THE IMPORTANCE OF UNDERSTANDING OCCUPANT BEHAVIOUR IN BUILDINGS: EXPLORING THE NEXUS OF DESIGN, MANAGEMENT, BEHAVIOUR, AND ENERGY USE IN GREEN, HIGH-RISE RESIDENTIAL BUILDINGS

by

CRAIG BROWN

B.A., York University, 2005
MES, York University, 2010

A dissertation presented to Ryerson University in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

in

The Program of Environmental Applied Science and Management

RYERSON UNIVERSITY
Toronto, Ontario, Canada, 2015

Author's Declaration

AUTHOR'S DECLARATION FOR ELECTRONIC SUBMISSION OF A DISSERTATION

I hereby declare that I am the sole author of this dissertation. This is a true copy of the dissertation, including any required final revisions, as accepted by my examiners.

I authorize Ryerson University to lend this dissertation to other institutions or individuals for the purpose of scholarly research.

I further authorize Ryerson University to reproduce this dissertation by photocopying or by other means, in total or in part, at the request of other institutions or individuals for the purpose of scholarly research.

I understand that my dissertation may be made electronically available to the public.

Craig Brown
The importance of understanding occupant behaviour: Exploring the nexus of design, management, behaviour, and energy use in green, high-rise, residential buildings
PhD, Environmental Applied Science and Management (Convocation 2015)
Ryerson University

Abstract

The quest to 'green' the built environment has been ongoing since the early 1970s and has intensified as the threat of exceeding 450 ppm of atmospheric carbon dioxide has become more real. As a result of this, many contemporary residential high-rise buildings are designed with hopes of achieving carbon emission reductions, while not sacrificing occupant satisfaction, or property value. Little is known about how the occupants of these buildings contribute to the energy and water consumed therein, nor the effects that these design aspirations have on occupant satisfaction. The present study relies on data collected in four recently built, Leadership in Energy and Environmental Design [LEED] certified, high-rise, residential buildings in Ontario, Canada. Using various sources of data (i.e., from energy and water submeters, questionnaire responses, interviews, and physical data relating to each suite) the extent to which physical, behavioural, and demographic variables explain suite-level energy and water consumption was explored. Energy use intensity differed by a factor of 7 between similar suites, electricity by a factor of 5, hot water by a factor of 13, cooling by a factor of 47, and heating by a factor of 67. Results show that physical building characteristics explain 43% of the heating variability, 16% of the cooling variability, and 40% of electricity variability, suggesting that the remainders could be a result of occupant behaviour and demographics. It was also discovered that 52% of respondents were not using their energy recovery ventilators [ERV] for the following reasons: acoustic dissatisfaction, difficulty with accessibility of filters, occupant knowledge and preferences, and a lack of engagement with training materials. Results suggest that abandoning mechanical ventilation in favour of passive ventilation could actually lead to greater satisfaction with indoor air quality and to decreased energy consumption. Using content analysis of questionnaire comments, the utility of contextual factors in understanding energy use and satisfaction in the study buildings, as well as their value in producing feedback for designers and managers, was explored. Combining quantitative and qualitative datasets was an effective approach to understanding energy use in this understudied building type.

Acknowledgements

I would first like to thank Dr. Mark Gorgolewski for all that he has done to make this dissertation possible. Over the past five years Dr. Gorgolewski has always accommodated me, taking the time to review my work, to involve me in interesting projects, and to generally help me navigate my role as a doctoral student and academic. Above all, Mark showed me how to maintain calmness and humor in the face of intense work pressures by modeling this behaviour himself. I'll always cherish our time together through this process.

I would also like to thank the other members of my supervisory committee for offering their guidance when they were called upon. In particular, I would like to thank Adrian Leaman of Building Use Studies, both for arranging the licensing of the BUS questionnaire, but also for his mentorship throughout the research process. His stance from outside the University was invaluable in giving my work the perspective that it has.

I would also like to thank the two development partners, condominium boards, property managers, and occupants who facilitated this work. A study needs participants, and I am thankful I found them where I did, when I did. Thanks also to Adrian Turcato, Moe Otsubo, and Matthew Tokarik of Ryerson University for their help along the way, and to the Department of Architectural Science for lending various indoor environmental quality testing equipment. This research was supported by the Social Sciences and Humanities Research Council (SSHRC) and by the Federal Economic Development Agency for Southern Ontario's Applied Research and Commercialization Initiative.

Finally, thank you to my friends and family for supporting me with their insights and laughter.

For all of the wonderful
women in my life

Table of Contents

List of Tables

List of Figures

List of Appendices

Note: Paper 3 (Chapter 4) does not appear in an appendix because it has not yet been published.

List of Abbreviations

BPE	Building performance evaluation
BUS	Building use studies
POE	Post-occupancy evaluation
ERV	Energy recovery ventilator
LEED	Leadership in Energy & Environmental Design
CaGBC	Canada Green Building Council
HDD	Heating degree day
CDD	Cooling degree day
IEQ	Indoor environmental quality
IAQ	Indoor air quality
PPM	Parts per million
OAA	Ontario Association of Architects
RAIC	Royal Architectural Institute of Canada

1. Introduction

The quest to 'green' the North American built environment has been ongoing since the early 1970s and has intensified as the threat of exceeding 450 parts per million of atmospheric carbon dioxide has become more real. The building sector in Canada accounts for over 30% of the total secondary energy use (NRCan, 2012) and is responsible for about 35% of greenhouse gas emissions (Environment Canada, 2012). Efforts to reduce the energy consumption of buildings have taken many shapes, including improved building design, innovative building materials, energy management strategies/technologies, rating/certification tools, codes and standards, control interfaces, commissioning protocols, conservation initiatives, and the like.

Toronto is Canada's largest city and the Government of Ontario (2014) projects that the Greater Toronto Area will add approximately 100,000 new residents per year until 2041. Of all North American cities, New York City is the only one with more buildings over 12 stories (including office towers) (McClelland, 2011). It is likely that as Toronto grows, the city will continue the trend of approving numerous high-rise residential developments. In the last decade, some Toronto developers have pursued green strategies and LEED certification for their high-rise residential projects (Nolan, 2013). As of 2015, there are 25 LEED certified high-rise residential buildings in Toronto (Canada Green Building Council, 2015). These new, green buildings are at least ostensibly meant to reduce the carbon emissions associated with this sector. Notwithstanding this discussion, this housing type is increasing in popularity, and is the subject of the work presented here.

1.1 Structure

This is a manuscript style dissertation, based on four journal articles presented in Chapters 2 to 4 (described in Section 1.4). The dissertation is organized with minor 'bridging' sections between each of the chapters in order to unify the manuscripts. What follows is the conceptual framework underlying all three of the chapters, including the various theoretical underpinnings which motivated, informed, and unify the present work.

1.2 Conceptual Framework

A fundamental thesis of this work is that building occupants play a significant role in determining building performance (e.g., Gill et al., 2010; Stevenson, Carmona-Andreu, & Hancock, 2013; Pilkington, Roach, & Perkins 2011). Designers need to understand the complexities and nuances of occupant behaviour in order that buildings can be designed to absorb and even leverage the myriad ways in which occupants respond to their buildings. In order for green buildings to achieve their various targets, occupant behaviour must be understood and optimized.

Therefore, evaluating buildings becomes important, academic work which benefits not only those who occupy the buildings, but society as well. Understanding the various discrepancies between predicted and actual performance (i.e., the performance gaps) for both hard indicators such as energy use, and qualitative indicators such as satisfaction with the indoor environment, is essential in delivering high performing buildings. Mallory-Hill, Preiser, and Watson (2012) write that "unfortunately, the majority of people who design, pay for, and formally judge the quality of architecture are not the ones who have to occupy those buildings. The result is a legacy of many unsuitable and unsustainable buildings" (p. 4).

To address this problem for occupants[1], and to make buildings more sustainable, those involved in the design and management of buildings must utilize feedback loops to improve current buildings, as well as future designs (Zimmerman & Martin, 2001). Leaman, Stevenson, and Bordass (2010) outline four areas in which feedback can be sought: i) how well the project has met the objectives laid out in the brief; ii) the design and building process (e.g., build quality, costs); iii) the building as a product (e.g., total costs, public reaction); and iv) the building's performance in use; and highlight that the "the third and especially the fourth points are what are now taken to be 'post-occupancy evaluation'" (p. 567).

The ways in which occupants inhabit their buildings is complex, and often poorly understood. Janda (2011) writes that "building users play a critical but poorly understood and often overlooked role in the built environment" (p. 20). People are unpredictable; they can choose the path of least resistance, or act in ways that appear to outsiders as irrational. Hewitt et al. (2015) write that "household energy consumption behaviours… span a spectrum from reasoned and deliberate to unplanned and automatic"

[1] The term 'occupants' has been used throughout because it is more commonly used in this field of research. However, the author would like to acknowledge that 'inhabitants' is useful in indicating (and perhaps eliciting) a person's integration and stewardship within a building (as per Cole et al., 2008).

(in press). Occupants adapt to conditions in unpredictable ways and often 'misbehave' vis a vis the intentions of the designers who prescribed their living conditions.

Given the intersection, or nexus, of buildings and their occupants, it is not surprising to find that the process of producing feedback about buildings is multidisciplinary. Collecting occupant feedback via questionnaires, for example, constitutes qualitative research. Stevenson and Leaman (2010) write that "traditionally, the evaluation of housing performance has consisted of either physical monitoring or occupancy satisfaction questionnaires, but quantitative and qualitative feedback are rarely related to each other as they span across the disciplines of building science and social science" (p. 437). In this sense, evaluations of buildings should seek to transcend what Robson (2011) calls the "quantitative-qualitative incompatibility thesis" (p. 162). In the building industry, this often takes the form of quantitative insights being prioritized over qualitative ones. Indeed, Leaman, Stevenson, and Bordass (2010) write that the "the pursuit of quantification obscures qualification" (p. 565).

What exactly is being obscured when quantitative insights are prioritized? Leaman asserts that prioritizing quantitative insights has led to too much emphasis on statistics and benchmarking in building evaluation work, which often ignores the fact that individual cases and outliers can be bellwethers (A. Leaman, personal communication, October 6, 2014). In other words, when researchers try too hard to quantify their findings, it is often at the expense of valuable contextual insights. User comments, interviews, and observations, for example, uncover how a building is meeting users' needs and how the users are experiencing and utilizing the building; they uncover the building's *context*. Leaman, Stevenson, and Bordass (2010) write that "building-performance studies should seek to expose and reveal contexts rather than controlling for them" (p. 571). Since case study research specializes in exploring specific context in detail, it is necessarily an element of the conceptual framework for the present work.

Speaking generally about case study research, Miles and Huberman (1984) write that "we cannot study individual cases devoid of their context in a way that a quantitative researcher often does" (p. 27). Context is popularly defined as "the circumstances that form the setting for an event, statement, or idea, and in terms of which it can be fully understood and assessed" (Stevenson, 2010). Occupant behaviour, management practices, technologies, social norms, all form part of a building's context.

Understanding context, and relating it to salient quantitative insights from buildings is valuable work for the building evaluator to conduct. The value of case study research is explored further in Section 4.1.1.

Having one's research characterized as case study precipitates certain problems. Leaman, Stevenson, and Bordass (2010) write that: "some academics regard case studies that draw on a variety of material and methods as being either too challenging or merely anecdotal. Our experience is the opposite. There is nothing better than a vivid case study to communicate lessons learned and underwrite decision-making" (p. 573).

There is often a pressure to provide statistically rigorous results when carrying out building evaluations; something which the case study is largely incapable of. This can lead to "performance research that investigates only a few factors across a broad study but without the depth or understanding of a case study" (Leaman, Stevenson, & Bordass, 2010, p. 568). Indeed, this exact phenomenon recently occurred in an evaluation of nine Canadian buildings that despite collecting a great deal of data, was unable to fully explore or report on the contexts of each of the study buildings (Bartlett et al., 2014).

The case study approach has utility in Ontario's residential building industry, where there is an absence of insight into the various contexts of newly built high-rise buildings. For example, when evaluating the performance of high-rise residential buildings (even those which have sought accreditation through the LEED program) there is a tendency to simply report modeled predictions, or to superficially verify energy performance in relation to targets and benchmarks. A more holistic approach would involve measuring occupants' satisfaction within the building, their use of innovative technologies, the effectiveness of management strategies, and the like.

A final major theoretical underpinning of the present work comes from the idea of real world research (Robson, 2011). Real world research refers to "applied research projects which are typically small in scale and modest in scope. They tend to be related to change and/or policy, often seeking to evaluate some initiative, service or whatever" (Robson, 2011, p. 3). This type of research usually takes place in the 'field', is interested in solving problems (i.e., concern for actionable factors), is client-oriented and carried out by generalist researchers using multiple methods (Robson, 2011).

In other words, this type of research is interwoven with a hope to increase the sustainability and/or quality of life within a society instead of only contributing to the academic canon. In relation to the building industry, Leaman, Stevenson, and Bordass (2010) write that

> This is not knowledge for its own sake, but knowledge with results aimed at helping designers and managers make more informed decisions to help improve the building being studied and, of course, to spread the knowledge further to improve future buildings (p. 565).

As will be shown, all of these attributes animate the present work, where, for example, the research methodology itself is also influenced by this preoccupation with real world research. Robson (2011) writes that if the purpose of a research project is "highly exploratory, trying to get some feeling as to what is going on in a novel situation where there is little to guide what one should be looking for, then your initial approach will be highly flexible" (p. 139). The present work is to a certain extent *emergent*. For example, the focus on ventilation behaviour in Chapter 3 was something which emerged as data was being analyzed, and not a focus that existed *a priori*.

Real world research applied to the evaluation of buildings calls forth the following difficult questions: "How best is the public interest served in the face of commercial self-interest? Where does duty of care to individual building users fit in, or indeed to the wider considerations of sustainable development?" (Leaman, Stevenson, & Bordass, 2010, p. 565). In other words, who will be the conscience of the building industry? Who will hold it accountable and ensure that its buildings are appropriate both for their occupants, and for a world facing environmental peril? Certainly, one answer is that these tasks ought to be carried out by the academic researcher. That being said, work of this nature runs the risk of becoming too rigorous, too academic, too abstract. As Adrian Leaman says "coherent strategies for the future are what's required, not theories" (A. Leaman, personal communication, October 6, 2014). Striking this balance represents a final theoretical underpinning of the present work.

In summary, the conceptual framework is based around the following theoretical underpinnings:

- Buildings ought to have feedback collected about their performance after occupancy;
- Building occupants play a significant role in determining building performance, their behaviour should be understood;
- Combining qualitative and quantitative data is valuable to building evaluations;
- Understanding a building's context is crucial to producing valuable feedback;
- Case study research is appropriate for this type of work;
- The tenets of real world research (Robson, 2011) are very applicable to building evaluations;
- Improving the building industry is something which building evaluators should aspire to.

1.3 Literature Review

What follows is a comprehensive review of relevant literature which has not been covered in the manuscripts (the integrity of which has largely been preserved), nor in the preceding section.

