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Space Planning and Energy Efficiency in Office Buildings: The Role of Spatial and Temporal Diversity

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Abstract: This research investigates the impact on energy use of the different ways in which office spaces can be organised and used. It explores typical UK office layouts, utilisation densities and intensities on a good practice-base case shell. This is achieved using the TAS, Lightscape and Excel software packages. For the average occupancy of 50%, the analysis indicates that the variations in combined thermal and lighting loads are 19% and 51% during the UK peak winter and summer respectively. The respective *per capita* load variations are 80% and 16%. The analysis demonstrates that space planning and utilisation have significant impacts on energy use and are important in assessing energy performance.

Keywords: Energy efficiency, Office buildings, Simulation, Space planning, Workplaces

Introduction

The overall objective of this work is to quantify the levels of energy use for typical configurations of groups of office users and user patterns, space plans, and environmental systems. Space planning, utilisation patterns and systems control strategies that deviate from those designated during the design stage of offices may result in energy inefficiencies in passive or low energy buildings or improve the performance of inefficient buildings. System and control specifications based on full occupancy may lead to energy inefficiency if spaces are characterised by varied occupancy. Many office building shells and environmental systems continue to be long-term entities while their interiors experience numerous shorter-term changes to accommodate different and changing organisations (Duffy & Powell, 1997; Fernandez, 2003; Lucas, Taylor, Miller & Platt, 1990). High rates of change may have implications on the energy performance of such buildings if there are inconsistencies between the objectives of 'shell and core' designers, interiors fit-out parties and clients/tenants. According to Lucas *et al.*, (1990), larger, older office buildings tend to experience a wider variety of changes more frequently than smaller, newer buildings.

Empirical evidence indicates that many office workspaces are empty most of the time. Eley and Marmot (1995) compared the use of desks over the working day in various organisations and the average occupancies they reported for three categories of staff (*often absent*, *mobile* and *sedentary)*, were 15%, 30% and 50% respectively. After taking into account the time the spaces were temporarily unoccupied, the respective averages were 30%, 50% and 80%. Duffy (1997) reported occupancies averaging 60% and 40% of open-plan and enclosed offices respectively, and 90% and 70% when the time the spaces were temporarily unoccupied is taken into account, while the average occupancy in meeting rooms was 25%. Duffy, Laing, Jaunzens and Willis (1998) indicate that office buildings are typically 50% empty most of the time. As a result, the paper focuses on the 50% occupancy in the analysis, although lower (25%) and higher (75% &100%) occupancy levels are also tested.

Unoccupied spaces of expected workers will, in many cases, need to remain environmentally comfortable or 'prepared' for occupation when the building is in operation. If energy consumption per user is taken into consideration, as opposed to the more conventional metric of energy use per square metre, such a need potentially leads to inefficiency as a result of the heating/cooling, or ventilation or artificial lighting energy of the unoccupied spaces. There may be a case to be made for maintaining a 'baseline' (minimum energy) condition in spaces where users of unoccupied spaces are expected, which is brought up to full comfort when the spaces get occupied. This has, to some degree, been addressed by systems such as lighting that can dim to a set baseline output. Most existing buildings however, still run traditional manual controls. While the response time

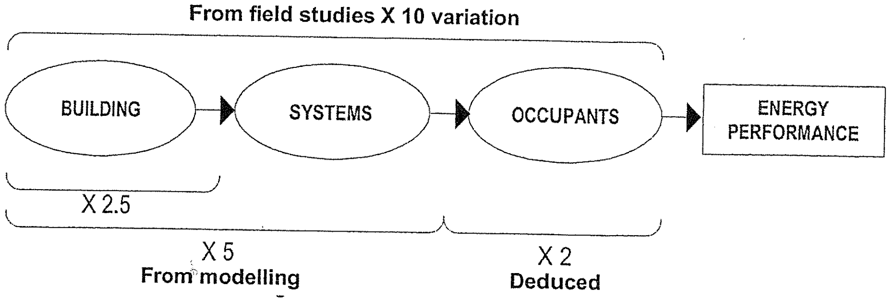


Figure 1: *Building, systems and occupant factors affecting energy consumption in non-domestic buildings. (Source: Baker & Steemers, 2000)*

from 'baseline-to-full' lighting and ventilation can be instant, that of thermal comfort conditions may be unsatisfactory depending on the heating or cooling system.

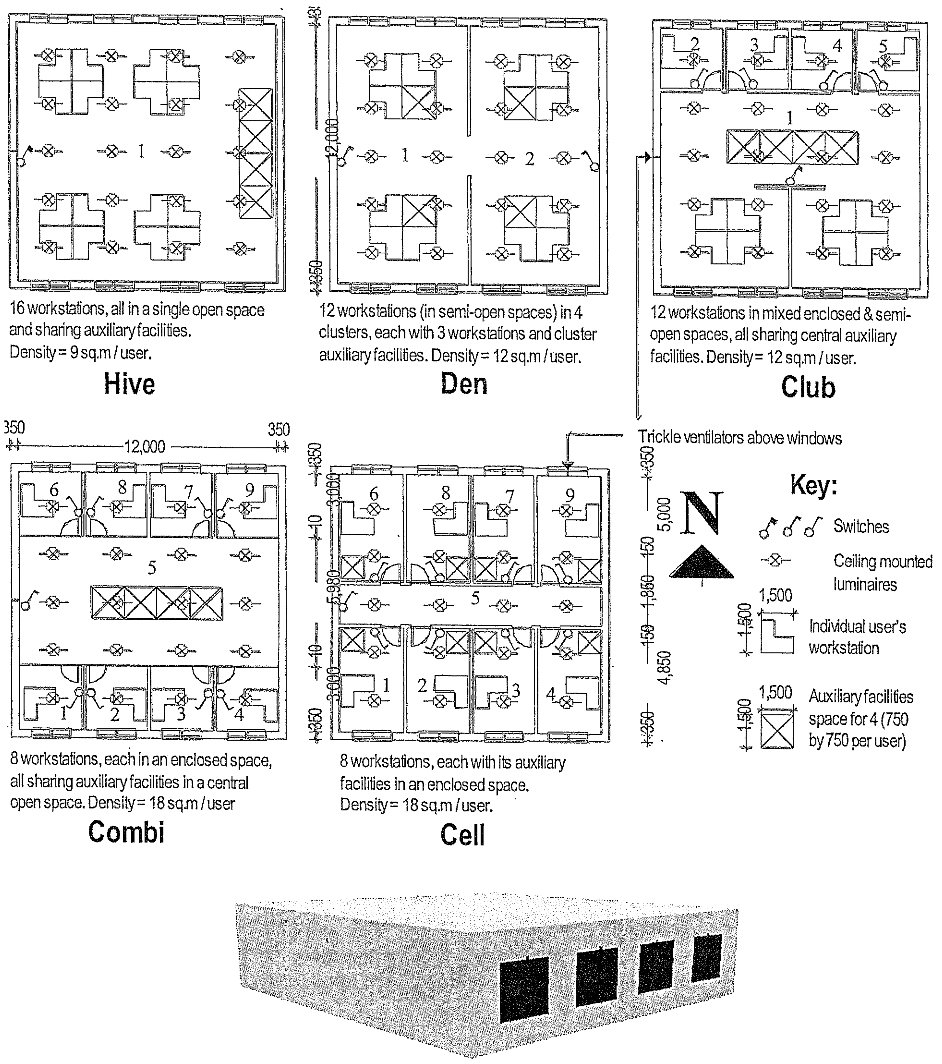
How much energy is wasted and how much can be saved? Data from UK buildings shows *avoidable waste* levels typically in the range of 25%-50%. In a building, with efficient energy use, for example with a building energy manager, *avoidable waste* levels of 15% are achievable (Ashford, 1997; BRECSU, 1995). Avoidable waste represents the difference between actual energy expenditure and the *base energy* (the minimum required to meet the user comfort needs and equipment requirements for a building operation). What are the potential links between energy efficiency and space planning? One example is a refurbishment that achieves a reduction in the floor area used by an organisation thereby reducing the energy needed and operating costs. Partitioning is another example, which affects daylight levels, airflow, density (space per user), operation of controls in spaces and consequently energy use. The levels to which energy consumption can be influenced by these factors is however, not usually clear. The hypothesis presented is that there is potential for significant energy savings through the formulation and adoption of space planning and utilisation strategies, which in turn must be in harmony with organisational requirements. It is important to note that the study does not explore space use patterns in relation to organisational requirements, but rather focuses on the energy implications of a range of space use patterns.

