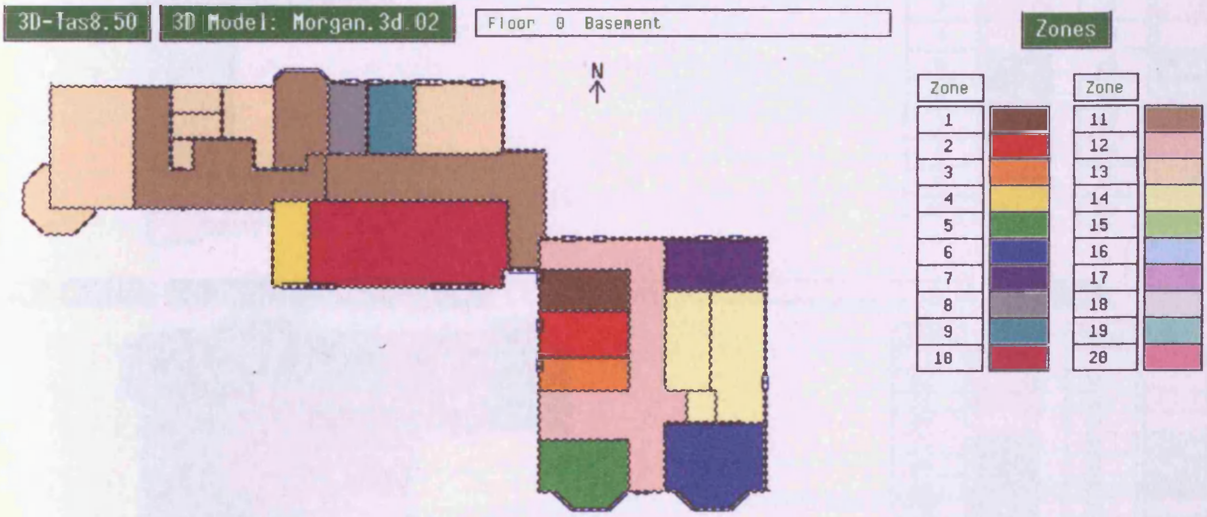
A2.1.1 Building Floorplans (not to scale) and DataLogger Positions

✚ = Logger Position

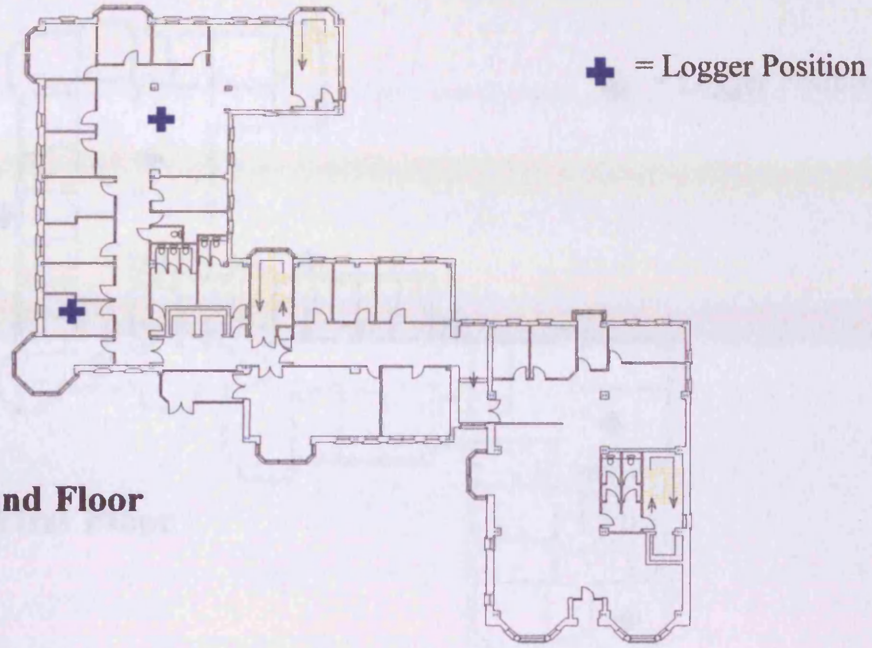


Basement Floor

A2.1.2 TAS Zoning -basement Floor

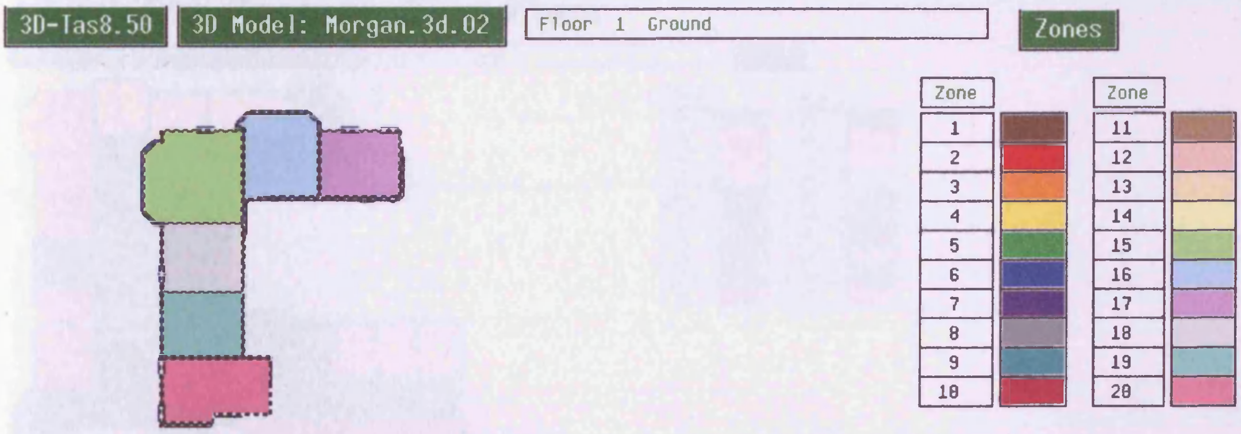


A2.2.1 Building Floorplans (not to scale) and DataLogger Positions



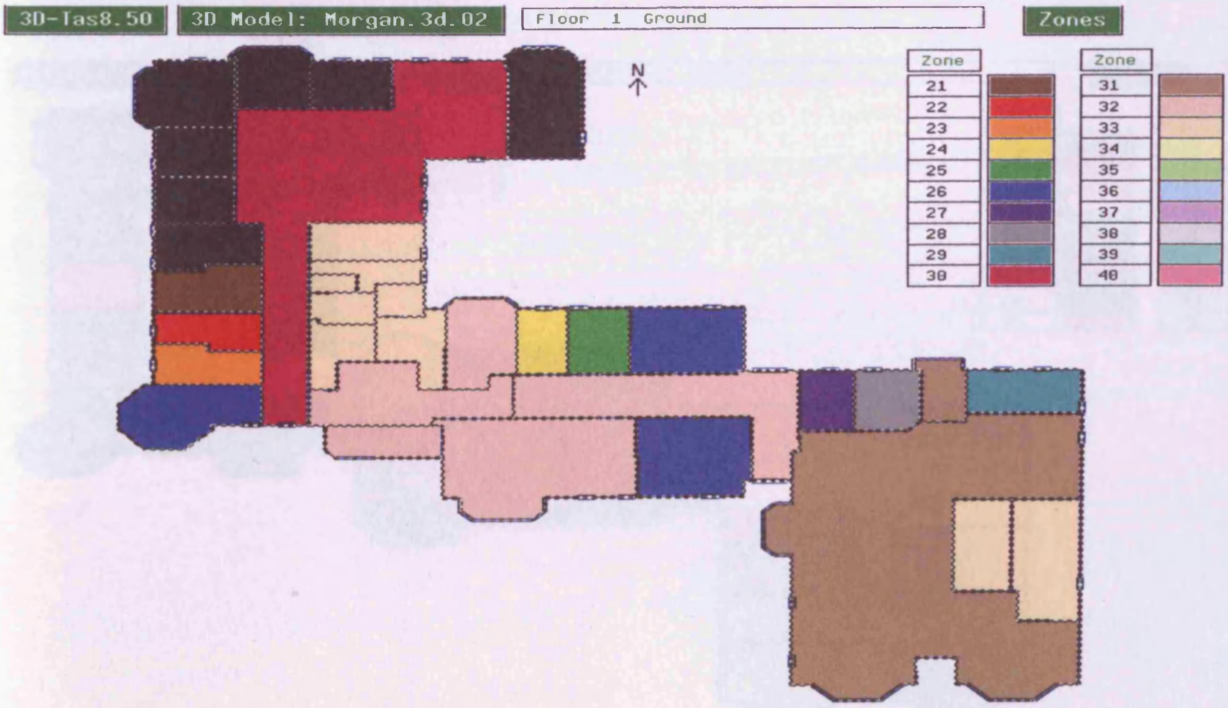
Ground Floor

A2.2.2 TAS Zoning - Ground Floor



3D Model: Morgan.3d.02

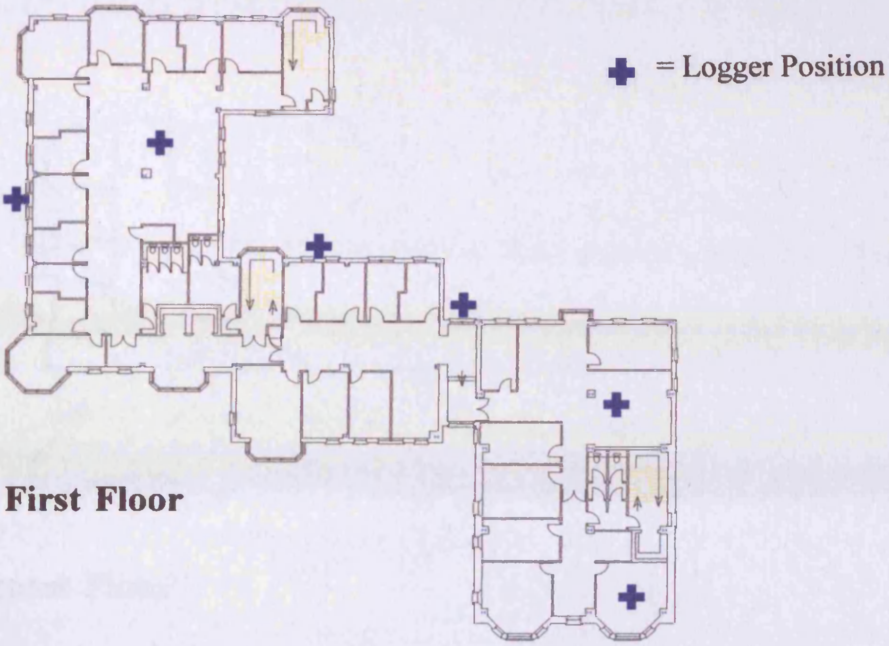
Floor 1 Ground



3D Model: Morgan.3d.02

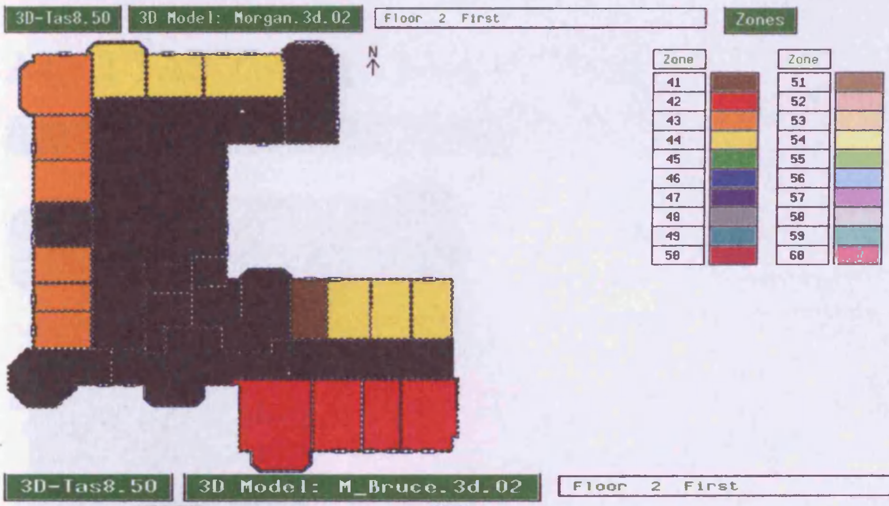
Floor 1 Ground

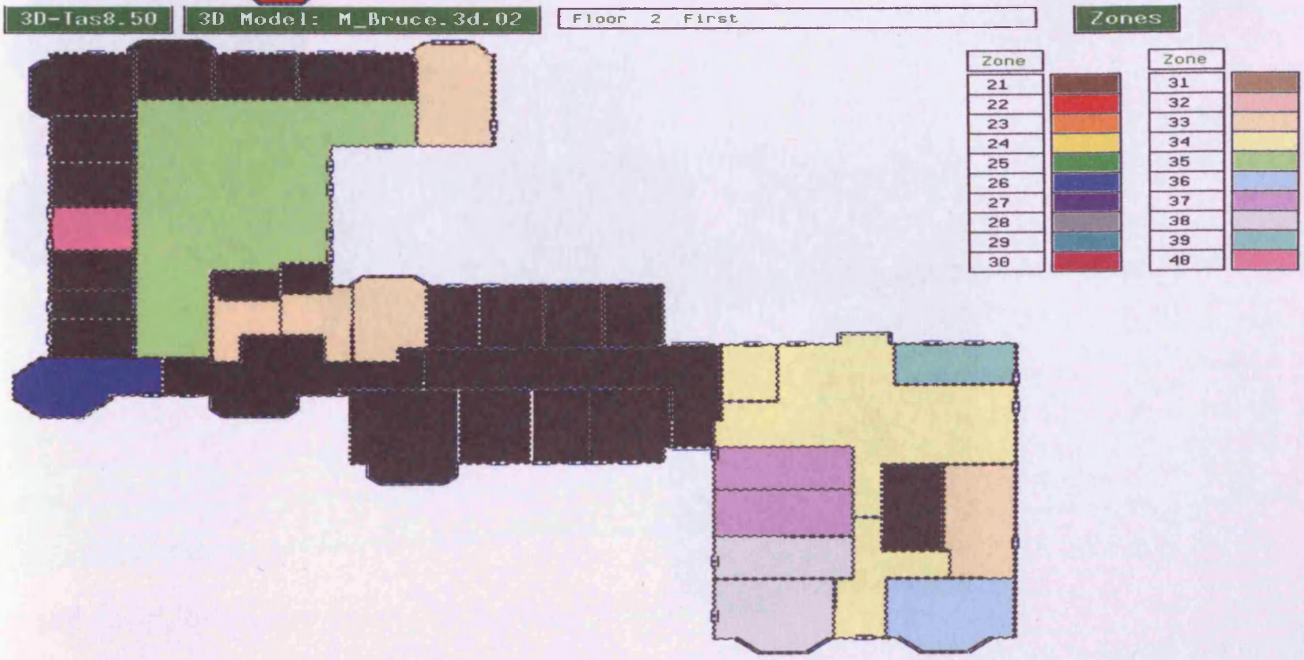
A2.3.1 Building Floorplans (not to scale) and DataLogger Positions