1.3.1 Building Performance Evaluation

Building performance evaluation [BPE] is a "systematic and rigorous approach encompassing a number of activities…that take place through every phase of a building's lifecycle" (Mallory-Hill, Preiser, & Watson, 2012, p. 3). In doing so, BPE "focuses on the relationship between design and technical performance of buildings in relation to human behaviour, needs and desires" (Mallory-Hill, Preiser, & Watson, 2012, p. 3). A salient aspect of the BPE methodology is its insistence on the collection of feedback from building occupants (usually from questionnaires) and the recognition that building users are both indicators *and* drivers of building performance. In other words, they are simultaneously a useful source of data and a significant factor in energy performance.

Post-occupancy evaluation [POE] is a related term that is often used in the industry and "focuses on the requirements of buildings occupants, including health, safety, and security; functionality and efficiency of work flow; social, psychological and cultural performance and fit, which includes visual-aesthetic quality and satisfaction" (Preiser & Schramm, 1997 in Mallory-Hill, Preiser, & Watson, 2012, p. 6). The landmark PROBE studies (Post-occupancy Review of Buildings and their Engineering) in the UK in the 1990s were a formative use of the POE approach and evaluated a number of buildings in use, identifying various performance challenges and successes.

BPE became a distinct field of inquiry in 1997 when Preiser and Schramm introduced it as a concept which recognized that "evaluation played a role throughout the entire design, construction, and life-cycle of building" (Mallory-Hill, Preiser, & Watson, 2012, p. 11). As was mentioned in Section 1.1, POE can indeed encompass the entire timeline of a project from design to occupancy, and therefore the distinction between the two terms is not entirely clear, or entirely useful. Because of this, the process of evaluating buildings in-use has usually been referred to as building evaluation throughout this dissertation.

The majority of building evaluations have been carried out in commercial and institutional buildings. UC Berkeley's Center for Built Environment has the largest collection of information about North American building performance in their Occupant Survey Database, which includes over 600 buildings. As of 2013, of the 32 Canadian buildings in this database none were residential (Center for Built Environment, personal communication, June 15, 2013). This is problematic because the various innovations in the high-rise residential sector need to be evaluated in order to determine if they are meeting designer and occupant expectations; and if they are contributing to carbon emissions reduction targets. Referring to a similar situation in the UK, Stevenson and Leaman (2010) write that "little real feedback exists on how housing is performing during occupation, which makes it difficult to ascertain whether targets are being achieved in reality" (p. 437). Gill et al. (2010) give this concern a practical edge: "the complexity and poor understanding of how user behaviours contribute to real-life performance deficits reduces the likelihood of achieving low- or zero-carbon aspirations" (p. 492). This is especially important given the increase in the number of green building designs (e.g., LEED, Passivhaus, Net Zero Energy Homes, Energy Star) that are being built in Canada.

But not only is there a dearth of residential building evaluation research (especially in Canada), there is also room for improvement in the way that residential evaluations are carried out. Abbaszadeh, Zagreus, Lehrer, and Huizenga (2006) highlight this by writing that most "studies of green buildings have focused on more easily quantifiable criteria such as energy use and physical measurements of environmental conditions, which at best give an indirect assessment of how the building is affecting the occupants" (p. 365). Moreover, Stevenson and Leaman (2010) write that "the evaluation of user perceptions and behaviour in relation to building performance in housing is…an emerging research area" (p. 437).

This final point is worth highlighting, and represents the second knowledge gap highlighted by this review (the first being the dearth of residential evaluations), as well as a source of motivation for the current project. Section 2.1 provides an in-depth review of the various ways in which occupant behaviour impacts energy and water consumption in homes, and an additional discussion can be found below in Section 1.3.4.

Despite a proclaimed need for qualitative data collection during residential BPE, the use of questionnaires is not always seen as a comprehensive way to elicit useful information from building occupants. Cole, Brown, and McKay (2010) write that:

> Existing post-occupancy evaluation tools such as questionnaires are limited in their ability to capture the wider range of measures known to influence how users experience buildings. The incorporation of additional means of understanding and evaluating human factors such as

interviews, focus groups, etc. could ultimately improve the relevance and accuracy of post-occupancy evaluation methodology (p. 347).

1.3.2 Residential Building Evaluation

Some significant work has been carried out using variations of the BPE methodology in residential buildings. Gupta and Chandiwala (2010) used various occupant feedback techniques in order to inform better practice in the design and management of low-carbon refurbishment projects. Stevenson and Rijal (2010) collected occupant feedback about the usability of control interfaces and occupant behaviour in order to demonstrate the importance of incorporating a rigorous understanding of occupant behaviour into design decisions. Williamson, Soebarto, & Radford (2010) used both quantitative and qualitative data to explore occupant satisfaction and energy performance and to show how aspirations to achieve carbon reductions associated with Australian houses can bring about certain challenges.

Shipworth et al. (2010) used survey data and logged temperature measurements to determine the extent to which design predictions about thermostat and heating system use were accurate, falsifying the assumption used during modeling that more control over heating would decrease energy use. Similarly, Gupta, Barnfield, and Hipwood (2014) combined monitoring, energy data, and occupant questionnaires to evaluated the effectiveness of energy retrofits in 27 homes, indicating success in the retrofit but identifying certain challenges that emerged during the process (e.g., IEQ quality).

Much of this work was done outside of the North American context. Beauregard, Berkland, and Hoque (2011) conducted a BPE which involved American LEED certified buildings, evaluating six single family homes in order to determine their energy performance as well as occupant satisfaction, finding that though performance targets were being accomplished, it was being done so at the expense of occupant comfort and satisfaction. Perhaps the most relevant research from the Canadian context is Bennet, O’Brien, and Gunay (2014) who measured and then modeled the role of occupant window blind use in a LEED certified high-rise in Ottawa, Ontario. By simulating the observed behaviour in an energy model, it was found that “blinds can be effective for mitigating overheating and reducing peak cooling loads” (Bennet, O’Brien, & Gunay, 2014, para. 1).

Additional work from Canada includes Finch, Burnett, & Knowles (2012) who performed an extensive review of envelope rehabilitation for multi-unit residential buildings in British Columbia, and in doing so explored energy use intensity and end-uses at the suite level, and also wrote that "to design more energy efficient MURBs, a holistic approach that better considers occupant behaviour and all building systems is required; an approach based on actual building performance data using a feed-back loop" (p. 3). Similarly, Samimi and Shoaeioskouei (2013) explored the energy efficiency aspirations of new multi-unit residential buildings in British Columbia, though only paid superficial attention to the role that occupants and their behaviours play in achieving this efficiency. A major work from Toronto explores energy and water consumption, but deals primarily with correlations between building characteristics and energy use, and not with occupant behaviour (Binkley, Touchie, & Pressnail, 2013).

1.3.3 Indicators

A building can be evaluated for a number of reasons, and a variety of indicators can be measured in the process. For example, an owner or researcher could be interested in measuring employee productivity, indoor air quality, or thermal comfort as a means of indicating the success of their project. The indicators measured during a building evaluation often correspond to the goals set out during the programing or briefing stage of a building project (NCARB, 2003). For example, Wingfield et al. (2009) used the BPE approach to evaluate the extent to which a particular masonry construction method was feasible, appropriate, and energy efficient.

Leaman, Stevenson, and Bordass (2010), offer guidance on which indicators should be used during building evaluations and which also require occupant feedback: "methods should cover basic user needs such as occupant comfort and control, use of space, storage, heating, lighting, cooling, noise, perceived health and productivity at work, image, location and safety" (p. 570). It is often the case that the number of indicators is culled in order to reflect the aims of the evaluator. For example, to investigate workplace design and comfort, Brown (2009) measured the following indicators: "occupant comfort, knowledge, perceptions of building performance, feedback and adaptive behaviour."

In order to determine how well green buildings were performing from their occupants' perspective, Baird (2010, p. 3) relied on questionnaires to measure the following indicators: **environmental** (i.e., temperature, air quality, lighting, noise, and comfort), **personal control** (i.e., control over heating, cooling, ventilation, lighting, and noise), **satisfaction** (i.e., with design, needs, productivity, and health), and **operational** (i.e., space needs, furniture, cleaning, room availability, storage, facilities, and image). It is interesting to note that Baird (2010) relied solely on occupant-generated feedback to measure indicators which are more often sensor-measured (e.g., light and noise levels). This harkens an often cited quote in BPE presentations that "people are the best measuring instruments, they are just harder to calibrate" (Raw, 2003). Similarly, Peretti and Schiavon (2011) write that "occupants can be a useful and inexpensive source of information about indoor environmental quality" (para. 2). In other words, certain indicators of building performance require occupant feedback for their measurement.

1.3.4 Occupant Behaviour

Brown, Dowlatabadi, and Cole (2009) highlight that "the drivers of building energy use have been intensely studied for almost four decades, with economic, social, behavioral, climatologic and technical factors all well documented" (p. 297). Indeed, one can find numerous explanations for individual energy behaviour, ranging from the role of economics in efficiency upgrades, to the role of social norms in thermostat settings. Similarly, Kim, Oh, and Kim (2013) write that recently "the importance of user experience (UX) – as a combination of users' sensibilities, emotions and affections – has been much emphasized" (p. 204). See Section 2.1 for a review of the specific drivers of household energy use.

For Combe et al. (2011) "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" (p. 84). Building owners are increasingly observing that there can be a performance gap between design predictions and actual performance (ASHRAE, 2012). Though these gaps can be variously caused (e.g., poor prediction methods, faulty construction, ineffective control interfaces) they are very often a result of the ways in which building occupants experience, use, and control their buildings (Birt & Newsham, 2009; Dietz, Gerald, Gilligan, Stern, & Vandenbergh, 2009; Gill, Tierney, Pegg, & Allan, 2010; Socolow, 1978). As Cole (2003) points out: "buildings designed with excellent green performance standards can be severely compromised because the specification and technical performance fail adequately to account for the occupants' needs, expectations, and behaviour" (p. 57). This not only happens in terms of energy and water use; there are also performance gaps associated with the quality of the indoor environmental (ASHRAE, 2012).

Brown (2009) points out that "the successful design of environmentally sustainable, adaptive buildings requires a heightened level of intelligence both in terms of building form, system integration, operation and management, as well as in terms of building occupants themselves" (p. 59). Similarly, Stevenson and Leaman (2010) write that "the reasons underpinning occupants' actions were due to partial understanding or because features were perceived to be unhelpful" (p. 438). Sunikka-Blank and Galvin (2012) discovered a prebound effect where German homes were using less heating than their home rating predicted, leading government to underestimate the potential savings that could result from occupant behaviour changes. In other words, the ways in which occupants interact with their buildings are complex. Indeed the building itself even plays a role; Leaman and Bordass (2007) point out that in green buildings "users tend to tolerate deficiencies rather more than they do with more conventional buildings" (p. 662).

1.3.5 Control and Complexity

There is a concern within the research community that a lack of usability in green buildings is leading to suboptimal energy efficiency and occupant dissatisfaction. Hence, Leaman and Bordass (2007) write that "green buildings are repeating past mistakes by creating unneeded and wasteful complexity" (p. 672). This complexity can occur in both technologically sophisticated buildings as well as low-technology ones (Cole et al., 2008).

The ways in which occupants respond to this complexity prompts two schools of thought to emerge: those who believe that occupants' access to controls should be limited, and those who believe that their access to controls, and their buy-in, are essential elements in making buildings more efficient and comfortable (Brown, 2009). At the one end of the spectrum is the completely automated building, and at the other is the approach typified by the Living Building Challenge's notion of participatory comfort, where designers are required to give occupants the opportunity to be involved in the provision of their comfort (Cole et al., 2008). Similarly, ASHRAE (2012) points out that "problems associated with the indoor environmental factors can sometimes be circumvented by providing the occupants suitable control over their environment" (p. 13).

Cole et al. (2008) point out that occupants of green buildings are often "more directly involved with building systems and operation by opening and closing windows, blinds, switches and other accessible manual controls" (p. 326). Cole et al. (2008) also suggest that the various systems and technologies (e.g., ventilation switches) "may involve new responsibilities and require a commitment from occupants" (p. 326). There are two issues here, access to controls, and the complexity of available controls.

Determining the appropriate amount of control to give occupants is a crucial decision made during the design of a building, and one that is not always made correctly. Stevenson and Leaman (2010) write that occupants should “be offered better control over their own comfort conditions through improved usability. This requires a better understanding of user expectations, attitudes, perceptions and behaviour” (p. 440). This sentiment clearly does not fall on the side of the philosophical divide which advocates for fully automated buildings.

Much of the work done in this area falls under the rubric of human factors research and is concerned with how building occupants interact with the various control surfaces in their homes (e.g., Slob & Verbeek, 2006). To this end Gill et al. (2010) insist that “human factor issues need to be addressed more adequately as standard practice in low-energy/carbon design” (p. 491). Similarly, Stevenson, Carmona-Andreu, and Hancock (2013) call for “more user-centred approach to design and testing of products, and… delivering low-carbon homes that are more controllable and therefore more comfortable” (p. 1). Cole et al. (2008) offer another useful perspective on this relationship: “there exists a kind of adaptive dance in which both the occupants and the building they occupy gradually approach mutually satisfactory outcomes” (p. 335).

Indeed, control over environmental conditions (e.g., comfort) is related to an occupant’s satisfaction in a building. Consider the concept of “satisficiers” put forth by Leaman and Bordass (2000) which posits that “people do not want perfection, but conditions which are ‘good enough’ more often than ‘just right’. If not, they like plenty of opportunities to correct things in their favour” (p. 297). Similarly, Baird (2010) writes that “the occupant also appreciated being able to see or feel the effect of their operating of any of the control systems to which they had access” (p. 21). In other words, having access to controls with which to affect environmental conditions is perhaps as important as the environmental conditions themselves.

1.3.6 Summary

Much of what was presented in this literature review could not be included in the published manuscripts because of space limitations, despite it forming the theoretical underpinning for the work and its findings. The following conclusions from the literature have been identified:

1. A lack of residential building evaluations;
2. The need for quantitative and qualitative data to be combined during building evaluations;
3. The value of augmenting questionnaires with interviews, etc.;
4. A lack of data about energy and water use at the suite-level in this building type;
5. A lack of research pertaining to the effects of occupant behaviours which result from the design and management of LEED certified, high-rise residential buildings;

6. A lack of understanding about the extent to which control and usability issues are arising in the study building type.

1.4 Research Questions

This work considers the role of the occupants in the performance of green multi residential buildings. It starts with the premise that occupants can be a significant factor in energy and water use in these buildings, and aims to better understand their role. In order for green buildings to achieve their various targets, occupant behaviour must be understood and optimized. To do this, certain indicators of building performance require occupant feedback for their measurement. The overall aim of the dissertation is to substantiate that the collection of qualitative data from building occupants can yield valuable (i.e., to designers, managers, and researchers) insights into the effectiveness of building design and management decisions, as well as providing an enhanced understanding of energy and water consumption.

Using gaps from the literature, the following research questions were developed:

1. How is energy being used in individual suites within the study buildings?
    a. To what extent can trends be explained by physical factors, and by behavioural and demographic factors?
2. What insights are possible when qualitative and quantitative data from the study buildings are combined?
3. What insights are made possible by purely qualitative feedback from users?
4. What design-related challenges have arisen in the study buildings?
5. How much control should these occupants have over their environment?