Potential energy saving through space planning and utilisation strategies would be particularly relevant to the existing building stock, which according to Steemers (2003) is the single biggest source of CO_2 emissions in the world and is central to the issue of mitigation. This would be particularly so to those buildings that pre-date fuel efficiency regulations; are very inefficient by current standards; and unlikely to be replaced because they are either structurally robust, or economics would not favour replacement. The study may also be important to situations where dealing with energy efficiency through the existing passive strategies has limitations. These situations call for alternative strategies and include polluted environments where mechanical ventilation may be necessary or very sheltered urban buildings where limited daylight availability may result in high demand for supplementary artificial lighting.

Buildings can have huge variations in energy performance even when located in the same place and are similar in type. A survey of 92 UK office buildings, for example, indicated that a well-designed day lit and naturally ventilated office such as the BRE Low Energy Office, with efficient and well controlled plant will have an annual energy cost 10 to 15 times less than an air-conditioned, deep-plan, over-glazed building with poor services design and control. The energy model in Figure 1 (after Baker & Steemers, 2000) presents a variation factor of at least 10 times for offices in the same geographic location. The model attributes a variation of five times to *building* and *systems factors*, with the remaining being an *occupant factor* contributing to a variation of two times. The *occupant factor* is deduced and has not been calculated through modelling or empirical methods. In later work, Steemers and Steane (2004) also point out that occupancy patterns have frequently been ignored despite the obvious significance of programmatic issues. There is therefore, a need to build up a better understanding of the *occupant factor*. This factor relates to occupant behaviour on the control of environmental systems. It also relates to work patterns and space use patterns such as occupancy, occupant density and worker interaction versus autonomy. It should not be confused with the terms *occupant gains* and *occupancy*, which are part of the *occupant factor*. As used in this paper, *occupant gains* refer to metabolic heat gains, while *occupancy* refers to the number of occupied workstations as a percentage of the total number of workstations.

Office Layouts Investigated

The physical definition of spaces in office interiors is often partly a function of work patterns. Although layouts are chosen to allow given patterns of work, it is also true that layouts determine the way a space is used, including density. The impacts of five common layouts of office spaces, namely: *Hive, Den, Club, Cell* and *Combi* are investigated in this paper. The first four are based on a classification in a study on 'New Environments for Working' (NEW) that classifies office work-pattern characteristics and space settings for different types of work (Duffy *et al.*, 1998). Although there are more layout types and ways of classifying workspace layouts (Brill, 2001; Loftness, 2004; Saari, Tissari, Valkama & Seppänen, 2006), Duffy's types were selected because they are classified based on the degrees of user *interaction* and *autonomy*, which relate to the temporal diversity and interior environmental control factors on which this research focuses. *Interaction* as defined in Duffy's classification refers to the personal, face-to-face contact that is necessary to carry out office tasks. *Autonomy* is the degree of control, responsibility and discretion each office worker has over the content, method, location and tools of the work process. According to Duffy, taken together, these explain



16 workstations, all in a single open space and sharing auxiliary facilities. Density = 9 sq.m / user.
Hive

12 workstations (in semi-open spaces) in 4 clusters, each with 3 workstations and cluster auxiliary facilities. Density = 12 sq.m / user.
Den

12 workstations in mixed enclosed & semi-open spaces, all sharing central auxiliary facilities. Density = 12 sq.m / user.
Club

8 workstations, each in an enclosed space, all sharing auxiliary facilities in a central open space. Density = 18 sq.m / user
Combi

8 workstations, each with its auxiliary facilities in an enclosed space. Density = 18 sq.m / user.
Cell

Figure 2: *Different layouts on a 12m x 12m office space and the 3D base case shell used in the computer simulations. All partitions are full ceiling height. The terms Hive, Den, Club, Combi, and Cell as used here refer to plan regime and not individual offices.*

the ways in which office layouts are likely to differ and the dynamics of change in office design. *Interaction* and *autonomy* affect workers' expectations about the layout, the work settings (the heights of the space-dividing elements for example), and their control over environmental services and lighting. Heavy interaction outside the organization is often connected with workers being in their offices intermittently.

It is worth noting that there are many ways of defining spaces in the selected plan types, such as full or part-height partitions and/or different floor levels. The plans used for the analysis in this paper are defined by full-height partitions. This is the factor expected to have the greatest influence on interior environmental diversity and workstation layouts and density of space use. Figure 2 illustrates the different layouts, where a *Den* space is an open plan or group room with simple settings and shared facilities. The *Club* has a wide variety of shared task-based settings while the *Hive* has uniform open-plan and impersonal space. In the *Cell*, each individual uses an enclosed space or a highly screened workstation for a wide variety of tasks. Larger *Cell* spaces may be planned for sharing by two to three users. It is worth noting that several of Duffy's setting types might co-exist within a single office layout. The *Combi* office started as a Scandinavian type originally conceived as a retrofit solution to the open landscape offices (Wyon, 2000) and "a response to the idea that cellular offices are an obstacle to interaction" (Meel, 2000). According to Wyon, *Combi* offices incorporate a design concept that places small individual offices, each with a window, on a building's perimeter around a common open space for informal meetings and common facilities such as shelving and printing. The perimeter offices have solid walls between them, but glass walls and glass doors separating them from the common central area in order to share daylight and view-out with the central area. All the walls are floor-to-ceiling height.

It is worth noting that many variations of these exist and that in reality, organisations are likely to have varied mixes of the different work patterns. The *Cell* and *Combi* are also used in this paper to represent situations where partitions fall at positions whose distance from the window is less than the *passive zone* depth of *2h* (2 x ceiling height; Baker & Steemers, 2002; CIBSE Guide F, 1998). This is typically 6m from the window wall, and for single sided ventilation in low heat gain situations, the zone could be as deep as 10m – especially in open-plan offices (BRE, 1994). By their very nature, the *Cell*