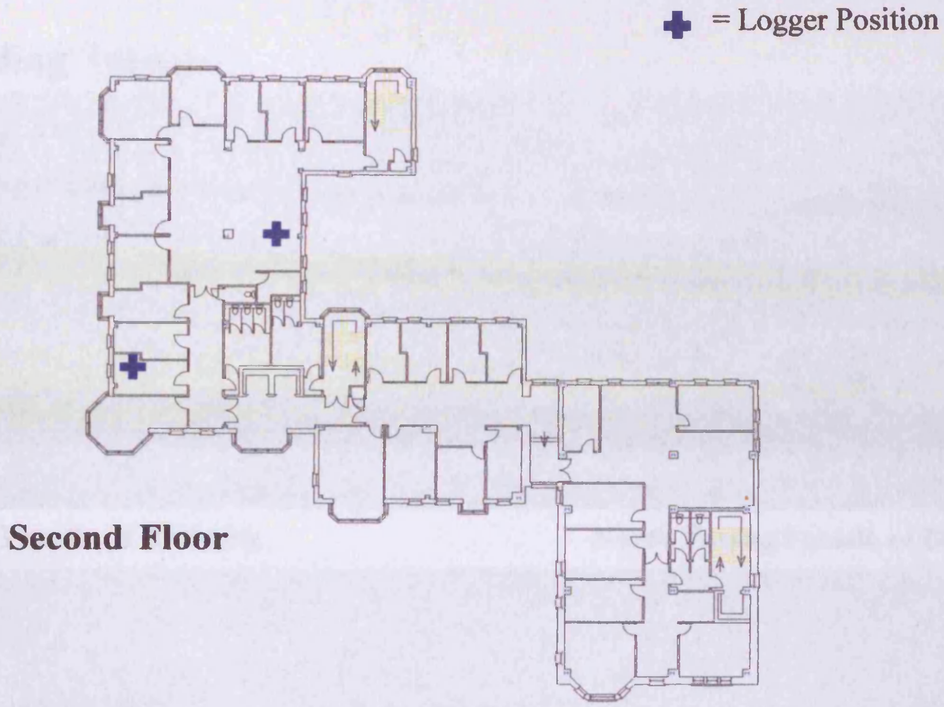
First Floor

A2.3.2 TAS Zoning - First Floor





A2.4.1 Building Floorplans (not to scale) and DataLogger Positions



A2.4.2 TAS Zoning - Second Floor

A3.0 MOD Procurement, Bristol - Case Study Building

A3.1 Building Images

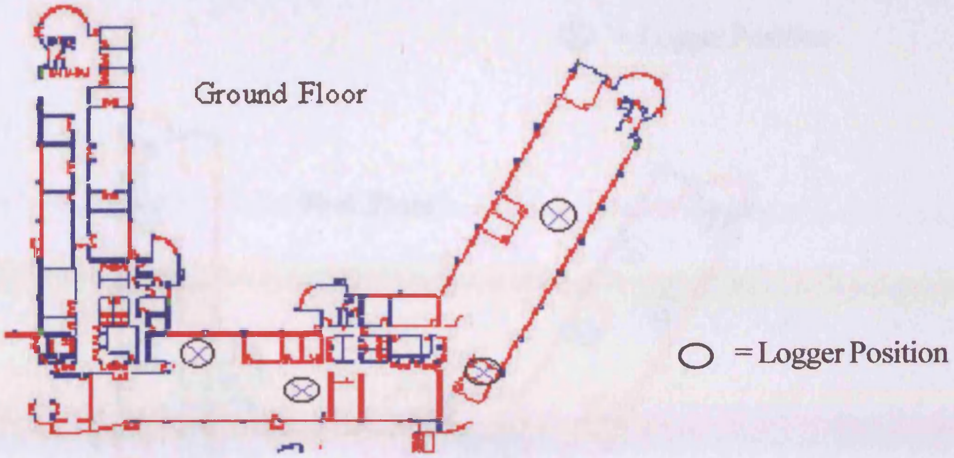
South Facing Facade of Building

North Facing Facade of Building

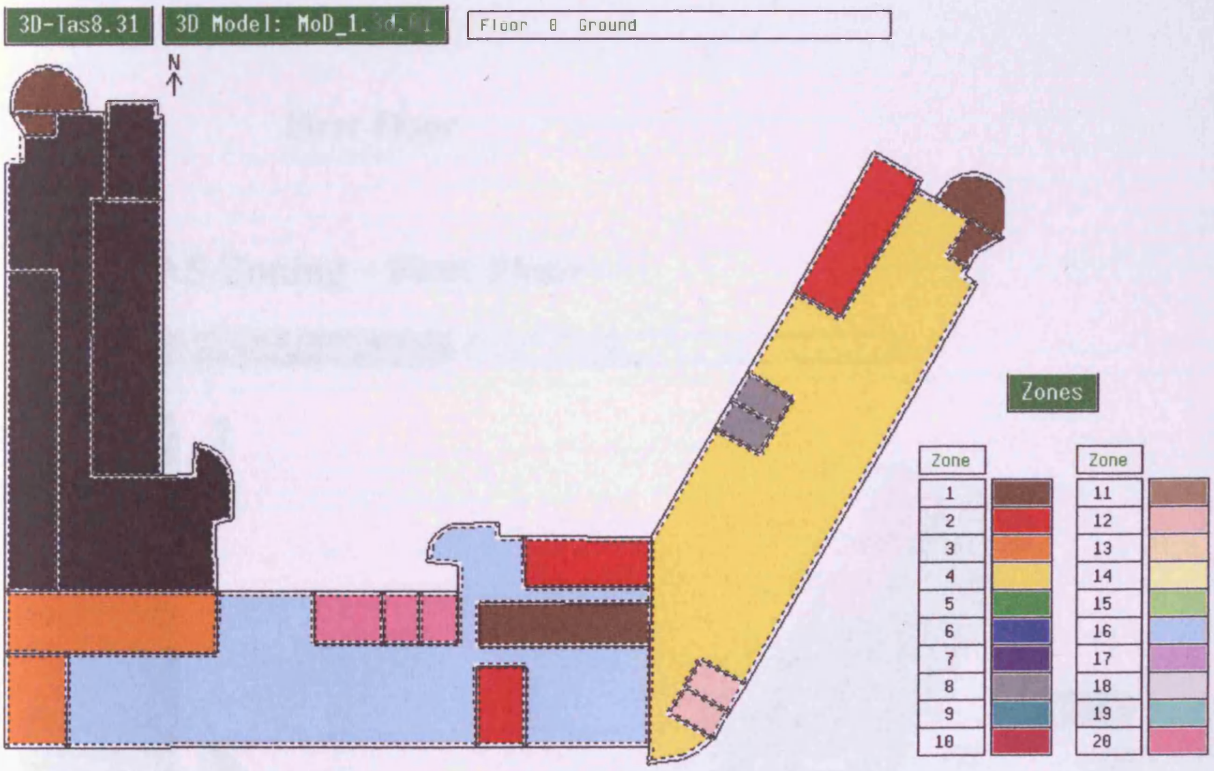
Central Section of Building

Main Open Plan Office Spaces - Views along width and length of 2nd floor

A3.1.1 Building Floorplans (not to scale) and DataLogger Positions



A3.1.2 TAS Zoning - Ground Floor



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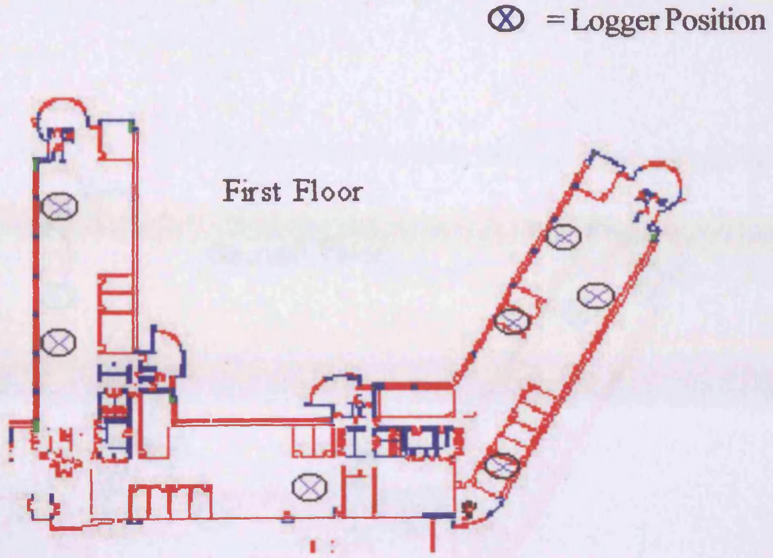
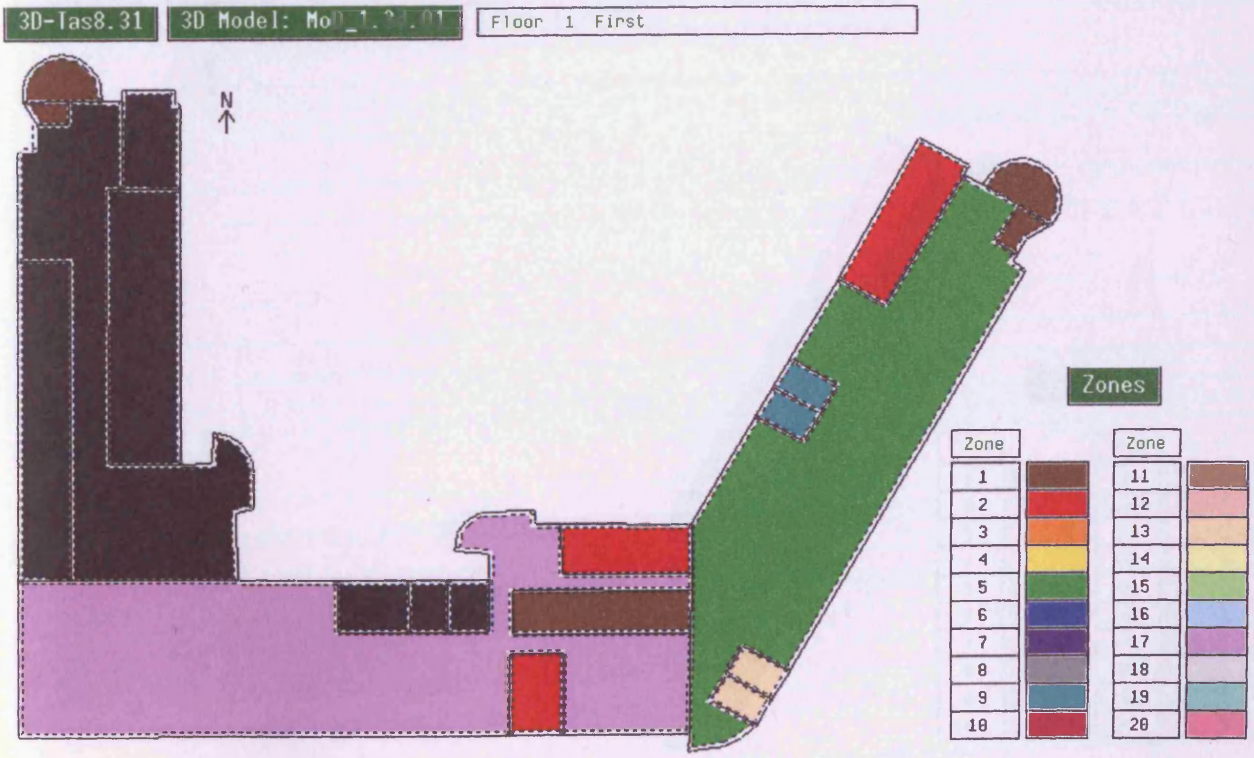


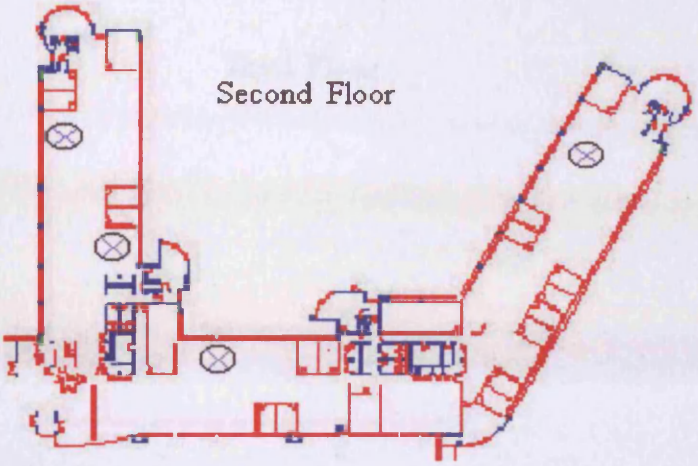
First Floor

A3.2.2 TAS Zoning - First Floor



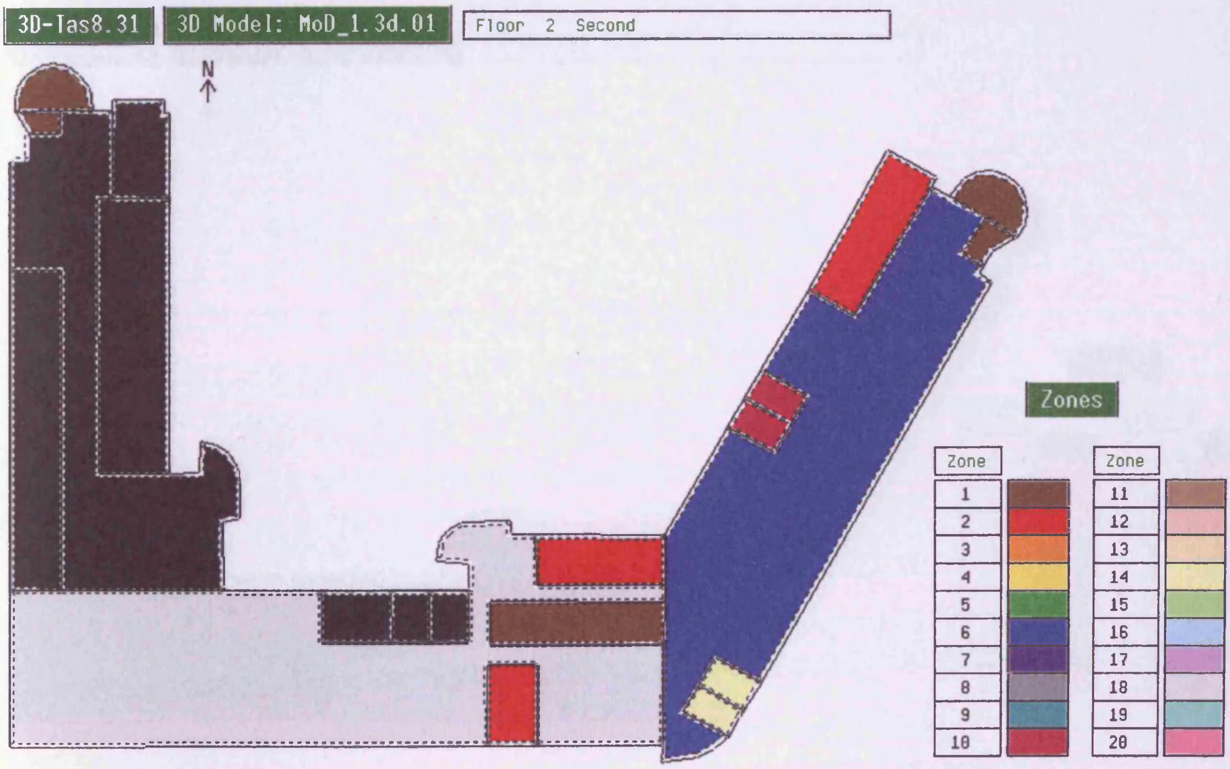
A3.3.1 Building Floorplans (not to scale) and DataLogger Positions

⊗ = Logger Position



Second Floor

A3.3.2 TAS Zoning - Second Floor



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8	⬜	18	⬜
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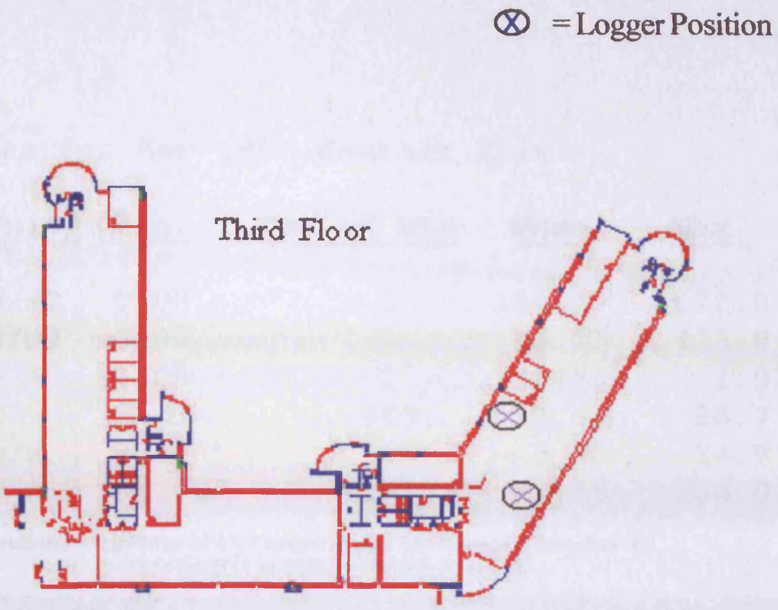
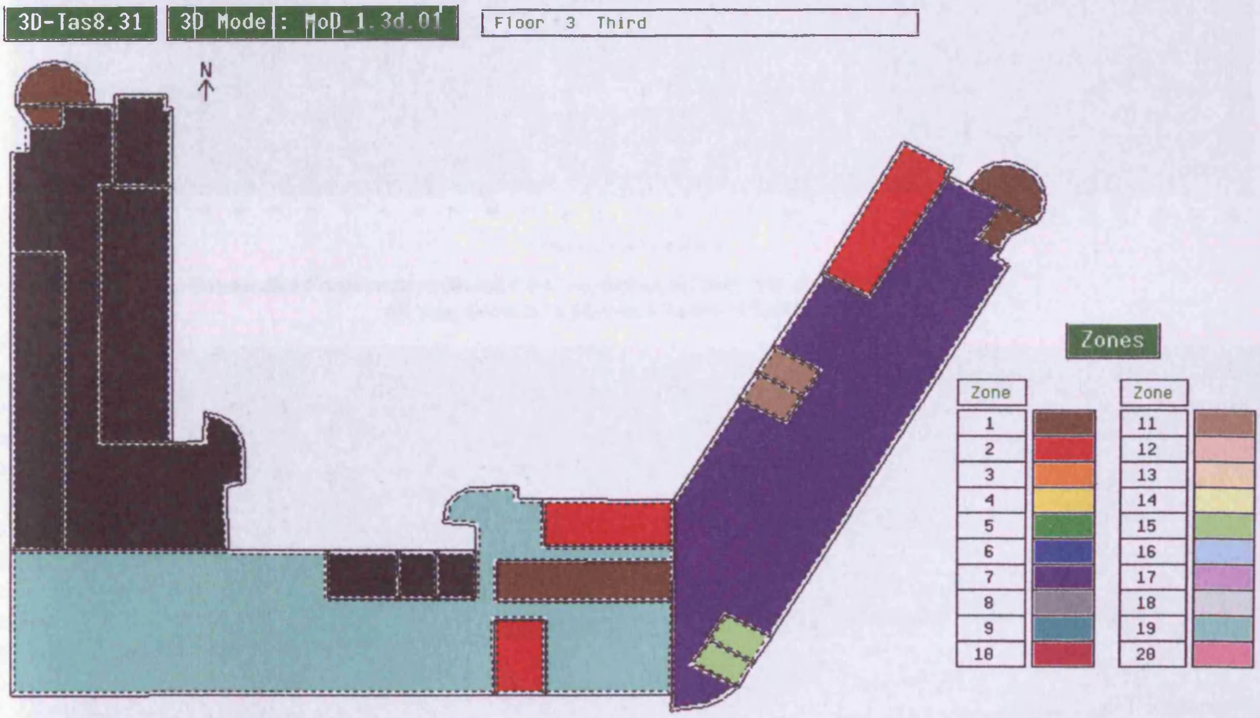