This dissertation is based on four journal articles (three published and one under review), though only three will be presented in their entirety as chapters. The fourth paper (see Appendix 6), which was written early in the research process, has had relevant sections (i.e., questionnaire scores compared to BUS benchmarks) added to Chapter 4. Doing so created a more complete fourth chapter, and reduced the redundancy that would have resulted from including the fourth paper in its entirety.

The three chapters will be briefly described below, followed by an explanation of how they form a coherent body of research. The chapters are all based on a series of studies carried out in four LEED certified, high-rise residential buildings in Toronto, with 165 suites participating in the work.

Paper 1 (Chapter 2): Brown, C., & Gorgolewski, M. (2015). Using physical, behavioural, and demographic variables to explain suite-level energy use in multi-residential buildings. *Energy and Buildings, 89*, 308-317.

This chapter provides a rigorous analysis of energy and water consumption trends in the study buildings, including how much energy and water consumption vary between similar units. The chapter also investigates the extent to which physical, behavioural, and demographic variables explain the variability in suite-level energy and water consumption data. In doing so, this manuscript answers questions "1", "1a", and "2" from above, as well as implicitly exploring others. This manuscript includes a combined results and discussion section.

Paper 2 (Chapter 3) Brown, C., & Gorgolewski, M. (2015) Understanding the role of occupants in innovative mechanical ventilation strategies. *Building Research & Information, 43*(2), 210-221.

This chapter uses quantitative and qualitative data to explore a very specific instance of occupant behaviour (i.e., ventilation control) that affects both comfort and energy use in the study buildings. Using 165 questionnaire responses, interviews, as well as physical measurements from the suites, the first accomplishment of this chapter is to uncover and explain why 52% of respondents were not using their mechanical ventilation system. Whereas Chapter 2 is a more general exploration of trends in energy use and the ability of quantitative and qualitative variables to explain them, this chapter uses the rich dataset at its disposal to fully explore how this aspect of occupant behaviour relates to the performance, and design and management of the study buildings. The chapter also explores issues around complexity and control that arise in this setting; highlighting the ways that occupants interact with novel technologies in unpredictable ways, with unpredictable consequences. In doing so it addresses questions "3", "4", and "5" from above. This manuscript includes separated results and discussion sections.

Paper 3 (Chapter 4) Brown, C. (Under review). The power of qualitative data in post-occupancy evaluations of residential high-rise buildings. *Housing, Theory, and Society.*

Paper 4 (edited for use in Chapter 4) Brown, C., & Gorgolewski, M. (2014) Assessing occupant satisfaction and energy behaviours in Toronto's LEED Gold high-rise residential buildings. *International Journal of Energy Sector Management, 8*(4), 492-505.

This chapter focuses largely on occupant questionnaire feedback to assess its value as a way of understanding a building's performance. The primary task was to conduct a content analysis using the comments received on the occupant questionnaires. In doing so, this chapter demonstrates the utility of contextual factors in understanding energy use and satisfaction in the study buildings, as well as their value in producing feedback for designers and managers. Comments are found to be valuable in uncovering and beginning to explain complex phenomena in the study buildings. In doing so, it answers questions "4" and "5" from above. This manuscript includes separated results and discussion sections. This Chapter includes some of the data analysis from a fourth paper, specifically IEQ scores and their respective BUS benchmarks.

1.4.1 Connections Between Chapters

The full extent to which the research questions above are answered by the manuscripts will be provided in Chapter 5. For now, a brief discussion follows which shows how the three chapters form a coherent body of work.

Collectively, the three chapters demonstrate both the methods of gathering occupant feedback, and the utility of doing so; providing comprehensive insights into behaviour in these towers, as well as the design related problems that have emerged. In doing so, they show the importance of evaluating such buildings, and of involving occupant feedback in these evaluations.

Though each in their own way, each chapter utilizes occupant feedback to enable the investigation of a particular issue, be it energy use, relationship to innovative ventilation systems, or satisfaction and performance challenges. Moreover, each chapter accomplishes the combination of qualitative and quantitative data in different ways. The sum total of this is a dissertation which uses a variety of approaches to demonstrate what happens when the building evaluation methodology is used in this building type, and which strives to disentangle the complex relationships between design, management, behaviour, satisfaction, and energy consumption.

The three chapters collectively form a holistic response to the call to action that results from the conceptual framework outlined above. For example, they all embody real world research, and seek to both communicate lessons learned and to underwrite decision-making; to explore the extent to which this methodology can serve in the public interest, both in terms of occupant satisfaction but also environmental sustainability.

In unique ways, each of the papers demonstrates the importance of understanding context, and the value of the case study approach. By approaching this problem from different perspectives, the chapters taken together allow for the reader to see the various ways in which the context of a building (e.g., occupant behaviours, management practices) enrich the insights available during building evaluations.

1.5 Methodology

The following section highlights elements of the methodology which are common to all three chapters. In doing so, parts of the methodology sections for each chapter have been significantly edited and differ from the published versions of the manuscripts found in the Appendices. What remains in each respective chapter are the methodological components unique to that chapter.

1.5.1 The Buildings

This dissertation utilizes data collected in four high-rise residential towers in Toronto, Ontario, Canada, all built between 2008 and 2010. None of the developers agreed to identifying their buildings in this work, and so the towers are referred to using A-D. All four buildings are centrally located within dense neighbourhoods in Toronto, with immediate access to transit and amenities. They all target the luxury end of the residential market and are rented or owned by people with a relatively high socio-economic status. These buildings were suggested by contacts from the authors' networks, and consent was sought from the board of governors for each building.

Table 1.1: General building information

Site	Size (m^2)	Units	Average suite size (m^2)	Age of building when studied (months)
Tower A	29,322	248	91.1	34
Tower B	18,964	172	73.8	34
Tower C	22,144	305	47.1	20
Tower D	18,691	198	88.4	34

Although three of the towers (A–C) are by the same developer, and Tower D is by a different developer, the four towers are similar. All four towers were certified LEED Gold, seeking 9 of 15 IEQ credits, and 10 of 17 energy credits, thus indicating performance aspirations in the areas of energy and IEQ (Canada Green Building Council, 2013). As well, all four towers are concrete slab construction, have suites which use fan coil systems to provide heating and cooling, and are equipped with an energy recovery ventilator (ERV). All four towers make for interesting sites in which to study occupant satisfaction and behaviour. Units in towers A, B, and C each contain operable windows, a balcony door, a master electricity switch which shuts down all lights and non-essential receptacles, a thermostat, and most salient to this study, an occupant controlled energy recovery ventilator (ERV) (discussed in detail Section 3.2.1).

Figure 1 demonstrates the range of suite sizes in the study buildings. These values were derived from scale floor plans and can therefore be assumed to be fairly accurate. They are used in order to area normalize suite level energy and water consumption throughout the chapters.

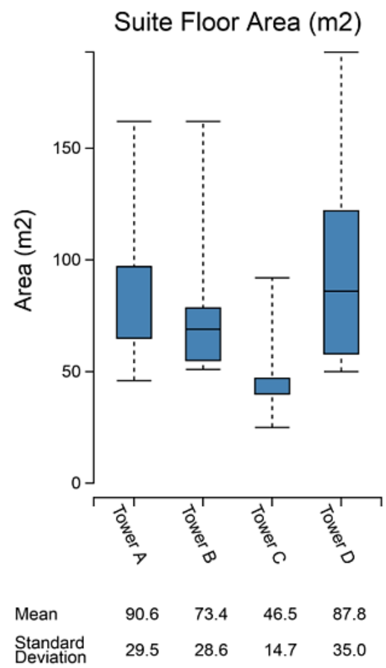

Figure 1.1: Floor area

1.5.2 Data Collection

NCARB (2003) suggests the following tools for use during a building evaluation: "interviews, questionnaire surveys, direct observation, mechanical recording of human behaviour, measurement of light and acoustic levels, recording with video and other cameras, and behaviour mapping" (p. 10). Leaman, Stevenson, and Bordass (2010) recommend similar methods, and advocate a drill-down approach wherein additional data can be collected to provided additional understanding. This study utilizes multiple data sources, including questionnaires, interviews, metered energy data, noise and indoor air quality [IAQ] measurements, and appliance specifications, and employed the drill-down methodology where possible.

1.5.2.1 Energy and Water Meter Data

Table 1.2 shows most of the data collected for this study (see each chapter for data specific to each). Submeter data was acquired from the building's energy management contractor from the beginning of each respondent's tenancy.

Heating and cooling data for Towers A-C was collected from thermal metering systems in each suite which measure flow rate and temperature change in order produce monthly ekWh values, which are used for billing. The focus was on energy delivered (in kWh or ekWh) to the suites and not source (or primary) energy. Heating and cooling data were weather normalized using the ratio method, which adjusts raw data according to the relationship between heating- and cooling-degree day data from the study period and a 30-year average. The Canadian Climate Normals 30-year average (1981-2010) for an 18^{o}C reference temperature at Toronto's Pearson Airport was used (3,873 HDD and 306 CDD). See Appendix 1 for a more detailed methodology. It should be noted that despite the buildings being in the same climate, weather normalization was performed in order to remove the effect of climate between years. Leaving the effect of the climate in the data would have increased the 'noise' and undermined the intention of this Chapter.

Table 1.2: Data collected

Building	Months of Data	# Of Suites With Usable Data	Thermal metering system?	Electricity Meter?	Hot Water Meter?
Tower A	24	36	Yes	Yes	Yes
Tower B	24	23	Yes	Yes	Yes
Tower C	18	47	Yes	Yes	Yes
Tower D	24	41	No	Yes	Yes
		Total # of suites for each meter type	106	147	127

Submetered suite level electricity data was available for all four towers and does not include energy used for hot water, heating or cooling. Instead, it includes fan coil and ventilation fans, lighting, receptacles, cooking (electric stoves in all suites), and appliances. Suite-level electricity data does not need to be weather normalized because they do not include cooling or heating energy.

Hot water was metered separately from cold water in Towers A-D. Hot water data was provided in cubic meters per month and was converted to a monthly ekWh (i.e., equivalent kWh) value using gas consumption data for central domestic hot water boilers in Towers A-D. The gas consumed by domestic hot water boilers was divided by the number of cubic meters consumed by all suites to establish that 8.5 cubic meters of gas is needed to produce one cubic meter of hot water. Using a conversion factor of 10.33 (NRCan, 2015), this equals 87.8 $ekWh/m^3$ of hot water.

The energy and water meter data have been carefully checked. First, suites with extremely high usage were checked to make sure that high usage was consistent from month to month. These suite numbers were then submitted to the data provider to ensure the high values were not the result of a malfunctioning meter. If both of these conditions were not met, the suite was removed from the study.

Next, suites with very low cooling or heating data (e.g., certain suites used no heating at all during winter) would only be included in analysis if they had consumed hot water during the same period. A value other than zero for hot water use led to the assumption that the suite was occupied during the period for which little or no heating or cooling was used, and that low values should be used in analysis.

1.5.2.2 Questionnaire

In the early phases of the research process it was decided that using an existing questionnaire was desirable rather than designing a new one because an existing one would likely be more rigorous (having been piloted and implemented and refined) and also because results from the present study could be compared to those from previous studies which used the same instrument. Though building evaluations are increasingly common, there were very few surveys that had already been designed which targeted the residential sector. The choice was between UC Berkeley's Center for Built Environment's *Occupant Indoor Environmental Quality (IEQ) Survey* and the *Building Use Studies Domestic Questionnaire.* The *Building Use Studies Domestic Questionnaire* (Building Use Studies, 2015) was chosen and was used (under license, see Appendix 2) to collect information from building occupants. The choice to use this survey was based on cost, availability, and the strength of the instrument.

This questionnaire is based on the one which was developed during the PROBE studies and core questions of the BUS questionnaire have been used in a variety of post-occupancy evaluations (e.g., Baird, 2010) and explore the areas of IAQ, thermal comfort, acoustics, lighting, design, health and general satisfaction. The same core questions were used in the residential setting by Gill et al. (2010) who writes that "based on the strong pedigree and implementation history of the [questionnaire], it was determined to provide an accurate and repeatable assessment of occupant comfort" (p. 494). Building Use Studies had worked to unsure that the questionnaire was as simple and effective as possible. Based on this assessment, and on consultations with advisors, it was decided that the questionnaire did not require pre-testing or validation (e.g., reliability, content validity).

The questionnaire had 63 scale items, most of which used a seven point summated rating (Likert) scale; the rest were non-scale questions (e.g., “yes” or “no” questions). Likert scale questions asked the respondents to rate some aspect of the building (e.g., satisfaction with acoustics) on a seven-point scale where “1” indicates dissatisfaction and “7” indicates a high degree of satisfaction.

Thirty-five of the 63 questions were added to the original BUS questionnaire in order to facilitate the current research. These additions included questions about control over heating, ventilation, and cooling [HVAC] systems, engagement with training materials, and feedback about energy bills. It is from the questionnaire responses that the demographic and behavioural variables used in Chapter 2 were created. The questionnaire also had thirteen comment boxes, which pertained to the section for which the respondent had just entered scores.

To analyze responses, the seven points on the scale are assigned a numerical value which is used to generate a frequency, mean value, and standard deviation for relevant variables. This is useful because it allows comparisons to *Building Use Studies (BUS)* benchmarks, which are described in Section 4.2. Questionnaire scores were processed using the statistical analysis software package SPSS. If a respondent skipped a question, their response was left blank and not included in analysis (as opposed to inserting the mean value in its place). The mean and standard deviation of questionnaire scores are presented where relevant.

In addition to this approach, Chapter 2 reports results using the categories ‘percentage satisfied’ and ‘percentage dissatisfied.’ 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). Percent dis/satisfied values have been rounded to the nearest whole number. The accuracy implied by rounding these values to the nearest tenth is inappropriate given the relatively small sample size. This level of categorical resolution provides context for the mean values, and is the most granularity that can be offered given that the original questionnaire items did not include text labels.

Questionnaires were delivered between January 2013 and June 2013, with the survey period lasting two weeks in each of the buildings (see Table 1.3). Due to logistics associated with gaining permission in each of the Towers, the questionnaire could not be delivered to all buildings at the same time. However, Towers A-C were all surveyed during winter conditions, meaning that respondents' insights about heating behaviours and perceptions of winter IEQ are based on recent conditions and so are likely reasonable; whereas responses about cooling conditions and summer IEQ may be less accurate since they were based on their memory of conditions during the previous summer. Though this limitation could ideally be overcome by delivering both summer *and* winter questionnaires, the results from the present study represent a 'snapshot' in time, and should be treated as such. That being said, comments, interviews, and informal conversations with occupants inspire confidence that people are generally aware of the conditions of their suite from the previous summer, as respondents were often able to elaborate in great detail the positive and negative aspects of their suites in all conditions.

Every unit in each building was asked to participate in the survey. This non-probability sampling method was chosen in order to maximize participation. In addition to being a convenience sample, this non-probability method was also purposive sampling, which Robson (2011) defines as "a sample is built up which enables the researcher to satisfy their specific needs in a project" (Robson, 2011, p. 275). The research need was to explore occupant satisfaction and behaviour in this building type, and the sampling method enabled this. As shown in Table 1.3, respondents completed either an online or paper version of the questionnaire in a self-completion fashion, with no guidance from the researcher.