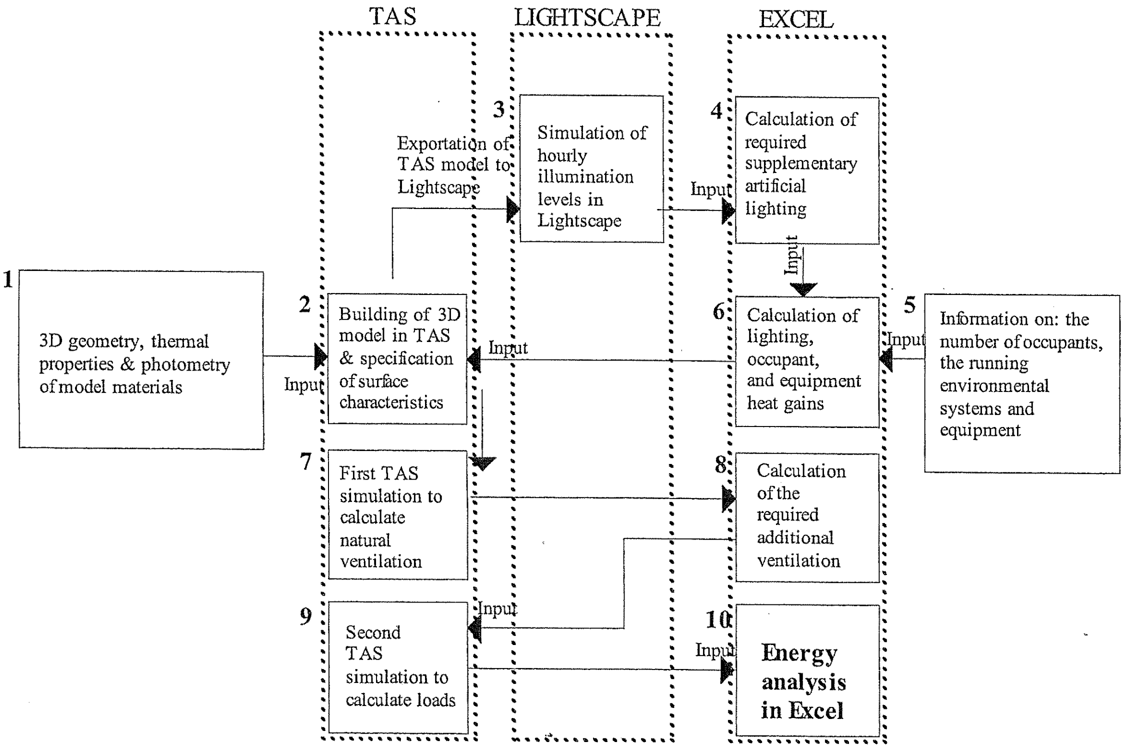


Figure 3: The simulation procedure.

and Combi and some layouts of the *Club* may not adhere to, or make full use of the passive zone for optimising daylight and natural ventilation. In addition, commercial considerations for space-lets by developers and letting agents result in a typical subdivision depth of 4.5m in offices (Yeang, 1996), therefore not fully using the passive zone potential.

Methodology

The investigations are done by computer simulations using the Thermal Analysis Software (TAS), Lightscape and Excel software packages as described in the following sub-sections. TAS is a suite of software products, which simulate the dynamic thermal performance of buildings and their systems. The main module is Tas Building Designer, which performs dynamic building simulation with integrated natural and forced airflow. Tas Ambiens (TAS, 2004) is a 2D CFD package that produces a cross section of microclimate variation in a space. The Lightscape software simulates the physical properties of light and materials. It is used in this research to visualize and quantify the photometric performance of lighting designs and products.

Two energy modelling tools (TAS and *Energy-Plus)* and two for daylight modelling (*Radiance* and *Lightscape*) were considered for selection although there are others such as IES and *ESP-r*. This was mainly based on their suitability for simulating diverse interior conditions & complex environmental interactions, and producing detailed analysis of the multiple factors under investigation. *TAS* and *Lightscape* have 3D compatibility, producing integrated results. *Lightscape* was better suited than *Radiance* to carry out numerous hourly simulations because of its faster rendering capability, and its stability and iterative capability to enable constant updating of inputs.

Procedure

The procedure for the simulations, as summarised in Figure 3, involves the following:

- Creation of a base case 3D envelope model in *TAS*.
- Specification of the characteristics of the construction elements, site location, orientation, and weather conditions. The building elements and constructions are a mixture of some from the *TAS* libraries (modified where necessary), and others created and attributed with the desired thermo physical and photometric properties.
- Introduction of partitions in copies of the base case to create different layouts.
- Exportation of each model from *TAS* to *Lightscape* to calculate illuminance levels for each room, which are then input onto Excel spreadsheets.
- Calculation of the required supplementary artificial lighting (and therefore lighting heat gains) in the Excel spreadsheets.
- Calculation of occupant heat gains (sensible and latent), and sensible equipment heat gains in the Excel spreadsheets.
- Input of the heat gains to the *Internal Conditions Data Editor* in *TAS*.
- Calculation of natural ventilation through permanent background vents from a first *TAS* run.
- Input of the results of the first TAS run into the Excel spreadsheets to calculate supplementary ventilation where natural ventilation does not meet the recommended minimum fresh air requirements. Where a result indicates over-ventilation, the level of waste is also calculated.
- Input of the hourly mechanical ventilation levels, where required, into the *TAS* models for each scenario.
- Second *TAS* run of the final dynamic response of the model to calculate the detailed airflow, temperature, humidity profiles and energy load breakdowns for each zone.

Simulation Model Layouts and Characteristics

Figure 2 shows the five typical layouts in a 12m wide office space slice, in a building 12m deep. It also shows layouts of luminaires & switches, auxiliary facilities, and workstations across the space plans. The *Hive* (open plan) serves as a base case for the analysis. The model depth is based on the *2h* (2 x ceiling height) definition of the passive zone, for a ceiling 3m high. Although this assumes the narrow floor plates in most European offices resulting from strict regulations on natural light and outside views in work places, office depths in other part of the world, such as America, may be considerably deeper. Office plans and floor plate shapes also vary considerably between world regions because of zoning laws and codes, and depending on whether they were built as cooperate headquarters, speculative offices, extensions or were conversions (Meel, 2000; Steadman, 1994). Even within the European context, there are varieties because of ownership structure, historical character and preservation, planning processes, and cultural aspects (Meel, 2000). The bulk of office spaces consist of workstations and their associated auxiliary spaces for files and equipment used on a day-to-day basis and the analysis in this paper focuses on these spaces since they are expected to use the largest proportion of energy. It does not explore spaces such as conference/meeting rooms and repositories for infrequently used files and equipment.

The glazing ratio is 30% and uniformly distributed on the north and south facades of the shell, with the east and west being windowless. This glazing ratio (30%) is the optimum for southern UK office buildings (Baker & Steemers, 2002) and the upper limit for avoidance of glare (CIBSE Guide F, 1998). Case studies suggest that buildings with a greater than 30% glazing ratio may often operate with blinds down and lights on because of the effects of glare (Leaman, Bordass & Bromley, 1995). For user appreciation of sunlight penetration, a window area of 30% of the window wall or 16% of the floor area has been defined as the lower limit in order to satisfy at least 70% of occupants (Baker & Steemers, 2002). Light reflectance levels of interior surfaces in the models are 0.3 for floors, 0.55 for walls and 0.7 for ceilings. A 300mm high fanlight is provided on each internal door – there are no external doors.

Background ventilation is through vents provided, one above each window and one on the west wall (Figure 2). The UK Building Regulations Approved Document AD Part F1 (CIBSE Guide H,1999) require a minimum size of background ventilation openings of 400mm^2 per m^2 of floor area and 4000mm^2 in rooms less than 10m^2. Background ventilation as defined in the Regulations is ventilation through openings to the outside such as: trickle ventilators in window frames, glazed openings or above window frames, air bricks or suitably designed opening windows such as vertical sliding sash or top-hung windows. The ventilation opening(s) should be adjustable by occupants and located (typically 1.75m above floor level) so as to avoid discomfort due to cold draughts and to prevent rain ingress.

