RESEARCH

PERFORMANCE OF SUSTAINABLE BUILDINGS IN COLDER CLIMATES

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ABSTRACT

Building performance evaluations (BPEs) were carried out for nine Canadian green buildings using a standardised assessment framework. The aim was to explore and measure the discrepancies between the operational performance of the buildings and their predicted performance, as well as to identify lessons for their owners, design teams and the construction industry. The objective of this paper is not to report individual buildings in detail (we refer the reader to the individual building reports) but to report on some general lessons that came from doing this study.

Overall these buildings performed well compared to benchmarks. However, the findings suggest that occupancy is not well understood and often incorrectly predicted during design, and that this affects various aspects of performance, including energy and water use. Also energy and water use modelling is often undertaken principally for building code/green rating compliance purposes and does not necessarily represent an accurate prediction of likely operational use. Combined with variations in occupancy this can lead to considerable discrepancies in performance from the modelled values. This may be understood by experts but is often misleading to building owners and others. Water use is often not well predicted and also not carefully managed in buildings and there is a lack of understanding of what constitutes good water performance.

Overall, it is important to recognise that each building has its own individual "story" that provides necessary context for effective management and improvement of the building during its ongoing life. It is proposed that a BPE process allows that context to be better understood, and enables more effective decision making about building management, improvements, occupant satisfaction, energy use, etc.

KEYWORDS:

building performance evaluation, post occupancy evaluation, indoor environment, building energy use

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1. INTRODUCTION

A variety of published reports have shown that buildings (particularly innovative green buildings) often do not perform as expected (e.g. Newsham et al., 2012, Bartlett et al, 2014, Bordass, Cohen & Field, 2004). Significant performance gaps have been identified between predicted (or modelled) performance and measured performance of buildings in areas such as energy use, greenhouse gas (GHG) emissions, water use, indoor environment and comfort. The American Society of Heating Refrigeration and Air-conditioning Engineers, (ASHRAE), acknowledges that there is a performance gap between *"design intent, the potential performance of the building as initially constructed, and the reality of everyday practical operation"* (ASHRAE, 2010). A recent report by Lewry (2015) suggests that in the UK operational energy ratings based on energy bills (Display Energy Certificates) are nearly always higher than Energy Performance Certificates, which provide a theoretical assessment of a building's capabilities under standardised conditions. Lewry suggests that this is due to non-standard hours of operation, occupancy patterns and unregulated loads, such as IT and office equipment. Akerstream et al. (2012) point out that most green building rating systems such as LEED, Green Globes and BREEAM have traditionally focused on predicted performance at the design stage; and projected performance is rarely verified voluntarily by building owners and is often not as expected.

As a result of the desire to reduce building energy use and GHG emissions, but also due to concerns about the quality of the indoor environment and its impact on well-being and productivity, a greater interest in real building performance has been evident internationally in recent years, as indicted by a variety of initiatives, including:

- Various municipal energy disclosure initiatives in many North American cities (City of New York, 2013, Energystar, n.d.)
- The European Directive on the energy performance of buildings (EU, 2010)
- Several studies of the performance of LEED and other green rated buildings (e.g. (Baird, 2010; Combe et al., 2011; Newsham et al., 2012; Stevenson & Leaman, 2010)
- Introduction of measurement and verification credits in green rating systems such as LEED (USGBC, 2014)
- An increase of energy guarantee clauses in building contracts (particularly public private partnership contracts).
- More focus on occupant well-being and productivity as indicated by the introduction of the WELL Building Standard (WELL Building Institute 2015)

Although formal measurement, verification, and benchmarking of energy use are becoming gradually more common for buildings with green ratings, few buildings have undergone a full performance evaluation that considers a variety of factors including, energy, water, indoor environment and occupant satisfaction (Abbaszadeh et al., 2006; Baird, 2010; Combe et al., 2011; Newsham et al., 2012; Stevenson & Leaman, 2010). As a result, it is often not known whether buildings are meeting their expectations, and therefore whether the green rating received is an accurate description of how they perform during their operating lifetimes. Additionally, more stringent building codes are being introduced in many jurisdictions around the world. If these are to make tangible reductions in energy use and GHG emissions, it is important to understand how buildings really perform.

Just as significantly, many of the new technologies and strategies deployed in innovative green buildings are not fully assessed nor are the lessons widely disseminated. A dearth of reliable data creates a lack of accountability for designers and isolates learning experiences. When results are not shared or fed forward, they only benefit the building in which they were collected. This can lead to additional costs to building owners, reduced occupant comfort and productivity, and buildings that fail to live up to their potential.

2. PERFORMANCE GAPS

There are a variety of reasons for discrepancies between predicted and measured performance. Bordass, Cohen and Field (2004) called this the credibility gap (now usually referred to as performance gap). Sometimes this gap is conceptualized as how buildings perform in relation to more traditional building stock (Scofield 2009; Newsham, Mancini, & Birt 2009), but for the most part it is defined in relation to design predictions such as whole building energy models. Bordass, Cohen and Field (2004) suggested that a primary cause is that assumptions used in modelling are not well enough informed by what really happens in practice. They suggest that discrepancies can occur due to factors that arise during briefing, design, modelling and estimation, construction and commissioning, and operation phases of the building.

Various reported building performance evaluations (BPE) have suggested that gaps occur due to modelling or prediction inaccuracies, envelope and systems integration problems, construction quality issues, occupancy changes, commissioning and handover processes, operational issues, motivation of occupants, and understanding of comfort (Newsham et al 2012; Cohen et al 2001; Baird 2010). Building management, maintenance and occupancy issues are key components of building performance, but they are commonly not considered at the design and code/green rating compliance stage. Many energy models are created merely to demonstrate compliance with codes or standards, and use standardised inputs that may not reflect the actual operating conditions.

Evaluating the performance of buildings during actual use to determine the causes for discrepancies is an important research objective towards greener (and more energy efficient) buildings in two ways:

1. The evaluation process will identify problems with the building's performance that should be resolved – feeding back information to the existing building stock to improve their actual operation
2. Lessons can be learned from these studies and shared with stakeholders to improve the design of buildings for the future. Therefore, there is a need for structured building performance evaluations for every building to complete the feedback and feed-forward loop.

BPE is an example of what Robson (2011) and others term real world research which refers to research that usually takes place in the 'field', is interested in solving problems (i.e., concern for actionable factors), and is client-oriented and carried out by generalist researchers using multiple methods (Robson, 2011). Such research is also pragmatic in that all variables and external conditions cannot be controlled, and the researcher must sometimes adapt to the situation in the field. Nevertheless, valuable insights are available that can have real world impacts.

The objective of this paper is to use the insights gained from nine building evaluations to expand the knowledge base about the actual performance of Canadian green buildings in the areas of energy, water, indoor environment, occupancy, and cost; and identify lessons for their owners, design teams, and the industry in general. Building performance evaluations were carried out for the nine buildings, documenting and comparing the differences between predicted performance, measured performance, and reference benchmarks for "typical" performance of similar buildings. The paper does not aim to report individual buildings in detail (we refer the reader to the individual building reports available at http://iisbecanada.ca/sb-14/ where a separate report, and set of posters are available for each building) but to report the general lessons and themes that emerged from these assessments.

3. BACKGROUND REVIEW

Evaluating building performance is not new. In the UK, in the 1960s the RIBA (Royal Institute of British Architects) plan of works used by architects to define their services included a Stage M for "Feedback", but this was later removed. More recently, interest in actual building performance has increased. Programs such as CarbonBuzz (see www.carbonbuzz.org) and EnergyStar (www.energystar.gov) have created greater awareness of actual building energy use and carbon emissions through the benchmarking of buildings. An increasing number of cities in the US now require owners of larger buildings (usually over 50,000 sq ft or 4,650 m^2) to report their building's annual energy use to the municipality (see IMT, n.d.). Although important, such benchmarking programs do not provide all the benefits of a full BPE as they usually focus only on energy and carbon, and do not identify causes of discrepancies or potential improvements in the buildings being studied, nor do they improve the design of future buildings. For that, more in-depth research is necessary.