Table 1.3: Questionnaire delivery

Site	Units in Building	Delivery timeframe	Delivery Method	Questionnaire Responses
Tower A	248	January 2013	Paper	41 (16.5%)
Tower B	172	February 2013	Paper and Online	27 (15.2%)
Tower C	305	March 2013	Online Only	52 (17.1%)
Tower D	198	June 2013	Paper and Online	45 (22.7%)
Total	**926**			**165 (17.8%)**

In addition to questionnaires, a small number of semi-structured interviews were conducted in the home of consenting participants and focused on gaining insight into how they operate their ventilation system using the same questions for each participant (see Table 3.1). Eligible participants indicated on their questionnaire that they would be willing to participate in a follow up interview, but only a relatively small number of interviews were conducted due to difficulty scheduling time with people and re-gaining access to the study buildings.

1.6 Contribution of Authors

In all three of the manuscripts, my contributions included: a) identifying research questions, b) research design (e.g., questionnaire design), c) research activities (e.g., data collection), d) data analysis and e) manuscript preparation and submission.

Chapter 2: *Using physical, behavioural, and demographic variables to explain suite-level energy use in multi-residential buildings*

In this chapter I was responsible for all research activities. This includes the research questions, methodological approach, data collection and analysis, literature review, and manuscript preparation. Dr. Mark Gorgolewski helped to edit the first submitted draft of the manuscript, but revisions were carried out by me (it should be mentioned that the anonymous reviewers provided very useful insight into the manuscript and influenced the final product). Dr. Gorgolewski also helped verify some of the calculations involved in the chapter. Dr. Alasdair Goodwill was briefly consulted while developing the various data analysis techniques used the chapter. Dr. Goodwill also reviewed the results section before the manuscript was submitted in order to ensure I was making appropriate statements about the findings.

Chapter 3: *Understanding the role of occupants in innovative mechanical ventilation strategies*

In this chapter I was responsible for all research activities. This includes the research questions, methodical approach, data collection and analysis, literature review, and manuscript preparation. Dr. Mark Gorgolewski helped to secure access to the research sites, and also helped with formation of fundamental concepts (e.g., the need for post-occupancy evaluation in these buildings). Dr. Gorgolewski also helped to edit the first submitted draft of the manuscript, and to verify that I had addressed reviewers comment sufficiently. Dr. Russell Richman urged the inclusion of noise measurements at an early committee meeting.

Chapter 4: *The power of qualitative data in post-occupancy evaluations of residential high-rise buildings*

In this chapter I was responsible for all research activities. This includes the research questions, methodical approach, data collection and analysis, literature review, and manuscript preparation. For Paper 4, limited contents of which appear in Chapter 4, all research activities were carried out my me, with some preliminary assistance from Dr. Gorgolewski in formulating the research questions, and in addressing revisions during the publication process.

2. USING PHYSICAL, BEHAVIOURAL, AND DEMOGRAPHIC VARIABLES TO EXPLAIN SUITE-LEVEL ENERGY USE IN MULTI-RESIDENTIAL BUILDINGS

2.1 Introduction

As buildings become better designed and constructed, the effect of occupant behaviour on performance increases (de Meester, Marique, De Herde, & Reiter, 2013). Various researchers have sought to understand the extent to which occupant behaviour explains variability in energy and water consumption between similar dwellings. For example, Kelsven (2103) compared gas and electricity use in similar single family homes and found the 5th and 95th percentile to differ by a factor of 4.3 for gas, and 5.7 for electricity. Gill et al. (2010) found that occupant behaviours account for "51%, 37%, and 11% of the variability in heat, electricity, and water consumption, respectively, between dwellings" (p. 491). Verhallen and Van Raaij (1981) found that household behaviour explained 26% of the variability in household energy use, and building characteristics explained 24%.

Using recently built, highly glazed high-rise residential towers in Ontario, Canada, this chapter has the following objectives:

1. Determine the extent to which heating, cooling, electricity, and hot water use vary between suites;
2. Determine the extent to which this variability can be explained by physical building characteristics, and by behavioural and demographic determinants.

Though these objectives have been addressed to certain extents in previous work (Steemers & Young, 2009; Santin, 2006; de Meester et al., 2013) the work in this chapter is novel in that the suites from which data was collected are within four very similar high-rise residential towers. This provides additional opportunities to explore energy use patterns.

A review of past work has shown that various determinants have been explored in relation to energy and water consumption in the residential setting. These include dwelling type, its configuration and size, how it is heated (Guerra-Santin, Itard, Visscher, 2009; Gram-Hanssen, 2010; de Meester et al., 2013), the number and age of occupants (Binkley, Touchie, & Pressnail, 2013; Liao & Chang, 2002; de Meester et al., 2013; De Groot, Spiekman, & Opostein, 2008), and their income level (De Groot, Spiekman, & Opostein, 2008; Vringer, 2005; Biesiot, & Noorman, 1999; Lutzenhiser, 1993; Steemers & Young, 2009). Beyond these demographics, individual characteristics have been studied including the role of repeated patterns of behaviour and thought (Lutzenhiser, 1993; Stern, 2000), preferences, upbringing, culture (Schweiker, & Shukuya, 2009), and the role of occupant perception, as exemplified by the rebound effect (Haas & Biermayr, 2000) and the prebound effect (Sunikka-Blank, & Galvin, 2012). There has also been work conducted into the role of feedback (Brown, Dowlatabadi, & Cole, 2009), the presence of submeters (Gunay et al., 2014), and the willingness of occupants to pay additionally for green design features (Chau, Tse, & Chung, 2010). Canadian Building Energy End-use Data and Analysis Centre (2010) found that "that tenants who do not pay for their own electricity use almost 70% more electricity per square foot than their counterparts who pay their own bills." Finally, window opening behaviour and the way in which occupants relate to control surfaces (Fabi et al., 2012), thermostat use (Santin, 2006; Gill et al., 2013), and ventilation behaviour (Brown & Gorgolewski, 2015a) have all been studied.

Due to constraints on the availability of data and resources, only some of the determinants above could be explored. The present chapter will explore the extent to which the variables in Table 2.1 explain variability in heating, cooling, electricity, and hot water consumption in the study buildings.

Table 2.1: Study variables

Variable	Reason for inclusion
Floor area (m^2)	Hypothesized to be correlated to heating, cooling, and electricity use.
Balcony width (m)	Hypothesized that as the number of linear meters of balcony increases, so too does heating consumption as a result of thermal bridging, which is as an increasing concern in Toronto due to poor balcony design.
Exterior wall area (m^2)	Hypothesized to be correlated to heating and cooling loads.
Insolation (kWh/m^2)	Hypothesized that as insolation increases, heating use declines and cooling use increases.
Irradiation (W/m^2)	Hypothesized that as irradiation increases, heating use declines and cooling use increases.
Fenestration ratio	A constant fenestration ratio of 70% has been assumed for all buildings.
Suite orientation	Using insolation and irradiation values specific to each orientation will allow for an exploration of the role of orientation in heating and cooling.
Storey	This variable has been included to explore if hot air rising in the building (i.e., the stack effect) is affecting heating consumption.
Number of occupants	Hypothesized to be a driver of heating, cooling, electricity, and hot water consumption.
Renter or owner	Though 97% of renters and owners in the study building pay for their own utilities, renters and owners may have different levels of stewardship over their suite.
Time spent at home (e.g., evenings and weekends)	Hypothesized to be a driver of heating, cooling, electricity, and hot water
Age of occupants	Older occupants may have different occupancy and consumption patterns than younger ones (e.g., less domestic hot water use).
Thermostat setpoint	Hypothesized to be a driver of heating and cooling consumption.

Hot water behaviours (e.g., showers per week)	To test to the ability of questionnaire responses to explain variability, and to meet objective two.
Electricity behaviours (e.g., use of master switch)	To test to the ability of questionnaire responses to explain variability, and to meet objective two.

2.2 Methods

As discussed in Section 1.4.2, this chapter relies on three types of data: submetered data from participating suites, questionnaire responses, and physical data relating to the each suite (e.g., floor area). In the following sections, the methods by which this data was collected and analyzed will be discussed.

2.2.1 The Study Buildings

Towers A-C were built by the same developer in the same time period, and certain design and construction attributes have been assumed to be similar across these three towers (Tower D is not used in the analysis of heating and cooling data). Table 2.2 shows exactly what was assumed to be constant across the three towers. It is acknowledged that these assumptions might not be 100% accurate, ideally each of the assumptions would have been physically measured (e.g., fenestration ratio) and included in the regression models alongside the physical variables from Table 2.1. However, given the similarity of the towers based on researcher observations, and the fact that they were designed and built by the same developer, the assumption of similarity is not a significant impediment to accomplishing the objective of determining the extent to which consumption data variability can be explained by physical building characteristics.

Table 2.2: Physical constants

Constants	Explanation
Wall height	Each suite was assumed to have an exterior wall height of 2.4m.
Window type	Towers A-C have thermally broken aluminum window frames with low-E coated, argon gas filled, double pane, sealed glazing units, with operable awning windows. The exact SHGC for these windows is not known, but is assumed constant across the towers.
Fenestration ratio	Estimated to be above 70% in all three towers based on researcher observations.
Heating and cooling system	All four towers use a two-pipe fan coil systems to deliver heating or cooling to the suites.
Envelope construction	Envelope construction (e.g., R-value, air tightness) is held constant based on being of a similar age, construction type and built to satisfy the same building codes.

Towers A-C share the exact same orientation, despite being located in different parts of Toronto (Tower D was not used in heating and cooling analysis due to a lack of thermal metering data). Figure 2.1 shows the actual orientations of the buildings, which are slightly askew to true north due to Toronto's grid pattern. At the time of study, a visual inspection revealed no tall buildings around Towers A, B, or C that would result in shading during a typical day.

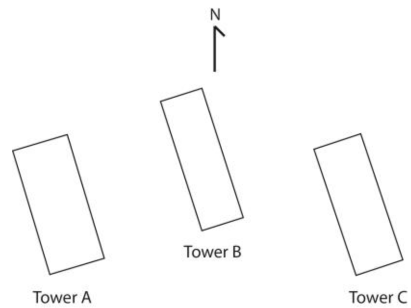

Figure 2.1: Actual tower orientations taken from Google maps

The orientation of the study buildings is significant, as Robertson and Athienitis (2009) point out, "buildings with east-and west-facing orientations have greater potential for overheating in the non-heating season and get little solar gain in winter" (p. 6) and "north-facing windows provide consistent indirect light with minimal heat gains, but can also create heat loss and comfort problems during the heating season" (p. 12). The extent to which these phenomena are occurring in the study building will be explored using the orientation-specific insolation and irradiation variables described below.

2.2.2 Physical variables

Scaled floorplans for Towers A-D were used to calculate accurate interior floor area as well as linear meters of balcony for each participating suite. Next, floorplans were used to determine the number of linear meters of exterior envelope for each suite in Towers A-C. This number was multiplied by the wall height (2.4 m) to produce a value for exterior wall area, which was used as a discrete predictor variable for heating and cooling consumption.

In order to analyze the role that orientation and window area played in determining heating and cooling consumption, EnergyPlus v8.2 was used to determine solar exposure on each of the exterior faces of the building. A shell model was created using the geometry and orientation of Tower A (the orientation of which is identical to Towers B and C) and an hourly simulation was performed using Canadian Weather year for Energy Calculation (CWEC) weather data for Toronto, ON (Lester B. Pearson International Airport station) (see Table 2.3).

Average values for the whole year, the heating season, and the cooling season were calculated for the incident solar radiation rate (i.e., insolation, kWh/m^2) and summed values were calculated for the radiation heat gain (i.e., irradiation, W/m^2) for the same time bins to create discrete variables for use in regression analysis (Vyas , 2012). The number of months included in the heating and cooling seasons does not need to equal 12; rather the relationship between them is what is important. To calculate values for a corner unit, the insolation values for each orientation were summed, reflecting the fact that a corner unit has more exterior wall. This value was multiplied by the fenestration area to give an average amount of insolation (kWh) for each season, specific to each suite.

For irradiation, the irradiation values for each face were averaged and then multiplied by the fenestration area to give an average amount of irradiance received in watts, for each season, specific to each suite. Both insolation and irradiation have been included in the regression analysis, though only the one with the strongest relationship was included in hierarchical regressions (described in Section 2.2.3).

Table 2.3: Discrete insolation values for each orientation

	North	East	South	West
	Insolation (kWh/m^2)			
Yearly	275.0	546.8	708.2	554.6
Heating season (Oct. - Mar.)	76.3	148.4	321.1	178.2
Cooling season (May - Aug.)	151.0	291.8	249.4	268.8
	Irradiation (W/m^2)			
Yearly	44.8	89.0	115.6	90.4
Heating season (Oct. - Mar.)	25.0	48.5	105.2	58.4
Cooling season (May - Aug.)	73.2	141.2	120.6	130.2

2.2.3 Data Analysis Procedures

Inferential statistical analyses are required to meet the second objective of the chapter (the first requires only simple arithmetic). Some initial data preparation was required because the consumption data was positively skewed, with the majority of consumption values on the lower end of the scale, and a few high consumers creating large upper quartiles (see Figure 2.4).

Outliers were identified and removed as a first step in addressing this skewness, and in order to minimize their effect on statistics such as the mean. Outliers were identified by converting raw data into z-scores and excluding those that were less than 2.58 (Field, 2009). In a normal distribution, 99% of all z-scores are less than 2.58. Using this value to exclude outliers, then, removes scores which deviate very significantly from the mean. This ensures that extremely high scores did not bias the results. It should be noted that though excluded during statistical analysis, these outliers have been included in the work for objective one, which seeks to report the extent to which energy and water use vary between similar suites.

Because the data were skewed, they did not pass tests for normality, which test the extent to which the study distributions differ from a normal (i.e., Gaussian) distribution. Data which is not normally distributed - as was the case in the present chapter - is generally thought to be less fit for use in linear regression models (Field, 2009). In similar work, Steemers and Yun (2009) and Santin (2011) performed square root transformations (i.e., taking the square root of each score) on their data in order to increase the normality of their distributions. Though useful in preparing data for use in regression models, transforming data suffers from the drawback that the results demonstrate the relationship between a predictor variable and the square root of the outcome variable, not the outcome variable itself.

For the purposes of this chapter, square root transformations were performed on the data and regressions involving transformed and non-transformed data will be reported, focusing on the R^2 value. Field (2009) points out that “the coefficient of determination, R^2, is a measure of the amount of variability in one variable that is shared by the other” (p. 222). Where relevant, hierarchical regression models will be used. These models use multiple predictor variables, entered sequentially into the model based on a logic determined by the researcher. The results demonstrate the combined effect of all predictor variables on the output variable.

Independent samples t-tests have been performed on demographic data, with results indicating whether the mean consumption values of two groups (e.g., renters and owners) differ significantly from one and other. Correlations have also been performed. Since directionality can be assumed (e.g., as linear meters of balcony increases, so too does heating consumption) one-tailed tests for significance are used. When a correlation is found to be significant (e.g., $p < 0.05$) it means that 95% of the relationships in the correlations are not a result of a chance occurrence. Cohen (1988) suggests the following interpretations for correlations: $r = 0.1$ indicates a small effect, $r = 0.3$ a medium effect, and $r = 0.5$ a large effect. In the present chapter, significant correlations are used to qualify a variable for use in a regression model.