In this paper, air-infiltration between rooms in the compartmented layouts is through 3240mm^2 gaps at the bottom of each door – assuming standard 800mm wide door shutters and that doors are closed. Partitions in the compartmented layouts are placed to ensure that the 30% glazing ratio is maintained and daylight, vents, and luminaires are distributed equally in the subspaces.

Table 1 shows the base-case construction characteristics of the roof, floor, walls and windows, compared with Building Regulations *maximum* and *best practice* values. The characteristics of these are kept constant in all the simulations. The only exception is the internal walls in the *Combi* plan, where 10mm glass partitions separate the central common space and the individual peripheral offices, but enable them to share daylight and view-out. Not all the simulations take into account the role of movable furniture and office equipment. These may have a role to play on the effectiveness of ventilation, lighting and thermal mass. The life spans of their settings can, however be very short, varying from day-to-day rearrangements (Duffy, 1997) to three months to ten years (Fernandez, 2003), and may be difficulty to quantify meaningfully. The furniture settings tested in Figure 2 are located to minimise the obstruction of radiators and exposed thermal mass surfaces, daylight and airflow between external wall vents and interior doors. They are also arranged to match closely the grid of ceiling-mounted lighting fixtures. Individual workstations and auxiliary facilities are 1500 x 1500mm and 1000 x 1000mm respectively and have heights of 750mm.

Lighting, Ventilation and Thermal Environments in the Simulations

The different internal heat gains, ventilation requirements, lighting and thermal environments are adjusted to match occupancy levels. The need to investigate the temporal aspects of occupants and systems operation called for hourly zone inputs of internal gains and systems control based on the occupancy in each zone. Simulations are therefore limited to a peak winter day and peak summer day – 21st December and 12th July respectively (Table 2). Occupant and equipment gains are 130W per occupant and 150W per computer. The occupant gains include 80W of sensible heat given off by radiation, convection, and conduction and 50W of latent heat given off in breath and by evaporation of perspiration.

For lighting, results of daylight distribution done in Lightscape simulation are used to calculate the probabilities of switching on lights in the different rooms, as a function of time of day and minimum daylight factors (after Littlefair, 2001). These are then used to calculate the required supplementary light and lighting heat gains. The Lightscape results indicate that:

- Lights would be switched on during the peak winter morning (9:00 hrs) in all rooms of the different layouts.
- The probabilities of switching them on would vary with layouts and rooms during the peak summer morning.

Figure 6 shows sample results using Lightscape for 21st December at 13:00 hrs and the probabilities of switching on lights in different spaces. Lightscape grid sizes and coordinates are specified to facilitate analysis of illumination for corresponding points in the various layouts. These are based on the spacing of the lighting fixtures and control strategy in the models. Light gains are calculated assuming an installed lighting capacity of 3W/m^2 for every 100 lux required. 3W/m^2 translates to the good practice capacity of 10-12 W/m^2 to achieve 400 lux (CIBSE Guide F, 1998).

Table 1: Characteristics of construction of building elements of the base case model.

Building element	**Description**	**Conductance** (W/m^2 °C) (This study) **Note:** Internal and external surface resistances are excluded.	**Maximum U-value** (Building Regulations part L2, DETR, 2002)	**Best practice U-value** (Building Regulations part L2, DETR, 2002)
Flat roof	15mm acoustic panel, 200mm air cavity (downward flow), 150mm concrete, 125mm expanded polystyrene sheet and 3mm asphalt.	0.266	0.25	0.13
Ground floor	5mm plastic tiles on 50mm screed on 125mm concrete on 75mm crushed brick aggregate on 1000mm sand.	0.29	0.25	0.20
External wall	25mm light weight plaster, 100mm aerated autoclaved concrete block, 100mm glass fibre, 50mm air cavity (horizontal flow) 105mm brickwork.	0.256	0.35	0.25
Internal wall	25mm lightweight plaster, 100mm foamed slag concrete blocks, 25mm lightweight plaster.	1.054	–	–
Windows	6mm kappa float – 12mm air cavity (horizontal flow) – 6mm clear float.	2.6	2.20 metal frames, 2.0, timber PVcu frames	1.80 metal frames, 1.80, timber PVcu frames

Other assumptions made in the determination of lighting gains in the simulations are the following:

- The common practice that manual switches for general lighting in each room are located in one switch panel (see Figure 2 for switch locations).
- That lights are manually controlled.
- That if the daylight factors call for switching on, users would switch on all the lights if switches were in one panel.
- That the lights would remain on until people leave the building (Baker & Steemers, 2000; Phillips, 2004; Tregenza & Loe, 1998).

Lights in shared auxiliary facility spaces are assumed to remain on even when the occupancy in private spaces around them is less than full capacity. For the *Club, Den* and *Hive* plans, interactivity requires that most of the lights remain on when occupancy in spaces is less than their full capacity, and this is what has been assumed in the simulations. The lighting assumptions are based on the requirements for *Hives, Cells, Dens* and *Clubs,* as outlined by Monica and Grinfeld (2003).

For ventilation, windows are assumed closed and natural ventilation is through the background vents – either cross and/or one-sided ventilation. In occupied rooms, where background ventilation does not meet the recommended minimum fresh air requirements of 8 litres per second per occupant (assuming a no smoking provision), the hourly deficit is input and assumed to be met by supplementary mechanical means. Fan power has not been taken into account. In unoccupied rooms, ventilation is only through background vents. Although the assumption in the simulation is that the air delivery system prevents occupants from opening windows when the mechanical system is on, it is not always the case. It is worth noting that although window opening is usually linked to the quest for fresh air and comfort, with globe temperature as the dominant factor, in addition to other comfort factors such as relative humidity, wind and rain, it is also linked to season and time of day (Brundrett, 1977; Rijal, Tuohy, Humphreys, Nicol, Samuel & Clarke, 2007). During summer, windows would typically be open if there is adequate wind unless the buildings strategy is to deliver air passively through ducting (via a cooling plenum for example) or is air-conditioned. Other situations where windows may remain closed include noisy, dusty and polluted environments; places where opening of windows would raise security concerns; and during weather conditions with very strong winds or storms. According to Givoni (1998), the decision whether or not to open windows when the outdoor temperature is higher than indoors, depends on the personal relative preference for a higher air speed with higher temperatures, or lower temperatures with still air. Given the predominantly southerly wind direction for the simulation in this paper, with an average speed of 1.6-3.3m/s and an air temperature above the comfort zone (25.3-32 °C) for the peak summer simulation hours (see Table 2), it is possible windows may be either open or closed. The simulation weather is that of BRE's Garston station – chosen partly because it is at Garston where the Building Research Establishment

Table 2: BRE-Garston station (UK) weather data used for peak winter (Day: 354) and peak summer (Day: 193) simulations (Tas Building Designer, 2004).