Building performance evaluations (BPE) have been recognized for the past several decades as important tools to understand the performance of buildings (Preiser, & Vischer, 2005, Leaman et al, 2010). Such research usually considers how well buildings match users' needs, and how well the design objectives of the original project have been met. However, the process of adoption has been slow to materialize due to a variety of barriers such as the relative cost and time required, and the fear of designers and building owners of criticism and bad publicity (or even litigation). Also buildings are complex systems that extend beyond the physical and technical systems, including the psychological and social aspect of individual's expectation and behaviours (Preiser, & Vischer, 2005).

Some researchers have sought to characterize the magnitude of the performance gap (Scofield, 2009; Newsham, Mancini, & Birt, 2009; Diamond et al., 2006; Fowler & Rauch, 2008; Turner & Frankel, 2008; Baylon & Storm, 2008), while others have taken the logical next step to try and identify solutions for reducing the gap in buildings (Innovate UK, 2014). Furthermore, advances in the availability of sub-metering technology have allowed researchers to move beyond basic utility data to gain a more profound insight into the buildings (Chisholm, 2009; Torcellini et al., 2006).

In addition to metered technical performance such as energy and water use, information from the occupant's perspective is collected regarding issues such as comfort, aesthetics, occupant satisfaction, and management using recognised surveying techniques (see Leaman, A., Stevenson, F., & Bordass, B. (2010). These can also be supplemented with measurement of environmental conditions such as temperatures, lighting levels, acoustical performance, and indoor air quality. BPE studies require a multidisciplinary approach which spans professions (architecture, services engineering, and facilities management being the most prominent, but potentially also involving behavioral experts and others) and is predominantly about empirical field work: visiting and studying real buildings in use, and surveying occupants.

The PROBE study (Post-occupancy Review of Building and their Engineering), carried out in the United Kingdom between 1995 and 2002, is a landmark study that used a standardised methodology to evaluate 23 commercial and institutional buildings in the UK (Cohen et al. 2001). The study investigated performance gaps for these buildings which often consumed more energy and had less satisfied occupants than expected and highlighted the lack in feedback about the actual performance of buildings. The PROBE studies increased awareness of building performance issues in the UK and beyond, and led to a number of follow on initiatives such as the Soft Landings Framework for better briefing, design, handover and building performance in-use (Way & Bordass 2009), and initiatives such as the Low Carbon Buildings Accelerator and the Low Carbon Buildings Programme which have provided feedback regarding the performance of buildings in use in the UK (Carbon Trust; 2011). Menezes et al. (2012) concluded that there is a need for more realistic input parameters in energy models, bringing the predicted figures closer to reality, and a set of evidence based benchmarks for energy consumption in office buildings to inform designers on the impact of occupancy and management on the actual energy consumption of buildings.

Canada has been slower to adopt these initiatives. In 2003/4 Keen Engineering (now Stantec) carried out a series of building performance evaluations on some of their Canadian projects and published the results (Hydes et al. 2004; and EcoSmart, 2006). They found that these "green" buildings consistently used less energy and had higher indoor air quality than typical buildings, leading to financial benefits to owners. Their findings also highlighted the role of occupants and the need for education for all to better understand the green features of these buildings, and the need for targets set during the design process in order to make possible subsequent assessment of whether a building has performed as intended.

More recently, Newsham et al. (2012) used a comprehensive BPE methodology consisting of questionnaires, physical measurements, and energy consumption data to compare the performance of 12 green office buildings to 12 conventional office buildings from Canada and Northern U.S.A. The study found that the green buildings consistently provide more comfortable and productive indoor environments, but do not always achieve lower energy consumption than their conventional counterparts. This work did not quantify the performance gap by comparing actual performance of the buildings to their design estimates, something this current work aims to address. Others have also studied the performance of LEED buildings in the USA. The Regional Green Building Case Study Project conducted by the Center for Neighborhood Technology (2009) examined 25 LEED-certified commercial buildings in Illinois. This study considered energy, water, greenhouse gas emissions, commute transportation, operating costs, and occupant comfort. The research highlighted the importance of tracking and monitoring the performance of a building once occupied, and using current performance as a baseline to measure potential improvements. Alborz and Berardi (2015) looked at the post occupancy performance of LEED certified halls of residence buildings in the USA and found large variations in energy and water consumption, and poor indoor air quality. The findings also indicate the LEED rating system may generate skewed savings expectations, as occupant behaviours and feedback are poorly considered.

One of the subjects gaining increasing attention is the role of occupants or "inhabitants" in the successful operation of buildings. Cole et al. (2008) speculate that: *"energy and water systems employed in green buildings, such as green roofs, energy-efficient equipment and policies,* *sustainable transportation, composting systems, etc., may involve new responsibilities and require a commitment from inhabitants to engage with positive environmental practices".*

There has been a general realization by engineers, designers, psychologists, sociologists, and economists that technology cannot achieve low-energy performance without suitable engagement of building occupants who are a significant factor in building performance. Social science methods need to be used to realize potential efficiencies. Janda (2011) points out, that: *"building users play a critical but poorly understood and often overlooked role in the built environment"* (p. 20). For Combe (2011), understanding occupant behaviour is important because *"designing a building in a sustainable manner… does not guarantee that the building will be energy efficient as consumption is heavily influenced by the behaviour of its occupants."*

It is generally accepted that a multi-tool approach to evaluating buildings yields the most accurate picture of both achieved performance and occupant satisfaction (Leaman et al. 2010). Potential tools to collect information include; observation, measurement of indoor conditions, interviews, and questionnaire surveys (Leaman et al. 2010, Newsham et al. 2012). Analyzing occupant satisfaction with buildings is an alternative way to understand the performance of a building and provides a valuable companion tool to hard measurements to highlight shortcomings in the performance of the project. Occupant feedback questionnaires that are available for wider use have been created by several organizations including CBE at Berkeley (http://www.cbe.berkeley.edu/research/survey.htm), Building Use Studies (http://www.busmethodology.org.uk) and Newsham et al. (2012).

4. PROJECT METHODOLOGY

This study was carried out by a multi-disciplinary team including researchers from three Canadian universities (Ryerson University, University of Manitoba, and the University of British Columbia), supported by industry and public funds (iiSBE Canada, Stantec R&D Fund, and NSERC). It involved developing a standardised BPE methodology and applying it to nine buildings. Building on the experience of previous work, the process began with a review of published BPE reports (such as Leaman et al 2010, Newsham et al 2010, ASHRAE 2010, Baird 2010) and published performance indicators for buildings (e.g. Eosmart 2006, Fowler &Wang 2010) to identify appropriate methods, practices and indictors. The intention was to compare each building's operational performance to its design stage objectives or predictions and to relevant benchmarks. The buildings are not compared to each other in terms of individual performance categories since they vary in size, use and location across Canada. However, general trends and lessons do emerge from the group of buildings studied. The following categories of performance were investigated: occupancy issues, energy use, water use, economic factors, and indoor environmental quality. Information was collected for:

- Actual building performance over a minimum of two years of operation.
- Predicted performance at the design stage (based on design stage modeling and green rating submissions).
- Reference values or benchmarks for typical buildings of similar use in the region based on Canadian statistics.

