Sustainable Buildings – best and worst performers in terms of Comfort, Health and Productivity

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Abstract

The author has undertaken user surveys of thirty commercial or institutional buildings, all with strong sustainability credentials. The main aim was to find out what features enhanced the comfort, health and productivity of the building users and what features would cause them to diminish.

The buildings were spread throughout 11 countries, and in virtually every case the client or the design teams (frequently both) were strongly committed to sustainability and energy efficiency. In addition to seeking basic demographic data the survey questionnaire asked respondents to score, on a 7-point scale, up to 45 variables grouped into Operational, Environmental (temperature, air quality, lighting, and noise), Control, and Satisfaction categories. The author spent time in all the buildings and interviewed members of the design teams for each.

Analysis of the responses yielded a mean value for each variable and enabled calculation of a Summary Index which took account of 11 key variables. While these analyses indicated a clear correlation between Comfort, Health and Productivity, perhaps unsurprisingly they also indicate that it is very difficult to achieve perfection in every respect. Even the ‘best’ building, in terms of its Summary Index, was perceived as performing relatively poorly in terms of Noise, for example. The corollary to that was also evident in that some buildings with low Summary Indices were perceived as performing relatively well in terms of particular factors, such as Lighting or Temperature in Winter. Nevertheless, the overall trends were clear and the paper will discuss the particular design features associated with these results.

Keywords: sustainable buildings, comfort, health, productivity.

1. Introduction

The overall mission of the author and his collaborators has been to provide independent and unbiased evaluations of how the users perceive some of our commercial and institutional sustainable building developments. It is still surprising that building designers (with rare exceptions) do not systematically evaluate their projects, if only for the benefit of their own practices.

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The overarching aim of the research described in this paper is to advance the practice of environmentally sustainable building design. A world-wide set of commercial and institutional buildings, all of which had well-recognised sustainability credentials or features, were sought out and evaluated. The intention was to find out the context for these projects, how they were designed, and most importantly, the users' perceptions of the performance of these buildings.

This paper focusses on the features of the 'best' and the 'worst' buildings as indicated by the scores for particular factors or categories of factor, in terms of the comfort, health and productivity of the users, and overall as indicated by a Summary Index. It must be emphasised that in this context 'best' and 'worst' simply means that the buildings were at opposite ends of the Summary Index scale for a set of buildings which it is believed would be at the 'best' end of a sample of buildings of this type. 'Worst' should not be taken to imply these buildings were particularly poor performers overall – quite the contrary.

1.1 The Buildings and their Users

The thirty buildings selected were all commercial or institutional in nature. Fourteen accommodated office activities predominantly, ten were tertiary-level academic teaching buildings, four housed laboratories or research organisations, and two contained a combination of light industrial and administrative functions. *V*irtually all were recipients of national awards for sustainable or low energy design, were highly rated in terms of their respective country's building sustainability rating tool, or in some way pioneered sustainable architecture.

Fifteen had Advanced Natural Ventilation systems, broadly defined as natural ventilation where some of the ventilation openings are automated or some specially designed natural ventilation elements have been incorporated into the design. Most of the remainder utilised a Mixed-Mode system of ventilation – these were predominately Changeover systems where the mechanical systems were designed to operate during cold or hot outside conditions, and the natural ventilation systems during mild conditions, though two buildings had Zoned systems where large parts of the building were either air conditioned or naturally ventilated. Only three of the buildings were fully air conditioned with predominantly sealed facades. Fuller details of the systems of environmental control in each building are described elsewhere (Baird, 2010). Most had been built or refurbished in the course of the last fifteen years, and all had been occupied for a year or more before the survey work was carried out, giving most occupants time to experience their surroundings over at least a full annual cycle.

1.2 Survey Methodology and Analytical Procedures

Generally speaking, these investigations involved undertaking several visits to each of the buildings to personally distribute and collect a questionnaire survey seeking the users' perceptions of a range of factors. The questionnaire used was the Building Use Studies (2011) standard two–page office version. During these visits a structured, recorded interview was conducted with a key architect and environmental engineer from the design team, and a detailed tour undertaken of each building and its facilities, photographing key features, and collecting relevant documentation.

The sixty or so questions of the standard two-page questionnaire used cover a range of issues. Fifteen of these elicit demographic information with the rest asking the respondent to score a number of aspects of the building on a seven-point scale and categorised as Operational, Environmental (temperature, air quality, lighting, and noise), Control, and Satisfaction.