	Peak winter							Peak summer						
Hour	Global solar radiation (w/m^2)	Diffuse Solar radiation (w/m^2)	Cloud cover (0 - 1)	Dry bulb temp (^{0}C)	Relative humidity (%)	Wind speed (m/s)	Wind direction (deg. E of N)	Global solar radiation (w/m^2)	Diffuse solar radiation (w/m^2)	Cloud cover (0 - 1)	Dry bulb temp (^{0}C)	Relative humidity (%)	Wind speed (m/s)	Wind direction (deg. E of N)
1	0	0	0.33	1.1	96	2.4	265	0	0	0.13	20.1	29	0.2	21
2	0	0	0.33	0.9	96	2.2	270	0	0	0.13	18.2	89	0.4	3
3	0	0	0.33	0.5	95	2.1	242	0	0	0.13	15.6	91	0.2	11
4	0	0	0.33	-0.5	96	1.2	213	0	0	0.13	15.0	92	1.0	30
5	0	0	0.33	0.3	96	2.2	300	0	0	0.13	14.7	93	0.5	3
6	0	0	0.33	1.0	96	2.4	288	21	12	0.18	16.3	92	0.6	15
7	0	0	0.33	-0.3	96	0.8	231	99	79	0.63	20.0	81	0.3	48
8	0	0	0.33	-0.6	96	1.1	279	373	100	0.00	22.8	70	0.4	81
9	8	7	0.33	0.3	96	1.0	321	523	134	0.00	25.3	60	0.9	169
10	71	53	0.54	2.0	96	1.9	309	630	139	0.00	28.1	46	1.6	167
11	153	58	0.00	3.5	94	3.0	310	665	144	0.00	29.3	38	2.4	179
12	261	109	0.00	4.9	85	3.3	307	712	160	0.00	30.4	36	2.4	185
13	250	113	0.02	5.7	80	3.6	309	686	206	0.00	31.3	32	2.7	189
14	183	76	0.00	5.9	78	2.8	307	606	204	0.00	31.8	32	2.9	227
15	105	51	0.07	5.7	78	2.5	294	590	201	0.00	32.0	31	3.3	223
16	21	21	0.99	4.8	83	1.8	255	567	199	0.00	31.9	30	3.2	248
17	0	0	0.23	3.5	88	1.3	244	451	169	0.00	31.7	29	3.3	221
18	0	0	0.23	1.9	91	0.7	236	129	74	0.23	30.2	32	2.9	224
19	0	0	0.23	1.2	94	1.0	216	99	74	0.54	28.8	34	2.3	343
20	0	0	0.23	1.5	95	1.0	221	49	42	0.74	27.3	31	1.1	13
21	0	0	0.23	1.2	96	1.2	197	0	0	0.15	25.8	16	0.8	338
22	0	0	0.23	1.6	96	1.5	230	0	0	0.15	24.3	47	0.7	269
23	0	0	0.23	1.1	96	0.8	227	0	0	0.15	22.8	47	0.7	269
24	0	0	0.23	0.3	96	1.0	229	0	0	0.15	21.5	53	0.7	323

(BRE) carried out research on the light switching behaviour of occupants. The results of the BRE research have been used to guide the lighting loads analysis in this study.

In practice, trickle ventilators for background ventilation usually have provisions for manual control but occupants rarely close or adjust them – partly because they are typically small in size and incorporated into windows or wall decoration. This camouflages and makes them obscure and not obvious whether open or closed. Occupants may not even know what they are, and would therefore unlikely open closed vents or close open ones. Automatic dampers are increasingly being installed in some new buildings and refurbishments but the assumption in this simulation is that the vents are manual and remain open throughout.

For the thermal environment, the plant is set with a one-hour preconditioning period to operate between 8:00 and 18:00 hrs in all cases. In occupied spaces, it is set to size automatically the maximum heating/cooling with indoor lower and upper temperature limits of 18 and 24°C respectively, while the respective relative humidity limits are 40 and 60%. The upper temperature limit for the summer simulations is also set at 24°C as recommended in the environmental criteria for design in CIBSE Guide A (1999). The guide suggests that the temperature range for comfort in offices should be 21-23°C in winter and 22-24°C in summer. It is however, worth noting that according to the Guide, higher summer temperatures may be acceptable in buildings that are not air-conditioned. According to Givoni (1998), it is likely users may feel comfortable in temperatures as high as 27°C in hotter regions with weather conditions as hot as those used in this paper for the peak summer simulations (see Table 2). The day (12th July) has unusually high temperatures for the typical UK summer, but represents hotter climates and probably future UK summers if global warming continues. In simulating the role of varied occupancy in different spaces, the natural temperature profiles are allowed to fall outside the comfort limits i.e., below 18°C and above 24°C in unoccupied rooms. Where the limit is allowed to fall below 18°C, the heating plant is set to provide a minimum temperature of 10°C to provide protection for the building fabric and its contents. This is the typical recommended temperature but may be lower (CIBSE Guide H, 1999).

It is worth noting that user control of the internal environment is related to space ownership and that individuals have their own preferences and expectations of environmental conditions.

The degree to which a space is owned is partly determined by the space plan. According to Littlefair (2001), people expect to control lighting in owned spaces for one or two occupants such as the owned spaces of the *Cell and Combi*. In shared multi-occupied offices such as the *Hive*, *Den* or the shared spaces in the *Combi and Club*, people may want to control lights in their area, but there can be conflicts with other occupants' requirements and lights tend to remain on even if not required. People expect unowned spaces such as circulation areas to be lit, but often do not expect to operate lighting controls. De Dear (1994) and Leaman and Bordass (1995) reported that the perceptions of control in office buildings decreased as working rooms got larger and deeper. Heerwagen (1992) also reported that people in individual rooms had higher perceived control than people did in cellular rooms with more than three occupants, and these in turn had more perceived control than people did in open spaces. Raw and Roys (1989) also found that perceived environmental control decreased when the number of people in a room increased.

In other studies (Brager & De Dear, 1998; Fishman & Pimbert, 1982; Rohles, Hayter, & Berglund, 1977; Rowe & Lambert, 1995), the level of individual control is associated with tolerance to indoor environments. Raja, Nicol and McCartney (2001) also recorded that occupants who have greater access to controls (e.g., those close to a window) report less discomfort than those who have less access (e.g., away from the window). Open-plan spaces tend to have a higher affinity for automated and centralised controls that would be expected to provide fewer opportunities for users to operate controls at localised and personalised levels than closed plans. User tolerance for wider margins and/or variations in environmental conditions is therefore expected to be higher in the *Cell*, *Combi* and the enclosed spaces of the *Club*, than in the *Hive* and *Den* plans.

Space use Density, Intensity and Distribution of Users

The layout densities used in the simulations are those typical in practice in the various layouts. The densities based on typical desk sizes in workstations of 1500 by 1500mm each, and recommended planning standards (Tutt & Adler, 1979), are as follows:

- *Cell* – 18m^2
- *Combi* – 18 m^2
- *Den* – 12 m^2
- *Club* – 12 m^2
- *Hive* – 9 m^2

This translates to 8 workstations in the *Cell* and *Combi*, 12 workstations in the *Club* and *Den*, and 16 workstations in the *Hive*, for the 144 m^2 of floor area in each plan. Occupants and computers are distributed into the workstations as shown in Figure 2. Although Yeang (1996) stresses that space use densities vary globally, he points out that these densities are typical of UK offices. It has therefore been thought reasonable to use them in the simulations.

The simulations also examine the energy impact of occupancy levels of 25%, 50%, 75% and 100% across the day, but in practice buildings may have fluctuating occupancy at different times of the day and seasons of the year. Although the simulated occupancy levels represent the wide ranges of levels reported in offices (Duffy, 1997; Duffy *et al.*, 1998; Eley & Marmot, 1995) it is worth noting that many building systems would normally be designed and specified assuming 100% occupancy.