2.3 Results and Discussion

2.3.1 Energy Use Intensity and End-uses

Table 2.4 presents suite-level energy consumption values for each of the study buildings using both area-normalized values, as well as gross (i.e., non-normalized) values. Results from all towers were used to produce a global average energy use intensity of 125.6 ekWh/m^2/year. This figure includes energy used in suites for heating, cooling, electricity, and hot water and is 27% less than the Ontario average for apartment dwellings, which is 172.2 kWh/m^2/year (NRCan, 2014a); though this figure was likely calculated by dividing the total energy used by the entire building by the number of suites. Unfortunately, the overall EUI of the study buildings cannot be accurately determined due to a lack of data about the energy used in common areas, and so, the comparison between the study buildings and the residential average is somewhat limited. Nevertheless, the study buildings appear to perform better that the average for Ontario apartments and this may be partly due to the demands of reaching the LEED green building rating requirements. It should also be noted that this chapter quotes delivered energy to the suite and that ekWh of heating, cooling, and hot water are being compared on a 1:1 basis with suite level electricity, despite there being various upstream inputs in generating these secondary sources of energy.

Table 2.4: Energy and water data

	Electricity (kWh)			
Building	Yearly suite average in kWh/year (Standard deviation)		ekWh/m^2/year	ekWh/month/suite
Tower A	3507.4 (1582.2)		38.8	292.3
Tower B	3283.4 (1305.3)		46.3	273.6
Tower C	2391.8 (893.5)		51.9	187.1
Tower D	3311.1 (1462.3)		39.4	275.9
Average	3243.4 (1301.8)		44.1	257.3
	Heating (ekWh)			
Tower A	1897.4 (1654.7)		22.4	164.3
Tower B	2001.1 (1653.2)		25.6	157.4
Tower C	1253.9 (1271.0)		26.9	115.1
Average	1717.5 (1499.6)		25.0	145.6
	Cooling (ekWh)			
Tower A	1249.7 (1281.9)		12.8	104.1
Tower B	1026.2 (975.0)		13.4	85.5
Tower C	789.0 (692.1)		16.3	65.8
Average	1021.6 (983.0)		14.2	85.1
	Hot Water			
	m^3/year	m^3/year/occupant	ekWh/m^2/year	ekWh/year/suite
Tower A	38.0 (24.9)	22.0	37.5	3337.6
Tower B	38.8 (23.7)	19.7	48.4	3410.5
Tower C	25.5 (15.0)	17.0	48.8	2242.1
Tower D	30.9 (16.2)	18.9	34.4	2714.6
Average	33.3 (20.0)	19.4	42.3	2926.2
	Energy Use			
Total	**8,909 ekWh/year**		**125.6 ekWh/m^2/year**	

The results from Table 2.4 were used to produce the end-use breakdown in Figure 2.2. These results can be compared to the end-use breakdown for all Ontario apartments in Figure 2.3 (NRCan, 2014b). Though Figure 2.3 uses non-normalized energy use values in petajoules [PJ], the percentages allow a point of comparison.

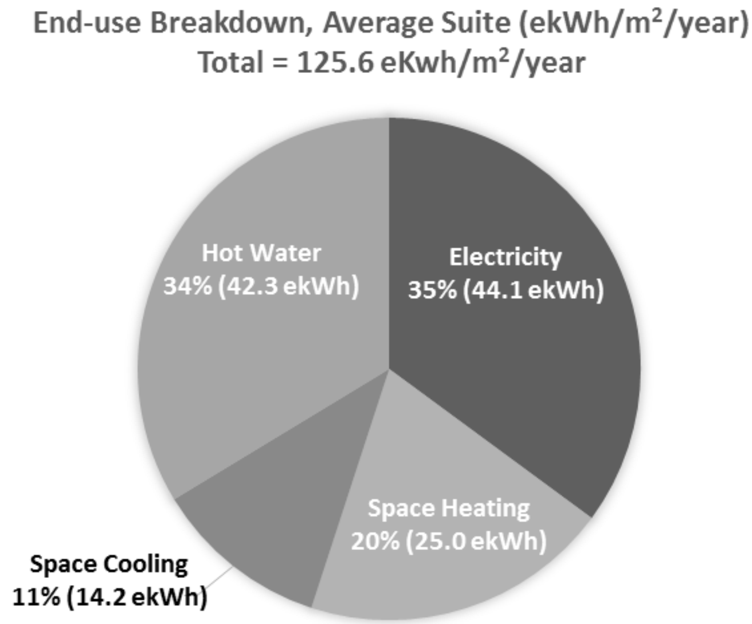

Figure 2.2: End-use energy breakdown for study suites

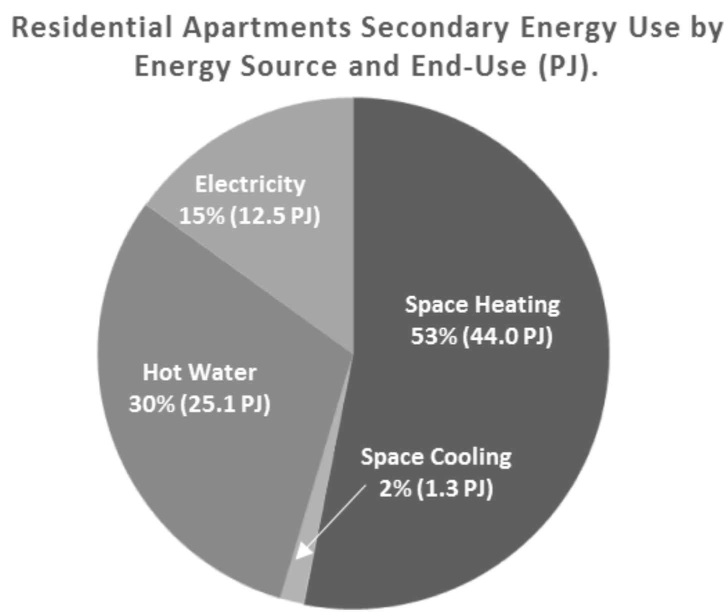

Figure 2.3: Ontario apartment end-use breakdown (NRCan, 2014b)

Hot water consumption is the only value which could be considered to be similar on a percentage basis, and is 4% higher in the study buildings than in Figure 2.3. Figure 2.2 indicates that the suites in the study buildings use considerably less heating and considerably more cooling than the Ontario average. The cooling finding is not surprising as the study buildings are tall, highly-glazed towers with large east and west façades, and that cooling is not present in all of the apartments used in the Ontario data. Part of the large discrepancy in heating loads could be a result of the Ontario average being generated by dividing the total energy used in the building by the number of suites, whereas the chapter EUI is generated using submetered data.

Figure 2.2 and 2.3 also show that electricity comprises a higher percentage within the study suites than in the Ontario average. Though the reasons for this are complex, it is worth mentioning that the study building has electric, and not gas, ovens and ranges. An additional point of context is that the electricity used for suite plug loads and lighting in the study buildings is 22% higher than the 36.2 kWh/m^2/year measured in 39 high-rise multi-residential buildings in the Lower Mainland of BC, and Victoria, BC (RDH Building Engineering Limited, 2012).

2.3.1.1 Variation Between Suites

This section will report the extent to which area-normalized heating, cooling, electricity, and hot water consumption vary between suites. Figure 2.4 graphically represents the variability for each end-use across all towers. Hot water is widely distributed, and differs by a factor of 13 from the lowest to the highest consumer. Electricity, which is also widely distributed, differs by a factor of 5. The variability in electricity consumption is caused largely by occupant behaviour; either directly (e.g., watching a lot of TV) or indirectly (e.g., installed lighting).

Because some respondents used zero ekWh per year for heating and cooling, the minimum score has been raised from zero to one in order to make a factor calculation possible. In doing so, it was found that normalized heating consumption differs by a factor of 67, and normalized cooling by a factor of 47. Using the 5th and 95th percentile results in a factor of 65 for heating and 38 for cooling. These large ranges are likely to be unique to high-rise buildings, where heated corridors, party walls, and stack effect enable some suites to go all winter using very little or no heating energy. Contextualization of these results is provided below (see "Summary of Space Conditioning Findings").

Total energy use intensity was found to differ by a factor of 7.3 between suites. This finding arose in a research setting in which accurate area-normalized data was used to compare between dwellings which are very similar to one and other (see Table 2.2). Next, physical, behavioural, and demographic variables will be used to explore the observed variability.

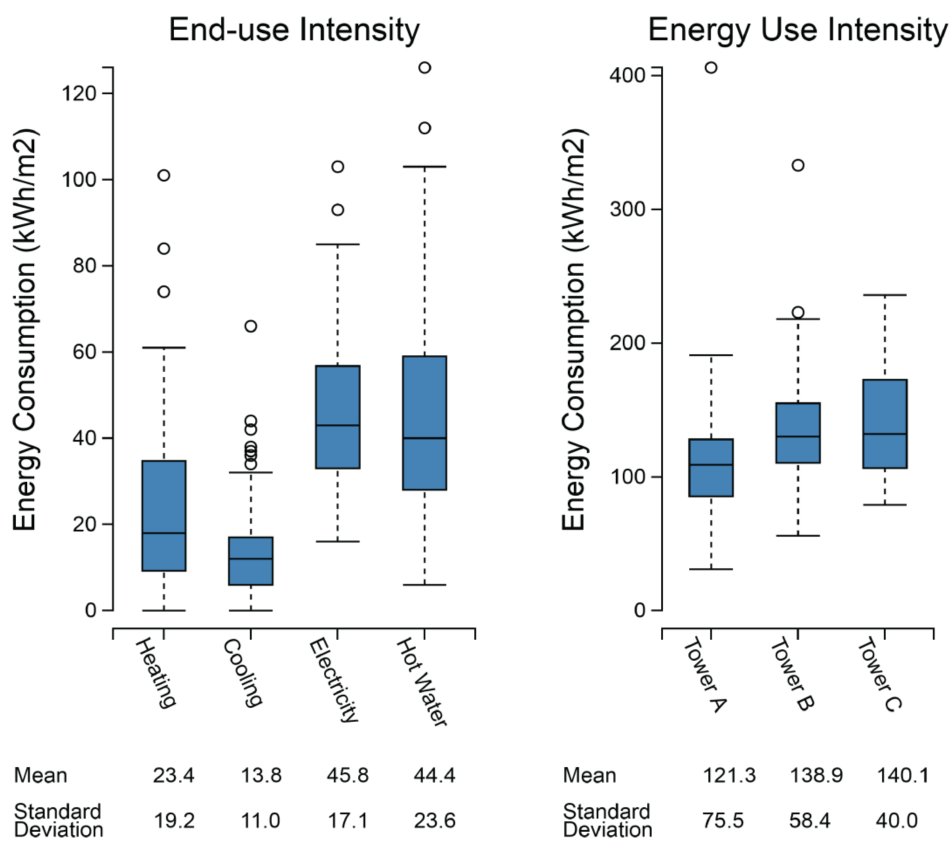

Figure 2.4: End-use, and energy use intensity

2.3.2 Exploring Variability

2.3.2.1 Space Conditioning

Physical Characteristics

The following section will use physical variables to explain the variability in heating and cooling consumption, which account for 20% and 11% of suite-level energy use intensity, respectively. In doing so, the amount of variability *not* explained by physical variables will be assumed to be related to occupant demographics and behaviour. In order to accomplish this, gross (i.e., non-normalized) data will be used as the outcome variable in regression models which explore the role of physical building characteristics in explaining heating and cooling consumption.

Table 2.5 shows linear regression results involving six physical variables (labeled “a” - “f”) and gross heating energy use. Results generated using transformed data indicate that exterior wall area is the most effective variable at explaining heating consumption, explaining 39.0% of the variability in the transformed data. As the results for ‘Hierarchy 1’ show, there is no R^2 change when floor area is added to a model containing exterior wall area. This is because exterior wall area is highly correlated to floor area (.833, $p < 0.01$) and therefore floor area becomes redundant in the model. Also, heat loss is dominated by the exterior wall area.

Table 2.5 presents the results of regression models involving the study variables and suite-level heating consumption. The R^2 value denotes the amount of variability explained by the variable, and the beta values display the change in units that results from an increase in the predictor variable. Insolation (kWh/m^2) explains 32.2% of variability in the transformed suite-level heating data and when added to a hierarchical regression with exterior wall area, together explain 43.2% of variability. This represents the strongest relationship between physical variables and transformed heating data. Table 2.5 also shows that storey and balcony are not very useful predictors of heating consumption. It should be mentioned, though, that as will be described (see: “Occupant Context”), drafty balcony doors, as reported by occupants, are likely driving heating loads in some of the suites, though not enough to contribute meaningfully in a regression model. Similarly, the role of the stack effect in these buildings is likely a driver of variable heating loads (see “Summary of Space Conditioning Findings”).

Table 2.5: Gross heating regressions, all towers

	Variable(s)	Unstandardized beta	Standardized beta	R^2
		Original data		
a	Exterior Wall Area	55.5	.618	.382
b	Floor Area	26.6	.506	.256
c	Insolation	592.5	.582	.338
d	Irradiation	670.8	.550	.302
e	Balcony Width	10.0	.246	.061
f	Storey	46.1	.195	.038
a + b	Hierarchy 1	58.3	.649	.382
a + c	Hierarchy 2	46.4	.547	.449
a +c + b	Hierarchy 3	47.0	.553	.449
		Transformed data		
a	Exterior Wall Area (a)	n/a	.625	.390
b	Floor Area (b)	n/a	.522	.272
c	Insolation (c)	n/a	.567	.322
d	Irradiation	n/a	.544	.296
e	Balcony Width (d)	n/a	.265	.070
f	Storey	n/a	.195	.038
a + b	Hierarchy 1	n/a	.627	.390
a + c	Hierarchy 2	n/a	.538	.432
a + c + b	Hierarchy 3	n/a	.496	.433

Table 2.6 shows similar data for cooling. It shows that the strongest model explains 15.7% of transformed cooling variability and resulted from a hierarchical regression with exterior wall area as the first entry, floor area as the second, and irradiation. This is only slightly higher than the R^2 value for floor area (0.14). Irradiation was found to be more effective than insolation, explaining 6.2% of transformed cooling variability. On the one hand this suggests that cooling is not highly determined by solar gain, and it may be more related to humidity which is high in the summer in Toronto. Another explanation is that window opening behaviour occurs much more frequently in the cooling season compared to the heating season, and that this behaviour (which was not measured) could be driving the observed variability.

The use of windows blinds is another likely a factor in producing these relatively weak regression relationships. The study buildings did not come with blinds installed; instead, it was an option people could choose during move-in. Laouadi (2010) found a 9% reduction in on-peak cooling demand in houses where shades were added. The lack of data about the installation and use of blinds in the study buildings is a limitation of the present chapter.