Analysis of the responses yielded a mean value on a 7-point scale for each variable and enabled the computation of a number of indices to provide indicators of particular aspects of the performance of the building or of its 'overall' performance. These include a Comfort Index which was dependent on a set of seven 'environmental' factors; a Satisfaction Index, which was dependent on the scores for Design, Needs, Productivity, and Health; and a Summary Index which is the average of these two indices (see Appendix). These are intended to 'provide snapshots of how a building works for its occupants' (Leaman and Bordass, 2001, 130).

In what follows the features of the buildings with the highest and the lowest Summary Indices will be described in more detail in an attempt to discern those particular features that may have led to such values. The Summary Indices and average scores for Comfort, Health and Productivity for all the buildings are listed in Table 1, together with their rankings.

2. Design features of buildings with High Summary Indices

In this section the reasons for high and low perception scores amongst those buildings with high Summary Indices will be explored, in an attempt to reveal the factors that influenced them, and the design features that could be involved. Five projects will be described in more detail – all had Summary Indices greater than +2 on a -3 to +3 scale:

2.1 NRG Systems Facility, Vermont, USA

Located at latitude 44.5^{O}N in a cold-temperate climate (winter/summer design temperatures -21^{O}C/+29 ^{O}C) this 4320m^2 floor area building houses a manufacturing facility with offices, workshops and a warehouse. With a Summary Index of +2.93, the highest of all the buildings in this set, average Comfort and Health scores of 6.56 and 5.47 respectively (on a 1 to 7 scale) and a Productivity increase of 19.51%, what design features might have influenced these perception scores?

The building was oriented to the sun, with its long axis E-W and its North side bermed into a hillside. It was well insulated and airtight, with carefully designed daylighting via high-level strip windows and skylights integrated with dimmable artificial lights. Pipes embedded in the exposed floor slab enabled under-floor heating and cooling of the entire building. The offices and workshops had CO_2-controlled mixed-mode ventilation via air handling units and opening windows, with red and green indicators letting the occupants know when opening or closing the windows was preferable (but not mandatory). The warehouse area was designed for natural ventilation mainly but had extract fans at either end. Clearly, these systems were combining to provide an environment that was perceived to be near-perfect by the building users. The project team for the NRG Systems Facility had conceived and executed a building in which all of the basic ‘rules’ of good passive design have been applied, coupled with transparent control systems and well documented procedures (NRG Systems, 2008).

2.2 Torrent Research Centre, Ahmedabad, India

Located at latitude 23^{O}N, Ahmedabad has three distinct climatic seasons - hot and dry with outside temperatures of +41.0^{O}C, warm and humid during the monsoon, and cool and dry with temperatures around +13^{O}C. Housing a pharmaceutical research organisation, the facility was comprised of five three-storey laboratory buildings radiating from a central core building, and linked to separate administration and utilities blocks. Two of the laboratory buildings were air conditioned (AC) while the administration block and the other three laboratories were equipped with a passive downdraft evaporating cooling (PDEC) system. Their total floor area was some 12,000m^{2}. Separate surveys were carried out of the AC and PDEC buildings (Thomas and Baird, 2006) and as can be seen from Table 1, their Summary Indices (2.83 and 1.95 respectively) placed these buildings 2nd and 6th.

The design team committed to a building that could function during daylight hours with the minimum use of electricity. The concept for all of the laboratory buildings was for a central corridor flanked by working spaces. Centrally-located towers provide fresh air via the corridor; having passed through the working spaces it is exhausted via a set of towers on the perimeter. In the case of the PDEC laboratories and administration building a fine mist of water is released at the top of these central towers during the critical hot season. This cools the air which then circulates through the building by natural convection. In the case of the two AC laboratories, the towers serve as routes for the distribution of conventional air conditioning ductwork. The overall structure is thermally massive and the external walls and roof are white. Both high and mid-level exterior windows are utilised – these are shaded from direct sun penetration by fixed horizontal overhangs and the perimeter towers.