Table 1 shows a section of the spreadsheet that was used for collecting data. The work required the research teams to collect both quantitative and qualitative data from several sources:

TABLE 1. Section of the data analysis spreadsheet used to compare performance

	No.	Performance Indicator	Reference standard	Predicted performance	Actual operational performance	Difference between Actual & Reference	Difference between Actual & Predicted	Units
E: Energy and Emissions								
Required	E1	Total delivered electricity		81.0	81.7		1%	kWh/m² *yr.
Required	E7	Building energy use intensity for all operating uses (E1+E2+E3+E4+E5 - E6)	372	81.0	81.7	-78%	1%	kWh/m² *yr.
Required	E8	Net delivered energy use intensity for all operating end uses (E1+E2+E3 - E6)	372	71.3	81.7	-78%	15%	kWh/m² *yr.
Required	E9	Greenhouse gas from delivered energy for all operating end uses.	55	8.0	10.0	-82%	25%	Kg GHG/m² * yr.
W: Water								
Required	W1	Delivered water per occupant to building	7.3	1.3	2.2	-70%	70%	m³ water delivered per occupant per year
Required	W2	Recycled or captured water used in the project (If available)		1.91	1.41		-26%	m³ per occupant per year.
Required	W3	Gross water use per occupants (W1+W2)	7.3	3.2	3.6	-51%	12%	m³ gross water use per year
Required	W4	Water use intensity (W1+W2) per m2 of conditioned area.	0.327	0.142	0.147	-55%	3%	m³ gross water use per m2 per year
$: Economic factors								
Required	$1	Construction cost	Not available		2899	0%		Cost per m2 of net floor area
Required	$2	Commissioning cost	Not available		Not available	0%		Cost per m2 of net floor area)
Required	$3	Annual operating water cost	Not available	0.40	0.41	0%	3%	Cost per m2 of net floor area per year
Required	$4	Annual operating energy cost	Not available	13.22	13.33	0%	1%	Cost per m2 of net floor area per year

- Metered data for energy use was collected for each building from utility bills or sub-meters. Energy use intensity (EUI) in kWh/m^2/yr was calculated and weather normalised using heating degree days (HDD) and cooling degree days (CDD). This was compared to design stage energy modelling results. All the buildings had been modelled at the design stage using one of the following tools: EQUEST, EE4, IES and DOE2.1 software. Unfortunately, the models were not verified by the research team due to availability of resources (this is a limitation of this study that it is hoped to address in future). In addition, the data was compared to the benchmarks of "typical" energy and water use for similar buildings for their region in Canada based on the Comprehensive Energy Use Database (NRCan) published by Natural Resources Canada. Greenhouse gas (GHG) emissions were calculated using provincial carbon intensity factors (Environment Canada, 2013).
- Water use intensity (WUI) was calculated using utility meter data for water consumption and dividing this by usable floor area to give a water use intensity in m^3/m^2/yr (of occupied space). Where an accurate occupancy number was available, metered water use was also normalised by occupancy in m^3/occupant/yr. This in-use data was compared to predicted water use modelled at the design stage using the methodology set out for LEED. The data was also compared to the benchmarks of "typical" water use for similar buildings using BOMA Best water use data (BOMA, 2013).
- Spot measurements for indoor environmental conditions were taken in a sample of work spaces in each building when occupied. The number of spaces tested varied between buildings from 10-15 spaces in smaller buildings up to about 60 spaces in larger buildings. The focus was on typical work spaces such as private and shared offices, or meeting rooms, and not transitory spaces. Measurements were taken for light levels, temperature range, relative humidity, background noise levels, CO_2 levels,

and particulate concentrations. Typically, only one reading for each environmental condition was taken in each space so the results only present a snapshot of the conditions in the space and do not constitute a comprehensive indoor environment survey. However, in association with other data they can be useful for pointing to problems.

- A standard survey of occupants (based on a survey developed by Newsham et al, 2012) was carried out for eight buildings (in one of the buildings the survey was postponed due to operational issues). This survey investigates the occupants' experiences and their levels of satisfaction with the building in general and the indoor environment in particular. Occupants received an email from the building management asking them to respond to the internet based survey. The survey was completed once in each building during the spring/early summer, and occupants were asked to recall conditions at other times of the year. Occupants provided scores of 1 to 7 (where 1 indicates dissatisfaction and 7 indicates a high degree of satisfaction) for their perception of a range of building characteristics, including lighting, thermal, acoustic and air quality issues. The seven points on the scale are assigned a numerical value which is used to generate a mean value. The results are reported using the categories *percentage satisfied* and *percentage dissatisfie*d. Responses of 1, 2, or 3 were grouped as dissatisfied; while responses of 5, 6, or 7 were grouped as satisfied (scores of 4 were treated as neutral and not reported). This level of categorical resolution provides context for the mean values. The results are also presented as box plots (see Figure 4), which indicate the quartile spread of responses around the median. The statistical validity of these surveys varies with response rate for each building which varied from 16% to 90% of occupants. Occupants were also able to provide comments on specific concerns.
- Interviews were carried out with representatives from the design team and the building manager/owner. These used a structured interview process with questions designed to identify issues related to building performance objectives and operational issues. Comments were noted and used to support other data findings.
- Observations were made during building visits to provide supplementary information. A structured walk through the building was conducted usually with the building manager and observations that may be relevant to building performance were documented. For example these could include noting use of blinds, additional portable heating devices, indications of disabling control systems, and other occupant strategies to mitigate conditions.
- Design documents including drawings and specifications, green building rating submissions (such as LEED or Green Globes) and energy models were used to identify predicted performance at the design stage.
- Predicted occupancy numbers were retrieved from design calculations for water or energy consumption of the building. Actual occupancy was calculated wherever possible based on records of human resources, class enrolment numbers, as well as class and recreational schedules. However, this was only possible in seven buildings due to lack of information.

This diverse data set enabled the research teams to document the achieved performance of each building and suggest performance issues. Qualitative and anecdotal data from interviews, observation and spot measurements were used to support the metered data and occupant survey.

5. BUILDINGS SUMMARY

Nine buildings across Canada were identified which had performance data available both for the design stage and for operations over at least two years. Tables 2 and 3 summarise the characteristics of the buildings. Five are academic buildings at universities or colleges, three are private or public office buildings, and one is a community building. All were constructed or had undergone a major renovation in the last ten years. In each case the client had set green objectives for a better than typical level of performance in areas such as energy use, water use and indoor environmental quality. The buildings range in size from 1,900 m^2 to 64,500 m^2 of net conditioned floor area. Construction costs varied from $1,950 to $5,611 per m^2.

TABLE 2. Details of the buildings in the study

Building	Location	Type	Net floor area (m^2)	ASHRAE climate zone	Construction cost (Can. $/$m^2$)	Type
MMM Group office	Kitchener Ontario	Small Office	1,900	6	$2,900	New build
Manitoba Hydro Place	Winnipeg Manitoba	Large Office	64,590	7	$3,550	New build
Surrey District Education Centre	Surrey, BC	Medium Office	11,420	5	$2,500	New build
Canal Building	Ottawa, Ontario	Medium Academic	7,310	6	$4,160	New build
Ron Joyce Center	Burlington, Ontario	Medium Academic	9,340	5	$1,980	New build
Roblin Centre	Winnipeg Manitoba	Large Academic	19,210	7	$1,950	Re-use & new build
Jim Pattison Centre of Sust. Building	Okanagan, BC	Medium Academic	6,780	5	$4,150	New build
Centre for Interactive Research on Sust.	Vancouver, BC	Medium Academic	5,500	5	$5,611	New build
Alice Turner Library	Saskatoon, Saskatchewan	Small Community	2,070	7	$3,200	New build & addition

A variety of established, new and innovative technologies were used in these buildings. Many focused on natural daylighting and natural or mixed-mode ventilation strategies, passive solar strategies including improved thermal insulation and the use of thermal mass. A wide range of HVAC systems from simple to complex were used. Five buildings included renewable energy systems and three included water collection/recycling systems. More information about each building is available at http://iisbecanada.ca/sb-14/.