To control the effects of orientation, the assumption is that the occupied workstations are in corresponding positions across the layouts when the occupancy is less than 100%. In each layout, for example, the assumption is that when the occupancy is 25%, the occupied workstations are only those on the right quarter of the plan (Figure 2). Workstation occupation then increases towards the left until all are occupied at the 100% occupancy. In practice, even with occupancy of 25% or less, occupants may be distributed on the whole plan. Two scenarios are simulated for the *Den* plan at the occupancy levels of 50% and 25%. Scenario 1 assumes the possibility that occupants may be concentrated in either of the two rooms and that lights in the unoccupied room are switched off. Scenario 2 assumes that users are distributed on the whole floor and that all lights are switched on.

Table 3 is a complete list of the model characteristics and environmental conditions that remain constant and those that vary in the simulations.

Results and Discussion

Figures 3-6 show the results of the simulations – comparing different loads and their variations across different scenarios and from their respective base case loads. The results are expressed as energy per layout and *per capita*. The former relates to the conventional expression of energy per area, while the latter relates to space use in terms of the density and organisation of individual workstations and associated auxiliary facilities. The references to energy per user/occupant in this paper therefore represent the energy loads of the total area divided by the number of occupied workstations. The references of load variations in percentage terms throughout this paper refer to the differences of the various loads from their respective base case loads expressed as a percentage of the base case loads. Figure 4a shows the variations of total combined thermal and lighting loads with plan regimes in peak winter and peak summer. Figure 4b shows the same combined thermal and lighting loads but expressed per occupant. They show variations that are more significant in the peak summer loads than peak winter loads. For both seasons, the overall combined thermal and lighting loads variations across layouts increase with the decrease in occupancy levels. For peak summer, for all occupancy levels, there are considerable differences in the loads across the layouts. The *Cell* and *Combi* have significantly lower and almost equal loads compared to the other three, and the *Hive* has the highest loads. Overall variations of the combined thermal and lighting loads across the five layouts, their typical space use densities in practice, and varied occupancy levels are 29% in peak winter and 64% in peak summer. The respective variations at the average occupancy in offices of 50% are 19% and 51% of the base case loads. At the 25%, 75% and 100% occupancy levels, the respective variations are 29%, 9% and 2% of the respective base case loads in peak winter and 64%, 44% and 40% in peak summer.

For the loads per occupant, the combined thermal and lighting peak summer loads of the partitioned options are generally higher than those of the open plan options except for the 25% occupancy and *Den 1*. This could be attributed mainly

Table 3: Summary of what remains constant and what varies in the simulations.

Constants	Variables
i. External envelope size: floor plate (12 x 12m) and ceiling height (3m). ii. Roof, floor and external walls: thermo physical properties. iii. Windows sizes, uniform glazing ratio of 30%, and positions. iv. All windows closed. v. Background vents: distribution and sizes. vi. Background vents all remain open throughout. Natural air supply is only through them. vii. Doors are closed – internal trickle air flows through gaps at the base of all doors both winter and summer. viii. Interior surfaces reflectances: Walls – 0.55, Floors – 0.3, Ceilings – 0.7. ix. Plant: one-hour preconditioning period and operation time 8:00 to 18:00 hrs in all simulations. x. RH%: lower limit – 40% and upper limit – 60%. xi. Ambient conditions. xii. Luminaire distribution. xiii. Indoor temperature limits: 18-24 °C. xiv. Internal partitions: all as in Table 1, except for the *Combi* plan where 10mm clear float glass walls separate the peripheral rooms from the central common space. xv. Occupant positions for various occupancy levels are harmonised in all the layouts to control the effects of orientation except that two scenarios are simulated for the *Den* plan with occupancy levels of 50% and 25%. Scenario one: occupants are concentrated in either of the two rooms and lights in the unoccupied room are switched off. Scenario 2: users are distributed on the whole floor and all lights are switched on.	i. Partitions (plan types) positions. ii. Number of switches and their positions. iii. Workstation numbers and layouts. iv. Auxiliary facilities layouts. v. Variable lighting gains. In winter, all lights are switched on in occupied rooms, and in summer, they are switched on in occupied rooms depending on the probabilities of switching on lights based on Daylight Factors (Lightscape analysis showed that lights would be switched variably at 9:00 hrs in the different layouts during summer). vi. Varied workstation capacities as typical in practice as follows: vii. Cell and Combi – 8, Den and Club – 12, and Hive – 16. viii. Varied occupancy: 25%, 50%, 75% and 100%. ix. Varied occupant gains – only in occupied rooms. x. Varied equipment gains – only in occupied rooms assuming one computer per occupant. xi. The assumed mechanical supplementary ventilation where the natural supply is inadequate is variable depending on natural supply afforded by the different plans.

to the differences in space use densities. The space per user in the *Cell*, for example, is twice that in the *Hive*. As shown in Figure 4b, the total energy per occupant generally increases with decrease in occupancy for both winter and summer, but the percentage variations across layouts decrease with the decrease in occupancy in winter. The maximum variations in *per capita* total loads from the respective base cases loads across the whole range of occupancy levels are 107% in peak winter and 46% in peak summer. At the average occupancy of 50%, the respective variations are 80% and 16% of the base case loads. At the 25%, 75% and 100% occupancy levels, the respective variations are 75% 90% and 107% of the respective base case loads in peak winter and 39%, 23% and 30% in peak summer.

The results of the total loads in Figure 4a show that organisations would save energy by implementing *Cell* and *Combi* layouts when weighed against implementing the *Club*, *Den* and *Hive* layouts. This applies to both the total area of 144m^2 and when the energy is analysed per m^2 or per occupant per m^2, and is generally the case for all occupancy levels during both seasons. The only exception is at the 100% occupancy in winter where the loads are almost equal across the layouts. The potential savings at each occupancy level are higher in summer than in winter. However, the saving potential profiles are completely different when the *per capita* energy is considered since the number of workstations, and consequently, the areas per occupant afforded across the layouts differ. The *per capita* results (Figure 4b) show that organisations would save energy in open plans (*Hive, Den*) compared to closed plans (*Cell, Combi*) during both seasons at all occupancy levels except at the 25% level in summer. From the occupancy studies cited in the Introduction of this paper (Duffy, 1997; and Duffy *et al.*, 1998; Eley & Marmot, 1995), 25% occupancy is less likely in practice and its results are therefore less significant.

It is worth noting how the two sets of results reveal the important distinction between the way conventional area-based loads are calculated and the per occupant usage calculation. The latter provides a better reflection of energy use versus demand i.e., where and when it is needed in terms of space use density and intensity. The area-based results of the 144m^2, for example, show the *Cell* having less overall loads than the *Hive* but to accommodate an equal number of workstations as those in the *Hive*, a *Cell* area of 288m^2 is required. To anticipate and realise significant energy savings the focus should be on achieving layouts and/or space-use programs that optimise the space per occupant and space use intensities within acceptable standards, in addition to measures towards cutting the energy per m^2. That way, savings with impact in the context of the current global energy and CO_2 concerns can be realised.