The AC buildings appeared to outperform the PDEC buildings in terms of Comfort (5.72 vs 5.16), Health (5.53 vs 4.74) and Productivity (+20.88% vs 13.66%). Nevertheless, the PDEC buildings scored well over the mid-point of their respective scales and significantly better than the relevant benchmarks. It is their performance that is arguably the more notable. To be ranked 6th overall out of this set of buildings, given the severity and variability of the climate, is remarkable. The effort to minimise solar heat gain through shading, exterior colour, insulation and mass, together with careful attention to the disposition of the fenestration have paid dividends. Of course these same efforts have benefitted the AC buildings too in terms of their overall performance.

2.3 Natural Resources Defence Council (NRDC), California, USA

Located in Santa Monica in the relatively benign climate of Southern California - latitude 34^{O}N with design temperatures around 31^{O}C and 6^{O}C – this 1,400m^{2} three-storey building houses the offices of the NRDC. As befits its high Summary Index of +2.82, Comfort and Health score 6.50 and 5.85 respectively while the perceived Productivity increase is +23.00%. The rectangular plan building is sandwiched between adjacent buildings on a 37m by 14m site. Three lightwells punctuate the plan and these, together with a 2m gap between the long facades and the adjacent buildings enable daylight penetration to the building. The perimeter windows are all openable to allow natural ventilation, and the upper glazed section of two of the lightwells is fitted with a louvred opening and an extract fan (NRDC, 2004).

Six small fresh air supply units deliver heated or cooled air at peak times. Thermostats in each office enable personal control of these systems, and care has been taken to ensure the staff are aware of conditions in the building and can respond appropriately. Not only are inside temperature and humidity readings on display at strategic points throughout the building, but CO_2 readings are also displayed, together with a warning light set to come on at around 750ppm as a way of reminding the occupants to open the windows.

The fenestration is fairly conventional and has no external shading. Minor noise issues (from colleagues mainly) appear to be a concomitant of natural ventilation strategies which tend to necessitate the use of large open passages across and even between floors, together with facade openings. The potential for airborne sound transmission within the building, and the entry of external noise is evident.

2.4 Military Families Resource Centre (MFRC), Toronto, Canada

Located at latitude 44^{O}N in a cold-temperate climate (winter/summer design temperatures of -17^{O}C/+29 ^{O}C) this 1840m^2 floor area building caters for the needs of the spouses and children of military personnel in terms of child care, counselling services and educational programmes. MFRC had the 4th highest Summary Index (2.45) of all the buildings and a matching profile of high scores: 5.92 for Comfort, 5.17 for Health and +20.00% for Productivity.

The outcome from what was reported as an intensely integrated design process was a compact two-storey circular plan, with sloping timber roof structures, with mainly offices and child-care facilities on the ground floor and a large multi-function space on the upper level (GBI, 2005). Roof, walls and floor slab were well insulated and clear double-glazing used throughout. The perimeter and roof-level glazing enables daylight penetration to the majority of the spaces that are in frequent use, such as the child care areas and the offices. Windows at both high and low level have openable sections to enable natural ventilation to take place when climatic conditions allow – typically spring through autumn. An under-floor system is the primary heating source for the building, while a small air handling unit distributes fresh air, heated or cooled as appropriate, to the occupied spaces, though there was a hint of the users finding it to be too hot in winter and too cold in summer.

6.5 The Erskine Building, Canterbury University, New Zealand

Located at latitude 44^{O}S in a medium-temperate climate (winter/summer design temperatures of -1^{O}C/+26 ^{O}C) this 11,551m^2 building is split approximately equally between a seven-storey academic block, containing staff and postgraduate student offices, and a four-storey undergraduate teaching block. The two blocks are linked by a glass roofed atrium space and a basement area containing mainly teaching and service spaces (Architectus, 1998). Lying 5th in the Summary Index rankings with a score of +2.39, Comfort and Health scored 5.86 and 4.52 respectively and Productivity +9.80%, all significantly better than their respective benchmarks.

The offices and the majority of the adjacent seminar rooms in the academic block are naturally ventilated and heated by a conventional radiator system. With their deliberately northerly orientation and fixed overhangs, exposed thermally-massive interior walls and ceilings, fixed and adjustable exterior and adjustable interior solar shading devices, and large number of window/natural ventilation opening options, the office modules are equipped with a full range of passive thermal environmental control systems. The undergraduate teaching block and basement computing laboratories have separate air handling units.

By the use, inter alia, of a well-insulated external envelope, internally exposed thermally massive construction, predominantly manually operated window openings and shading devices, and deliberate orientation of staff studies to the sun, this building has been able to satisfy the varying needs of a diverse staff and student population. However questions regarding control of sun and sky glare remain.

