HIGH QUALITY INDOOR ENVIRONMENTS FOR SUSTAINABLE OFFICE BUILDINGS

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ABSTRACT

The quality of office indoor environments is considered to consist of those factors that impact occupants according to their health and well-being and (by consequence) their productivity. Indoor Environment Quality (IEQ) can be characterized by four indicators:

- Indoor air quality indicators
- Thermal comfort indicators
- Lighting indicators
- Noise indicators.

Within each indicator, there are specific metrics that can be utilized in determining an acceptable quality of an indoor environment based on existing knowledge and best practice. Examples of these metrics are: indoor air levels of pollutants or odorants; operative temperature and its control; radiant asymmetry; task lighting; glare; ambient noise. The way in which these metrics impact occupants is not fully understood, especially when multiple metrics may interact in their impacts. While the potential cost of lost productivity from poor IEQ has been estimated to exceed building operation costs, the level of impact and the relative significance of the above four indicators are largely unknown. However, they are key factors in the sustainable operation or refurbishment of office buildings.

This paper presents a methodology for assessing indoor environment quality (IEQ) in office buildings, and indicators with related metrics for high performance and occupant comfort. These are intended for integration into the specification of sustainable office buildings as key factors to ensure a high degree of occupant habitability, without this being impaired by other sustainability factors.

The assessment methodology was applied in a case study on IEQ in Australia's first 'six star' sustainable office building, Council House 2 (CH2), located in the centre of Melbourne. The CH2 building was designed and built with specific focus on sustainability and the provision of a high quality indoor environment for occupants. Actual IEQ performance was assessed in this study by field assessment after construction and occupancy. For comparison, the methodology was applied to a 30 year old conventional building adjacent to CH2 which housed the same or similar occupants and activities. The impact of IEQ on occupant productivity will be reported in a separate future paper.

Keywords: office, air, thermal comfort, noise, lighting

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1.0 BACKGROUND

The CRC for Construction Innovation initiated a project “Regenerating Construction to Enhance Sustainability” in 2005, with the overall objective to ‘re-life’ an office building to an “A Grade” standard using cost effective practices for ecologically sustainable design and best-practice technologies. The expected outcome was the delivery of superior refurbished *office* buildings according to a core set of four sustainability criteria:

- Eco-efficiency: minimising ecological footprint
- High indoor environment quality (IEQ): demonstrable improvement in key IEQ criteria, including thermal performance and indoor air quality
- Healthier and more productive working environment: as measured by the performance of occupants determined before and after refurbishment and
- Waste minimisation.

This report considers only the core criterion *high indoor environment quality*. A previous report described available knowledge and developed the research plan for this project (Brown 2006) as follows:

- Identify and define *key indicators* for high quality indoor environments
- Specify *sampling and measurement protocols* for performance measures (metrics) of key IEQ indicators
- Specify reliable, *scientific procedures* by which performance measures can be evaluated
- Recommend *performance criteria* for each metric
- Consider *design and specification implications* of performance targets
- Document the application of the indicators in a *target building before and after refurbishment.*

2.0 IEQ INDICATORS

IEQ indicators (Brown and Kivlighon 2005) were considered to be encompassed in the following indicators:

- indoor air pollutant levels
- thermal comfort
- lighting, and
- noise.

Building ventilation rate will have a significant impact if uncontrolled, but historically this has been tightly regulated in the Building Code of Australia (BCA) and was not *directly* included as an indicator assuming that ventilation performance was generally optimised. A key consideration in selecting the indicators was that they could be represented by performance metrics relevant to their potential impacts on occupant satisfaction and acceptance of office environments.