TABLE 3. Summary of building characteristics

Building	Features
MMM Group office	Three storey commercial office building. Narrow 12m floor plate with 40% window to wall ratio providing good daylighting and natural ventilation. High performance building envelope with walls of insulated concrete formwork construction -wall RSI of 4.3 K m2/W (R 24), and roof Rsi is 4.8 K m2/W (R 27). The windows comprise are triple-glazed low-E argon-filled glazing units. The building was tested for air tightness and achieved a level of 1 ach at 50Pa. Heating and cooling is from 3 variable refrigerant flow (VRF) multi-split air-source heat pumps which directly condition 60 zones located around the building, each provided with a fan coil unit. Nine energy recovery ventilators (ERVs) are supplied by fresh air pre-warmed through a 600 mm diameter concrete earth tube 4 m below ground. Automated shading provides for control of sunlight on the south elevation. A 5 kWh PV system is located on the roof. Rain water is collected for reuse.
Manitoba Hydro Place	Large multi-storey commercial office building, including some retail and food services spaces. The building's A-shaped plan of two 18-storey towers that converge to the north and open to the south to maximize solar gain. Includes many passive design features: Three South facing atria (or winter gardens) with waterfalls pre-treat and humidify incoming air. A 115m tall solar chimney draws exhaust air through the building without use of fans. High performance building envelope. Double-wall facades with automated exterior window vents and operable windows. Eighty-five percent daylighting and high efficiency artificial lighting and controls. Space conditioning is from a geothermal heating and cooling Advanced computer based Building Management System helps to coordinate and maximize the performance of active systems.
Surrey District Education Centre	Four-storey office building with private and open-plan offices, and small meeting rooms. Cast-in-place concrete flat slab and the columns and shear-wall construction Exterior walls are typically curtain wall with an Rsi of 2.8 m^2W/C (R16) insulated spandrel panels, and double-pane low-E glass. Roof has Rsi of 3.5 m^2W/C (R20) rigid insulation over steel decking. 92% of the occupied areas have views to the perimeter glazing, The primary heating system of the building is a geo-thermal constant volume modular heat pump providing heat through in-slab radiant heating. Ventilation is by central mixed air-handling system, with a heat recovery. Cooling is by active chilled beams Solar thermal hot-water panels provide domestic hot-water (DHW) pre-heating. A natural-gas boiler further heats the water.
Canal Building	University building with lecture halls, computer labs, offices, and graduate laboratory space. Masonry façade steel stud cavity wall, and partially a curtain wall system with 40% window to wall ratio. Wall Rsi 4.8 m^2 K/W (R27). The roof Rsi is 5.3 m^2K/W (R30), and is partially covered by a green roof. Heating is by a central steam plant supporting ceiling mounted radiant heat panels. Cooling is provided by chillers supporting a VAV box system. Ventilation and air distribution is provided by a single ducted VAV system. Ventilation air is exhausted through an ERV to minimize energy lost to the exterior. A 10 kWh PV system is located on the roof.
Ron Joyce Center	University's business school includes classrooms, lecture theatre, cafeteria, and rental catered space. A central atrium space allows daylight to enter deep into the core of the structure. A curtain wall system is used for maximum daylight penetration, insulated to Rsi of 3.5 m^2W/C (R20) for the walls and Rsi 5.3 m^2W/C (R30) for the roof. The building does not have operable windows. Heating and cooling is provided by a hybrid mechanical system comprised of a water loop heat pump system, serving water source heat pump units, in conjunction with an outdoor air makeup unit for fresh air ventilation. Also radiant floor heating is included on the first floor along the perimeter and fan coil heaters in designated zones. C02 sensor demand-controlled ventilation as well as a HRV energy recovery wheel for waste heat recovery reduce ventilation energy use. Occupancy sensors are used throughout the building to minimize lighting related energy consumption.

Roblin Centre, Red River College	College’s multimedia center which provides education spaces and is also rented for workshops, conferences and receptions. Features adaptive re-use of an existing heavy timber warehouse with new additions and conservation of other facades. Careful historic preservation, extensive salvage of on-site materials as well as the minimal use of new materials provides an industrial “raw” aesthetic of brick walls, concrete floors, exposed mechanical systems and open ceilings. Space heating and cooling system uses 180 four-pipe fan coil units to provide a high level of zonal control. Heat is from the five condensing natural gas-fired boilers which also serve the three make-up air units through two heat exchangers Includes a large quantity of regional, salvaged, recycled and rapidly renewable materials. Every effort was made to reduce the amount of new materials. A small PV system is integrated into glazing
Jim Pattison Centre of Sustainable Building	College building with classrooms, laboratories, trade shops, meeting rooms, offices, gymnasium. Comprised of wood structure, which supports a steel deck with polished concrete and a radiant floor system Natural cross-ventilation system consists of operable windows, trickle vents, and solar chimneys that enhance the natural stack ventilation throughout the building. Heating is by an open-loop geo-exchange system that supplies heat pumps. The mechanical system is based on a dedicated outdoor air system (DOAS) that supplies preheated outdoor air (using heat pumps) by displacement diffusers to occupied spaces and returns air through building exhaust fans. Vertical solar light tubes introduce natural light from the roof and support the T5 fluorescent lights that dim down when light levels are sufficient. A 259 kW solar photovoltaic (PV) array on the roof of the building is predicted to meet 45% of the building’s energy demand Solar thermal hot water heating consists of vacuum tube solar panels and flat plate solar panels, for hot water (DHW) and additional heat. Potable water is reduced using well groundwater and treated effluent water (TEW), that is provided by the City of Penticton’s Advanced Waste Water Treatment Plant. used for irrigation and toilet flushing The roof is covered by a reflective material and an extensive green roof.
Centre for Interactive Research on Sustainability	University building with offices, classrooms, and lecture theatre designed as a demonstration of leading edge sustainable design. 10-m-wide narrow floor plates with extensive glazing provides natural light. Wooden structure; combination of pre-fabricated glulam members, dimensional lumber, plywood, local non-FSC certified wood. Low-e glazing; living green wall and roof; increased roof and wall insulation. The primary heat source is from heat-recovery coils that are connected to the lab exhaust of the adjacent Earth and Ocean Sciences (EOS) Building. Secondary heat is from a series of heat-recovery coils located in the CIRS exhaust air stream that feed heat back into the hot-water loop. Domestic hot water (DHW) is provided by a 40 square meter array of evacuated tubes on the roof, and supplemented by heat from the heat pumps. A 25-kilowatt photovoltaic (PV) array is located on shading devices for windows. Low-flow water fixtures; rainwater harvesting system; on-site rainwater treatment system and wastewater treatment system; and storm-water runoff system.
Alice Turner Library	Single storey community library Wood frame construction above a precast concrete floor Rsi 3.5 K m^2/W (R 20) in the walls and Rsi of 5.3 K m^2/W (R 30) Fenestration includes spectrally selective double-pane argon-filled clear low-e glazing with high performance thermally-broken frames. Heating by four high-efficiency condensing boilers supporting radiant floor heating in combination with a four-pipe fan coil secondary system. Cooling is provided by an air-cooled chiller supporting a four-pipe fan coil system. Ventilation is decoupled from conditioning loads and provided by a multi-speed central supply and exhaust system with an enthalpy heat recovery wheel.