3. Design features of buildings with Low Summary Indices

In this section the reasons for high and low perception scores amongst those buildings with low Summary Indices will be explored, in an attempt to reveal the factors that influenced them, and the design features that could be involved. Five projects will be described in more detail – all had Summary Indices less than zero on the -3 to +3 scale, but none under -1.0.

3.1 Institute of Technical Education, Bishan, Singapore

Located close to the Equator (1.5^{O}N) in the hot-humid climate of Singapore (1% temperature range 23 to 32^{O}C) this 20,300m^{2} building caters for 100 staff and 1,600 students. Twin parallel teaching blocks (one four storeys, the other three) place the building squarely in the path of the prevailing winds. The designers' aim was to respond to the challenges of a tropical climate with the least use of energy (Powell and Akitek Tenggara, 1997). Thus the majority of classrooms were designed for cross-ventilation, with fixed and adjustable openings on opposite sides, extensive solar shading, and wall mounted fans. Some specialist classrooms, a large lecture theatre and administration offices were air conditioned. Unfortunately, the condensers from some of these were located close to the opening windows of the naturally ventilated classrooms.

The Summary Index for the staff was around -0.80, the lowest figure for this particular set of buildings. Comfort and Health scores were 3.29 and 3.00 respectively, while perceived productivity was decreased by 10.61% on average. Designing for natural ventilation in the climate and culture of Singapore was always going to be a challenge, and the designers are to be congratulated in resolving it as well as they did. The difficulty lies in the constant transfer of staff and students from air conditioned to naturally ventilate spaces, with the inevitable 'thermal shock' that involves and having to acclimatise after every move, making the achievement of a satisfactory thermal balance or comfort problematical. But locating the condensers from the air conditioned spaces under overhangs just outside the opening windows of the naturally ventilated spaces is almost guaranteed to sabotage thermal comfort in the latter and, just to add insult to injury, lead to additional noise issues.

3.2 Liu Institute, University of British Columbia, Vancouver, Canada

This Institute, comprising office accommodation and a conference space, is located in a cold-temperate climate at latitude 49^{O}N and with 1% design temperatures of -4.7^{O}C and

23.2°C. Sustainability targets were set and an integrated design process adopted, resulting in a three-storey main office building in which natural ventilation, external shading and daylighting strategies have been applied. With offices on either side of a central corridor and fresh air supply via perimeter windows, transom openings allowed air transfer to the corridor and then to vertical ducts for exhausting to outside at roof level. The building envelope was well insulated and the thermally massive internal surfaces exposed. Low temperature hot water is supplied to under-sill heating terminal units (Macaulay & McLennan, 2006).

Despite the great effort put into its design, the Summary Index for this building is a disappointing -0.71. At 3.55, the average Comfort score is below the mid-point of the 7-point scale and worse than the benchmark; while that for Health, at 3.70 is similar to the benchmark. However, in terms of Productivity, the users perceive that to have been decreased by 13% on average.

A degree of trade-off had been agreed between acoustic privacy and the free flow of air, but noise appeared to be a key issue in this building, not helped by the preponderance of hard surfaces. Remedial measures, designed to reduce sound transmission but without impeding air movement were being investigated. This is not a unique problem, but is important for knowledge workers for whom acoustic privacy can be essential.

3.3 General Purpose Building, University of Newcastle, NSW, Australia

Newcastle is located in the warm-temperate climate of New South Wales at latitude 33°S, with winter lows of 4°C and summer highs reaching up to 40°C. Completed in 1995, the General Purpose building was one of the first on this campus to explore the limits of purpose designed natural ventilation, at a time when such a move was not typical. The building is four storeys high and consists of three floors above a public ground level. It has offices to the north on three levels, larger classrooms or staffrooms to the south, and a central north facing atrium acting as the building circulation/airflow spine. Exposed masonry walls provide thermal mass running internally through the atrium of the upper two levels. In summer the walls provide an internal heat sink and utilise night ventilation for cooling. The same walls are warmed in winter by sunlight entering north facing clerestory windows (Dixon, 2006) .

Considering the pioneering nature of the design and the characteristics of the climate, the Summary Index has worked out at a creditable -0.39. While the Comfort score of 3.48 was less than the mid-point and worse than the benchmark, that for Health (at 3.55) was similar to its benchmark. Disappointingly, perceived Productivity was down by 11.9%.