2.1 Indoor Air Quality Indicators

Poor indoor air quality (IAQ) can be a significant health, environment and economic problem, and has become a public health issue and liability for employers and building managers who fail to provide a ‘safe’ working environment. IAQ measures must determine how well indoor air (a) satisfies thermal and respiratory requirements of occupants, (b) prevents unhealthy accumulation of pollutants, and (c) allows for a sense of well-being. International research has established the occurrence of a range of building-related illnesses, many with identifiable and diverse causes. A subset of these illnesses - termed the ‘sick building syndrome’ (SBS) - includes mainly subjective symptoms (mild irritation of eyes, nose and throat, headaches, lethargy). SBS symptoms are believed to arise from multiple causes which, while not clearly understood, are associated mainly with air-conditioned office buildings. Australian studies have been limited, but indicate similar occurrence to other developed countries for building-related illnesses, SBS-like symptoms and dissatisfaction with office air environments (Brown 1997, 2005).

Regulatory actions related to *indoor* air quality in Australia are limited, especially in comparison to outdoor air quality and industrial workplace air, a situation also common overseas. Some guidance has been provided by the NHMRC (formerly recommended health-based advisory IAQ goals), the enHealth Council, the Australian Safety & Compensation Council (ASCC, occupational exposure standards), National Industrial Chemicals Notification & Assessment Scheme (NICNAS) and the World Health Organization (WHO, health-based environmental air quality guidelines for Europe). Some pollutants have been investigated in Australian buildings in detail, but for others few observations are available. Based on this limited data and international research, the most appropriate strategies are to reduce exposures to health-based criteria by reducing pollutant sources, controlling moisture, and ventilating to current standards (Brown 2005). Based on this background, key metrics for IAQ *in offices* are recommended in Table 1. Note that an order of priority was assigned to each, according to the level of quality of indoor air that is likely to be achieved by their application in an office building where members of the public and children may have access.

Table 1. Key indicators for indoor air quality

Indoor air pollutant	**Possible sources**	**IAQ criterion (averaging period)**	**Priority**
Formaldehyde	Partitions, furniture, shelving, flooring	100 $\mu g/m^3$ (peak)	High
Total VOC (TVOC)	Building materials, furniture, office equipment	500 $\mu g/m^3$ (1 h)	High
VOC: benzene	As for TVOC, auto exhausts	10 $\mu g/m^3$ (1 y)	High
VOC: toluene	“	4100 $\mu g/m^3$ (24 h)	High
VOC: xylene isomers	“	1200 $\mu g/m^3$ (24 h)	Low
PM2.5	Auto exhausts	25 $\mu g/m^3$ (24 h)	High
Carbon monoxide	Auto exhausts	9 ppm (8 h)	High
Carbon dioxide	Exhaled breath	800ppm (1h)	High
Ozone: at equipment exhausts	Copiers, printers	0.1 ppm	Low
Micro-organisms	Persistently damp surfaces, mechanical ventilation system	Absent on inspection	High
Asbestos	Insulation, sheeting, flooring	Inspection + risk evaluation	Low-Medium

2.2 Thermal Comfort Indicators

Thermal comfort is commonly defined as that ‘condition of mind which expresses satisfaction with the thermal environment’ (ISO 1994). Since people vary greatly in physiological and psychological factors, it is accepted that it is impossible to satisfy the thermal comfort of all occupants. However, based on existing data it is possible to statistically define conditions that a specified proportion of office occupants will find thermally comfortable. As well as physical parameters - air temperature, radiant temperature, air speed, humidity - a person's activity levels and the insulation received from clothing will also influence thermal comfort but these are specified here as default values which are typical levels for office environments.

A significant factor to thermal comfort is whether a space is *mechanically* conditioned or *naturally* conditioned – these are known to require different conditions for thermal comfort since occupant expectations in the latter are shifted due to different thermal experiences and availability of individual control. Only mechanically conditioned offices will be considered here (American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE 2004) provides guidance for naturally conditioned spaces). For given values of humidity and air speed, the thermal comfort zone can be defined in terms of operative temperature or in terms of combinations of air temperature and mean radiant temperature (ASHRAE 2004), defined as follows:

- operative temperature: the uniform temperature of an imaginary black enclosure in which an occupant would exchange the same amount of heat by radiation plus convection as in the actual non-uniform environment. In most practical cases, this can be calculated as the mean of the air temperature and the mean radiant temperature. Also, in the absence of radiant heating/cooling panels, heat generating equipment, envelope insulation and large window solar heat gain, the assumption that operative temperature equals air temperature is acceptable
- air temperature: the temperature of air surrounding the occupant
- mean radiant temperature: the uniform surface temperature of an imaginary black enclosure in which an occupant would exchange the same amount of radiant heat as in the actual non-uniform space.