Third Floor

A3.4.2 TAS Zoning - Third Floor



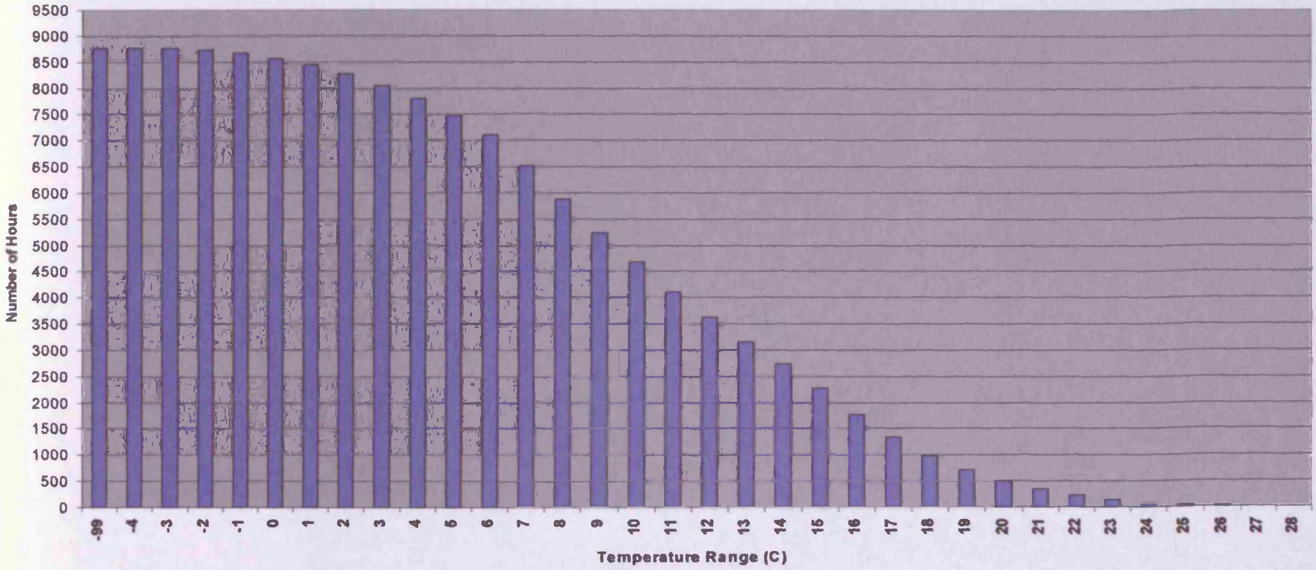
A4.0 TAS Dynamic Thermal Modelling Weather File Data

A4.1 Kew, London 1967 - Entire Year

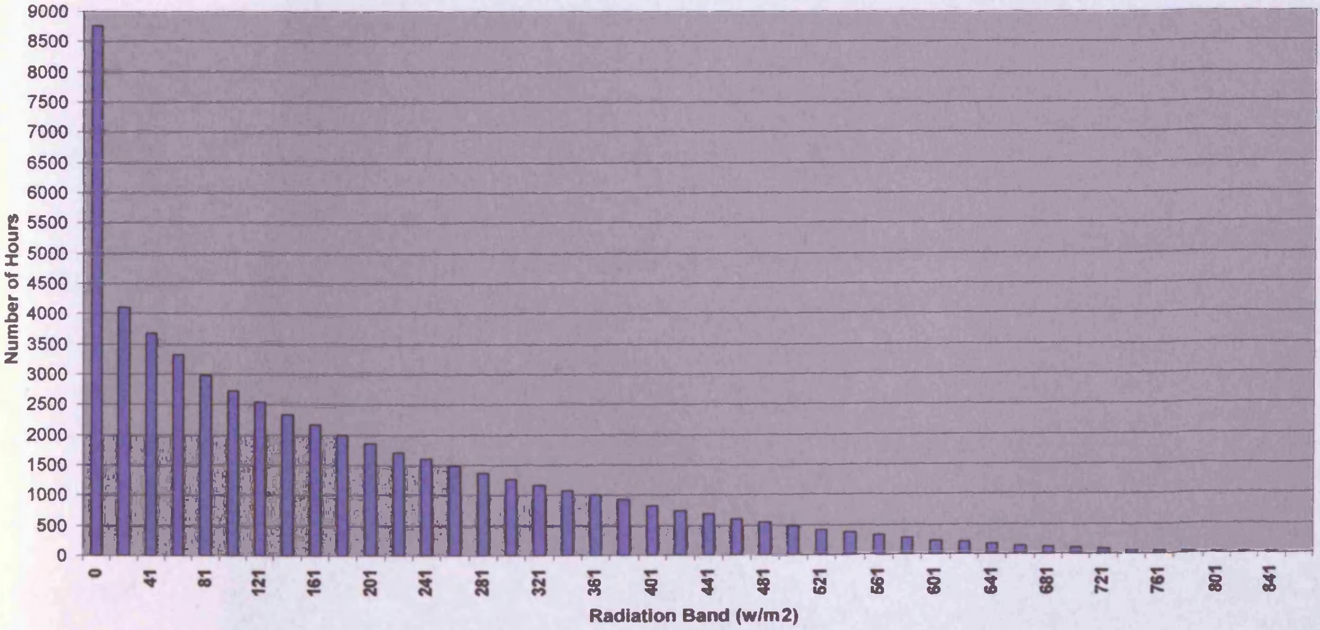
Statistics for Kew 1967 Weather File

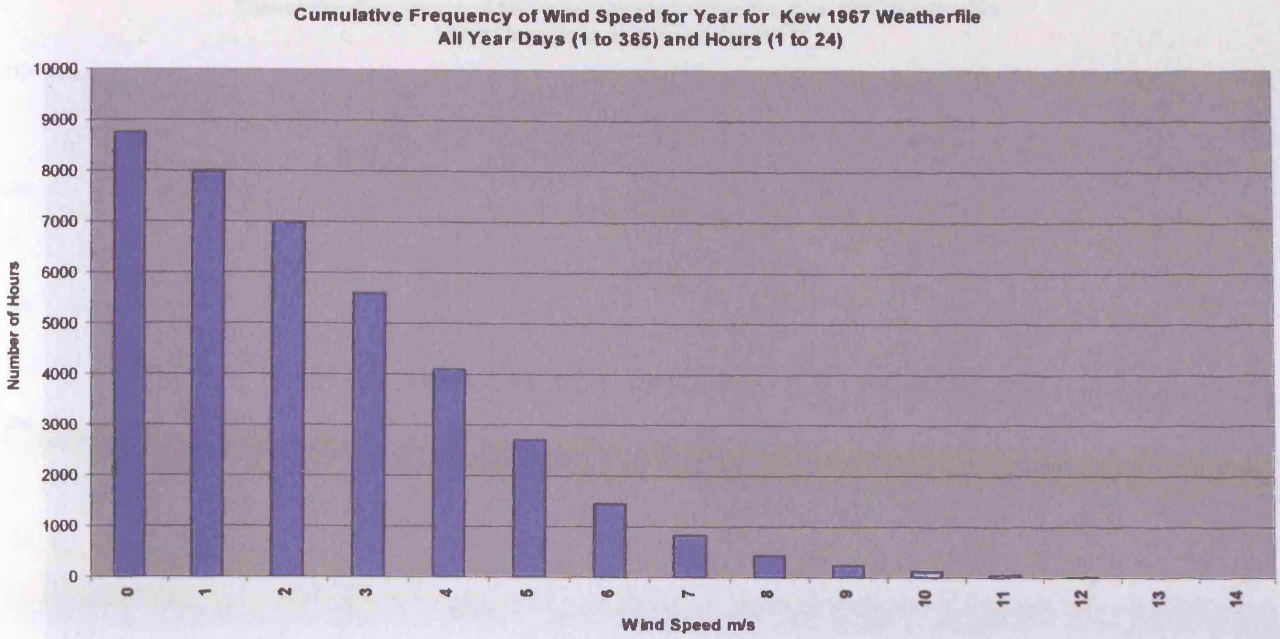
Variable	Units	Min.	Day of Min	Mean	Max.	Julian Day of Max
Global solar	W/m2	0.00	1	110.17	872.0	167
Diffuse solar	W/m2	0.00	1	63.23	473.0	210
Cloud Cover	-	0.00	1	0.64	1.0	4
Air Temp.	C	-5.20	343	10.83	28.7	198
Wind Speed	m/s	0.00	26	3.93	14.7	290
RH	%	24.00	165	77.15	100.0	31

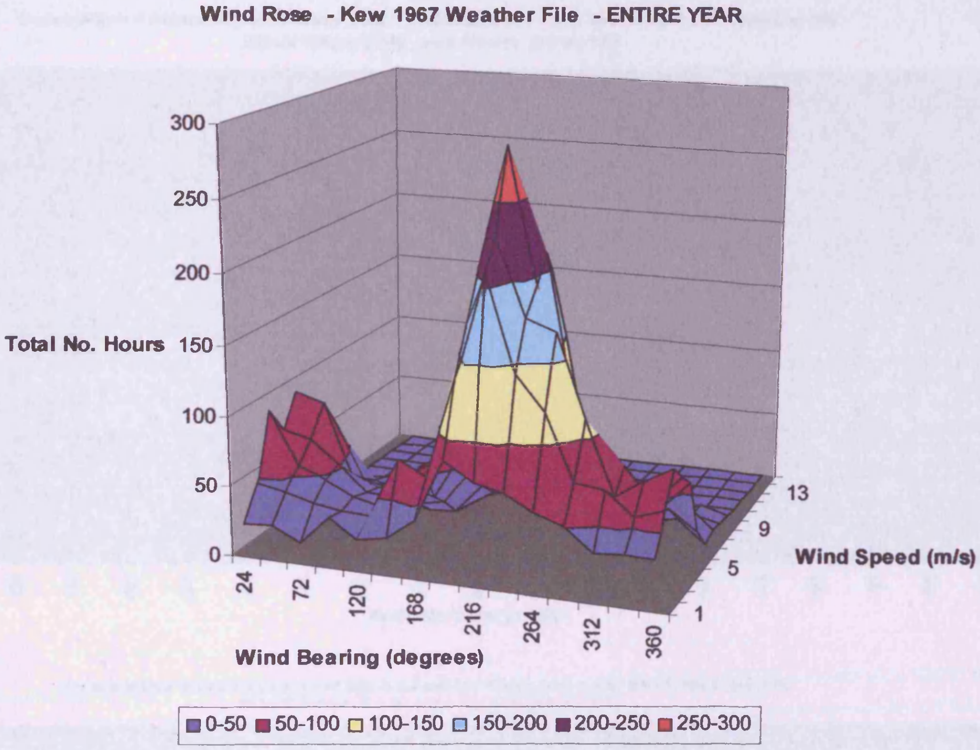
Cumulative Frequency of Air Temperatures for Kew 1967 Weatherfile
All Year Days (1 to 365) and Hours (1 to 24)

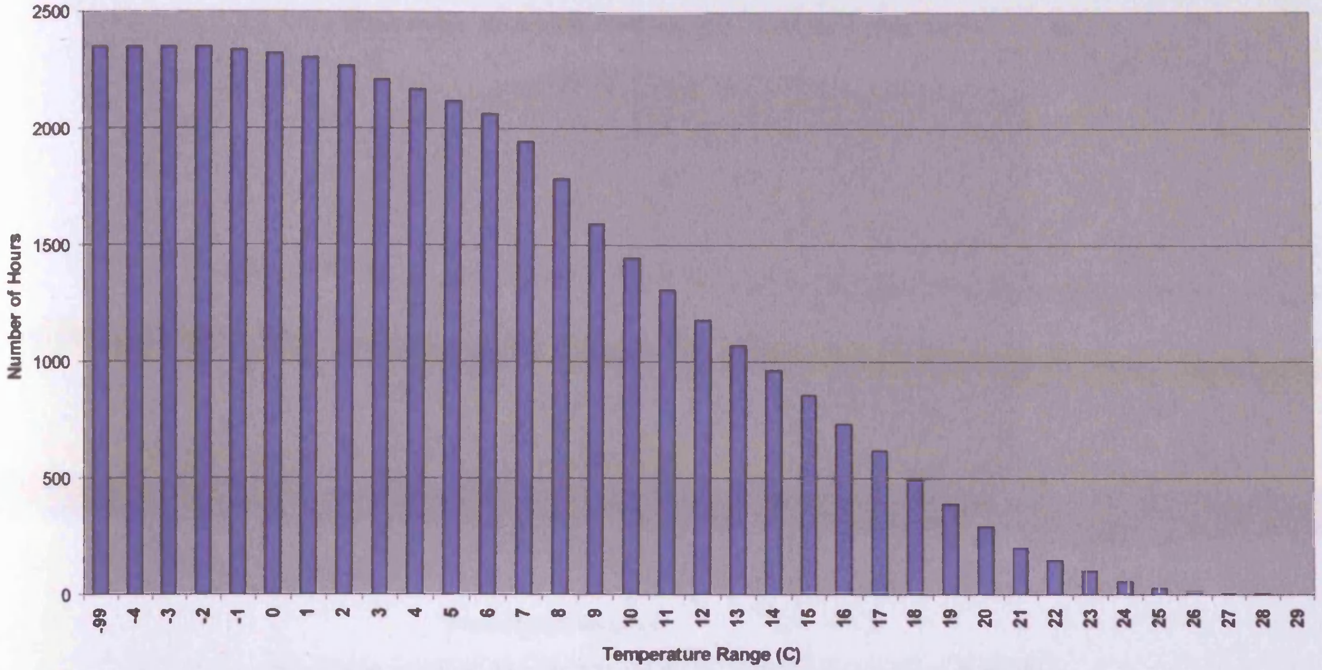


Cumulative Frequency of Global Solar Radiation for Year for Kew 1967 Weatherfile
All Year Days (1 to 365) and Hours (1 to 24)

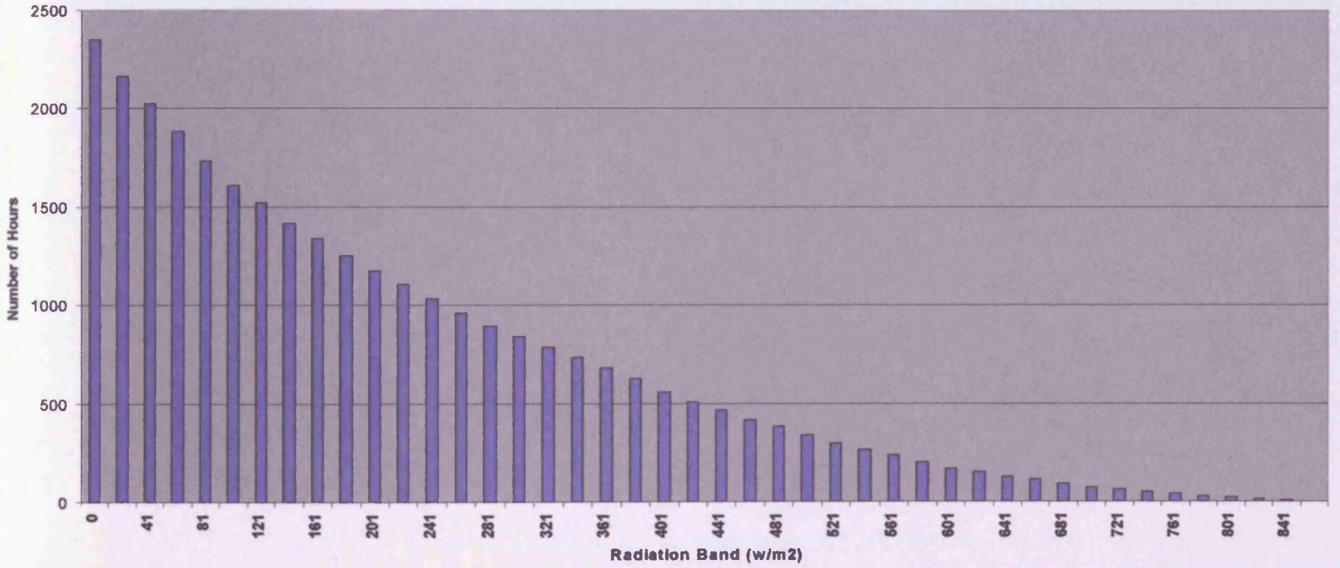



Cumulative Frequency of Wind Speed for Year for Kew 1967 Weatherfile
All Year Days (1 to 365) and Hours (1 to 24)
Number of Hours
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
Wind Speed m/s