Users commented how summer and winter temperature discomfort and the uncontrollable infiltration of noise were impacting on overall comfort and productivity. The building is well oriented to the north, utilises natural light, opens up to natural airflows and makes best use of thermal mass. In simple terms it covers all the requirements for good passive design. Unfortunately the provision of personal 1kW heaters has not successfully dealt with the winter cold in office spaces and the fans provided in all spaces have failed to combat the effects of summer humidity and high temperatures. Reported noise from visitors in corridors, and both outdoor and indoor sources generally indicates a building fabric that is susceptible to noise transfer, possibly due to the open nature of the natural ventilation system.

3.4 The Red Centre Building, University of New South Wales, Sydney

This 150m long, six/eight storey, 17,500m^2 gross floor area building was first occupied in 1996. University policy was for air conditioning not to be installed in other than specialist areas with high internal heat gains - a definite challenge to the designers, given the latitude and climate of Sydney - 34^{O}S and with 1% design temperatures of 6.8 and 29.5^{O}C.

The main accommodation comprises offices, classrooms, studios, lecture theatres and computer rooms, only the last of which is air conditioned (Cantrill, 1997). Air shafts are integrated into the vertical cross section of the building so that air can move readily between selected floors, and thermal chimneys provide the method for exhausting air from the majority of the classrooms in the lower two-thirds of the building. Substantial sections of the glazing on the facades and some of the internal partitions are fitted with ventilation louvres and large sliding doors to allow fresh air entry and air transfer across the building. Manual control of the window openings, the ventilation louvres, the ceiling fans, the gas heaters, and the blackout roller blinds, is left in the hands of the staff.

The Summary Index worked out at -0.37 for this building, while Comfort and Health scores were 3.75 and 3.72 respectively, just under the mid-point of the scale and similar to the benchmark. For the staff, perceived Productivity was decreased by 5% on average, and the building was too cold in winter, too hot in summer, and suffered from what appear to be the inevitable noise problems of naturally ventilated spaces.

3.5 Scottsdale Forest Ecocentre, Tasmania, Australia

Completed in 2002, this three-storey building has a floor area of around 1,100m^2. It is located at latitude 41^{O}S. The building consists of an inner 15m square three-storey office structure inside a truncated cone which houses an exhibition space and café (Spence, 2002). Thermal environmental control is through a combination of high and low level automated louvred openings on the external envelope, manually adjustable sliding windows on the inner envelope, transfer grilles on the office doors, and cones in the vent running up the centre of the offices with a reversible fan at the top, enabling air to be transferred as appropriate to the prevailing climatic conditions.

The volunteer staff of the ground floor Visitor Centre, scored 6.00, 4.11, and +5.00% on average for Comfort, Health, and Productivity and achieved a Summary Index of +1.29. The office staff were less enamoured with conditions. Overheating in the top floor offices and glare issues, led to the installation of a small air-conditioning system. With a Summary Index of -0.28, the office staff scored the building 4.04 and 4.10 for Comfort and Health, and perceived Productivity to be decreased by 4.29%, all of which were similar to the corresponding benchmarks. While winter conditions were fine, summer conditions were found to be too hot, and noise was a key issue, not so much from colleagues, but from the adjacent Visitor Centre. Air transfer paths had become routes for noise transmission and the dangers of combining two quite different functions under the same roof had become evident.

4. Conclusions

This final section will summarise the features of these buildings that had an influence on their users' perceptions. While the focus of this paper has been on the users' perceptions of Comfort, Health and Productivity and on identifying key design features associated with the 'best' and 'worst' performing buildings, it is by no means the whole story. Informed readers will be well aware that the priorities of the client, the experience of the design team, their commitment to integrated design, and the time available for the whole process can all have a profound influence on the building and its eventual performance.

Without exception, it was found that the clients for these buildings were highly committed to the principles and practice of sustainability. This commitment to sustainability was also evident in the client's choice of architect. All of them were established practitioners familiar with the culture and climate of the locality and employed integrated design methods. All had strong track records and in several cases a philosophical commitment to the application of environmentally sustainable design principles.