The operative air temperature for buildings recommended by ISO (1994) was between 20°C and 24°C (22°C ± 2°C) for winter conditions and between 23°C and 26°C (24.5°C ± 1.5°C) for summer conditions, and these values were endorsed by the Australian Government (1995). The ASHRAE (2004) specified operative air temperature according to two equivalent procedures: a simplified graphical method or a computer program based on a heat balance model; only the former will be presented. The graphical method may be applied to spaces where the occupants have activity levels between 1.0-1.3 met, where clothing provides 0.5 – 1.0 clo of thermal insulation, and air speeds are not greater than 0.2 m/s, *conditions that occur in most office spaces.* The ranges of operative temperature presented in Figure 1 are for 80% occupant acceptability (based on 10% dissatisfaction for whole body- and 10% for partial body-comfort). Note that the thermal comfort zone extends across an operative T from 19°C to 28°C, the specific operative temperature depending on clothing and humidity levels. These are set at default values of 1.2 met activity and 0.5 clo (summer) /1.0 clo winter) as specified in ISO (2005).

Other thermal comfort metrics are:

- Relative humidity (RH) that is too high or too low can lead to skin, eye and respiratory irritation (ASHRAE 1992). ISO (2005) recommended that the relative humidity should be from 30% to 70% for summer and winter conditions. RH above approximately 70% can cause microbial growth and damage to surfaces within buildings, especially when surface condensation occurs (Brown et al 1997)
- Air velocity should be within the range 0.05 – 0.2 m/s. ASHRAE (2004) specified that air speed may be increased above 0.2 m/s to increase the maximum temperature for acceptability *if occupants are able to control the air speed.* The amount of increase is limited to 3°C with air speed to not exceed 0.8 m/s
- Vertical and horizontal radiant temperature asymmetry, specified by ASHRAE (2004) as warm ceiling < 5°C, cool wall < 10°C, cool ceiling < 14°C, and warm wall < 23°C.

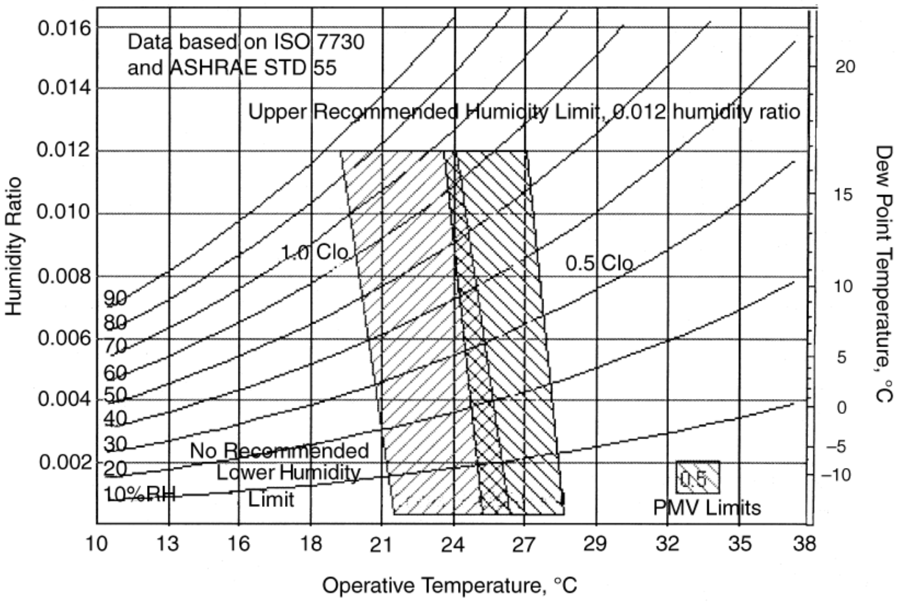

Figure 1. Acceptable ranges for operative temperature and humidity in 'typical' office spaces (ASHRAE 2004)