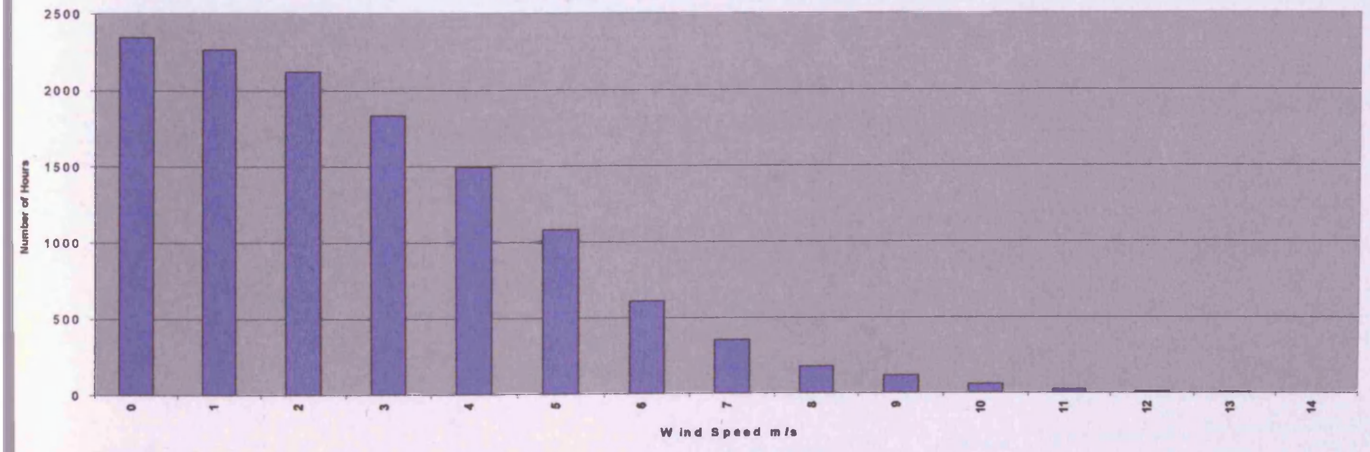

Wind Rose - Kew 1967 Weather File - ENTIRE YEAR
Total No. Hours
300
250
200
150
100
50
0
24
72
120
168
216
264
312
360
Wind Bearing (degrees)
13
9
5
1
Wind Speed (m/s)
0-50
50-100
100-150
150-200
200-250
250-300



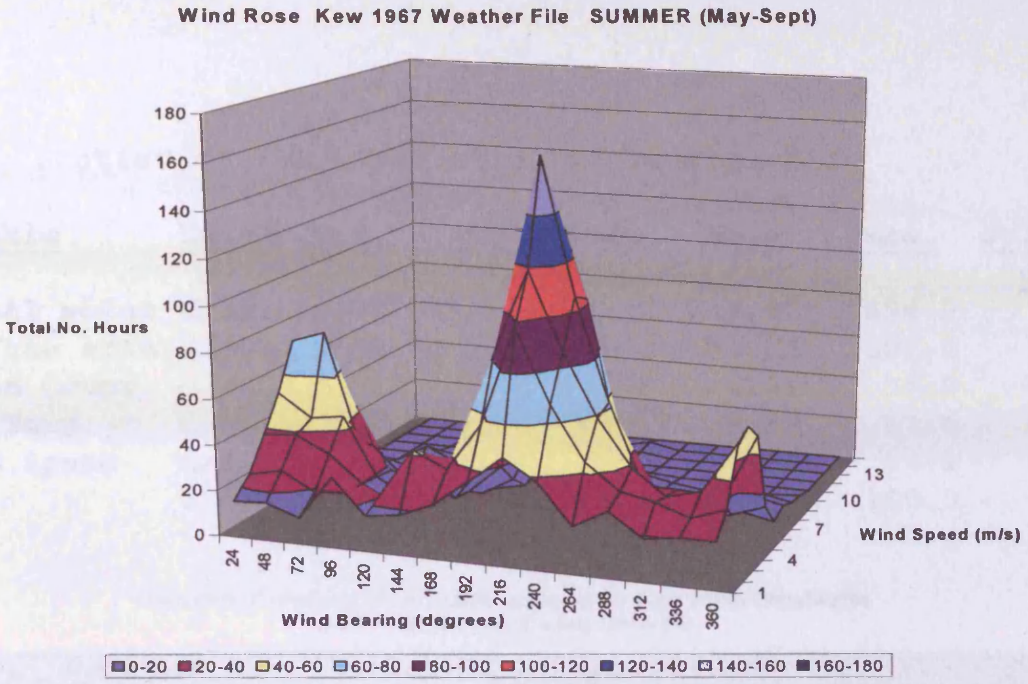
Cumulative Frequency of Air Temperatures for Yearfor Kew 1967 Weatherfile
Week Days Only and Hours (09 to 17)



Cumulative Frequency of Global Solar Radiation for Year for Kew 1967 Weatherfile
Week Days Only and Hours (09 to 17)



Cumulative Frequency of Wind Speed for Year for Kew 1967 Weatherfile
Week Days Only and Hours (09 to 17)

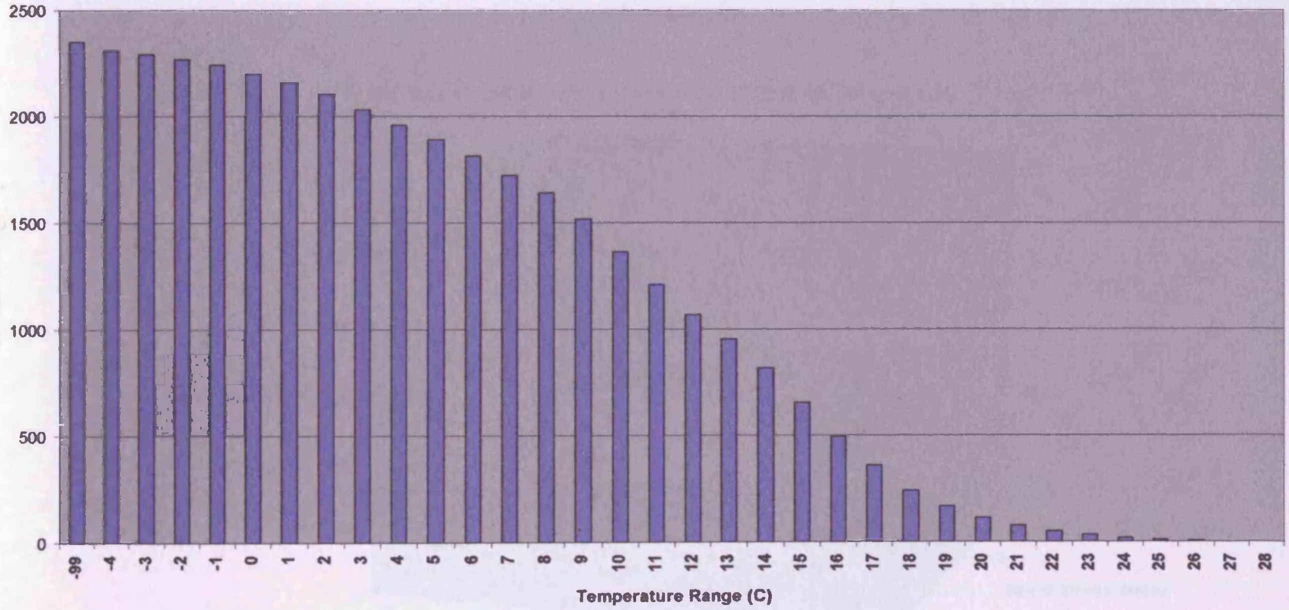

Wind Rose Kew 1967 Weather File SUMMER (May-Sept)

A4.2 Bristol - Entire Year

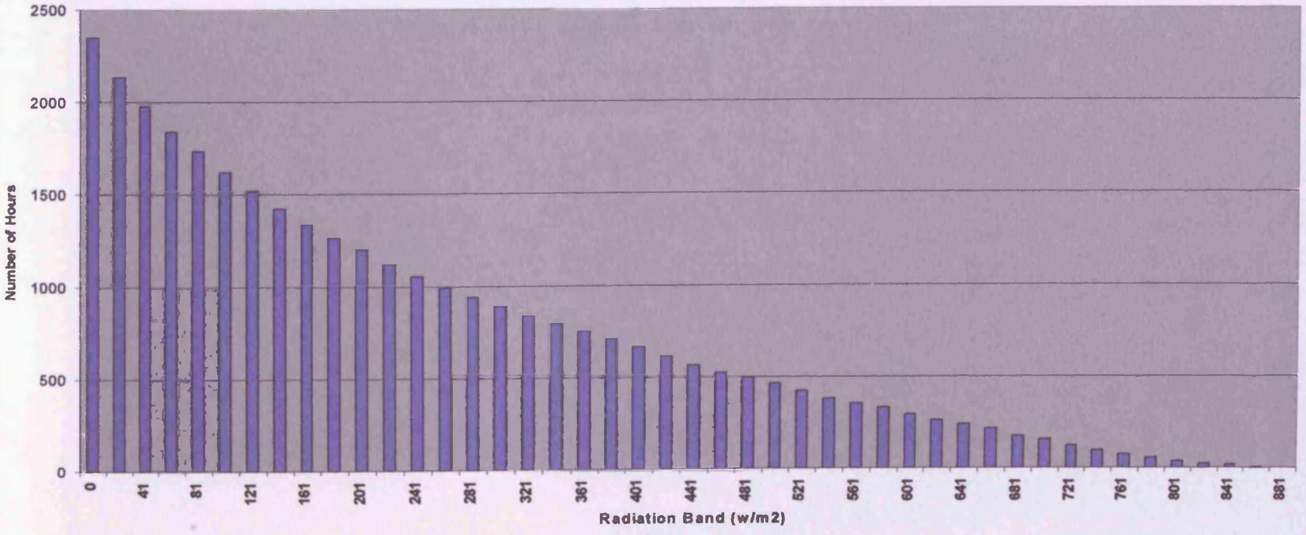
Statistics for UK Bristol EWY Weather File

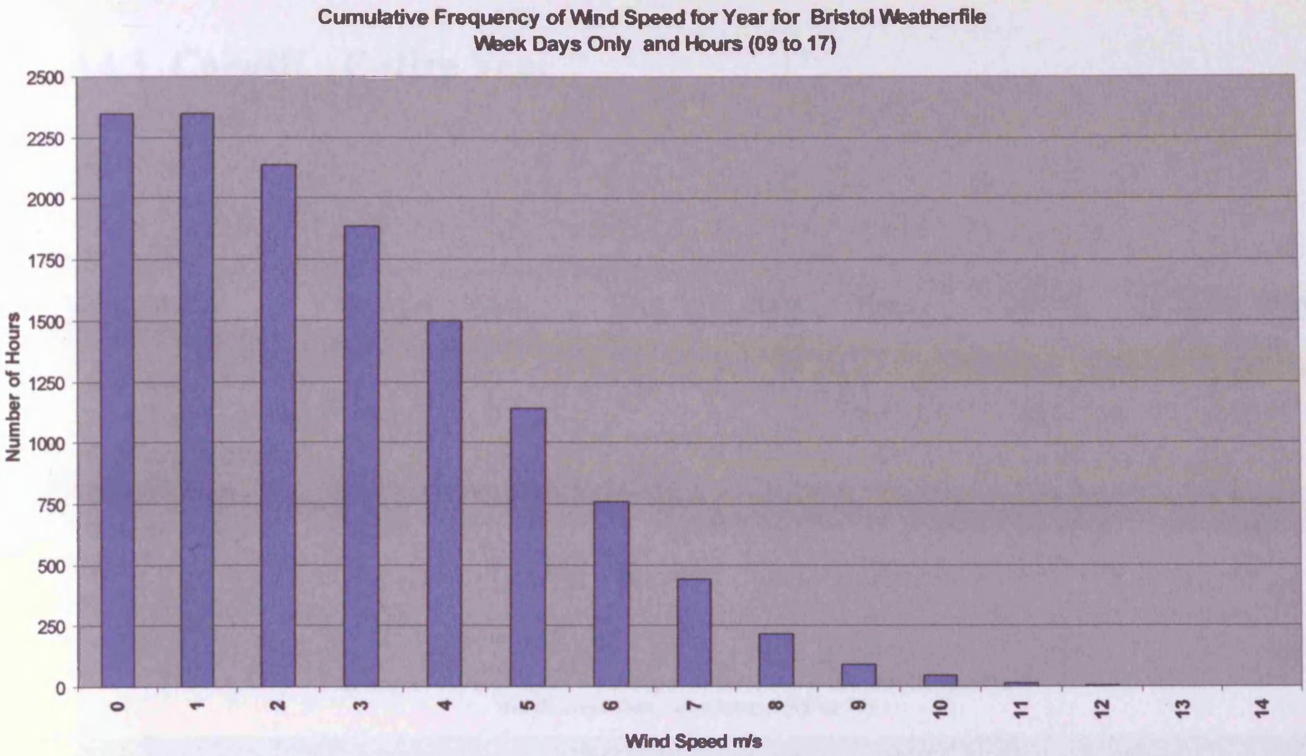
Variable	Units	Min.	Day of Min	Mean	Max.	Julian Day of Max
Global solar	W/m2	0.00	1	113.96	898.0	190
Diffuse solar	W/m2	0.00	1	69.25	687.0	128
Cloud Cover	-	0.00	1	0.71	1.0	4
Air Temp.	C	-11.10	43	8.82	27.6	206
Wind Speed	m/s	1.00	2	4.23	13.1	27
RH	%	25.00	189	83.92	100.0	8

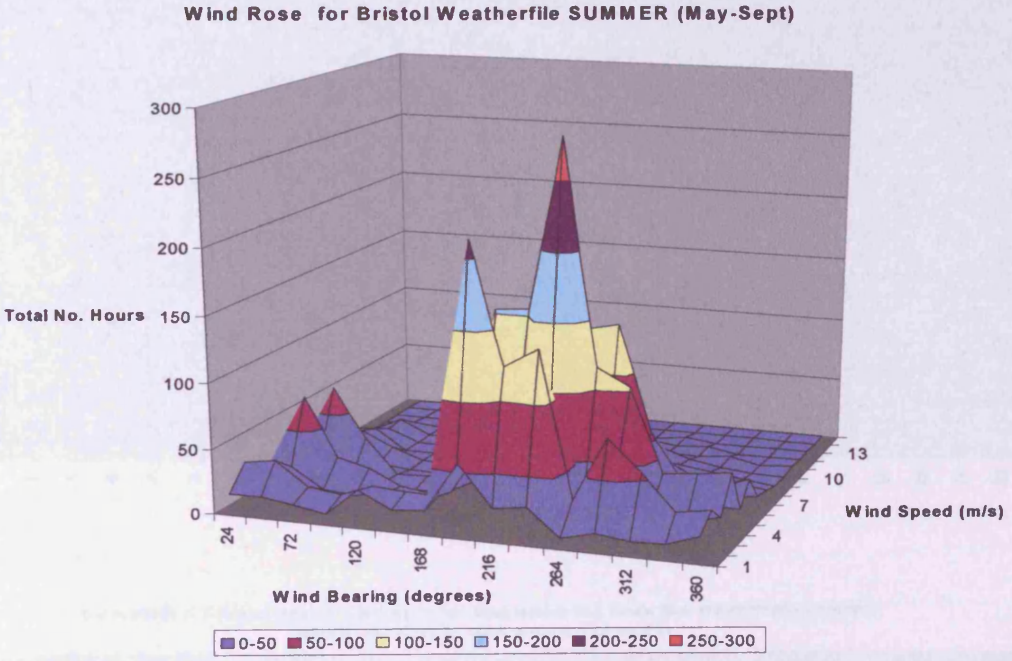
Cumulative Frequency of Air Temperatures for Year for Bristol Weatherfile
Week Days Only and Hours (09 to 17)



Cumulative Frequency of Global Solar Radiation for Year for Bristol Weatherfile
Week Days Only and Hours (09 to 17)




Cumulative Frequency of Wind Speed for Year for Bristol Weatherfile
Week Days Only and Hours (09 to 17)
Number of Hours
0
250
500
750
1000
1250
1500
1750
2000
2250
2500
Wind Speed m/s
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14