One of the main drivers of all of these projects was to maximise daylighting while minimising the adverse effects of unwanted solar heat gains and glare via the windows. This was particularly evident in the window arrangement at NRG Systems and at the Torrent Research Centre. Even buildings on restricted sites were set back in a variety of ways to enable daylight penetration.

An equally important driver, was to enable good natural ventilation. This too influenced the building planning and layout in fundamental ways to enable cross-ventilation and stack-ventilation to take place. Where deep plans were necessary, atria or other types of vertical openings between floors were utilised and in some cases special devices employed to enhance the air flow. Some of the change-over mixed-mode ventilation buildings featured a simple visual system which informed the occupants when it would be appropriate to open the windows, and in one naturally ventilated case even let the occupants know when the CO_2 level had exceeded 750ppm. Provision for night ventilation had been made in several instances.

Where the sites allowed, the high latitude buildings were oriented appropriately to make best use of winter solar heat gains, while in those closer to the equator strenuous effort had been made to minimise the year-round solar heat gains to which they were inevitably subjected. In the former case measures taken ranged from simply arranging the long axis of the building to be on an east-west axis to 'turning' the plan to face the sun. Shading systems of one kind or another were used to good effect in many of the buildings. These ranged from deep reveals and fixed external shading to automated internal louvres and blinds.

It should go without saying that all of the buildings were well insulated and designed to be as air-tight as possible, and virtually all had double glazing. The hot-humid climate zone buildings had white or light coloured walls and roofs to help reduce the effects of year-round solar heat gain. Judicious use of exposed thermal mass was evident in a number of the buildings – from the floor slabs at NRG Systems, to the internal walls at Erskine – all with insulation located appropriately.

Despite these efforts to provide a thermally comfortable environment, summer overheating was noted in several of the naturally ventilated or mixed-mode temperate zone buildings. Of particular interest was the finding that many of the buildings in warm-temperate climates were felt to be on the cold side in winter – an indication that more attention should be given to this aspect of design. Nevertheless, there were hints of a growing acceptance of a wider temperature band and tolerance for internal thermal conditions to change gradually in accordance with the seasons.

Other design issues that were revealed by this investigation included noise and glare – issues that could usefully be given more attention in future projects. In the case of noise, juxtaposing offices with other activities such as auditoria, meeting rooms, showrooms, visitor areas, even corridors with hard surfaces and wooden floors is best avoided. Noise and disturbance within the open plan offices themselves could probably be alleviated by the establishment of appropriate etiquette and some education of the staff on the implications of moving from cellular to open-plan offices, as well as appropriate layout and acoustical design. Direct glare from the sun was noted in buildings in every climatic zone and is somewhat surprising, given the predictability of sun angles and the effort put into shading systems – perhaps more care needs to be taken with internal layouts and the positioning of workstations in relation to the windows.

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Table 1: List of buildings in descending order of Summary Index, together with scores for Comfort and Health (on a 1 to 7 scale where 7 is best) and the percentage by which the users' Productivity was perceived to be increased or decreased.

Note: superscripts indicate the relative ranking of each factor out of all 30 buildings.