Table 2.6: Gross cooling regressions, all towers

	Variable(s)	Unstandardized beta	Standardized beta	R^2
		Original data		
a	Exterior Wall Area	38.8	.232	.054
b	Floor Area	25.1	.273	.075
c	Insolation	682.4	.199	.039
d	Irradiation	530.6	.297	.088
a+b	Hierarchy 1	24.4	.262	.075
a+d	Hierarchy 2	500.7	.662	.115
a+b+d	Hierarchy 3	13.8	.500	.192
		Transformed data		
a	Exterior Wall Area	n/a	.301	.091
b	Floor Area	n/a	.374	.140
c	Insolation	n/a	.163	.027
d	Irradiation	n/a	.250	.062
a+b	Hierarchy 1	n/a	.402	.141
a+d	Hierarchy 2	n/a	.767	.096
a+b+d	Hierarchy 3	n/a	.446	.157

Demographic Determinants

In order to explore the role of demographics in heating and cooling consumption, results will be presented from independent samples t-tests. As discussed in Section 2.2.3, these results indicate whether the mean consumption values of two groups (e.g., renters and owners) differ significantly from each other. If a significant result is found, it indicates that 95% of the time the two means do not differ as a result of chance. The column "Mean difference" shows the differences in the two mean scores regardless of significance.

Table 2.7: Heating and demographics

Factors	Mean heating (ekWh/m^2)	SD	*t*	*df*	Sig.* (2-tailed)	Mean difference
Single occupied	20.3	16.7	1.734	89	.086	.35
More than one occupant	27.3	21.8				
Home all the time	25.0	15.2	-.324	77	.747	.07
Evenings and weekends	26.8	21.8				
Under 30	23.3	20.0	-.421	89	.675	.08
Over 30	25.1	20.3				
Renters	22.6	20.5	-1.006	88	.317	.19
Owners	26.9	19.9				

** $p < 0.05$*

Table 2.7 shows that the only demographic variable which causes a significant difference in heating consumption is whether the suite has one occupant, or more than one occupant. It is somewhat unclear as to why this relationship exists. After all, a single-occupied suite still needs to be heated all winter long. It could be that suites with one or more occupant experience more manual overrides to thermostat programs, due to one of the occupants preferring warmer or cooler conditions than the other, but this was not measured. It is also noteworthy that those that who are home all day do not seem to use significantly more energy than those who are home only evenings and weekends. We can speculate that this is because occupants do not use thermostat setbacks for non-occupied periods. There also seems to be little impact of age on the amount of heating used, but this could be a function of the questionnaire items being too simplistic. There is not a large difference between renters and owners in the study buildings, perhaps because 97% of participants paid for their own utilities, regardless of whether they owned or rented.

Table 2.8 shows that the only significant demographic factor determining cooling use is whether people are home all the time or only on weekends. This suggests that respondents are setting back or disabling their cooling while away from home. This is surprising considering the observation above about heating. One explanation for this is that since cooling costs more (approximately $0.06/ekWh, compared to $0.04/ekWh for heating), residents are incentivized to setback or disable cooling when not at home. Another explanation may be that heating is expected by occupants, while cooling is optional. Further work could look at the extent to which this occurs by determining how and when people engage their heating and cooling systems.

Table 2.8: Cooling and demographics

Factors	Mean cooling (ekWh/m^2)	SD	*t*	*df*	Sig.* (2-tailed)	Mean difference
Single occupied	19.3	39.5	.916	103	.916	.32
More than one occupant	14.6	10.6				
Home all the time	26.8	47.3	.2.305	90	.019*	2.16
Evenings and weekends	12.4	9.4				
Under 30	13.4	10.4	.792	103	.430	.32
Over 30	17.7	29.9				
Renters	15.5	13.0	-.319	102	.750	.10
Owners	17.1	34.1				

** $p < 0.05$*

Overall, it seems appropriate to say that these types of demographics and analyses are not very useful in explaining the remaining heating (57%) and cooling (84%) variability not accounted for by the physical variables. Nevertheless, due the rigor with which the physical variables were created and analyzed, it is reasonable to say that the remaining variability is likely caused by behaviour and demographics, though further work is required to accurately ascertain this.

Occupant Context

Comments received on questionnaires were useful in suggesting additional explanations for the variability in heating and cooling consumption. For example, comments indicated that some corridors were overheated during winter (e.g., "hallway is too warm in winter and too cool in summer"). This could conceivably lead to less heat being used by suites which are on floors with overheated corridors and could help to explain why some suites use no heating energy at all. For example, one respondent who used very little heating energy reported that their suite "is always hot in winter, at least 70-71. We installed overhead fans for cooling and black-out shades and leave two windows open at all times, unless extremely cold out." A similar complaint was received from their neighbour: "sometimes have to open balcony doors to cool the place down during winter." Meanwhile other suites in the same building indicate that they "always need heat in the winter."

The two suites that did not require heating were located on floors 22 and 23 of 26 in study Tower B. It is possible that the movement of heated air in the building could be playing a role in determining heating use in some of the study suites. The stack effect is the phenomenon of heated (lower density) air moving upwards in buildings (Lstiburek, 2014). This effect is exacerbated in the study building type through air moving up vertical spaces such as elevator shafts. As Lstiburek (2014) writes, "the taller the building the greater the stack effect. The colder the temperature the greater the stack effect." Further, RDH Engineering Ltd. (2013) writes that "buildings that are built to meet a specific performance requirement that will be verified through testing typically are more airtight than comparable buildings without this requirement." However, since LEED energy characteristics are not verified by testing, it is unknown the extent to which the study building are more airtight than conventional buildings.

It is worth exploring the role of stack effect in the heating and cooling variability observed in the study towers. Figure 2.5 shows the heating consumed of individual suites within the four study towers plotted against the floor on which the suite is located. It shows no observable trend between storey and the amount of heating energy used (*r*=-0.01). Though this result suggests that an effect does not exist, it is possible that a more sensitive analysis procedure may uncover some correlation. Figure 2.6 shows the same analysis performed on cooling consumption data. Again, a non-significant correlation (*r* = -0.06) was found. This is a further area of work suggested by the present study.

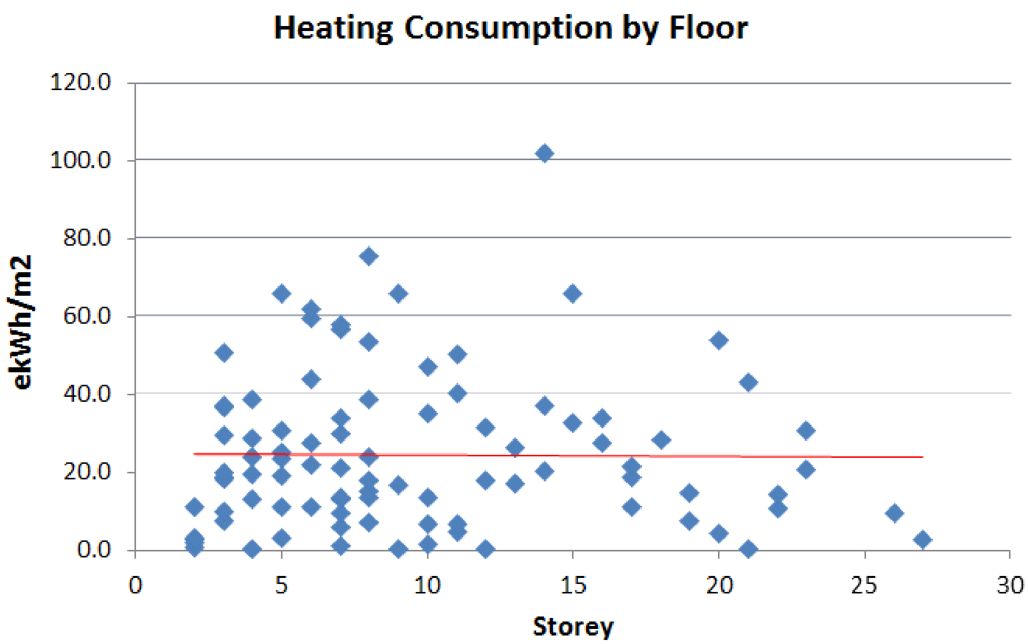

Figure 2.5: Heating consumption by floor

In order to explore this phenomenon more fully, researchers could estimate the neutral pressure plane and take measurements of heating and cooling consumption there, using these values as the most accurate indicators of heating and cooling use. In addition to this, temperature measurements in common corridor spaces could be taken and used in a heat gain calculation to determine the extent to which suites are benefitting/suffering from overheated corridors. Similarly, embedding logging IEQ measurements devices in suites which use very little and very high amounts of heating or cooling consumption would provide valuable insights in the environmental conditions in these suites and suggest additional explanations of their energy use.

Finally, further work is also required to determine the extent to which the floors are compartmentalized from one and other (Lstiburek, 2014). In other words, it would need to be determined the extent to which the buildings were designed such that air from one floor was blocked from migrating the another floor. A separate but related issue to this is the level of air-tightness of the study buildings. If air-tightness was suboptimal, then it is likely that suites on higher floors would be more susceptible to wind pressure and stack effect.

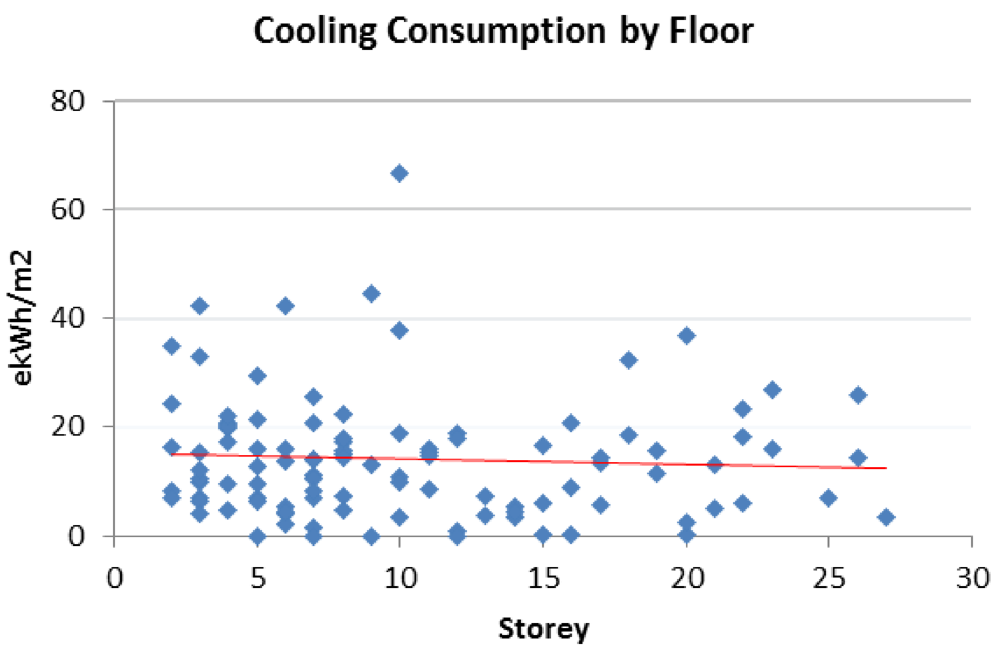

Figure 2.6: Cooling consumption by floor

Related to the stack effect are the various comments where respondents indicated that their drafty balcony door let a significant amount of cold air in during the winter (e.g., “draft by balcony door, can have ice buildup there”). The fact that some occupants experience this while others do not again speaks to the possible influence of the stack effect and/or the effect of wind pressures on different faces of the building. As mentioned above, this is likely driving heating use in some suites, though not enough to register in the regression modeling. Neither of these phenomenon were measured in the present chapter, but are insights gathered via occupant feedback and are areas for further research in similar buildings. Chapter 4 provides a more full explanation of these insights.

Summary of Space Conditioning Findings

Heating differed by a factor of 67, with physical factors accounting for 43.2% of the variability. This number may seem high, but other researchers have found that heating consumption resulting from occupant behaviour in similar dwellings varied by a factor as low as 10 and as high as 37 (Urban, 2013; Gram-Hanssen, 2010; Pilkington, Roach, & Perkins, 2011). Cooling in the study buildings differed by a factor of 47, with physical variables explaining 15.7% of the variability. To provide context, Parker (2002) found cooling loads differing by a factor 21 in a study of cooling loads in 204 Florida homes. Pratt et al., (1993) found that heating and cooling were the first and second most distributed residential end-uses, respectively.

The ranges observed for heating and cooling in the study building are very wide, a trend which in large part is due to some suites using very little heating or cooling energy. Though it must be said, that there are still others who use, as much as 60 ekWh/m^2/year for heating and 35 ekWh/m^2/year for cooling. It is difficult to determine the extent to which these wide ranges represent a success or a challenge in the study buildings, in part because of the unknown role of stack effect. Further work in the role of stack effect in these towers is required to answer this one way or the other. For now, it is worth noting that these ranges are likely unique to this building type, and though they signify the importance of occupant behaviour in driving heating and cooling use, there may be other factors related to the location of each suite within the building.

The findings above suggest that 56.8% of the heating variation, and 84.3% of the cooling variation is caused by something other than building type, floor area, heating/cooling type, exterior wall area, glazing ratio, insolation, balcony width, and orientation. It is interesting to point out that Gill et al., (2010) found that 51% of variability in heating consumption could be explained by occupant behaviour. The analysis above seems to support this or even a higher % due to occupant behaviour and demographics, though this was difficult to explore with the data available for the present chapter. Though behavioural and demographic determinants were not very useful in explaining the remaining variability in heating and cooling consumption data, anomalies were better understood through questionnaire comments, which highlighted corridor temperature and drafty balcony doors as potential physical determinants. Understanding these two physical phenomenon are pieces of further work to be conducted in the study buildings.

Another limitation of the present chapter is the lack of insight about thermostat use. As Meier et al. (2011) point out, “residential thermostats control 9% of the total energy use in the United States and similar amounts in most developed countries” (p. 1891). Even understanding on/off behaviour would have been useful; Steemers and Yun (2009) found that “the reported frequency of air-conditioning use accounts for 47% of the variation in cooling energy” (p. 629). Wi-fi enabled, logging thermostats would be required for this type of analysis, and certainly this is an avenue for further work given the increasing popularity of these thermostats.

2.3.3 Electricity

As shown in Figure 2.2, electricity is the largest contributor to suite-level energy use intensity at 35%. Normalized electricity consumption differs by a factor of 5 from the lowest to the highest consumer (see Figure 2.7).

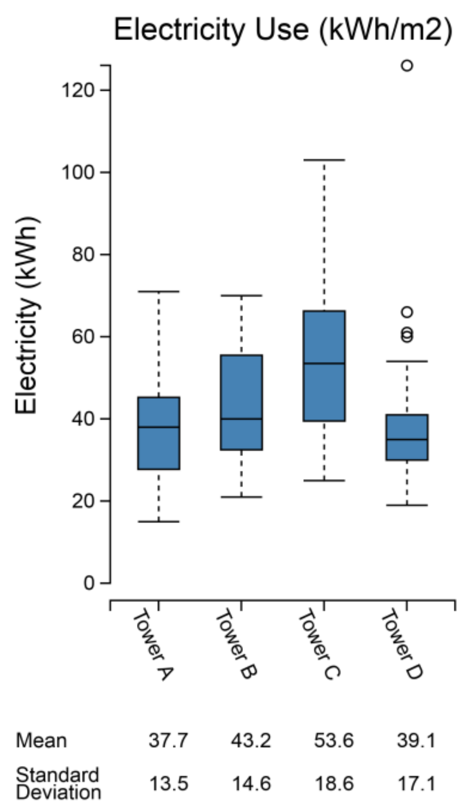

Figure 2.7: Normalized electricity use

Table 2.9 shows that non-normalized electricity use and floor area are correlated (.632, $p < 0.01$), indicating a strong relationships and justifying inclusion in a regression analysis. When floor area is used to predict electricity, the resulting $R^2 = .394$, indicating that floor area accounts for 39.4% of the variability in normalized electricity consumption. This suggests that floor area is a relevant factor in electricity use in the study buildings. Since the essential appliances in each suite are the same (e.g., dishwasher, fridge, washer, and dryer) this variability is likely caused by the amount and type of personal electronic appliances, lighting choices, and other behavioural and demographic determinants.