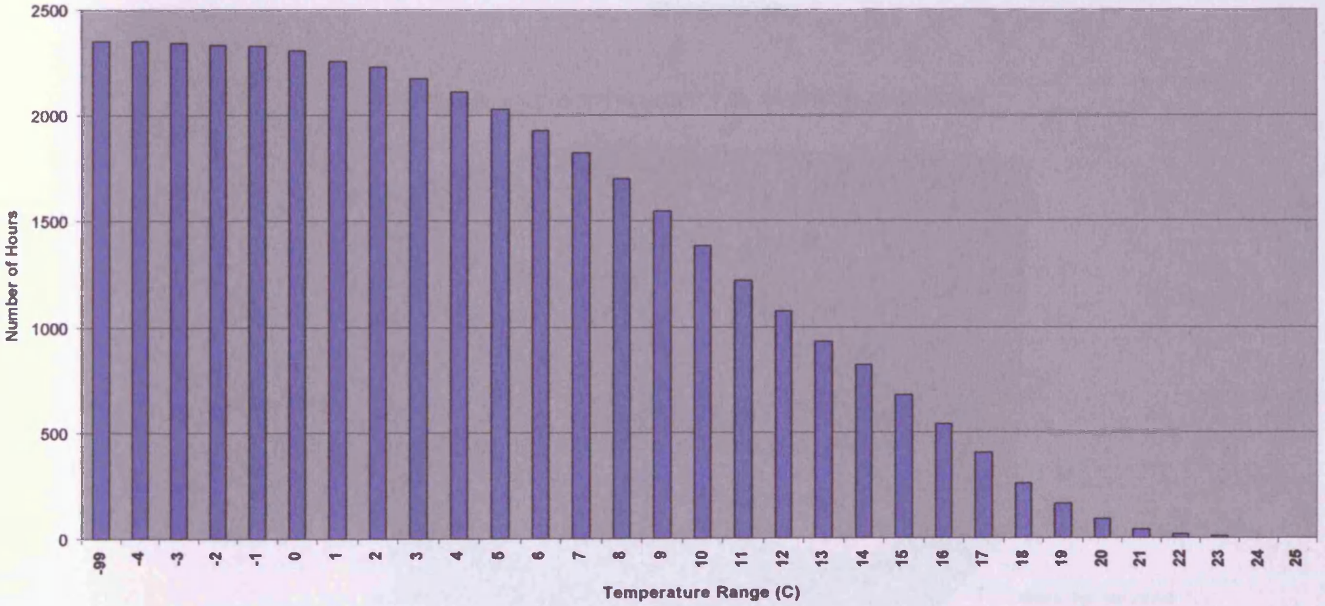

Wind Rose for Bristol Weatherfile SUMMER (May-Sept)
Total No. Hours
0
50
100
150
200
250
300
Wind Bearing (degrees)
24
72
120
168
216
264
312
360
Wind Speed (m/s)
1
4
7
10
13
0-50
50-100
100-150
150-200
200-250
250-300

A4.3 Cardiff - Entire Year

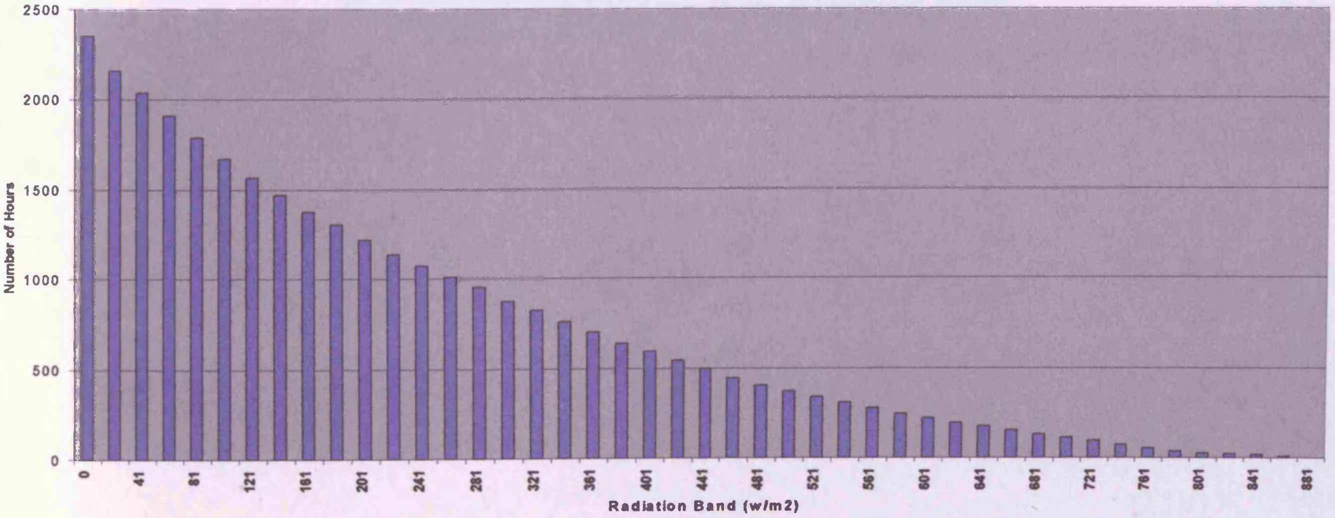
Statistics for UK Cardiff Weather File

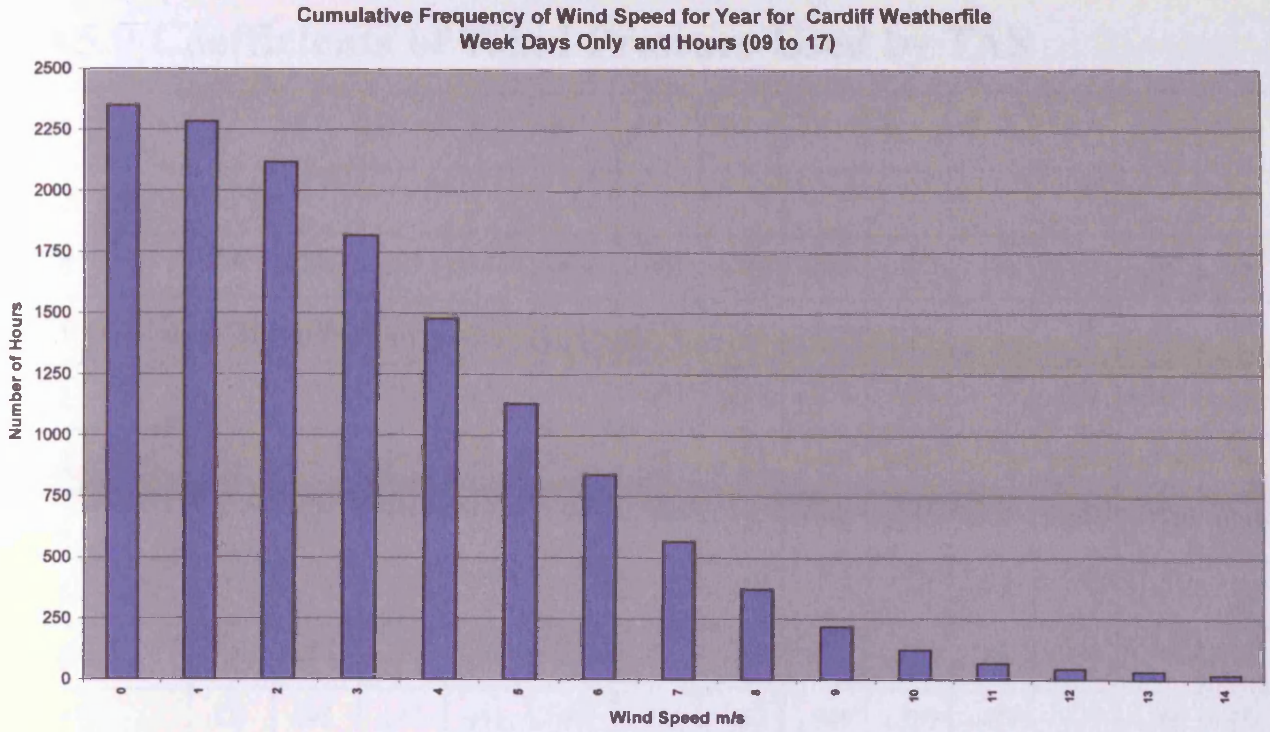
Variable	Units	Min.	Day of Min	Mean	Max.	Julian Day of Max
Global solar	W/m2	0.00	1	112.12	881.00	155
Diffuse solar	W/m2	0.00	1	68.56	419.00	185
Cloud Cover	-	0.00	5	0.76	1.00	1
Air Temp.	C	-4.80	45	9.78	24.50	203
Wind Speed	m/s	0.10	70	5.19	18.20	28
RH	%	42.00	119	79.41	100.00	15

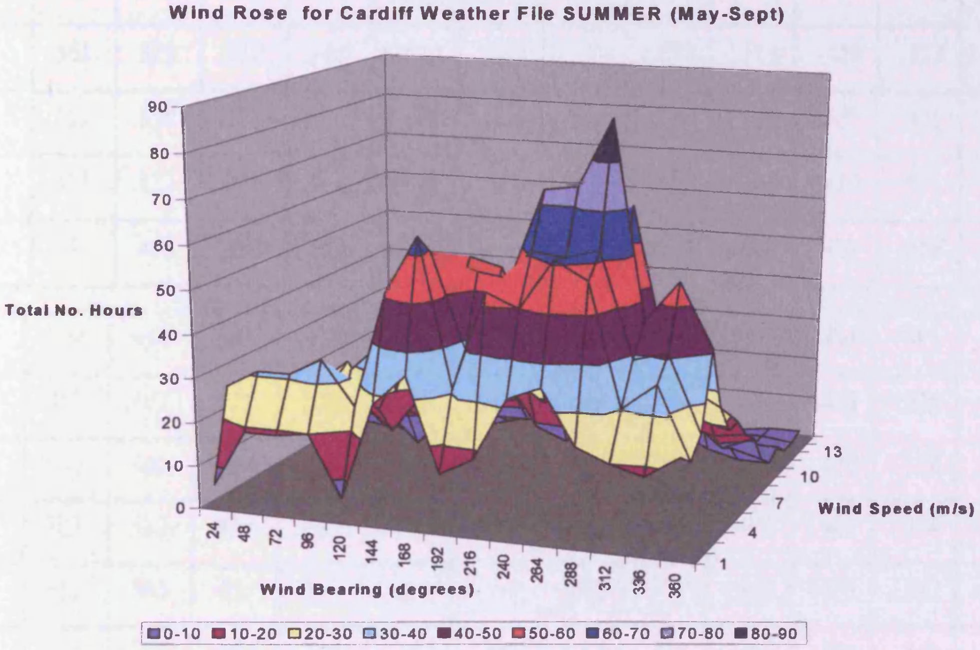
Cumulative Frequency of Air Temperature for Year for Cardiff Weatherfile
Week Days Only and Hours (09 to 17)



Cumulative Frequency of Global Solar Radiation for Year for Cardiff Weatherfile
Week Days Only and Hours (09 to 17)



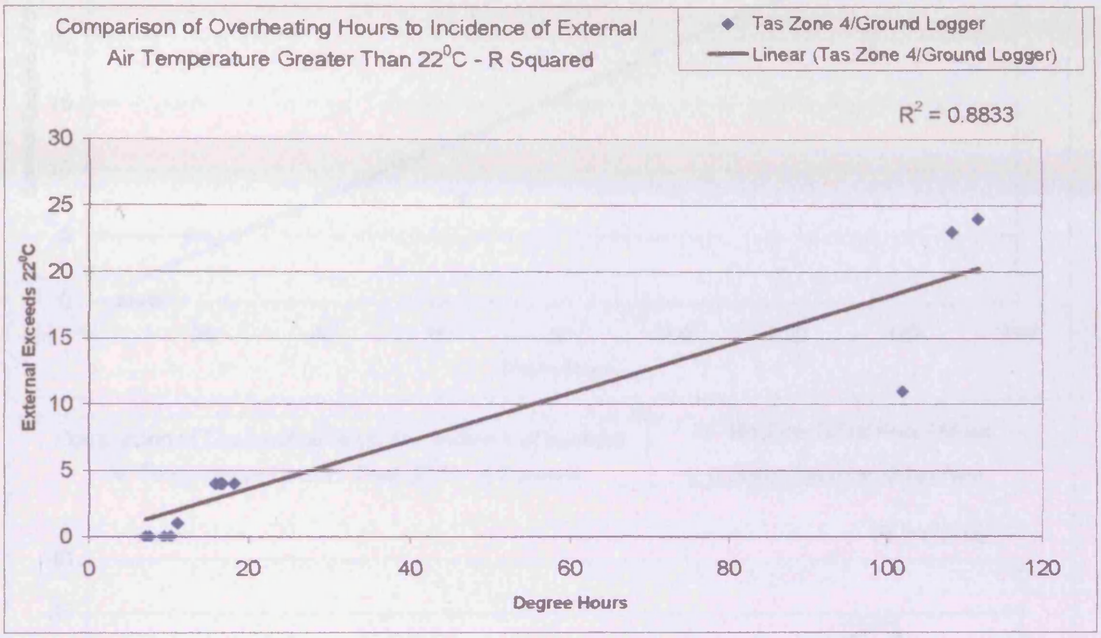

Cumulative Frequency of Wind Speed for Year for Cardiff Weatherfile Week Days Only and Hours (09 to 17)

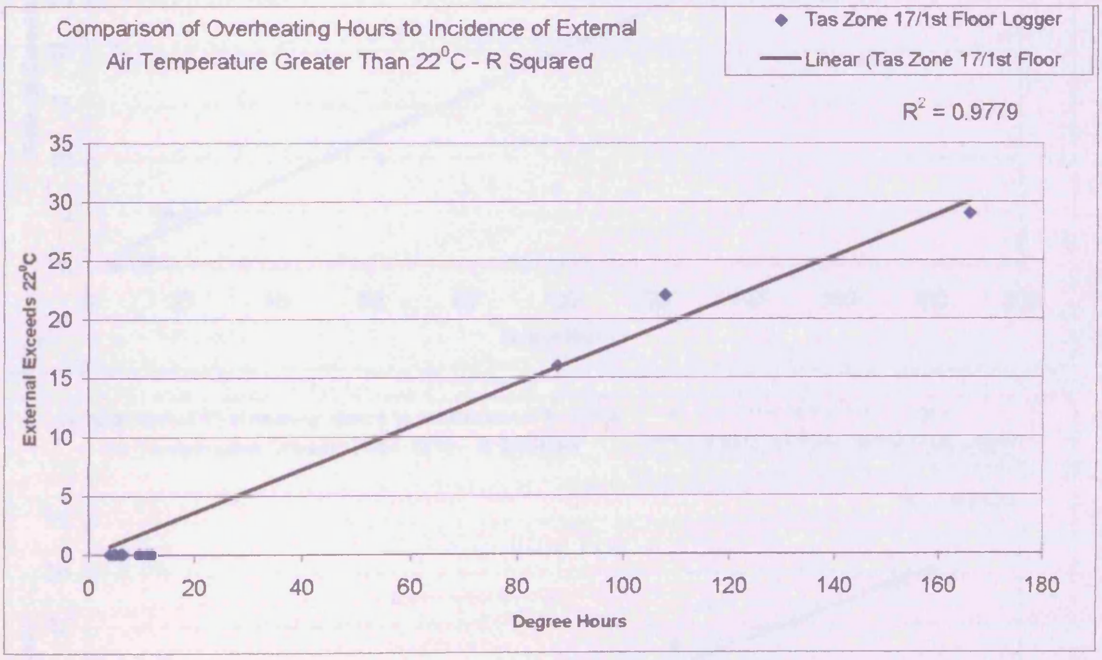

Wind Rose for Cardiff Weather File SUMMER (May-Sept)

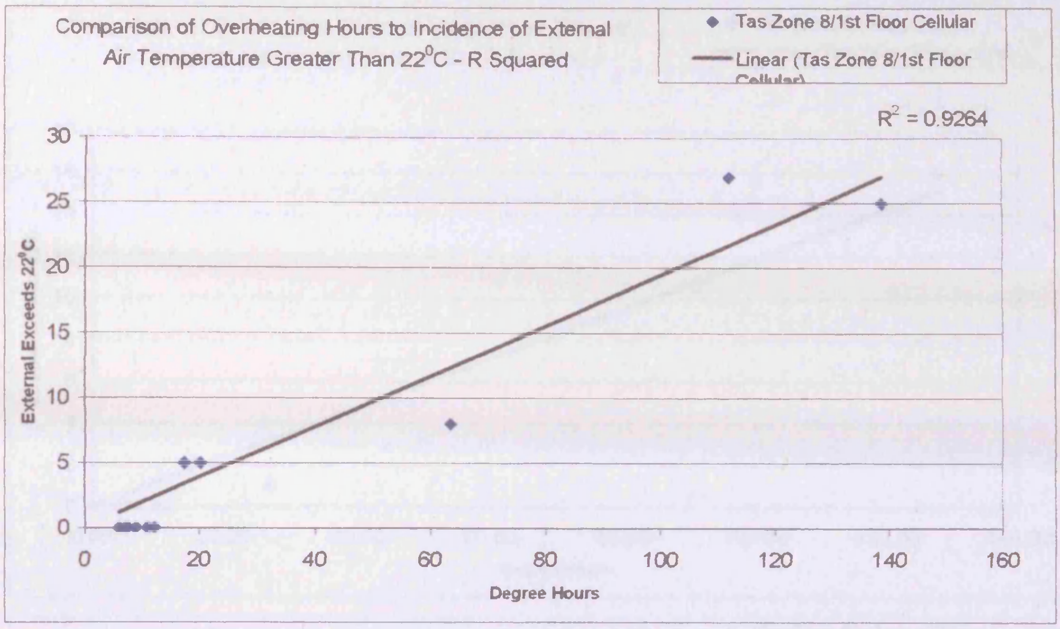
2	.311	.262	.216	.124	-.021	-.159	-.313	-.458	-.490	-.441	-.358	-.
3	.312	.265	.219	.124	-.027	-.181	-.354	-.480	-.496	-.443	-.360	-.
4	.313	.269	.222	.124	-.032	-.201	-.393	-.499	-.501	-.442	-.365	-.
5	.315	.275	.225	.125	-.035	-.220	-.430	-.515	-.505	-.440	-.370	-.
6	.320	.284	.230	.127	-.038	-.237	-.463	-.529	-.508	-.437	-.374	-.
7	.329	.295	.237	.131	-.040	-.254	-.493	-.540	-.510	-.434	-.377	-.
8	.343	.310	.246	.137	-.042	-.269	-.519	-.550	-.511	-.431	-.378	-.
9	.361	.328	.259	.145	-.044	-.283	-.541	-.558	-.511	-.428	-.377	-.
10	.385	.350	.275	.155	-.045	-.295	-.560	-.565	-.510	-.425	-.375	-.
11	.413	.375	.295	.168	-.045	-.306	-.576	-.570	-.508	-.422	-.371	-.
12	.445	.403	.318	.183	-.044	-.315	-.588	-.574	-.506	-.419	-.366	-.
13	.479	.434	.343	.201	-.041	-.322	-.599	-.577	-.503	-.416	-.361	-.
14	.515	.467	.371	.220	-.036	-.327	-.608	-.579	-.499	-.413	-.355	-.
15	.550	.500	.400	.240	-.030	-.330	-.615	-.580	-.495	-.410	-.350	-.
16	.583	.532	.429	.260	-.022	-.331	-.622	-.580	-.491	-.407	-.346	-.
17	.612	.563	.455	.280	-.014	-.330	-.628	-.579	-.486	-.403	-.342	-.
18	.634	.588	.478	.296	-.005	-.327	-.634	-.578	-.482	-.399	-.341	-.
19	.648	.606	.494	.309	.004	-.324	-.639	-.576	-.478	-.394	-.340	-.
20	.650	.615	.500	.315	.010	-.320	-.645	-.575	-.475	-.390	-.340	-.
21	.638	.610	.494	.312	.012	-.317	-.650	-.574	-.472	-.386	-.340	-.
22	.610	.589	.470	.298	.008	-.317	-.654	-.575	-.471	-.382	-.340	-.
23	.563	.545	.426	.269	-.006	-.321	-.656	-.577	-.471	-.380	-.338	-.
24	.494	.476	.356	.221	-.032	-.331	-.655	-.582	-.472	-.379	-.332	-.
25	.400	.375	.255	.150	-.075	-.350	-.650	-.590	-.475	-.380	-.320	-.