Currently, ASHRAE (2004) and ISO (2005) specify three performance levels for thermal comfort by these metrics, as presented in Tables 3 and 4, since in practice the levels attained will depend on technical, cost, environment and energy considerations.

Table 3 Three categories of thermal environment

Thermal state of the body as a whole				Local thermal discomfort (%PD caused by)		
Category	**PPD %**	**Predicted mean vote (PMV)**	**Draught rate, DR %**	**Vertical air temperature difference %**	**Warm or cool floor %**	**Radiant temperature asymmetry %**
A	< 6	- 0.2 < PMV < + 0.2	< 10	< 3	< 10	< 5
B	< 10	- 0.5 < PMV < + 0.5	< 20	< 5	< 10	< 5
C	< 15	+ 0.7 < PMV < + 0.7	< 30	< 10	< 15	< 10

Table 4. Criteria for operative temperature for typical buildings (Olesen 2004)

Type of building	Clothing (clo)		Activity (met)	Category	Operative Temperature (ºC)	
	Summer	Winter			Summer	Winter
Office	0.5	1.0	1.2	A	24.5 ± 0.5	22.0 ± 1.0
				B	24.5 ± 1.5	22.0 ± 2.0
				C	24.5 ± 2.5	22.0 ± 3.0
Cafeteria / Restaurant	0.5	1.0	1.4	A	23.5 ± 1.0	20.0 ± 1.0
				B	23.5 ± 2.0	20.0 ± 2.5
				C	23.5 ± 2.5	20.0 ± 3.5
Department Store	0.5	1.0	1.6	A	23.0 ± 1.0	19.0 ± 1.5
				B	23.0 ± 2.0	19.0 ± 3.0
				C	23.0 ± 3.0	20.0 ± 4.0

Note in Table 4 that while the *mean* operative temperatures are the same for the different categories, the *allowable spread* of operative temperatures changes markedly across categories.

2.3 Lighting Quality Indicators

Lighting levels need to be of a quality that provides an environment in which it is easy to see so that office tasks can be safely performed without eye strain. During typical working hours, lighting inside offices tends to rely on a combination of both daylight from windows and electric lighting. There is little doubt that people prefer to work by daylight and enjoy a view outdoors. Also, this mixture of lighting enables a degree of flexibility which is a useful outcome. Windows can assist in avoiding or reducing eyestrain by allowing an individual to focus on distant objects rather than prolonged viewing of close objects such as computer screens. However, the use of windows needs to be balanced with respect to any adverse thermal effects or unwanted lighting effects such as glare.

Even though a task may be three dimensional, it is generally carried out in more or less one plane and it is common to provide illuminance on that plane (called the 'working plane'). Note that achieving higher illuminance on working planes will facilitate the task visibility but does not necessarily achieve the desired visual appearance or comfort of a space. In general, there are three key factors to task illuminance:

1. increasing the illuminance on a task produces an increase in performance following a law of diminishing returns
2. the illuminance at which performance levels off is determined by the visual difficulty of the task (the smaller or the lower contrast in a task, the higher the illuminance level)
3. it is not possible to bring a difficult visual task to the same level of performance as an easy task simply by increasing the illuminance (e.g. consider the improvement from using a magnifier for tasks difficult to the unaided eye).