6. OCCUPANCY

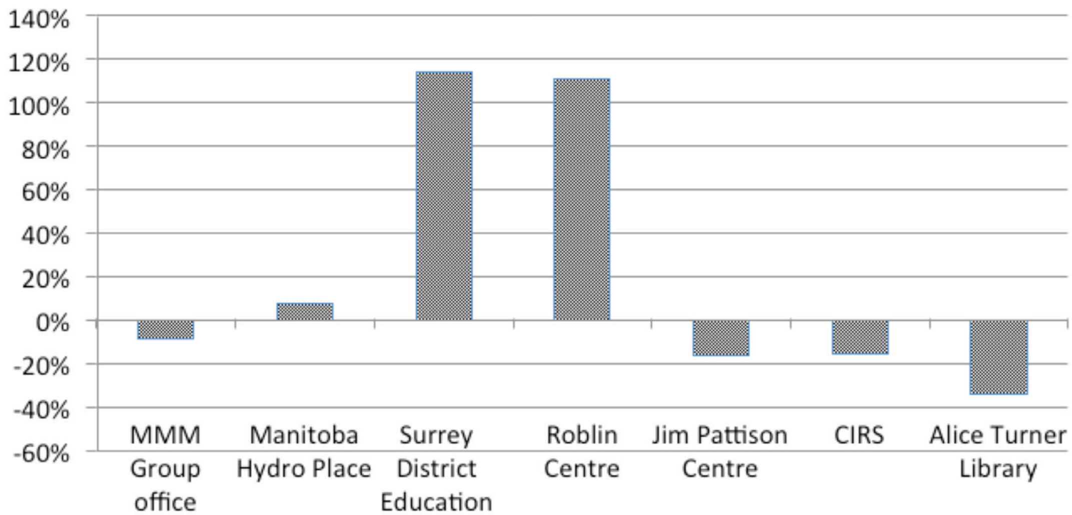
Although not a direct measure of environmental performance, occupancy is an important factor that affects building performance. The project aimed to establish occupancy levels (numbers of people, and hours of use) as an indicator of how each building was being used compared to expectations, and also to allow certain other indicators to be normalised. In some buildings this proved to be difficult. For office buildings such as the MMM office or Manitoba Hydro Place, occupant numbers were more easily ascertained through the presence of employees at workstations in the building. However, for the five educational buildings occupant numbers were far more difficult to establish. Academic facilities are particularly challenging due to the combination of both full and part-time staff and variable levels of students whose presence in the building changes from hour to hour and throughout the year. For two buildings it was not possible to establish accurate actual occupant numbers.

TABLE 4. Comparison of predicted and actual occupancy levels

Building	Typical daily occupancy during operating hours (persons/hr)			Typical weekly operating hours (no. of hrs)		
	Predicted	Actual	Difference	Predicted	Actual	Difference
MMM Group office	85	78	-8%	57	57	0%
Manitoba Hydro Place	2000	1800	-10%	50	60	20%
Surrey District Education	396	465	17%	45	82	82%
Roblin Centre	2200	2649	20%	40	70	75%
Jim Pattison Centre	250	137	-45%	45	69	53%
CIRS	378	252	-33%	45	57	27%
Alice Turner Library	42	32	-24%	66	57	-14%

Table 4 shows the predicted (at the design stage) and actual daily average number of occupants and the typical weekly operating hours for seven buildings. This suggests that buildings are being used in a considerably different pattern than expected. The actual number of daily occupants varied from predictions by a range of -57% to +20%. Five of the seven building are being used for longer hours than originally predicted. These ranged from +82% to -14% occupied hours. Figure 1 shows how weekly occupant hours (no. of occupants x average occupied hours) vary from predictions for seven buildings. Only three of the buildings were within 20% of their predicted usage rate, and two were used at more than double the predicted rate. In one of the most extreme examples, the Roblin Centre has 20% more people for 75% more hours per week. This works out to more than doubling of weekly occupant hours from 88,000 to 185,430. This unexpected major increase in its occupancy and operational hours helps to explain some of the variation in other indicators for this building (see further sections). The Surrey Education Centre is being used for nearly double the hours each week that were expected and this has increased its weekly occupant hours significantly. The obvious effect of occupancy on the buildings' performance in several categories highlights the challenge of accurately predicting and measuring occupant loads, both at the design and post-occupancy evaluation stage.

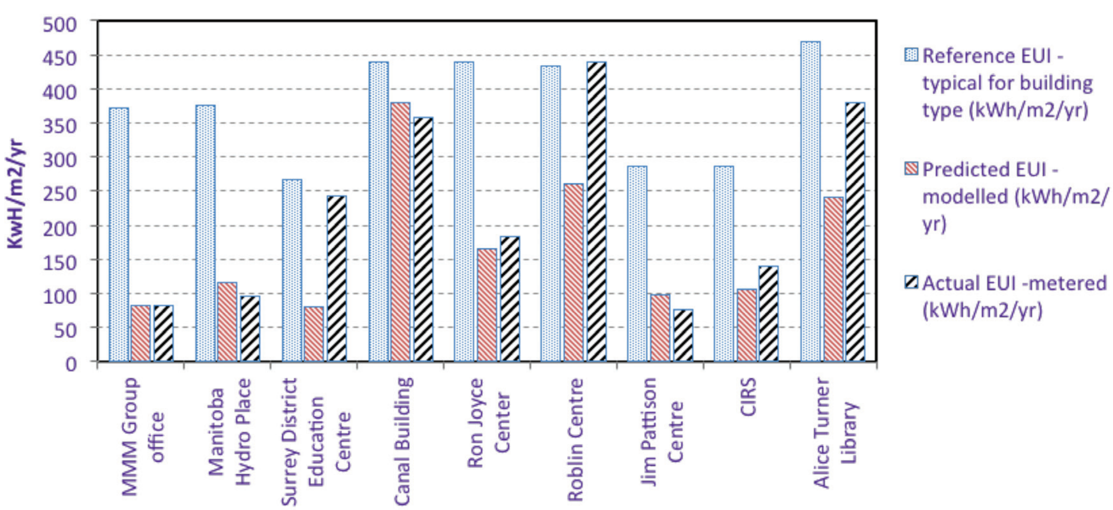
FIGURE 1: Variation of building weekly occupant hours (average no. of occupants/hr x hrs of operation per week) from predictions.



7. ENERGY

Figure 2 shows a comparison of modelled, measured and reference values for energy use intensity (EUI) for the nine buildings. This demonstrates that the gap between measured and predicted performance varies significantly. All but one building perform better than the reference benchmark, five are more than 50% below their reference benchmark. This confirms that these buildings are generally performing considerably better than typical buildings. When compared to their modelled predictions, some buildings, such as the MMM office and Manitoba Hydro place perform close to their expected energy use although in most cases it took several years of refinement and fine tuning for the building to reach this level. Three buildings fail to meet their predicted performance by a significant margin.

FIGURE 2: Comparison of building EUI (kWh/m2/yr) predicted, actual and reference.



However, it is important to understand the reasons for these discrepancies. Some buildings, such as the Surrey District Education Centre, had technical and operational problems related to the HVAC system that affected its energy consumption and meant the building did not function as expected. Although the building consumes 9% less energy than the reference benchmark, the actual EUI (242 kWh/m^2/yr) is significantly higher than expected. The evaluation process helped to identify some technical issues related to mechanical systems, and they can now be addressed. However, it is also important to consider how the building is being occupied and managed. The Surrey District Education Centre is in use for considerably longer hours than predicted; the occupancy data shows that this building is in use each week for 82% more hours than expected and with 17% more occupants than predicted (see Table 4). The overall impact is 114% more weekly occupant hours and this will inevitably have an impact on building performance. Similarly, the Roblin Centre uses 69% more energy than predicted (although still less than a reference building of similar size and function), even after initial performance was improved by retro-commissioning. A major reason for this is a 75% increase in the number of hours the building is occupied compared to what was predicted, and a 20% increase in the average number of occupants. Rather than construct another building the college uses this popular facility more intensively and so the higher EUI is not a necessarily a negative since it has avoided the need to construct another building. Conversely, the Jim Pattison Centre performs better than predictions, with an EUI 22% lower than expected in part because occupancy (weekly occupant hours) was 16% lower than expected.