Building	Summary Index (-3 to +3)	Comfort Scores (1 to 7)	Health Scores (1 to 7)	Productivity % (up or down)
NRG Systems Facility, Vermont	2.93^{1}	6.56^{1}	5.47^{3}	19.51^{4}
Torrent Research Centre (with AC)	2.83^{2}	5.72^{5}	5.53^{2}	20.88^{2}
Natural Resources Defense Council	2.82^{3}	6.50^{2}	5.85^{1}	23.00^{1}
Military Families Resource Centre	2.45^{4}	5.92^{3}	5.17^{5}	20.00^{3}
Erskine Building, Christchurch	2.39^{5}	5.86^{4}	4.52^{11}	9.80^{10}
Torrent Research Centre (with PDEC)	1.95^{6}	5.16^{12}	4.74^{7}	13.66^{6}
St Mary's Credit Union, Navan	1.73^{7}	5.67^{6}	4.67^{10}	10.83^{8}
40 Albert Road, Melbourne	1.42^{8}	5.65^{7}	4.73^{8}	10.00^{9}
Min Energy Water & Communication	1.33^{9}	$5.20^{10=}$	4.77^{6}	16.00^{5}
60 Leicester Street, Melbourne	1.23^{10}	5.62^{8}	5.24^{4}	11.39^{7}
AUT Akoranga, Auckland	1.18^{11}	$5.20^{10=}$	4.18^{13}	3.64^{15}
Arup Campus , Solihull	0.96^{12}	$4.93^{14=}$	4.16^{14}	4.47^{14}
Nikken Sekkei Building, Tokyo	0.88^{13}	4.98^{13}	3.94^{18}	8.51^{11}
Computer Science & Engineering	0.81^{14}	4.91^{16}	3.86^{20}	2.54^{17}
Gifford Studios, Southampton	0.73^{15}	4.73^{19}	3.91^{19}	2.80^{16}
Renewable Energy Systems	0.58^{16}	5.41^{9}	4.72^{9}	5.77^{12}
Tokyo Gas, Yokohama	0.48^{17}	4.75^{18}	4.44^{12}	5.62^{13}
City Hall, London	0.48^{18}	4.76^{17}	3.75^{22}	-1.64^{20}
Student Services Centre, Newcastle	0.34^{19}	4.52^{23}	3.44^{28}	-2.04^{21}
National Engineering Yards	0.33^{20}	4.53^{22}	3.81^{21}	0.19^{18}
Science Park, Gelsenkirchen	0.13^{21}	$4.93^{14=}$	3.57^{26}	-2.27^{23}
Institute of Languages, Sydney	0.12^{22}	4.65^{20}	4.04^{16}	0.48^{19}
Landcare Research, Auckland	0.09^{23}	3.97^{26}	3.66^{25}	-2.18^{22}
ZICER Building, Norwich	0.07^{24}	4.41^{24}	3.31^{29}	-7.81^{27}
Foundation Building, Eden Project	0.05^{25}	4.63^{21}	4.03^{17}	-7.00^{26}
Scottsdale Ecocentre	-0.28^{26}	4.04^{25}	4.1^{15}	-4.29^{24}
Red Centre Building, Sydney	-0.37^{27}	3.75^{27}	3.72^{23}	-5.00^{25}
General Purpose Building, Newcastle	-0.39^{28}	3.48^{29}	3.55^{27}	-11.9^{29}
Liu Institute, Vancouver	-0.71^{29}	3.55^{28}	3.70^{24}	-13.00^{30}
Institute of Technical Education	-0.80^{30}	3.29^{30}	3.00^{30}	-10.61^{28}

Appendix - Calculation of the Summary Index

First, it should be made clear that each of the factors has been assigned a benchmark (copyright BUS) on its 7-point scale. At any given time, these benchmarks are simply the mean of the scores for each individual factor, averaged over the last 50 buildings entered into the BUS database. As such, each benchmark score may be expected to change over time as newly surveyed buildings are added and older ones withdrawn. Nevertheless none of them was observed to have changed significantly during the five years or so over which these buildings were surveyed.

The Summary Index is simply the arithmetical average of the Comfort and Satisfaction Indices.

The Comfort Index involves temperature, air quality, lighting and noise factors. It encapsulates, in a single figure, an overview of users' perceptions of that aspect of the building's performance. This index is formulated from the Z-scores for Comfort Overall, together with the main environmental factors of Lighting Overall, Noise Overall, Temperature Overall in both winter and summer and Air Overall in both winter and summer. The Z-scores are derived from (actual score – benchmark) / (benchmark standard deviation). They are standardized scores with mean = 0 and standard deviation = 1, and are used here to give equal weights to the seven constituent values of the index.

The formula for calculating this index is simply the average of the Z-scores for these seven factors, i.e.

$$CI = (Z_{comfort} + Z_{light} + Z_{noise} + Z_{tempwinter} + Z_{tempsummer} + Z_{airwinter} + Z_{airsummer}) / 7$$

The Comfort Index is based on a scale of '-3' to '+3', where '+3' is considered 'best' (the mid-point lies on zero).

The Satisfaction index Involves design, needs, health, and productivity factors. In a similar way to the Comfort Index, the Satisfaction Index encapsulates, in a single figure, the users' overall satisfaction with the building. It is formulated from the Z-scores of the overall ratings for Design, Needs, Health and Productivity. The formula for calculating this index is simply the average of the Z-scores for these factors, i.e.

$$SI = (Z_{design} + Z_{needs} + Z_{health} + Z_{productivity}) / 4$$

As before, the Satisfaction Index is based on a scale of '-3' to '+3' where '+3' is considered 'best' (the mid-point lies on zero).