The standard international unit that is used to measure the amount of light per unit of surface area, also known as illuminance, is lux (symbolized lx). Australian Standards for interior lighting for office and screen based tasks recommend a minimum of 160 lx on the working plane so that eyes are not strained due to a deficiency of light. Also, the uniformity of illuminance within a room should not be less than 0.7 (i.e. the minimum illuminance on a given plane should not be less than 70% of the average illuminance). Good task visibility depends on both the luminance of the task and its surroundings and optimum levels exist for the ratio of the luminances of task: immediate surrounds: general surrounds at approximately 10:3:1. The average *initial* illuminances for office-based tasks that should be provided by the lighting system will need to be significantly higher than the *recommended maintenance illuminance* in order to allow for the progressive loss of light due to lamp ageing and dust accumulation. Standards Australia (1994) specifies recommended values for maintenance illuminance according to specific tasks and room types, from 160 lx for keyboards, 320 lx for reading/writing/typing, to 600 lx for tasks with fine details (e.g. draughting).

Other key lighting metrics are Glare, Colour temperature, and Flicker from electric luminaires (Brown 2006).

2.4 Noise Indicators

Sound level is defined in terms of the unit decibel (A) which is measured at the frequencies over which humans generally hear, 20 to 20 kHz, using an 'A' filter. Equivalent continuous A-weighted sound pressure level ($L_{Aeq,T}$) is a term that is used to indicate the sound level over a defined number of hours. For sound that is encountered during working hours,

usually an 8 hour day, the continuous A-weighted sound pressure level is denoted by $L_{Aeq,8h}$. Background sound tends to be of a low intensity and is present for most of the time in any environment. Sources of background sound in an office include: computers, lights and ventilation systems. Excessive amounts of background sound can cause stress which can impede upon an individual's ability to work well. The UK's Sustainable Development Unit recommended that separate rooms/offices should have an
$L_{Aeq,8h}$ value of less than 40 dB(A) and an open plan office less than 45 dB(A) (UK Government, 1999). Standards Australia (2000) recommended levels for different occupancies as a range from satisfactory (for most) to maximum (unsatisfactory for most). These were to be measured with the building unoccupied but ready for occupancy, and varied from 35-40 dbA (private offices), 40-45 dbA (general offices), 45-50 dbA (computer rooms).

Impact sound is of a high intensity but lasts for only a short amount of time. Impact noise within in an office can come from sources such as electric staplers or doors slamming. High intensity impact noise can damage hearing, but it is considered highly unlikely to occur within an office environment, and so the averaged 8 hour noise level is considered to be the appropriate metric. Also, sound from short-term sources, such as printers and photocopiers, can be minimised by keeping them in a separate room.

2.5 Occupant Questionnaire on Environmental Comfort

While the above air and physical metrics aim to assess the key indicators of IEQ, it is considered that the complexity of IEQ and the environment-occupant interaction are such that a direct feedback of occupant experience must also be part of IEQ assessment. Applied to a statistically significant but random sample of occupants (approx. 30), this can provide a direct measure of the comfort levels experienced by occupants. Occupant experience can be assessed with a questionnaire developed from the 'Office Environment Survey' by the UK Health & Safety Executive (Raw 1995). This was a two-page, self-administered questionnaire, described in Brown and Kivlighon (2005), and applied to the occupants at the time of IEQ assessment. Key questions related to:

- Working conditions
- Discomfort from indoor climate in preceding two months
- Symptoms or health complaints in preceding two months linked to presence in office.

3.0 APPLICATION TO AN OFFICE REFURBISHMENT

It was considered that IEQ assessment should be carried out with the following over-arching guidelines:

- Assessment only during working hours with the building occupied
- Assessment both before and after refurbishment
- Each assessment to be duplicated for two seasons (summer and winter), the first being as close as possible to the building refurbishment,
- Provided that all levels of offices had a common air supply system and occupants had similar tasks/activities, measurements to be made on 3 levels (approximately bottom, mid- and top levels) over 5-8 consecutive work days,
- Measurements should be made at two distant locations on each level, with duplicate measurement on separate days.