Generally the reasons for energy performance gaps can be grouped into the following categories:

- Occupancy numbers and patterns
- Occupant behaviour
- Technical problems with HVAC equipment and controls
- Insufficient resources/knowledge to manage/operate the building efficiently
- Lack of thorough commissioning of building systems
- Construction problems

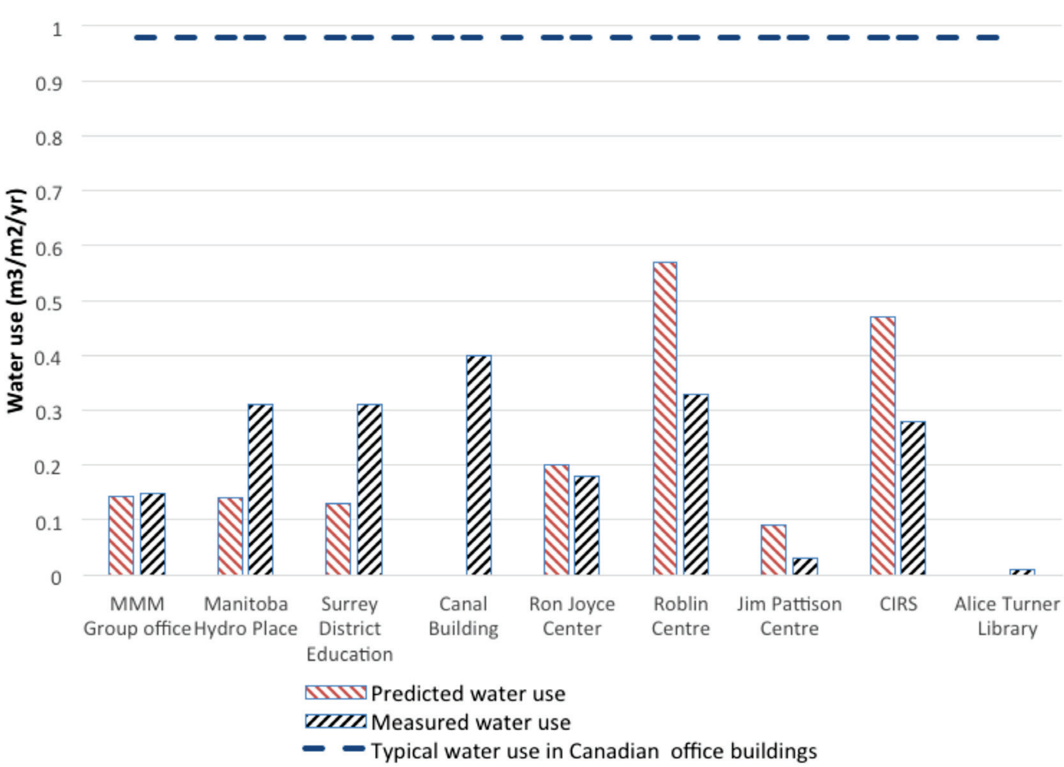
Furthermore, as mentioned earlier, energy models are often commissioned to compare the relative impact of different design options, and for the purpose of code (and green rating) compliance. This means that significant loads such as unregulated loads and external lighting are often not included. Occupancy is often assumed using default values that are based on norms that may be outdated or unrealistic and often do not reflect how these buildings are used in practice (which may be difficult to predict at the design stage). Also, the models assume a level of control, especially of lighting and plug loads that may not be realistic (Turcato 2015). Thus, comparing measured energy use with modelled energy predictions created to demonstrate code compliance may be misleading and imply a performance gap that is not real. It is not intended to suggest that modelling methods should not be used for prediction, but rather the need to recognize the real conditions within which they are used, and thus their limitations. Without a full and rigorous reconciliation between projected and actual energy performance such comparisons can be misleading. Reconciliation was beyond the scope of this project, but would typically include methodologies such as revising performance projections made at the design stage to reflect actual building occupancy patterns, as well as resolving energy use with greater resolution (e.g., specific end-uses) which requires sub-metering (see Samuelson et al. 2014). Reference benchmarks (assuming they have been rigorously calculated) are able to provide useful context, these are average values for similar buildings of that type in that location. They provide a comparison to typical performance and so indicate how far a building has exceeded the general performance characteristics of the built stock.

8. WATER USE

Water use intensity in $m^3/m^2/yr$ was calculated for each building. Water use in m^3/occupant/yr was also calculated where reliable occupant numbers were available.

Figure 3 compares metered municipal water use intensity of all 9 buildings with predicted (where available) water use intensity. Also shown is a reference benchmark for water use in typical Canadian office buildings (REALPac 2012). All the buildings perform well and have low water use compared to the benchmark, but some are considerably above their predicted usage. The predictions vary widely and it may be that these are sometimes unrealistic or not accurate. This indicates that perhaps the industry is not as familiar with water use intensity indices and predictions as they are with energy indices and modelling tools are not accurately used. In some cases such as the Surrey District Education Centre higher occupancy levels than predicted appear to have a direct impact on water use. Interestingly, the Roblin centre has a higher occupancy rate than expected but a lower water use. This appears to be due to a major retrofit of water fixtures in the building several years after construction.

FIGURE 3: Comparison of water use for 9 buildings - predicted vs. actual vs reference (predicted water use was not available for the Canal building and Alice Turner library)



The MMM Group office and Jim Pattison Centre both included rainwater collection/reuse systems which reduced municipal water consumption considerably to below 0.15 $m^3/m^2/yr$. However, neither was able to achieve complete reliance on rainwater. The other buildings achieved low water use by careful specification of fixtures and with minimising irrigation water use. Most of the buildings used little or no water for landscape irrigation which was a major factor in reducing water use. In some cases such as the Ron Joyce Centre a conscious decision was made not to have any irrigation and design the landscape accordingly. Others, such as MMM, included drought-tolerant landscape and even urban gardening plots for office staff, and rainwater collection for irrigation. The Alice Turner library uses very little water, which appears to be due to the transient population of a branch library where most visitors stay for only a short time, and only staff regularly uses the washrooms.

9. INDOOR ENVIRONMENTAL QUALITY IEQ

Spot measurements for lighting, thermal, acoustics and air quality provide only a snapshot of the indoor environmental quality (IEQ) at the moment measurements are taken. Long term monitoring was beyond the scope of this project but an occupant survey was able to provide additional valuable information and was supported by observations and comments from building managers. The survey data was collapsed into five general IEQ categories (see Newsham et al. 2012 for a discussion of this process) and presented for each building in the format shown in Figure 4 which indicates a mean, standard deviation and a quartile range for the answers to the different sections of the questionnaire.

FIGURE 4: Survey results for the key IEQ factors for the MMM building (based on 53 survey responses). This plot shows the range of all data points, the median (which is the central bar in the box) and the four quartiles into which that data is divided (thus 25% of the data points occur in each quartile).

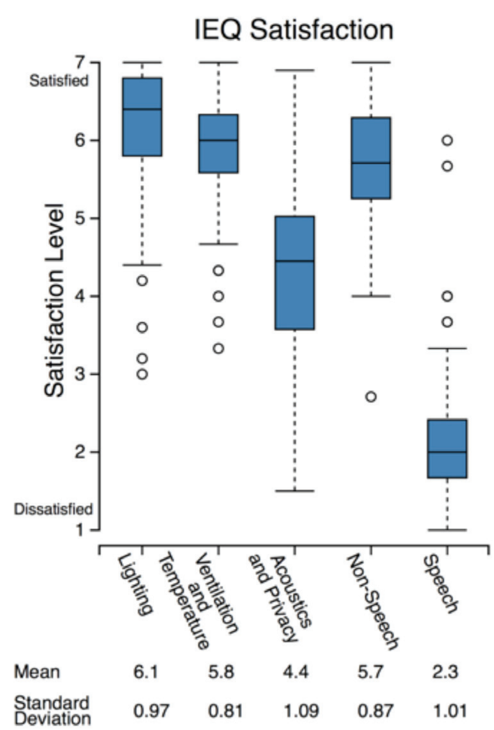


FIGURE 5: Questionnaire mean scores for eight buildings compared. Questions used a 7 point scale, with 1 indicating dissatisfaction and 7 indicating satisfaction. The scores for all questions are collapsed into these 5 general IEQ factors (see Newsham et al., 2012 for a discussion of this process).