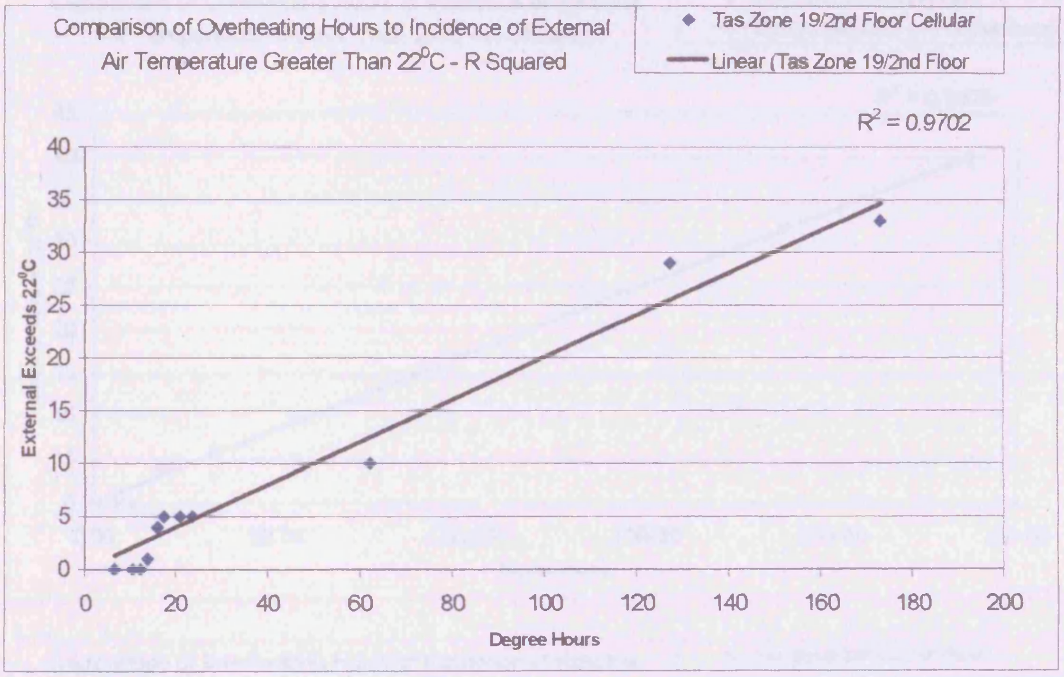
A6.0 Correlation of Hours Overheating for Proposed Overheating Guideline to Degree Hours >22°C

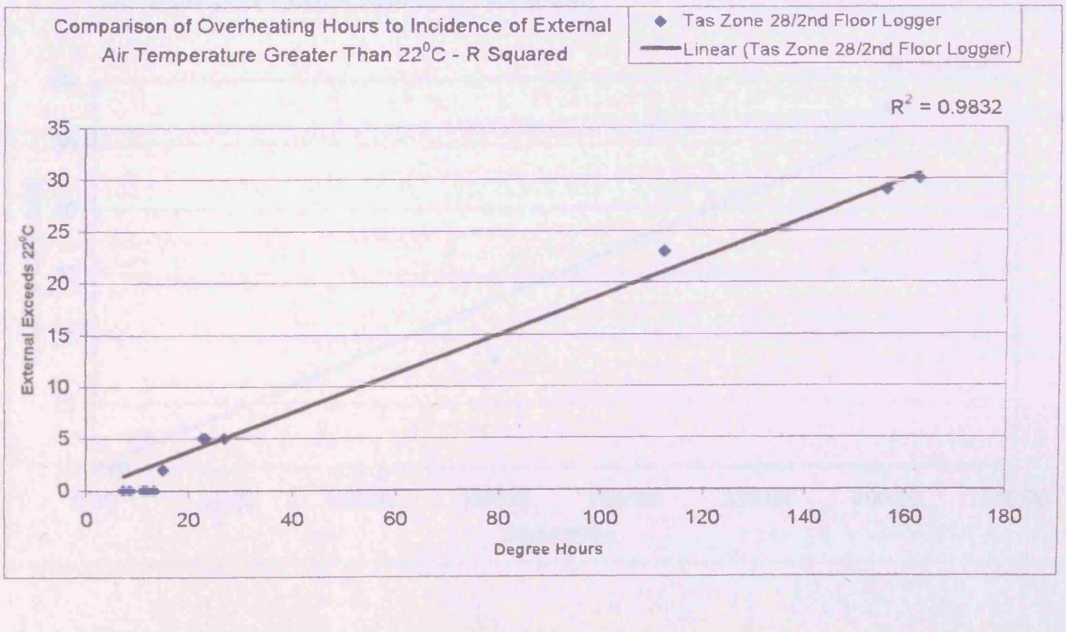
A6.1 Barnardos



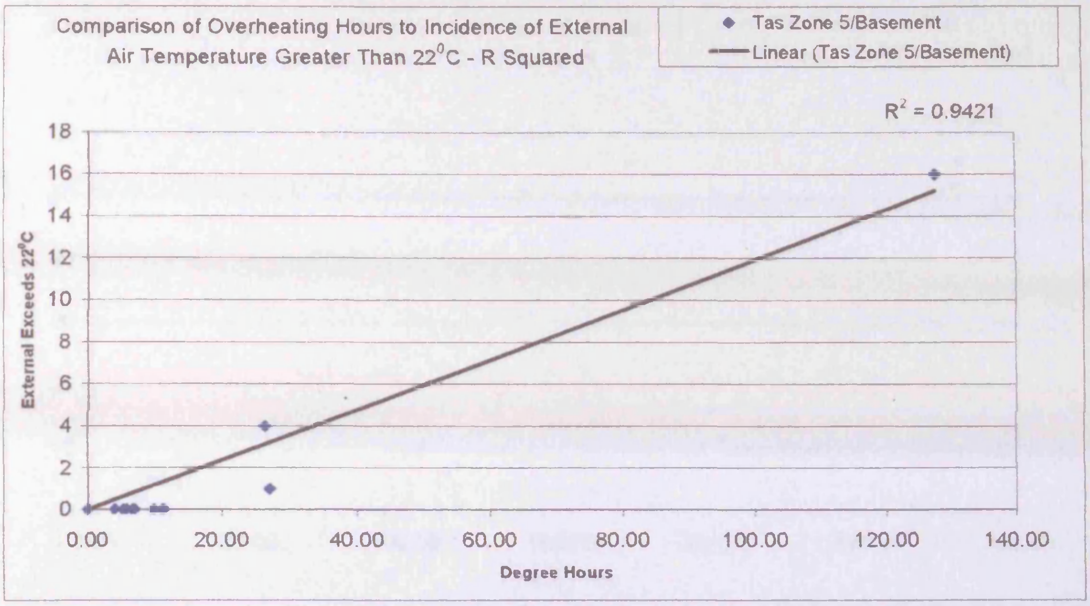


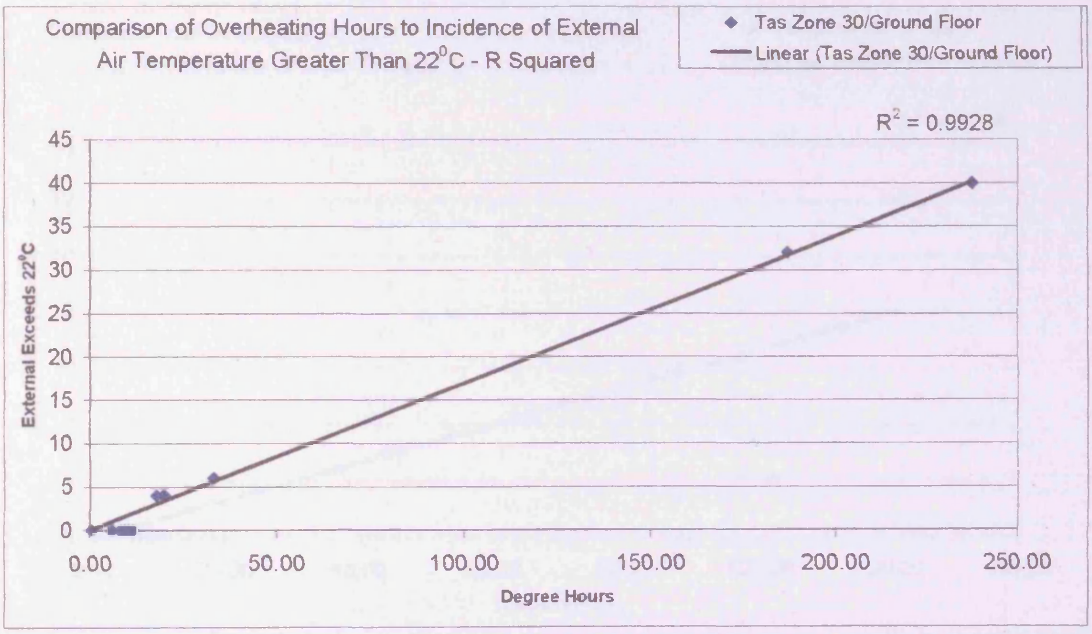

Comparison of Overheating Hours to Incidence of External Air Temperature Greater Than 22°C - R Squared
Tas Zone 8/1st Floor Cellular
Linear (Tas Zone 8/1st Floor Cellular)
R² = 0.9264
External Exceeds 22°C
0
5
10
15
20
25
30
Degree Hours
0
20
40
60
80
100
120
140
160

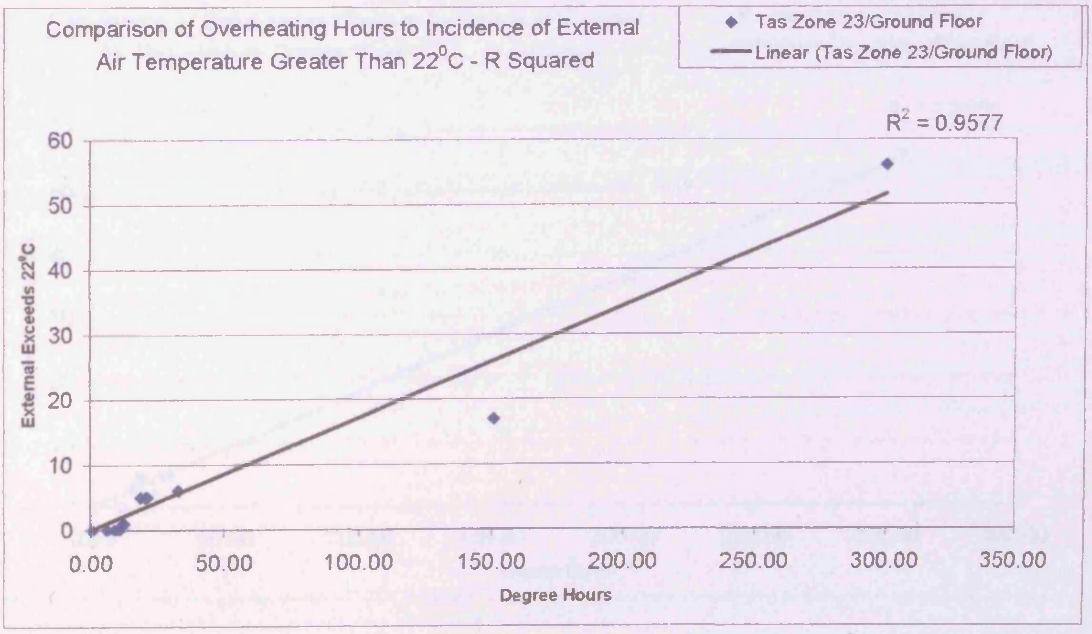

Comparison of Overheating Hours to Incidence of External Air Temperature Greater Than 22°C - R Squared
Tas Zone 19/2nd Floor Cellular
Linear (Tas Zone 19/2nd Floor
R² = 0.9702
External Exceeds 22°C
0
5
10
15
20
25
30
35
40
Degree Hours
0
20
40
60
80
100
120
140
160
180
200

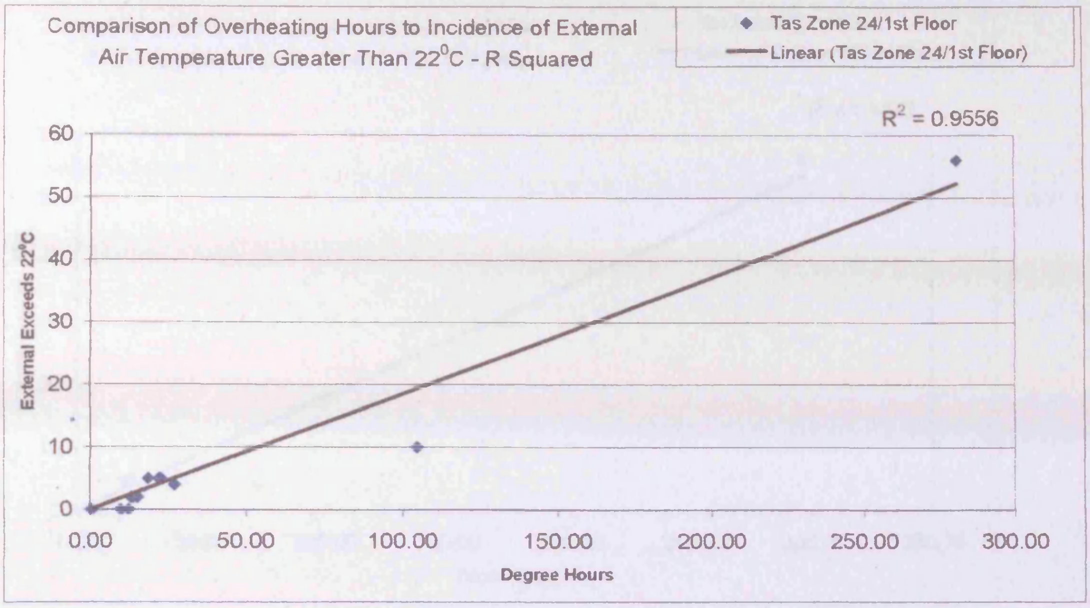

Comparison of Overheating Hours to Incidence of External Air Temperature Greater Than 22°C - R Squared
Tas Zone 28/2nd Floor Logger
Linear (Tas Zone 28/2nd Floor Logger)
R² = 0.9832
External Exceeds 22°C
0
5
10
15
20
25
30
35
Degree Hours
0
20
40
60
80
100
120
140
160
180