Melbourne City Council had an office building in Melbourne city centre with two lower levels of car-parking, six levels of offices occupied by its staff, and a plant room on the 9th level. This building, referred to as Council House 1 (CH1), was constructed in 1970 and *was* planned to be upgraded and refurbished in 2006. An IEQ assessment plan was developed for Levels 1, 4 and 6 of CH1 based on the above discussion, and these were carried out in

July 2005 and February 2006. However the Council decided not to implement the refurbishment and so a replacement MCC building, Council House 2 (CH2), was used as a surrogate for CH1. The CH2 building was designed and built with a specific focus on sustainability and provision of a high quality indoor environment for occupants, similar to planning for CH1. Also approx. ½ of the CH1 staff were to be housed in CH2. An identical IEQ assessment was carried out for CH2 on Levels 2, 6 and 8. CH2 consisted of shops at ground level (with own ventilation systems) and nine office levels housing approx, 540 staff, some relocated from CH1 but most from other MCC buildings. It was designed to be a benchmark sustainable high rise building and was the first building in Australia to receive a 6-star design rating from the Australian Green Building Council. Key features of CH2 included:

- a sewer mining plant to deliver up to100,000 litres of recycled water per day (note this had not yet started operating at the time of IEQ assessments);
- a low energy cooling system based on phase-change material;
- automatic windows that open at night to cool the building in summer (these operated when the concrete slab ceilings exceeded 21°C and the outside temperature was 2 or more °C below that of the concrete ceiling)
- vaulted concrete ceilings to improve air circulation, cooling and natural light, with ceiling mounted chillers;
- 100% fresh-air supply, nominally at 2 air changes per hour, from floor vents in a suspended floor and operated on a timer with 1 h in front of occupant arrival and 1 h after departure; the building also has a CO2 monitoring system to control ventilation rate to keep it below 800 ppm;
- a facade of louvers to track the sun and shade the Western side;
- roof-mounted wind turbines to draw hot air out of the building;
- use of low-emission fit-out materials (the major interior surface was uncoated concrete, with some areas of paper gypsum-board painted with low-emission paint; mechanically fixed carpet tiles were used throughout; most office furniture was powder coated low emission MDF and low-emission plywood sealed with a water-based lacquer)
- an open-plan office lay-out, common for both staff and managers.

CH2 was occupied by MCC staff in October 2006 and 'tuning' of the operation of the building was considered to be a requirement by the building designers over its first few months of occupancy. Hence CSIRO could not assess IEQ until March 2007 (summer) and August 2007 (winter), 5 and 10 months after occupancy, once tuning had been completed. Note that the first assessment would ideally have been carried out within 1 month of occupancy since VOC and formaldehyde pollution are expected to be greatest then (Brown 2002). Also of special significance was the upgrading of the lighting system the month before the August 2007 assessment, by adding extra strip lighting and adjusting light levels to suit workstations.

3.1 Key observations in CH1

General IAQ findings for CH1 were:

1. There was a high level of consistency found for IAQ and occupant perceptions of indoor environments in both winter and summer
2. Most IAQ measures were within the recommended criteria, with the exception of formaldehyde concentration and the occupant comfort survey, in particular on level 6
3. Formaldehyde concentrations on level 6 exceeded the IAQ criteria, especially in summer, but no specific source for the formaldehyde could be identified and it was concluded that there were dispersed formaldehyde sources (e.g. office furniture, wall partitions) on this level