A breakdown of the loads (Figure 5) indicates that *Ventilation/Infiltration/air movement,* and *Lighting gains* are

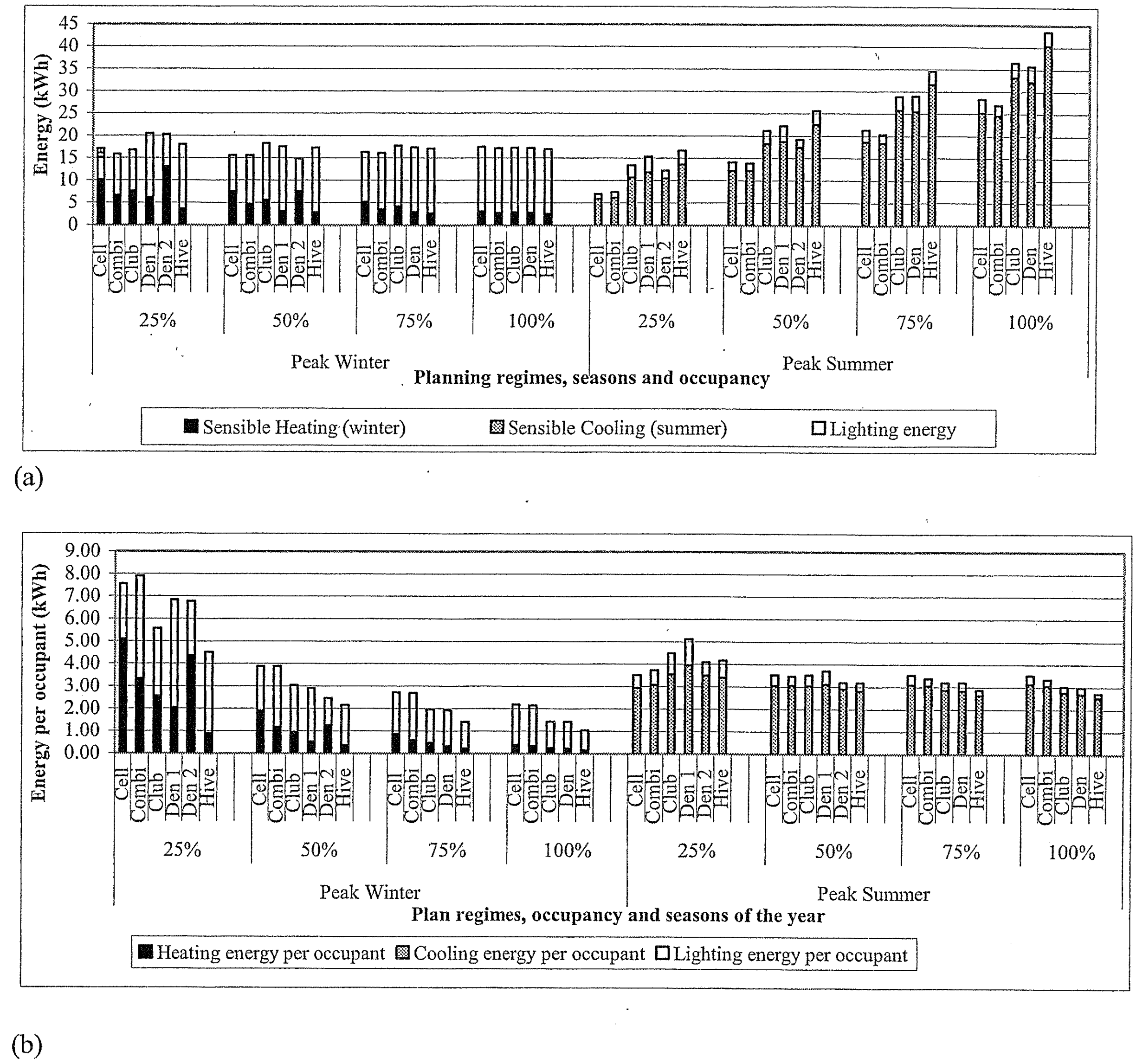


Figure 4: Heating and lighting loads for different occupancy levels on 21st December and 12th July (8:00 to 18:00 hrs) assuming: 1) the typical occupancy densities as happens in practice for each plan regime; 2) lights and heaters/coolers are running in occupied rooms and off in unoccupied rooms; and 3) computers that are running are equal in number to occupants. (a) Shows the total energy for the total area of 144m² and (b) shows the energy per occupant.

the factors related to the building fabric that make the most significant contributions to the variations in overall loads. The contributions of *occupant* and *equipment* gains relate to the space use densities afforded by the different layouts and the occupancy levels. The contributions of *ventilation/infiltration/air movement* relate to the impact of interior partitions on air supply and environmental interaction between the rooms. The simulations indicate that in the partitioned layouts, the minimum background vents result in over-ventilation in some rooms on the windward side while there is under-ventilation in others on the leeward side. This implies that the analysis includes some potentially avoidable energy waste where spaces are over-ventilated – representing a common phenomenon in practice. The avoidable waste increases with the decrease in occupancy, and the *Hive* and *Den* have the greatest potential for waste. Although occupants could minimise over-ventilation waste, in practice, they rarely adjust background vents since, as mentioned earlier in this paper, the vents are typically obscure.

The lighting load differences relate not only to the influences of partitions on the penetration of daylight and how it is reflected internally, but also on the manner in which planning affects the distribution of users, type of lighting systems and the degrees to which users can operate lighting controls. This can be demonstrated using the sample Lightscape results for 21st December at 13:00 hrs in Figure 7. Although the probabilities of switching on lights in the open layouts based on the daylight factors are on average lower than those of the closed layouts, general lighting in the former could remain on even when the occupancy in spaces is less that 100% and off in unoccupied rooms in the latter.

It is important to note the differences in the lighting and thermal components in the total loads. The lighting loads

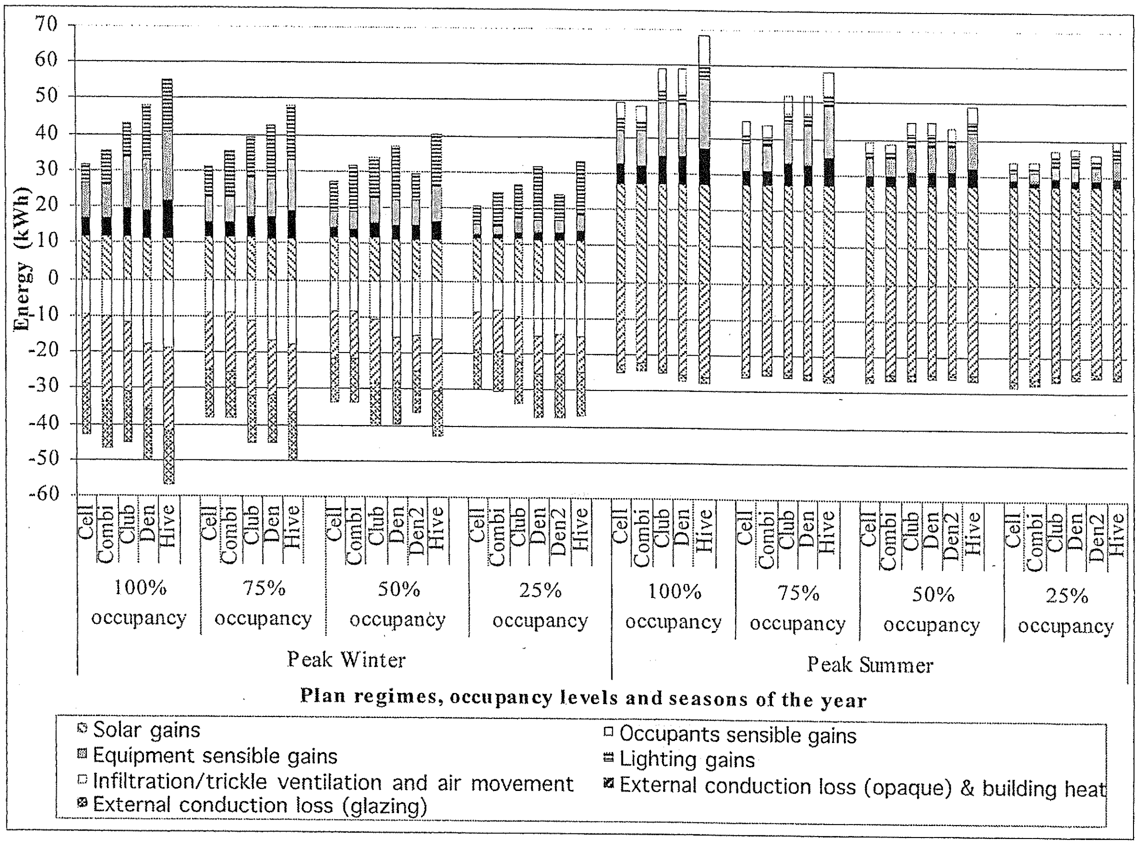


Figure 5: Breakdown of the component loads leading to the overall loads in Figure 4(a).

across occupancy levels and layouts generally vary by wider margins than the variations in the overall loads. Although the focus here is on the overall loads, the distinction between the variations of the proportions of the component loads is important especially if the primary energy sources for heating and lighting have different CO_2 and cost implications.