Table 2.9: Electricity and floor area correlations

	r	*p*-value
Tower A	.548	< 0.01
Tower B	.489	<0.05
Tower C	.289	n.s
Tower D	.716	< 0.01
All towers	.632	< 0.01
n.s. = non-significant		

Respondents in Tower D were asked to rate the number of electronic appliances in their suite on a 7-point scale ranging from less than average to more than average (occupants in Towers A-C were not asked this question because it had not been considered relevant at thet time). They were also asked to report the number of times per week that they used their clothes dryer. Table 2.10 shows how results from these questions are correlated to area-normalized electricity use. The number of times a person uses their dryer per week is not correlated to normalized electricity use, but a significant correlation was found between number of electronic appliances and normalized electricity consumption. Though only a medium strength relationship, this offers some suggestion for why electricity consumption varies as it does. Unfortunately, this item cannot be used in a regression due to questionnaire responses not being a continuous variable.

Table 2.10: Electricity behaviour correlations

Variable	*r*	*p*-value
Dryer/week	-.065	n/a
Number of electronic appliances	.359	<0.05

Another electricity-related behaviour which was measured on the questionnaire was respondents' use of the master electricity switch. This switch is located in the suite near the entry door and turns off all lights and the majority of receptacles, with the intention of reducing phantom loads and unnecessary electricity consumption. Table 2.11 shows that people who use the master switch in their suite do not use a significantly different amount of electricity that those who do. Indeed, the mean values only differ by 3%.

Table 2.11 shows that all four of the demographic questions result in significantly different means. It should also be noted that on an absolute basis, the means differ by as much as 37%. Some of these relationships are interrelated, for example younger people use less electricity than those over 30 because they are 4.2 times more likely to be home only on weekends and evenings. For context, Binkley, Touchie, and Pressnail (2013) found that buildings "designated as seniors' homes tend to exhibit lower energy use" (p. 33).

Table 2.11: Electricity and demographics

Factors	Mean electricity (kWh)	SD	t	df	Sig. * (2-tailed)	Mean difference
Single occupied	2443.2	1095.3	-4.418	142	.000*	.37
More than one occupant	3345.9	1331.6				
Home all the time	3554.4	1534.8	3.060	129	.003*	.29
Evenings and weekends	2762.7	1157.0				
Under 30	2597.3	940.2	-2.979	145	.004*	.24
Over 30	3221.7	1484.8				
Renters	2734.0	952.0	-2.274	129	.025*	.17
Owners	3206.8	1522.1				
Use master switch	3097.6	1367.6	.425	144	.672	.03
Don't use master switch	3000.2	1387.7				

In summary, electricity use differed by a factor of 5 and floor area accounted for 39.4% of the variability. Neither weekly dryer use nor use of a master kill switch were found to be significant predictors of electricity use. Demographic determinants appear to be more effective than behavioural variables at explaining the 60% of variability in electricity consumption not explained by floor area. These results suggest that using behavioural variables to explain the variability in electricity consumption is difficult, and that careful attention needs to be paid to the creation of effective behavioural variables.

2.3.4 Hot Water

Hot water is the second largest component of suite-level energy use intensity, at 34%, and was found to vary by a factor of 13 from the lowest to the highest user. This section aims to explore the reasons for this high variability, which is entirely driven by occupant behaviour.

All suites were sold furnished with low flow showerheads and sink aerators. Though some of these low flow fixtures have likely been replaced with higher flow ones, we assume that the majority are still in place. Aside from this possibility, there are no other physical characteristics that could be thought to drive hot water use. This section will begin by using demographic and hot water-behaviour questionnaire items to explore variability.

Table 2.12 uses the same four demographic questions used above to perform t-tests with hot water consumption data. The only significant relationship exists between suites with one occupant and suites with more than one occupant. This is intuitive as water use is driven by occupancy. It was also found by Binkley, Touchie, and Pressnail (2013) who found that "domestic hot water energy is a function of the number of occupants" (p. 26). To illustrate this using data from the present chapter, questionnaire results show that families with children in the study buildings use the dishwasher 117% more per week, take 25% more showers and 210% more baths per week than suites with one or two occupants and no children.

Table 2.12: Hot water (m^3)

Factors	Mean hot water (m^3)	SD	t	df	Sig. * (2-tailed)	Mean difference
Single occupied	21.6	13.1	-4.756	125	.000*	.58
More than one occupant	34.2	16.8				
Home all the time	36.5	22.7	1.537	127	.127	.20
Evenings and weekends	30.5	20.4				
Under 30	30.2	25.7	-.656	141	.513	.09
Over 30	32.9	19.6				
Renters	29.3	16.3	-5.403	140	.134	.18
Owners	34.7	24.4				

To further explore the effect that water-use behaviours have on consumption, Table 2.13 shows that dishwasher use, showers per week, and baths per week are significantly correlated with hot water use. It is not surprising that washing machine use is not correlated as most laundry is presumably done with either warm or cold water.

Table 2.13: Behaviour and hot water consumption

Variable	***r***	***p*-value**
Dishwasher/week	.423	<0.01
Showers/week	.511	<0.01
Baths/week	.550	<0.01
Laundry/week	.480	n.s.

Table 2.14 shows that self-reported water use behaviours can account for 50.6% of variability observed in hot water use. When number of occupants was added as a fourth item in this hierarchical regression model it only resulted in an R^2 change of .003, indicating that it is not a significant contributor to this model when these other variables are entered first. The remaining 49.4% of unexplained variability is likely to be caused by kitchen and bathroom sink behaviour, and the duration of showers and baths, which were not captured on the questionnaire.

Table 2.14: Behaviour and hot water consumption

	Variables	Unstandardized beta	Standardized beta	R^2
a	Dishwasher/week	3.73	.401	.160
b	Showers/week	1.81	.455	.207
c	Baths/week	2.46	.554	.307
a+b	Hierarchy 1	N/A	.480	.426
a+b+c	Hierarchy 2	N/A	.307	.506

Anomalies

Though there are many suites with high hot water use, one outlier is worth discussing in particular. This suite used 163.8 m^3 of hot water per year (based on consistently high monthly data). This is 479% higher than the average amount of hot water used per suite which is 34.2 m^3 per year (see Table 3). To put this number into context, the volume of an average bathtub is 0.26 m^3, meaning that this outlier consumes over 600 bathtubs of hot water per year (U.S. Environmental Protection Agency, 2012).

One possible explanation for this extreme usage was uncovered from various questionnaire comments which talked about the long time that it took for hot water to come out of their taps. For example, one respondent indicated that they would "run all the taps, including shower, for 15-20 minutes (no exaggeration) before any hot water came...we would actually set an alarm early to just turn on shower, then go back to bed, then wake up 15 minutes later." This water would pass through the hot water meter whether it was hot or not, and could explain high usage, though more study is required for a more definitive insight. As was the case with heating and cooling data, this insight would not have been known without questionnaire comments.

In summary, hot water was found to differ by a factor of 13, with self-reported water use behaviours explaining 50.6% of this variability. Aside from number of occupants, demographic factors were not found to offer significant explanations of variability. Despite number of occupants being significant in t-tests, it was not a significant predictor when included in hierarchical regressions involving self-reported frequency of hot water behaviours. As was the case with heating and cooling data, the insight that delayed hot water delivery could be driving high hot water consumption was made possible by questionnaire comments and again shows their merit in this type of research.

2.4 Conclusion

The relationship between occupant behaviour and energy use is complicated, and varies widely in different environments. This chapter demonstrated the usefulness of combining quantitative building data with qualitative occupant data to understand energy use patterns in high-rise residential buildings.

The average suite-level energy use intensity was found to be 125.6 ekWh/m^2/year, 27% less than the Ontario average for apartment dwellings. The average end-use breakdown is 35% for electricity, 34% for hot water, 20% for heating, and 11% for cooling. It was also found that energy use intensity differed by a factor of 7.3. The above analysis, using variability not explained by physical factors, suggests that occupant behaviour and demographics could be responsible for as much as 57% of the heating variability, 84% of the cooling variability, and 60% of electricity variability. For hot water, 51% of variability was explained by self-reported behaviours, with the rest of the variability being explained by behaviours which were not measured.

Methodologically speaking, the high R^2 values reported in the hot water section (r = .506) suggest a high level of criterion validity for those particular questionnaire items, and generally suggest that the questionnaires were answered truthfully by participants. However, in order to better understand the relationship between behaviour, demographics, and energy and water use, a more detailed questionnaire would be required, alongside logging sensors and other monitoring equipment. Another methodological point is that the R^2 values in the space conditioning findings were higher when using transformed data, suggesting that this approach is merited with positively skewed energy and water consumption data, and that the choice to transform the data was well advised. Negative binomial regression is another method that future work could employ.

A limitation of the present chapter is that it was not able to sufficiently explore the relationship between high glazing ratios, use of window coverings, and cooling loads. The buildings in the study surpassed the ASHRAE 90.1 preferred glazing ratio of 40% (by offsetting with other efficiencies) in order to maximize views with large east and west faces, which as discussed are the most prone to overheating. As Straube (2008) points out, “the size of a building’s air-conditioning plant is almost always defined by the glazed area” (para. 4). The results clearly demonstrate that these suites required more cooling use (both raw and percentage) compared to Ontario residential averages. Unfortunately, understanding cooling behaviour has proved to be illusive. Specifically, the study buildings use more cooling than the Ontario average, yet this usage could not be sufficiently explained using physical or behavioural variables. One reason for this is that the use of window coverings was not measured.

One of the major merits of this chapter is that the above insights were gathered in suites with a high degree of similarity. Though there may be slight differences which were not accounted for, it can be said that they are much more similar to one and other than single family homes, and afforded a higher degree of control compared to previous work done in this area. It is hoped that this work will provide reliable values for modelers, researchers, and managers to use as they consider how to make buildings more efficient, and better at reducing peak demand.

In summary, this chapter showed:

1. The average suite-level energy use intensity was found to be 125.6 ekWh/m^2/year (not including heating, cooling and lighting for common spaces);
2. The average end-use breakdown is 35% for electricity (plug loads and lighting), 34% for hot water, 20% for heating, and 11% for cooling;
3. Energy use intensity differed by a factor of 7 between similar suites, electricity by a factor of 5, hot water by a factor of 13, cooling by a factor of 47, and heating by a factor of 67;
4. Results suggest that occupant behaviour and demographics could be responsible for 57% of the heating variability, 84% of the cooling variability, and 60% of electricity variability;
5. For hot water, 51% of variability was explained by self-reported behaviours, with the rest of the variability being explained by behaviours which were not measured.

2.5 Bridging Section

The work presented in Chapter 2 is a first step in a dissertation which works towards substantiating that the collection of qualitative data from building occupants can yield very valuable insights into the effectiveness of building design and management decisions, as well as providing an enhanced understanding of energy and water consumption. This chapter particularly addressed the latter part of this mission statement, and explored the role of the occupant in overall energy use in the case study buildings. It aimed to put into context the relevance of occupant behavior and demographics compared to physical features of the buildings. The statistical methods used provide an accurate picture of the extent to which the behaviour of the occupants in the study buildings contributed to the energy and water used therein.

This chapter demonstrates the types of insights that are possible when qualitative and quantitative data are combined. In fact, the chapter is greater than the sum of its parts, which on their own (i.e., questionnaire results and energy data) would have resulted in an inferior understanding of energy consumption at the suite level. A detailed explanation of how the chapter answered specific research questions can be found in Chapter 5.

The chapter began to explore contextual elements in the study buildings (e.g., hot water delivery), though a more complete exploration of context and its importance in residential building evaluations is carried out in the proceeding chapters. Put differently, this chapter has explored the role of behaviour and demographics in determining energy and water consumption, but was not able to explore in detail any specific behaviours. Having explored the effect that behavior and demographics has on energy use, Chapter 2 begs the question: why are occupants behaving this way, and what can be done to engender more beneficial behaviours? To this end, the next chapter explores the role of the occupant in the successful adoption of a new and innovative ventilation technology that is aimed at energy savings and improved comfort.

It should also be noted that this chapter was not able to explore in detail the type of feedback generated by respondents. Despite offering many insights, the chapter does have its limitations. The insights it provides are valuable, but rather one dimensional, in that the findings are primarily concerned with describing energy and water use and explaining it using regression analysis. It was not able to explore how the context of the building relates to energy and water consumption, as well as occupant satisfaction. This work is taken up in Chapter 4.

3. UNDERSTANDING THE ROLE OF OCCUPANTS IN INNOVATIVE MECHANICAL VENTILATION STRATEGIES

3.1 Introduction

It is commonly accepted that good design and the latest new technologies on their own are not sufficient in creating efficient and healthy buildings. Building occupants play a role in affecting building performance (e.g., Gill et al., 2010; Stevenson, Carmona-Andreu, & Hancock, 2013; Pilkington, Roach, & Perkins 2011). Despite this importance, there can be a disconnect between the intentions of designers and the expectations and capabilities of users which can affect performance (Hauge, Thomsen, & Berker, 2011). For example, Leaman (quoted in Yudelson & Meyer, 2013; Bordass and Leaman, 1997) claims that unmanageable complexity can be a result of this disconnect and can lead to buildings being poorly operated.

Although giving occupants access to controls is a factor in them being satisfied with their surroundings (Baird, 2010; Leaman & Bordass, 2001, Combe et al., 2011) there are often numerous ways in which an occupant can interact with a design strategy (Berker, 2011). This variability can be difficult to account for during the design and modeling phases of a project, but is nonetheless important.

There is also a certain amount of buy-in that must occur on the part of occupants if design strategies are to become successful. Leaman (in Yudelson & Meyer, 2013) asserts that occupants may not be interested in having to operate complex buildings. Cole et al. (2008) similarly insist that a willingness on the part of occupants is crucial to the success of new systems and designs. This relationship between the buy-in of occupants and building performance is sometimes articulated by referring to building occupants as inhabitants instead of occupants, implying an active role for both their integration and stewardship within buildings (Cole et al., 2008). As mentioned in Section 1.1, occupants has been used throughout for simplicity’s sake.

Though achieved performance is most often thought of in terms of energy use, occupants also play a role in achieving high IEQ and can negate the expectations predicted (and certified) during design. This is especially true in buildings which give occupants a high degree of control over heating, cooling, and ventilation (Yudelson & Meyer, 2013). The buildings in the present chapter use innovative, non-standard mechanical ventilation systems, something Yudelson and Meyer (2013) argue exacerbates the likelihood of so-called performance gaps in the indoor environment. However, the study buildings also provide passive ventilation, which gives occupants an opportunity to rectify IEQ performance gaps passively.