4. CO_2 levels ranged from 560-710 ppm, much below the criterion 800 ppm, indicating that ventilation was adequate to remove occupant odours
5. VOCs, formaldehyde, fungi/bacteria and fine particles ($PM_{2.5}$) were present in CH1, while ozone from office equipment and carbon monoxide were absent. Indoor air concentrations of VOCs and formaldehyde exceeded those outdoors, showing there were indoor sources for these pollutants. Fungi and $PM_{2.5}$ were much lower indoors than outdoors, by a factor of 10- to 20-fold, showing there to be no indoor sources and significant cleaning of intake air due to filtration by the mechanical ventilation system
6. Similar indoor air VOCs were observed in both seasons and there was no specific and consistent trend in the VOC concentrations according to the location sampled. This is considered to indicate that VOC sources within CH1 were uniformly dispersed through the building. Sources for the VOCs were not known, though several were considered to originate with outdoor air used to ventilate the building (e.g. benzene, hexanal, benzaldehyde and 1,2,4-trimethylbenzene), others (ethanol, acetone, and limonene) were clearly indoor source-related (probably from consumer products used by occupants), and some (toluene and xylene) were contributed by indoor sources and outdoor air
7. Indoor formaldehyde concentrations showed a trend in both seasons for increased formaldehyde concentrations at higher building levels, but this was not found to be significant ($p \leq 0.05$). However a seasonal effect for higher formaldehyde levels in summer was significant for Level 4 and near-significant for Level 6. This effect could be related to the higher indoor temperature/humidity in summer c.f. winter since this factor is known to increase formaldehyde emissions from wood-based panels
8. The occupant survey found that there were indoor environment complaints in CH1 from (in decreasing prevalence): air stuffiness, poor temperature control, dry air, lighting and noise (the latter two at ~1/2 the prevalence of the former)
9. Higher levels of occupant reported symptoms were observed on level 6 than other levels, more so in summer, consistent with the higher formaldehyde concentration observed on this level. The most prevalent daily/weekly symptoms on level 6 in summer were dry eyes (39%), lethargy/tiredness (36%), dry skin (20%), blocked nose/sore throat (16-19%), headache (12%) and chest tightness (8%).

General findings for thermal comfort, noise & lighting were:

1. Winter thermal comfort exhibited low dissatisfaction levels (range 5-15%) while Summer thermal comfort was more variable (dissatisfaction range 5-25%) especially for the early morning measurements at the building perimeter. By comparison, occupant questionnaire responses showed high levels of complaint of *daily* temperature variability in both winter (38% complaint) and summer (27% complaint)
2. The background *office activity* noise was extremely low for the open office areas, probably due to the highly sound absorbing environment which contributed to a more 'dead' than 'lively' acoustic quality. Work area measurements in an 'active environment' with people conversing were below 55 dB(A) c.f. a normal conversation level of 60-65 dB(A). Generally, the target level of 40-45 dB(A) was exceeded, but AS2107-2000 specifies this for buildings that are operating but *unoccupied*. Reverberation times showed that there was little to no reverberation within the large open office environments. This may lead to difficulties in occupants adjusting to a livelier environment in the future.
3. Task illuminance exceeded 160 lux in all cases but the target of 320 lux was not achieved in ~30% of cases, with a bias to lower illuminance at lower Levels, probably due to lower daylight penetration. Occupant questionnaires showed a similar level of dissatisfaction with lighting at each Level with ~40% reporting dissatisfaction, but on a less than weekly frequency. That is ~80% or more of occupants were satisfied with lighting on a weekly basis.

In overview, CH1 was considered to exhibit poor indoor air quality due to formaldehyde (esp. on Level 6), though other air quality metrics were acceptable, and while thermal comfort, noise and lighting were of good quality the occupants exhibited continuous, high frequency complaints of stuffy air and temperature variability (both too hot and too cold). In both seasons, occupants reported high (20-30%) symptom prevalence related to building occupancy for dry eyes, lethargy/tiredness and headache, with greatest prevalence on Level 6. Notably, this level had the highest formaldehyde levels, exceeding acceptance criteria in summer.