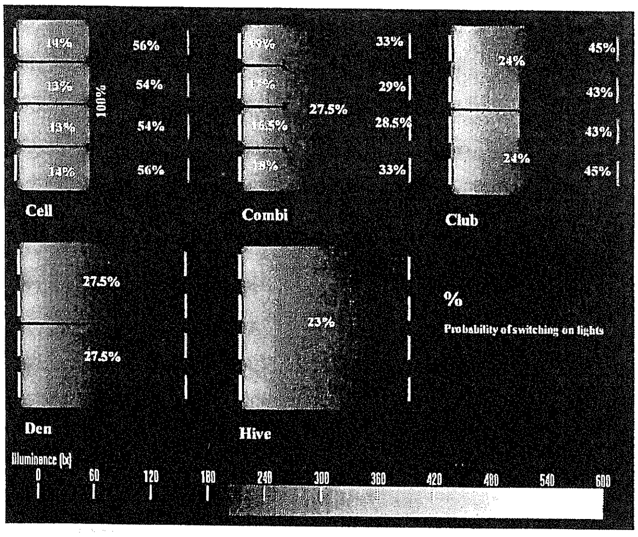


Figure 6: Illuminance distribution and probabilities of switching on manually controlled lights as a function of minimum Daylight Factor on 21st December at 13:00 hrs.

Conclusions

This work sought to investigate the impact of space planning and/or utilisation on energy use in office buildings. The results confirm that the different ways in which interior spaces can be organised not only influence the occupant density, but are also significant determinants of energy performance. At the average occupancy of 50%, the total loads vary by 19% and 51% from the base case loads in peak winter and peak summer respectively. At the 25%, 75% and 100% occupancy levels, the respective variations are 29%, 9% and 2% of the respective base case loads in peak winter and 64%, 44% and 40% in peak summer. The partitioned layouts generally have a better match between the total energy loads and occupancy levels, with the *Cell* and *Combi* being the best performers in this respect at all occupancy levels. However, the results of *per capita* loads show a different picture - those of the partitioned layouts are generally higher than those of the open layouts. At the average occupancy of 50%, the *per capita* loads vary by 80% and 16% from the base case loads in peak winter and peak summer respectively. At the 25%, 75% and 100% occupancy levels, the respective variations are 75%, 90% and 107% of the respective base case loads in peak winter and 39%, 23% and 30% in peak summer. As expected, the *per capita* total loads increase with the decrease in occupancy in all layouts during both seasons.

The *per capita* loads imply that the traditional analysis, based on floor area, may not adequately reflect the energy performance of a building if its usage is taken into consideration. They provide a better reflection in terms of the use of energy where and when it is needed in relation to space use density and

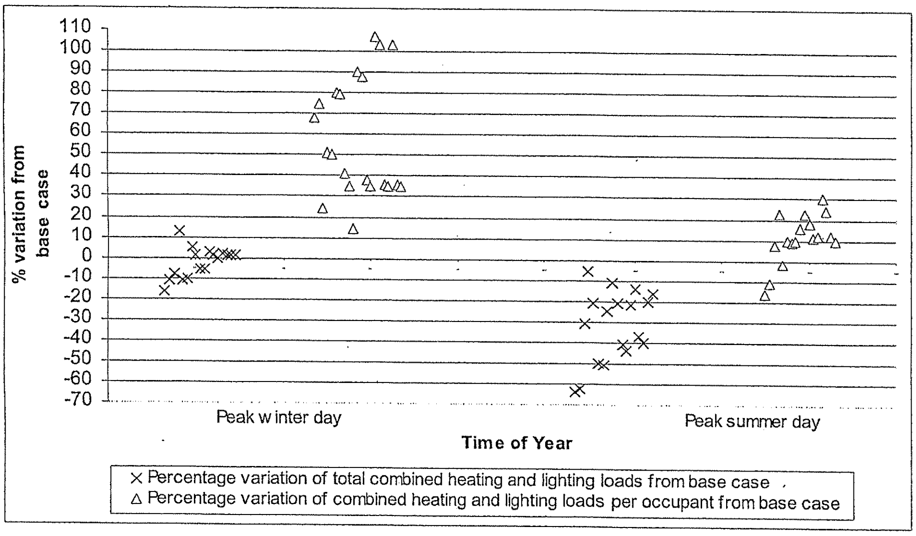


Figure 7: *Summary of variations of total loads from base case (Hive) loads assuming varied layout densities as happens in practice.*

intensity. They confirm the importance of the occupant as a basis of assessing energy performance, particularly for spaces whose occupancy is typically less than their full capacity such as offices. The area-based analysis of the 144m^2, for example, shows the *Cell* having less overall loads than the *Hive*, but to accommodate an equal number of workstations as those in the *Hive*, a *Cell* area of 288m^2 is required. On the other hand, the *per capita* analysis shows the *Hive* having much lower loads than the *Cell* since the former accommodates sixteen workstations while the latter accommodates eight workstations for an equal area of 144m^2.

Although the simulations do not take into account all the complex factors related to occupant behaviour on environmental controls, these variations begin to suggest the energy levels that can be saved, the choices and/or tradeoffs that a designer can make between options for space planning and given space utilisation patterns. Also suggested are the ways in which organisations must use pre-planned spaces in order to save energy. In order to realise savings with a wider impact than the energy per m^2, and meaningfully address global energy use and CO_2 concerns, energy performance must be based on *per capita* expenditure. Also the focus being on achieving layouts and/or space-use programs that improve efficiency in terms of occupant density and space use intensities, including in existing wasteful office buildings. This should be in addition to strategies towards improving the energy per m^2, and demand-control of energy consuming environmental systems. Based on the *per capita* analysis, the most energy savings would generally be made in the open layouts (*Hive* followed by the *Den*) followed by the mixed layout (*Club*) then the closed layouts (*Combi* and *Cell*) at all occupancy levels. Additional savings could be made by adopting the best mixes of these layout types to achieve a reduction in the overall floor area used by an organisation.

The findings enhance, within the limits of the factors considered, the understanding of the deduced *occupant factor* in the energy model by Baker and Steemers (2000). They are potentially of value to the relationships between the energy efficiency objectives of building shell designers, interior designers and/or tenants. They imply that the design for energy efficiency should not end soon after a building base shell is constructed. Since offices experience frequent changes in interior configurations, there should be continuous, dynamic review and adaptation, guided by monitored patterns of space use, to facilitate continuing achievement of intended passive and/or low energy objectives of their shells.

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