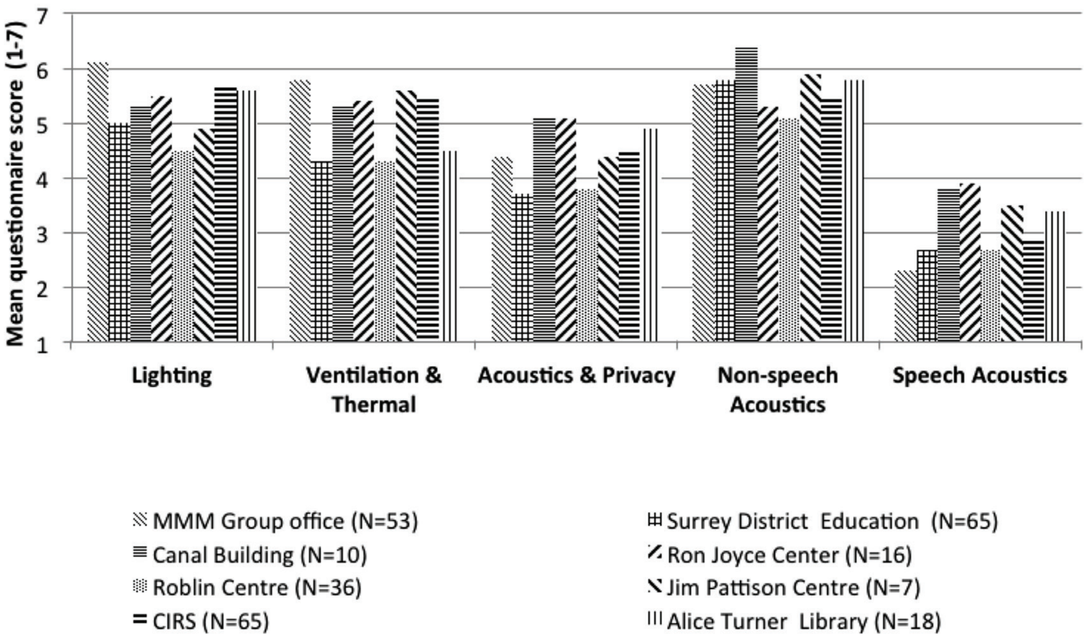


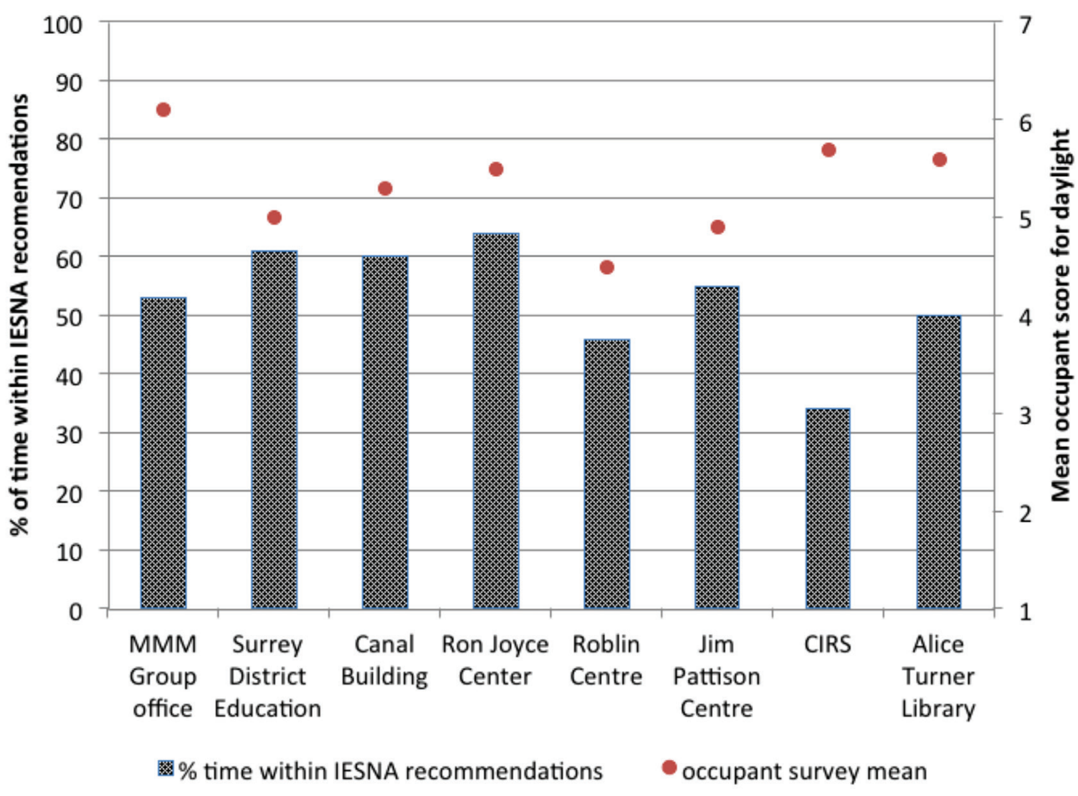
Figure 5 compares the mean occupant survey scores (from 1 to 7 with 7 being good) for eight buildings surveyed using the five general IEQ categories (it has not yet been possible to survey the ninth building due to operational issues). Although the range of responses varied widely from building to building, and also within each building, respondents generally expressed satisfaction with lighting conditions and poor satisfaction with speech privacy. Thermal performance had generally good results, although some buildings had significant variations in occupant satisfaction between winter and summer performance.

The occupant survey also allowed for comments, and these are useful for identifying specific problems that occur at individual workstations (e.g., cold air from vents). A keywords review of the responses suggested that the most consistent areas of concern appear to be personal control of their internal environment. Concerns were expressed by occupants about insufficient control over lighting, thermal comfort and acoustics. Comments generally revealed a desire for more personal control over windows, ventilation, temperature and noise. Many comments by occupants centered on specific technologies and local problems.

The buildings generally perform well in the lighting category with scores ranging from 4.5 to 6.1 with an overall mean score for all buildings of 5.3 (see Figure 5). This was supported by positive comments about daylighting in several buildings, and this was seen as a strong feature in these buildings. The building with the lowest score is the Roblin Centre, which is an adaptive reuse of an existing building and so had some limitations to the daylighting strategy. Other buildings such as the MMM offices and CIRS were designed specifically to maximise daylight, and the scores suggest that this has been successful. However, even when a building has a good overall score it is important to look beyond the averages and identify problems that occur at individual workstations. Survey comments are useful for this. For example, at the Canal building, although overall satisfaction with daylight was good with a score of 5.3, some private offices on the "saw-tooth" façade on the south west expressed frustration with the amount of glare caused by the orientation of the office windows which was caused by a late design change to the intended façade treatment.

Figure 6 compares the percentage of time that spot measurements of lighting at workspaces met IESNA recommendations with occupant satisfaction. This suggests that in some cases occupant satisfaction is high even when lighting conditions appear not to meet the IESNA recommended levels for office spaces (too high or too low). This is the case for most of the buildings in this sample but the most extreme example is the CIRS building where only 34.5% of the measurements reported light levels within the IESNA recommended range of 300-750 lux, with the majority of measurements being above the acceptable range, due to high levels of daylight. Yet occupant satisfaction with daylighting was high with a mean score of 5.7 out of 7. It may be that for naturally daylight spaces occupants are willing to accept a higher illumination level than is suggested in the guidance.

FIGURE 6: Lighting measurements and occupant scores compared.



The ventilation and thermal category in Figure 5 also scored well, with a range of 4.3 to 5.8 and a mean score of 5.1 out of 7. In support of the questionnaire data thermal spot measurements of temperature and relative humidity were plotted onto ASHRAE 55 thermal comfort zones (see Figure 7 for an example) to show the proportion of measurements that fall into the relevant ASHRAE thermal comfort zone for summer or winter. Generally these confirmed that conditions within most spaces were within the ASHRAE comfort range.