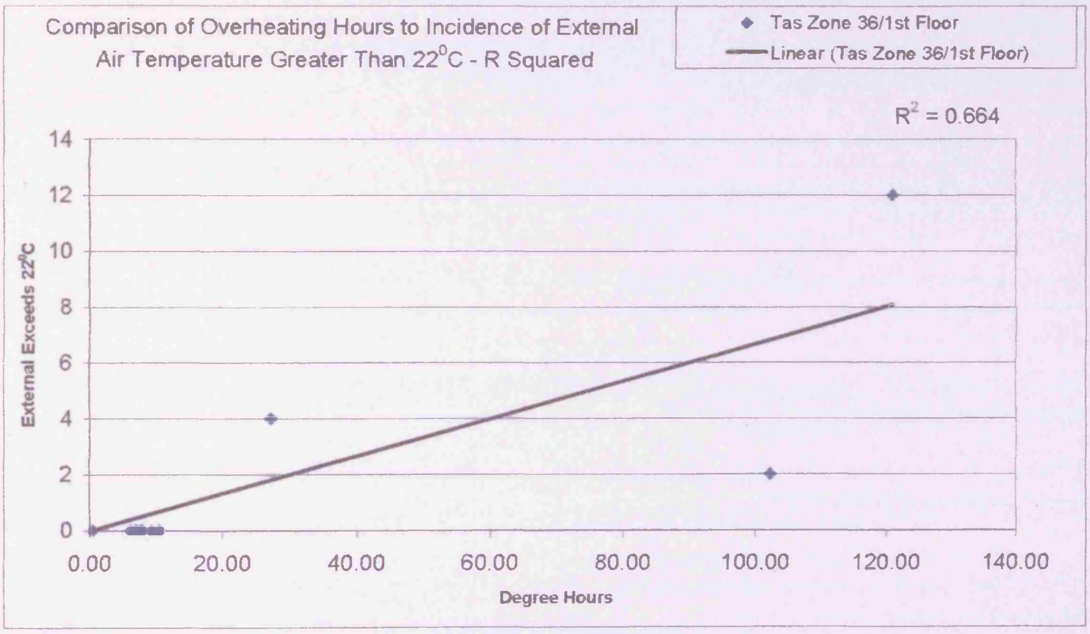
A6.2 Morgan Bruce

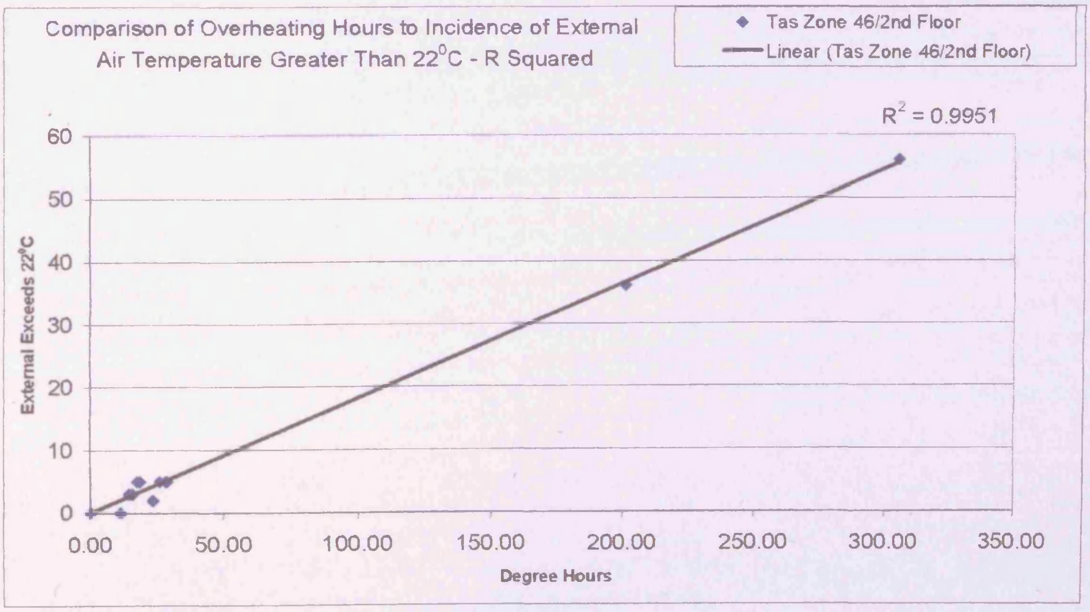


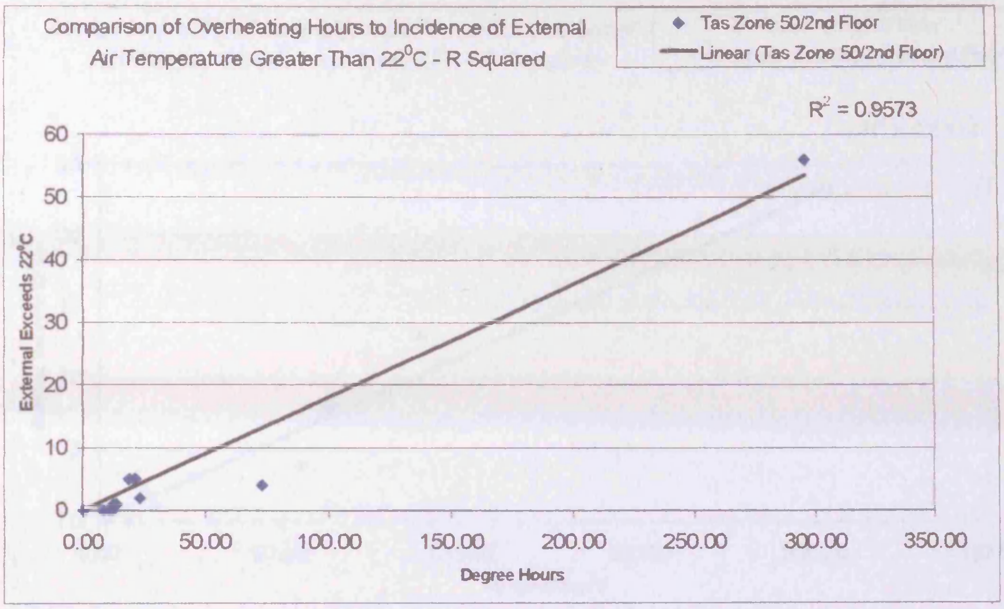




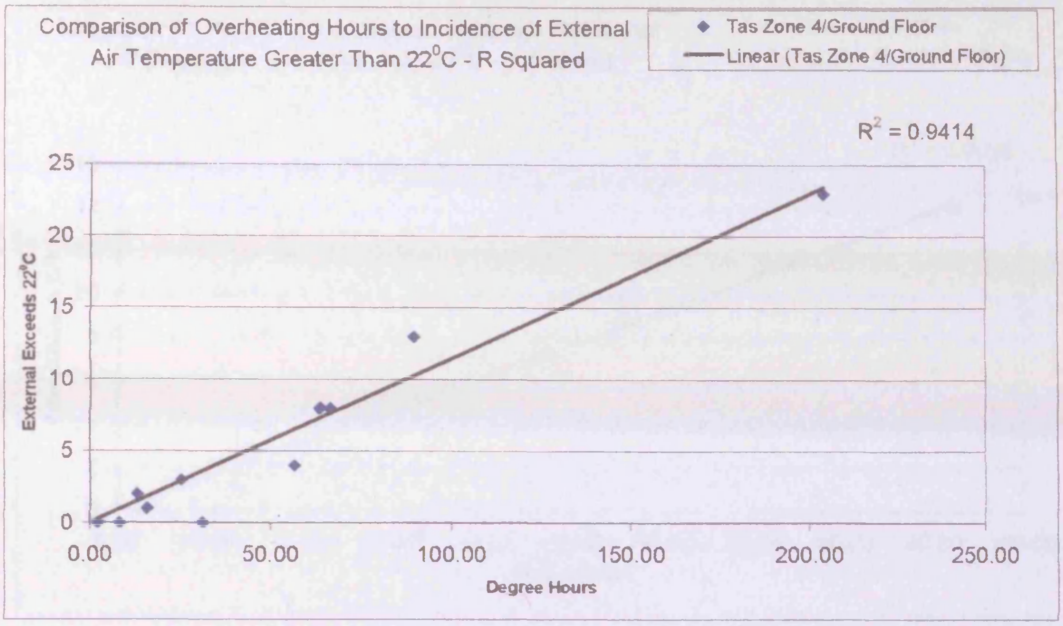

Comparison of Overheating Hours to Incidence of External Air Temperature Greater Than 22^{0}C - R Squared
Tas Zone 24/1st Floor
Linear (Tas Zone 24/1st Floor)
R^2 = 0.9556
60
50
40
30
20
10
0
0.00
50.00
100.00
150.00
200.00
250.00
300.00
External Exceeds 22^{0}C
Degree Hours

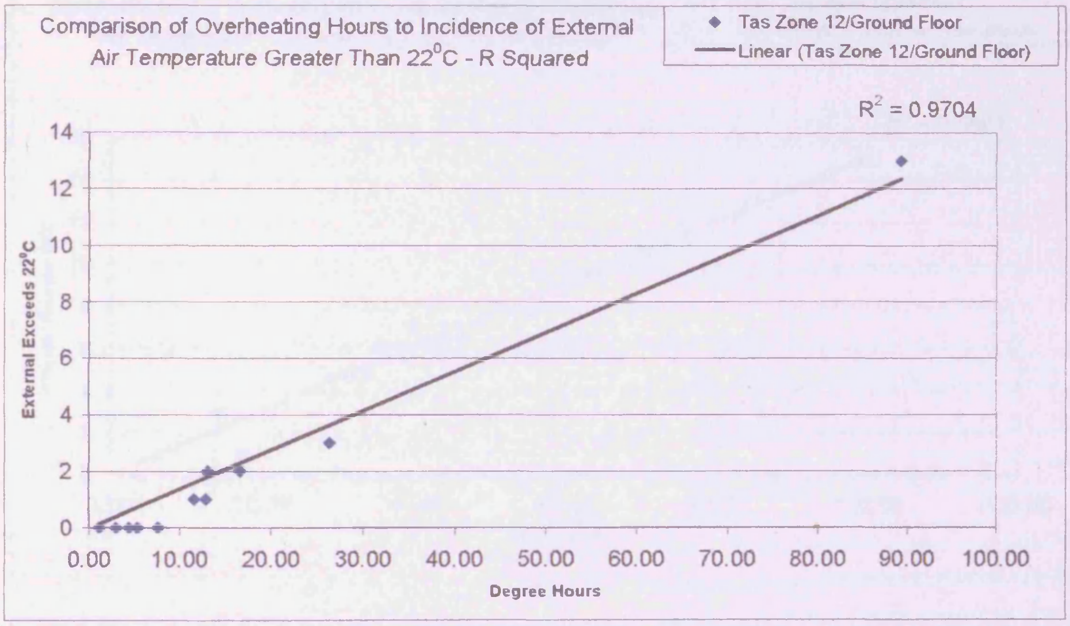

Comparison of Overheating Hours to Incidence of External Air Temperature Greater Than 22^{0}C - R Squared
Tas Zone 36/1st Floor
Linear (Tas Zone 36/1st Floor)
R^2 = 0.664
14
12
10
8
6
4
2
0
0.00
20.00
40.00
60.00
80.00
100.00
120.00
140.00
External Exceeds 22^{0}C
Degree Hours

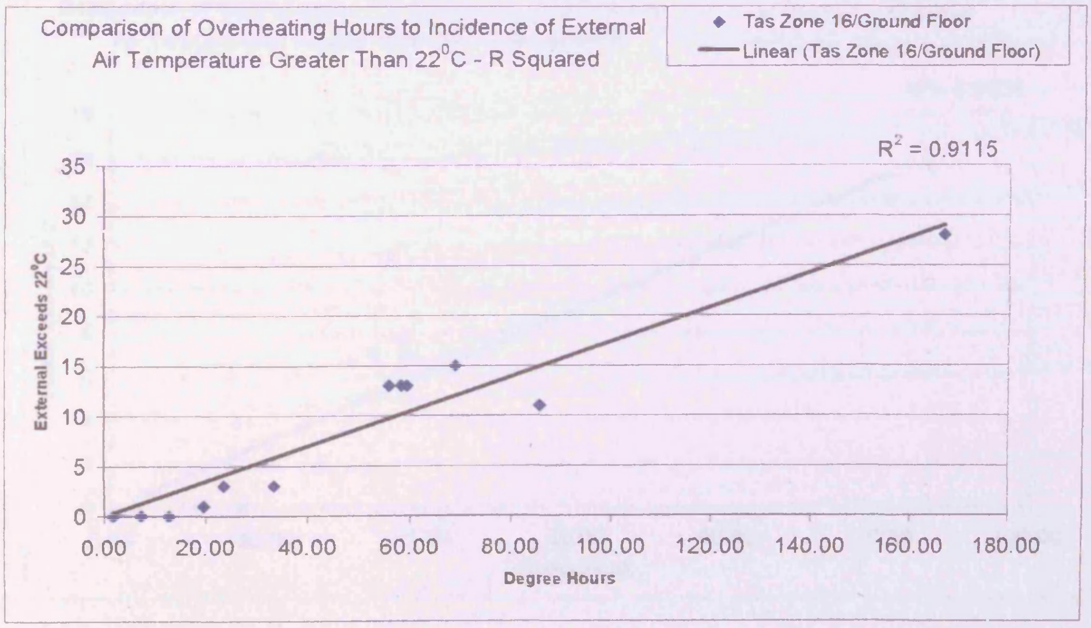

Comparison of Overheating Hours to Incidence of External Air Temperature Greater Than 22^{0}C - R Squared
Tas Zone 46/2nd Floor
Linear (Tas Zone 46/2nd Floor)
R^2 = 0.9951
60
50
40
30
20
10
0
0.00
50.00
100.00
150.00
200.00
250.00
300.00
350.00
External Exceeds 22^{0}C
Degree Hours

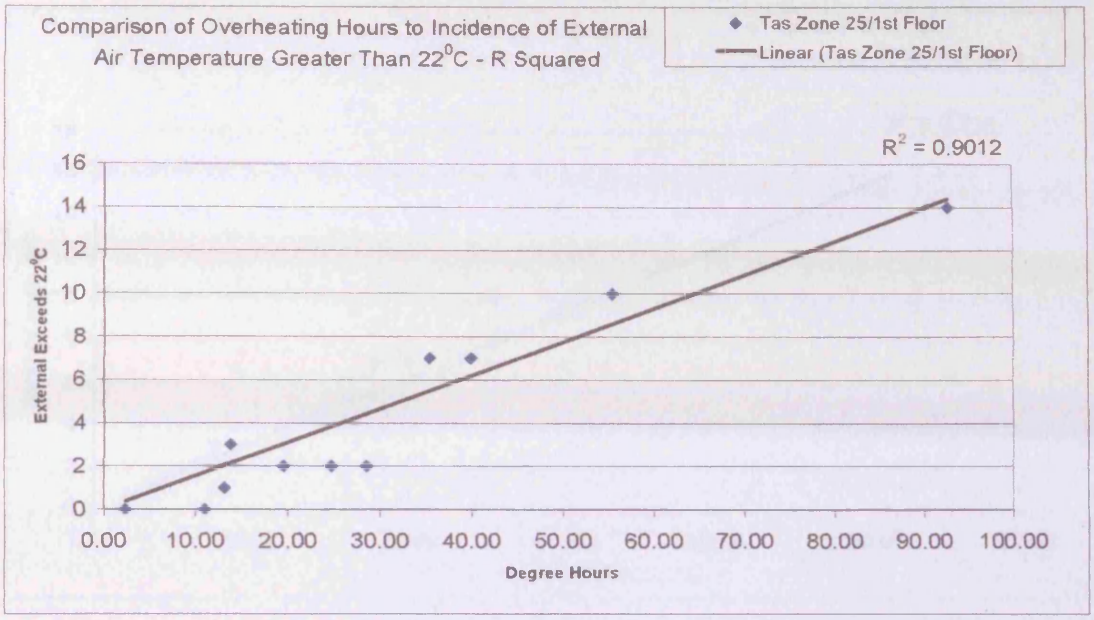

Comparison of Overheating Hours to Incidence of External Air Temperature Greater Than 22⁰C - R Squared
Tas Zone 50/2nd Floor
Linear (Tas Zone 50/2nd Floor)
R² = 0.9573
60
50
40
30
20
10
0
External Exceeds 22⁰C
0.00
50.00
100.00
150.00
200.00
250.00
300.00
350.00
Degree Hours