3.2 Key observations in CH2

At present, only IAQ and occupant survey assessments have been fully evaluated and will be presented. General IAQ findings were:

1. There was a high level of consistency found for IAQ and occupant perceptions of indoor environments in both winter and summer
2. All IAQ measures were within the recommended criteria, with the formaldehyde concentration being much lower than levels normally seen in office buildings (such as found in CH1) probably due to the low-emitting office furniture used
3. CO2 levels ranged from 500-690 ppm, much below the criterion 800 ppm, indicating that ventilation (based on 100% fresh air) was adequate to remove occupant odours
4. VOCs, formaldehyde, fungi/bacteria and fine particles ($PM_{2.5}$) were generally uniformly distributed in CH2, while ozone from office equipment and carbon monoxide were generally absent. Indoor air concentrations of some VOCs exceeded those outdoors by approximately 3-fold, showing there were indoor sources for these pollutants, though indoor TVOC levels were approx. one-third the criteria level. VOCs measured by GC/MS were similar in both seasons, varying from a TVOC concentration of <50 $\mu g/m^3$ outdoors to 50-180 $\mu g/m^3$ inside CH2, this level of elevation normally being found in typical *established* buildings (Brown 2001), whereas *new* buildings (1-3 months old) can exhibit TVOC concentrations in thousands $\mu g/m^3$. TVOC concentrations above 500 $\mu g/m^3$ are considered to indicate the need to remove strong VOC sources from buildings. CH2 was assessed at 5 and 10 months after construction and would not be classified as 'new'
5. Fungi and $PM_{2.5}$ were much lower indoors than outdoors, by a factor of 10-fold or more, showing there to be no indoor sources and significant cleaning of intake air due to filtration by the mechanical ventilation system
6. Similar indoor air VOC species were observed in both seasons and there was no specific and consistent trend in the VOC concentrations according to the location sampled or the season. Also, there was little difference between the dominant VOC species found in CH2 or CH1. This is considered to indicate that VOC sources within CH2 were uniformly dispersed through the building and from similar sources as in CH1
7. The occupant survey found that there were indoor environment problems in CH2 from (in decreasing prevalence): poor lighting, noise, poor temperature control and air stuffiness, with the poor lighting complaint persisting in winter after the lighting system had been modified
8. High incidences of occupant reported symptoms were observed for irritation/watering of eyes (approx. one-half of all occupants) in both seasons, possibly associated with poor lighting. In winter, there were also high incidences of lethargy (34-44%) and headache (24-60%). Note that these are not consistent with the IAQ measurements, but may correlate to physical environment metrics.

In overview, CH1 was considered to exhibit poor indoor air quality due to formaldehyde (esp. on Level 6), though other air quality metrics were acceptable, and while thermal comfort, noise and lighting were of good quality the occupants exhibited continuous, high incidence complaints of stuffy air and temperature variability (both too hot and too cold). Occupants reported high (20-30%) symptom prevalence related to building occupancy and for both seasons for dry eyes, lethargy/tiredness, and headache, with greatest prevalence on Level 6. Notably, this level had the highest formaldehyde levels, exceeding acceptance criteria in summer. CH2 was considered to exhibit high quality indoor air, but occupants perceived the building to be poorly lit, noisy, variable in temperature and with stuffy air. Physical metrics are yet to be assessed for such potential impacts on occupants.

4.0 CONCLUDING REMARKS

A range of physical and air pollutant factors have been selected for measuring IEQ in office buildings relevant to their impacts on occupant well-being and comfort in office environments. These have been measured in a target ‘traditional’ building and a new sustainable design building, both without significant problems or inconsistencies. Generally, IAQ metrics have been found to be well distributed through the buildings and to show high consistency across seasons. This is considered to indicate that IAQ assessments can be made with fewer measurement locations and times than used here. In the traditional building, high formaldehyde concentrations were found on one Level and occupant complaints of non-specific illnesses were highest on this Level. Physical measurements indicated good thermal comfort for this building, but approximately one-third of occupants considered temperature control to be poor. The sustainable design building exhibited very low pollutant levels but the proportion of occupants reporting ‘stuffy’ air still exceeded 20%. Poor lighting was reported as a significant problem in this building by approximately one-half of occupants and this may have been a factor in the high symptom prevalence for irritation/watering of eyes, but physical measurements are yet to be assessed to confirm this.

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