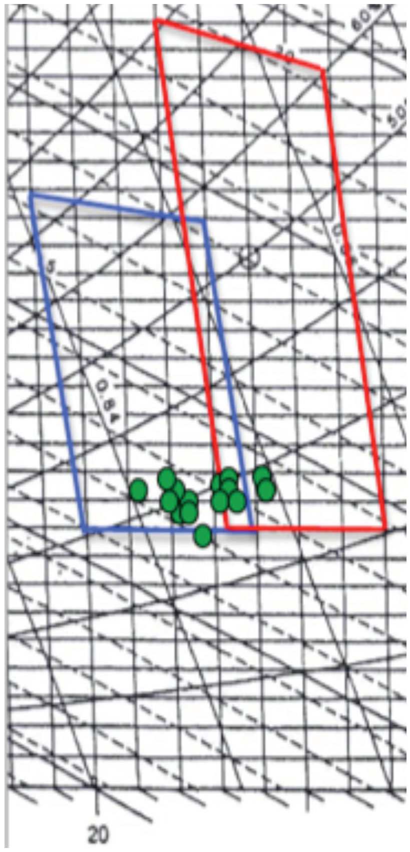


FIGURE 7: ASHRAE 55 provides thermal comfort zones for summer and winter plotted on a psychrometric chart, which show combinations of temperature and relative humidity conditions that are considered comfortable. The left quadrilateral indicates winter comfort zones, while the right quadrilateral indicates summer comfort zones. This figure shows spot measurements (taken in April 2014), at the Ron Joyce Centre indicating that most spot measurements fell within the winter comfort range.

Compared to other aspects of the indoor environment, occupants in all these buildings showed lower levels of satisfaction with acoustics and privacy, and were especially dissatisfied with speech conditions. Non-speech noise which deals with occupant perception of disturbance from noisy equipment and external noise disturbance was not a major concern, except for occasional noise from machines in the trade shops. Figure 5 clearly identifies speech acoustics as the category with which occupants are most concerned. This category addresses the occupants experience with whether the space is suitable for conversations and provides the necessary privacy. The occupant scores for each building range from 2.3 to 3.9 with a mean score for all the buildings of 3.2. This is considerably worse than the other IEQ categories. Sound pressure levels were measured in A-weighted decibels, and then converted into Noise Criterion Balanced (NCB) values so they could be compared to appropriate reference standards. Table 5 shows that only 45% of open plan spaces and 55% of private offices were below the maximum NCB rating.

Acoustic concerns were also the issue most consistently raised in questionnaire comments. Specific comments revealed the sources to be noise from other people, distraction from speech in open-plan offices, and an inability to obtain speech privacy. Occupants were disturbed by the transmission of sound within the open plan office areas and from nearby classrooms, meeting rooms, washrooms and circulation space. The position of openings was shown to be important. This is further backed up by researcher observations and survey self-reports of people using headphones to block out unwanted noise. It is reasonable to assert that speech noise and a lack of speech privacy are significant sources of dissatisfaction for employees in these buildings, and measurements verified that they are not performing optimally. This finding is all-too-common in research on green building performance (e.g., Baird & Dykes, 2010; Newsham, 2013), and represents an important area for design improvement.

TABLE 5. Mean acoustic measurements for 9 buildings

Type of Space	Reference Maximum NCB	Mean measured NCB	% of Measurements in Compliance
Open office	NCB 40	NCB 42.3	45%
Private office	NCB 35	NCB 40.6	55%

10. CONCLUSIONS

The objective of this paper is not to report individual buildings in detail (we refer the reader to the individual building reports available at http://iisbecanada.ca/sb-14/) but to provide some general lessons that came from this study. The scope did not allow for the rigorous reconciliation between projected and actual performance. Reconciliation would include methodologies such as revising performance projections made at the design stage to reflect actual building use and occupancy, as well as resolving energy and water use to a greater degree of granularity (e.g., specific end-uses). This requires more resources than were available, and access to data that for many buildings may not exist, such as a calibrated energy model (which existed only for two of the buildings), and sub-metered energy data which was available only for four buildings.

To understand and assess a building's performance it is important to consider the context, or the building's own individual "story", that provides an appropriate framework for effective management and improvement of the building during its ongoing life. A BPE allows that story to be better understood, and enables more effective decision making about building management, upgrades, improvements, occupant satisfaction, energy use, etc. For example, a building may not meet its energy or water targets because it is being used more intensively. This may be beneficial as it avoids the construction and operation of additional space, but may add to energy and water use intensity and create IEQ challenges. In contrast, a building may meet its energy targets, but it may be underused, with lower occupancies, or its location may result in increased travel distance and lower use of public transportation by its occupants, leading to increased carbon emissions. Some lessons from these nine study buildings include:

- Actual building occupancy is not well understood and often varies considerably from original design assumptions (predictions). This can lead to operational issues (energy and water use etc.). Furthermore, actual numbers can be difficult to determine if not monitored and recorded on an ongoing basis. This is a key aspect that must be addressed going forward.
- Care needs to be taken when comparing design stage energy models and water predictions with actual metered use in the building. As Bordass et al. (2004) indicate it is not so much that predictive techniques are wrong, but discrepancies occur because the assumptions used are not well enough informed by what really happens in buildings once occupied. Design stage models often exist to compare the relative impact of different design options and therefore may not be intended for accurate prediction of actual

final performance. Designers and building owners should be aware of this, and if accurate predictions are expected, appropriate care needs to be taken with the modelling.
- Providing more context are the reference values or benchmarks for each indicator, although finding relevant, accurate, local, reference benchmarks can be challenging. Generally, benchmarks are available for energy, but for the other categories such as water use and indoor environment benchmarks are far more inconsistent. In other words, it is difficult to determine which standard a high-performance building should be compared to.
- The most pervasive building performance issue in these buildings was acoustic quality, with speech privacy being the main concern. Speech conditions are continually raised by occupants as a problem, although external sources did not appear to be an issue.
- There does not appear to be a good correlation between conventional lighting level metrics or standards and occupant satisfaction with lighting. More specifically, high levels of daylight well beyond accepted lighting level standards did not appear to detrimentally affect lighting satisfaction, and may in fact have contributed to it. Definitive conclusions in this regard require further study.
- Commissioning and ongoing building management issues are crucial to successful building operation yet are often overlooked by building owners. The exemplary actual performance of several projects appeared to be directly related to building management and operational staff. Those projects generally correlated with higher management and operational capabilities and capacities. This reiterates findings from the PROBE studies and others that complex buildings need appropriately qualified management staff, and if they are not available, designers should avoid complex technologies that are not well understood by the industry. Related to the above, a number of building performance issues could be directly attributed to commissioning gaps. Continuous commissioning was also instrumental in sustaining or improving the performance of several of these projects.
- A lack of sub-metering and/or data acquisition was a significant obstacle in the assessment of a number of projects, as well as clearly limiting the building operator's ability to monitor, maintain and improve the performance of their buildings.
- Water use needs to be better understood both at the prediction stage and during operations.

From a methodological point of view the mixed mode (qualitative & quantitative) data collection techniques provided a more complete picture of building performance. For example, spot measures of indoor conditions provide a good picture of indoor environment but only for one point in time. Conversely, occupant surveys provide a response based on longer term experience and can identify trends and provide a perspective on building performance that is not readily obtainable by direct measurement. Similarly, the important role of the semi-structured interviews / walk-throughs with designers and maintenance staff provided insight that may not be immediately apparent on site.

Finally, our occasional but considerable difficulty collecting appropriately detailed data indicates that if the industry is to carry out effective BPE on a wider scale, it is important that better documentation of design assumptions and provision for collecting performance data for later use be considered at the design stage. Despite these concerns the high-level analysis in this study did uncover several trends and relationships that will prove useful in improving building design, construction, and operation, as well as contributing to the further development and implementation of building performance evaluation methodology.

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