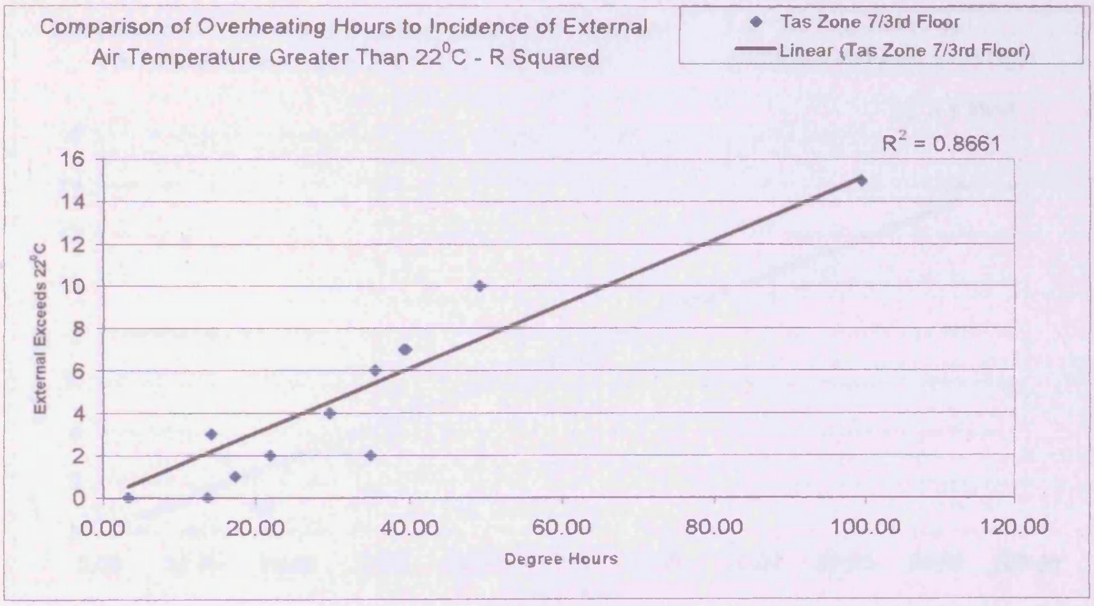
A6.3 MOD

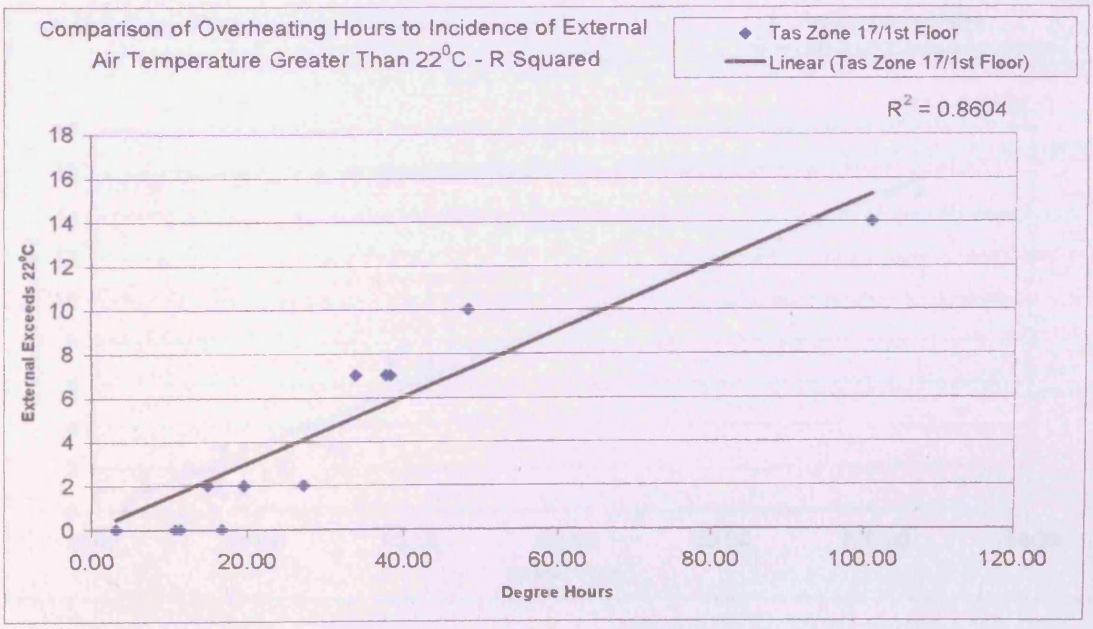

Comparison of Overheating Hours to Incidence of External Air Temperature Greater Than 22^{0}C - R Squared
◆ Tas Zone 4/Ground Floor
—— Linear (Tas Zone 4/Ground Floor)
$R^2 = 0.9414$
External Exceeds 22°C
25
20
15
10
5
0
0.00
50.00
100.00
150.00
200.00
250.00
Degree Hours

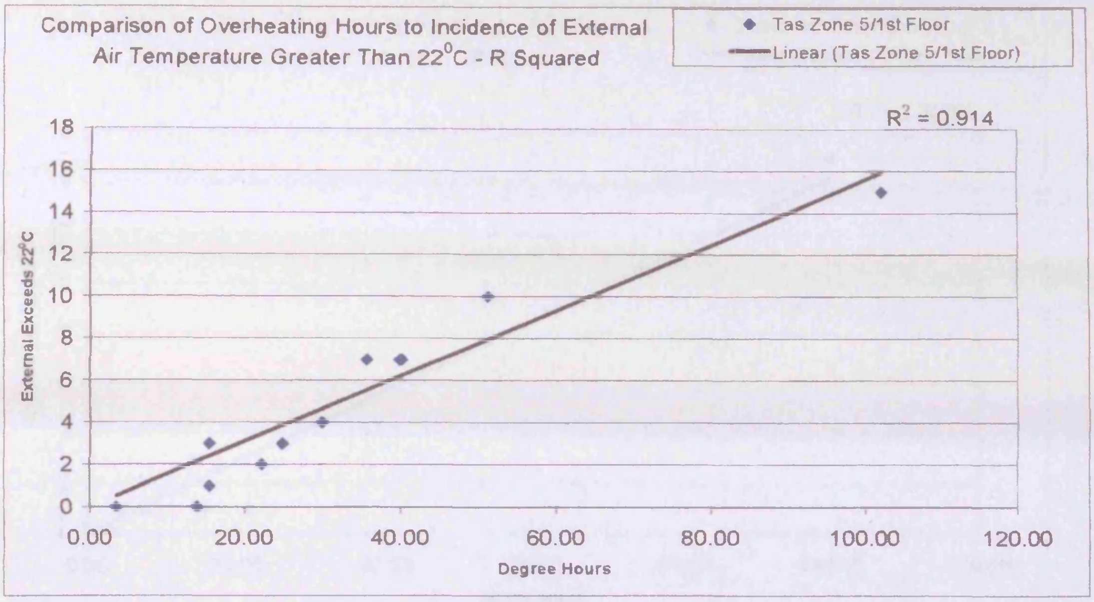

Comparison of Overheating Hours to Incidence of External Air Temperature Greater Than 22^{0}C - R Squared
◆ Tas Zone 12/Ground Floor
—— Linear (Tas Zone 12/Ground Floor)
$R^2 = 0.9704$
External Exceeds 22°C
14
12
10
8
6
4
2
0
0.00
10.00
20.00
30.00
40.00
50.00
60.00
70.00
80.00
90.00
100.00
Degree Hours

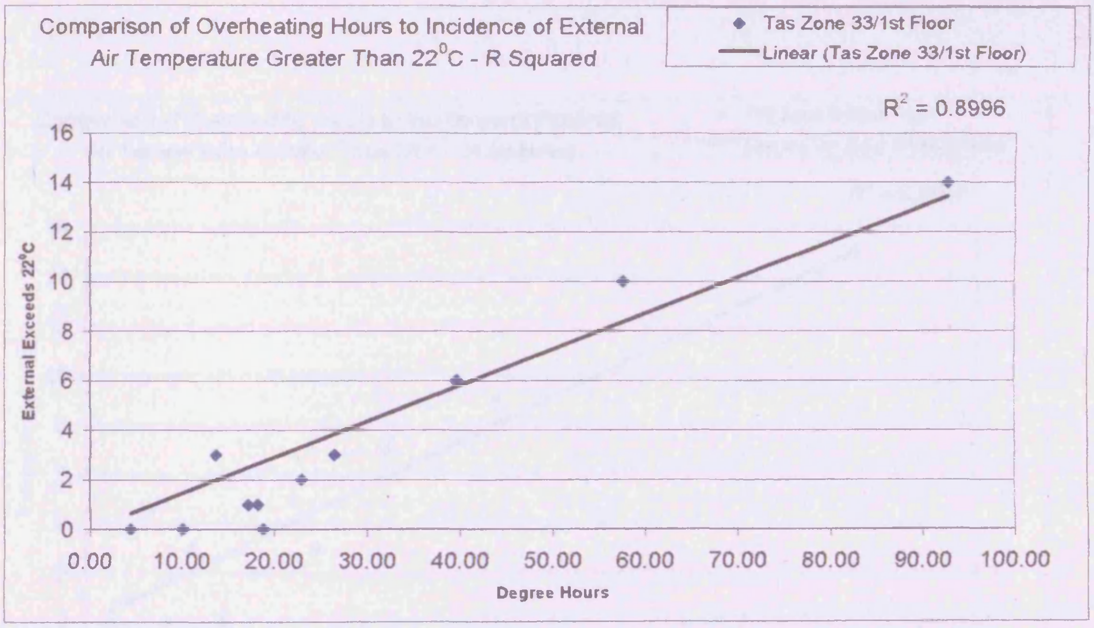

Comparison of Overheating Hours to Incidence of External Air Temperature Greater Than 22^{0}C - R Squared
◆ Tas Zone 16/Ground Floor
—— Linear (Tas Zone 16/Ground Floor)
$R^2 = 0.9115$
External Exceeds 22°C
35
30
25
20
15
10
5
0
0.00
20.00
40.00
60.00
80.00
100.00
120.00
140.00
160.00
180.00
Degree Hours

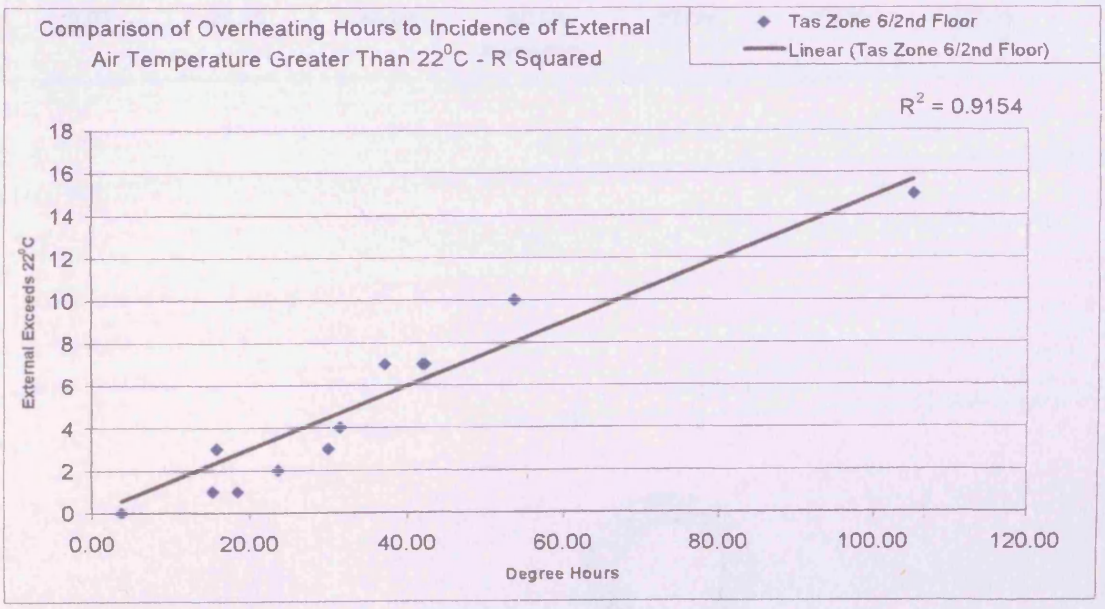

Comparison of Overheating Hours to Incidence of External Air Temperature Greater Than 22^{0}C - R Squared
◆ Tas Zone 25/1st Floor
Linear (Tas Zone 25/1st Floor)
R^2 = 0.9012
External Exceeds 22^{0}C
0
2
4
6
8
10
12
14
16
0.00
10.00
20.00
30.00
40.00
50.00
60.00
70.00
80.00
90.00
100.00
Degree Hours

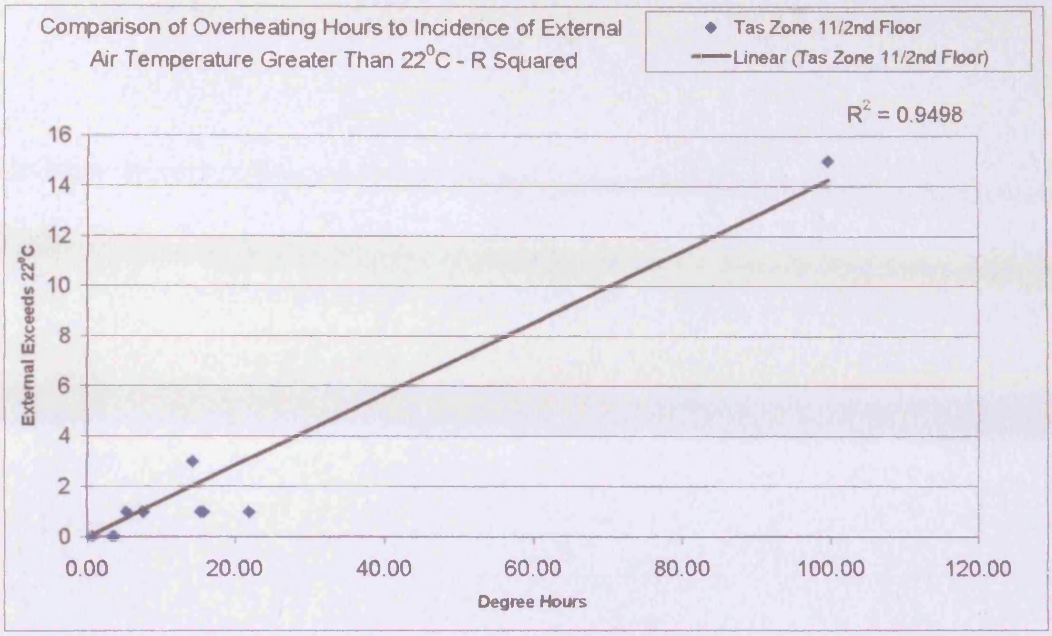

Comparison of Overheating Hours to Incidence of External Air Temperature Greater Than 22^{0}C - R Squared
◆ Tas Zone 7/3rd Floor
Linear (Tas Zone 7/3rd Floor)
R^2 = 0.8661
External Exceeds 22^{0}C
0
2
4
6
8
10
12
14
16
0.00
20.00
40.00
60.00
80.00
100.00
120.00
Degree Hours

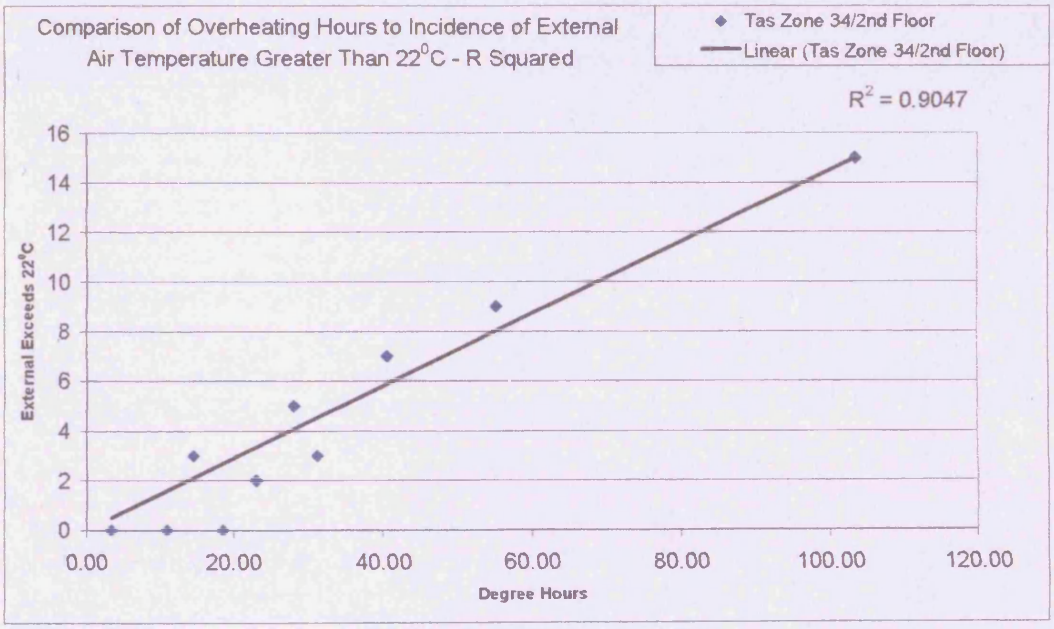

Comparison of Overheating Hours to Incidence of External Air Temperature Greater Than 22^{0}C - R Squared
◆ Tas Zone 17/1st Floor
Linear (Tas Zone 17/1st Floor)
R^2 = 0.8604
External Exceeds 22^{0}C
0
2
4
6
8
10
12
14
16
18
0.00
20.00
40.00
60.00
80.00
100.00
120.00
Degree Hours


Comparison of Overheating Hours to Incidence of External Air Temperature Greater Than 22^{0}C - R Squared


Comparison of Overheating Hours to Incidence of External Air Temperature Greater Than 22^{0}C - R Squared


Comparison of Overheating Hours to Incidence of External Air Temperature Greater Than 22^{0}C - R Squared


Comparison of Overheating Hours to Incidence of External Air Temperature Greater Than 22°C - R Squared
Tas Zone 11/2nd Floor
Linear (Tas Zone 11/2nd Floor)
R² = 0.9498
16
14
12
10
8
6
4
2
0
External Exceeds 22°C
0.00
20.00
40.00
60.00
80.00
100.00
120.00
Degree Hours


Comparison of Overheating Hours to Incidence of External Air Temperature Greater Than 22°C - R Squared
Tas Zone 34/2nd Floor
Linear (Tas Zone 34/2nd Floor)
R² = 0.9047
16
14
12
10
8
6
4
2
0
External Exceeds 22°C
0.00
20.00
40.00
60.00
80.00
100.00
120.00
Degree Hours