This chapter explores the causes and implications of some occupants choosing to avoid or abandon usage of their mechanical ventilation system. Similar work in single family homes found that less than 40% of the occupants of dwellings surveyed used their mechanical ventilation systems as they were designed to be operated (Gill et al., 2010). Similarly, Carmona-Andreu, Stevenson, & Hancock (2013) found that poor handover procedures led to poor understanding, control over, and maintenance of, mechanical ventilation systems. This chapter reinforces the idea that design-intent and advanced technologies do not guarantee performance, and that careful attention must be paid to the capabilities, preferences, and satisfaction of occupants.

Beyond exploring the importance of occupants in achieving energy and IEQ predictions, this chapter serves to demonstrate that the BPE methodology - which relies largely on occupant feedback - is useful in understanding the causes and implications of technology adoption by occupants of high-rise residential buildings.

3.2 Methods

3.2.1 Ventilation Design

In conventional Canadian high-rise residential towers, centralized ventilation systems deliver heated or cooled air to corridors, pressurizing them and forcing the treated air under entry doors and into dwellings. This ventilation strategy is often accompanied by electric baseboard heaters, and rarely involves delivering conditioned air in the summer. This method requires large air handling units and can result in suboptimal indoor air quality within suites (indeed it is pejoratively referred to as the ‘carpet filter’ method of ventilation). These buildings usually also have a centralized heating system with no thermal submetering. As a result, variable temperatures in the winter can result in some suites having their windows open, while other suites are too cold. Overheating is a very common problem in these buildings, it is most commonly addressed with the use of window air conditioning units (where allowed).

Beginning in the early part of this century, some Toronto designers began designing buildings in which dwelling entry doors were entirely sealed from corridors, meaning that occupants were fully responsible for their heating, cooling, and ventilation needs; a strategy aimed at improving energy efficiency, indoor air quality, and occupant satisfaction. It should be noted that due to the Toronto climate, passive ventilation through windows is often not desirable. This is due to energy loss and humidity fluctuations during the extremes of summer and winter in particular.

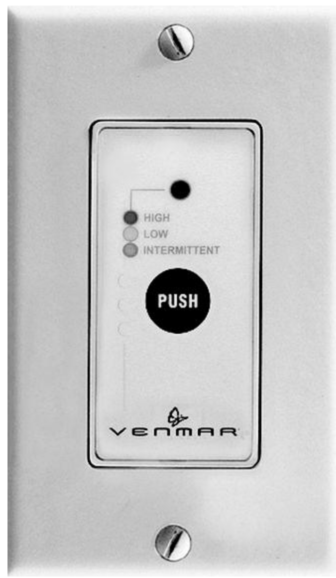

Figure 3.1: ERV control

In Towers A, B, and C, occupants use a switch in their bathroom (see Figure 3.1) to control their ERV, which then operates in low, high, or recirculation mode; it can also be shut off entirely by the pushing the button an extra time. The system is intended so that at the very least it is left in intermittent (recirculation) mode, where it operates at low speed (approx. 23.6 l/s) for twenty minutes out of each hour; sending fresh air to the fan coil unit where it is heated or cooled as need and distributed throughout the suite. In Tower D, there is no control for the ERV. Instead, a constantly running exhaust fan in the bathroom ceiling is ducted to the ERV. This fan delivers indoor air to the ERV where its energy is exchanged with outdoor fresh air and then delivered to the dwelling via the fan coil unit. In addition to this system, Tower D also utilizes a small gap under entry doors to deliver additional fresh, treated air from the central air handling unit.

Acoustic measurements were carried out using a class 2 integrating sound level meter and real time octave band spectrum band analyzer (CESVA SC-160). These measurements were carried out according to instructions received from a departmental colleague with expertise in acoustics that were based on ASHRAE measurement protocols for commercial buildings (ASHRAE, 2012). Various noise ratings (e.g., Sones, QAI, RC Mark II) can be generated from the data this equipment collects. Indoor air quality measurements were taken using a 3M EVM 7 Environmental Monitor, and included CO_2, air temperature, humidity, particulates (i.e., PM 2.5) and volatile organic compounds. It should be noted that these were indicative spot measurements and not long term logged measurements, and a full indoor environment survey was not carried out. Therefore these measurements should be treated as supplementary to some of the more comprehensive data presented in this chapter. Certainly further research should involve logging IAQ parameters and noise measurements in all different types of suites.

Table 3.1: Additional data collection

Site	Noise Measurements	Individual Interviews	Air Quality Measurements
Tower A	2	2	1
Tower B	0	3	1
Tower C	0	0	0
Tower D	6	6	0
Total	**8**	**9**	**2**

Thermal submeter data was collected for all participants who completed a questionnaire in Towers A, B and C.

3.3 Results

Of the 165 respondents, 75% were over 30 years old, 64% were female, 11% of dwellings had children living in them, and 39% of dwellings were occupied by only one person. The majority of respondents (59%) owned their dwelling, while the remainder were renters. Data related to occupancy patterns suggests that 59% of people are typically home only during evenings and weekends, whereas 33% of people reported being home most of the time. Finally, 38% of respondents had previously owned a single family house.

On the questionnaire, occupants were asked to report whether or not they use their ERV, as well as how often they use it in the winter. These responses were used to create a dichotomous variable (ERV user and ERV non-user) into which respondents were grouped. Over half of respondents from Towers A, B, and C (52%, n=56) have been grouped as ERV non-users, indicating on the questionnaire that either they did not know about their ERV, or that they use it either rarely or never. Comments from ERV non-users range from “Not sure about ventilator - I believe building operates” to “I don’t know anything about the ERV.” An unpublished internal study conducted in 2009 by the developer of Towers A, B, and C found that 49% of respondents did not know if their dwelling had an ERV, supporting the grouping used in the current chapter. In Tower D, at least 27% of respondents are ERV non-users, this number having immobilized their ERV by disconnecting their bathroom fan.

Control and Usability

Table 3.2 shows the results of several questions relating to usability and control of the HVAC systems. A higher mean score expresses greater satisfaction. Table 3.2 indicates that respondents from Towers A, B and C felt the least amount of control over ventilation (with a mean score of 4.5 out of 7), compared to the amount of control they feel they have over heating and cooling (with mean scores of 5.6 and 5.4 respectively). Satisfaction percentages similarly show that occupants feel the least amount of control over the ventilation in their suites. This trend was also observed in Tower D.

Table 3.2: Questionnaire scores for HVAC system control and usability

		Mean (Ideal = 7)	Percent Dissatisfied	Percent Satisfied
Towers A, B, and C				
	Control over heating	5.6	9%	83%
	Control over cooling	5.4	12%	77%
	Control over ventilation	4.5	27%	52%
	Usability of thermostat	5.3	21%	68%
	Usability of ERV control	5.4	8%	49%
Tower D				
	Control over heating	5.7	20%	76%
	Control over cooling	5.3	15%	65%
	Control over ventilation	4.0	41%	40%

Despite poor satisfaction with the control over ventilation, respondents rated the usability of their ERV control (5.4) marginally higher than thermostats (5.3). On open-ended questionnaire items (i.e., comments), complaints about thermostat usability outnumbered those for the ERV control twenty to zero. This suggests that the usability of the ERV control is not a likely cause of dissatisfaction with control over ventilation.

Occupants in Towers A, B, and C are required to clean and change their own ERV filter to ensure optimal operation. On the questionnaire, 39% of respondents (n=41) reported that they had never done this, and of those who provided comments on their questionnaires, 16% said that the filter was too difficult to clean. For example, one respondent commented: “tried to clean ERV filter, way too difficult, did not bother.” Maintenance of the ERV filter is a usability parameter with which occupants appear to be challenged.

Acoustics

Unwanted noise is a potential factor in occupants abandoning usage of their ERV. Only occupants in Tower D were asked specifically to rate their satisfaction with amount of noise generated by their HVAC systems (this was due to an oversight by the researcher). Their scores (shown in Table 3.3) suggest dissatisfaction with the noise caused by their ventilation system. Additionally, all of the 27% of respondents who had disabled their ERV did so because of its objectionable noise.

Table 3.3: Acoustic satisfaction

Satisfaction with…	Mean	Percent Dissatisfied	Percent Satisfied
Noise from HVAC equipment	4.1	39 %	48%
Overall acoustic conditions	5.6	9%	78%

Respondents from all four Towers used open-ended questionnaire items to complain about, or praise, the acoustic conditions in their suites. There were three main areas of acoustic complaints: noise from neighbours, noise from common areas, and noise from HVAC system. As was the case with controls, these comments were largely negative and the majority focused on the noise caused by the HVAC system, suggesting that HVAC noise is something with which respondents are dissatisfied.

Table 3.4 shows the results of noise measurements taken in eight different units in Towers A and D. Results from the octave band analyzer were entered into a spreadsheet calculator which was developed by Dr. Densil Cabrera, Director, Audio & Acoustics Program, The University of Sydney. This calculator measured decibels from eight octave bands to calculate Quality Assessment Index (QAI) which is a part of the RC rating and denotes the predicted character of the sound, as well as likely objectionable qualities (Forouharmajd, Nassiri, Monazzam, Yazdchi, 2012). The American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) guidelines for noise caused by residential ventilation equipment state that “a QAI that exceeds 5 dB but is less than 10 dB represents a marginal situation, in which acceptance by an occupant is questionable. However, a QAI greater than 10 dB will likely be objectionable to the average occupant" (ASHRAE, 2011). ASHRAE also prescribes that ventilation systems be free from "fluctuations in level such as throbbing or pulsing" (ASHRAE, 2011).

The QAI results for Tower D show significant variation, but overall the readings confirm respondents' questionnaire responses that HVAC noise is a source of dissatisfaction (see Table 3.3). The results from the two measurements taken in Tower A are in the ASHRAE marginal category, indicating that dissatisfaction could be justified.

Table 3.4: Noise measurements

Location	QAI (dB)	Predicted Objectionable Qualities
Tower D: Bathroom fan	10	Hiss
Tower D: Bathroom fan	7	Slight hiss
Tower D: All fans	13	Mid-frequency roar
Tower D: All fans	8	Rattle
Tower D: Bathroom fan on high	20	Mid-frequency roar
Tower D: Bathroom fan on high	13	Hiss, rattle
Tower A: All fans	7	Slight hiss
Tower A: Bathroom	5	None predicted

Indoor Air Quality Measurements

Table 3.5 shows data collected by the IAQ monitoring device and indicates better indoor air quality in the suite belonging to an ERV user. Only two suites could be measured due to a lack of access to the study population for this phase of the study. Both suites were measured on the same day in March 2014, and both had the same thermostat setpoint, with occupants who had been away at work all day and had not showered or cooked since they returned home. One had their ERV running in intermittent mode all day, the other had it switched off for the last three months. It should be noted, however that the IAQ measurements in the ERV non-user suite are within the guidelines recommended by Health Canada (Health Canada, 2013).

Table 3.5: Indoor air quality measurements

	CO_2 (ppm, avg.)	Humidity (avg.)	PM 2.5 (avg. mg/m^3)	VOC (ppb, avg.)
ERV User	572	24.2%	0.003	552
ERV Non-user	673	21.7%	0.014	617

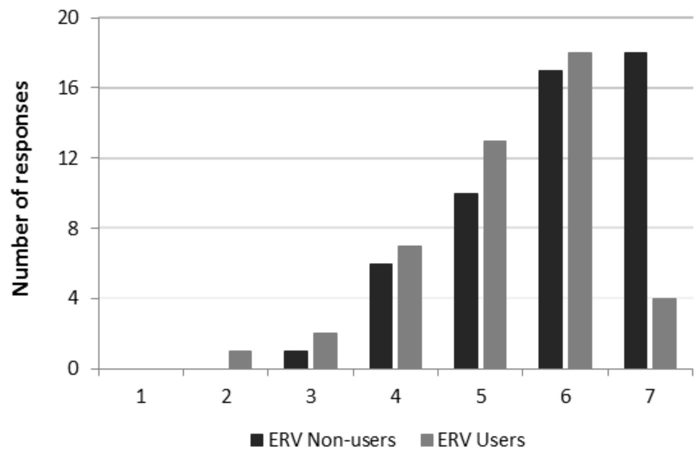

Figure 3.2: Questionnaire scores for satisfaction with overall IAQ

Table 3.6 shows the results from questions which asked occupants to rate their satisfaction with indoor air quality. Results for overall satisfaction have been show graphically (Figure 3.3) in order to further represents the range of responses received. Interestingly, ERV non-users reported higher satisfaction with overall IAQ, but slightly lower satisfaction with the freshness of their air.

Table 3.6: Indoor air quality satisfaction in ERV users and non-users

	Mean	Percent Dissatisfied	Percent Satisfied
Overall IAQ satisfaction (Ideal = 7)			
ERV user	5.27	6%	67%
ERV non-user	5.87	13%	87%
Freshness of air (Ideal = 1)			
ERV user	3.29	10%	37%
ERV non-user	3.42	21%	48%

Knowledge and Preferences

The majority of respondents (76%) from Towers A, B, and C indicated that either the balcony door or their operable windows were the primary means by which they provided fresh air into their suite during winter (15% responded that they primarily use their ERV). In Tower D, 63% of respondents reported using their balcony door or windows (19% responded that they use their ERV). These results clearly suggest a preference for passive ventilation which will be discussed.

Though this chapter was not explicitly designed to understand the knowledge of occupants, interviews with two ERV non-users revealed that ventilation for them meant getting fresh air into the suites via operable windows (i.e., passively). One respondent indicated how great it was to finally have a balcony door that she could use to get more air into the suite, instead of only having windows.

There is also evidence that respondents do not know how to use their ERV to rectify IEQ problems in their suites. For example, an ERV non-user reported during an interview that condensation occurs on the inside of windows during winter. This would occur because of excess moisture from cooking, bathing, and breathing which was not exhausted sufficiently. This respondent had abandoned use of their ERV because of perceived ineffectiveness, despite it being able to improve the conditions in their suite (i.e., the ERV can regulate humidity in winter by exhausting excess moisture and by using a desiccant core to transfer moisture to incoming air). Passively ventilating would not work well in such conditions because it would be letting in too much cold winter air. Interestingly, this family rationalized their condensation problem by saying that it was not as bad as the condensation they observed on the widows in the conventional residential tower they could see from their 'green' dwelling.

Learning

Over half of the respondents from Tower D (52%) said that it became easier over time to control the indoor environment of their suites, suggesting that achieving IEQ satisfaction is an iterative process which improves over time. In Towers A, B, and C, ERV use appears to be positively related to length of tenancy. Fifty-seven percent of people that have lived there for longer than a year were ERV users, whereas only 25% of those who have lived there for less than one year used their ERV. One possible reason for this is that respondents who have been in their suite for over a year were more likely to have been involved in the initial handover process which included a training manual.

To explore this, Table 3.7 shows the cross tabulation results between reading the training manual and using the ERV. It should be noted that aside from the training manual presented during the initial handover, no further training about the ERV or any other systems in the dwellings has been carried out.

Table 3.7: Cross tabulation results involving training materials

	Yes	No
ERV user	74%	29%
ERV non-user	25%	71%

Even at first glance, Table 3.7 suggests a positive relationship between reading the training manual and using the ERV. In order to explore this further, Pearson's chi-square statistic was used to determine whether or not a statistically significant relationship exists between the two variables. SPSS conducts this test by comparing the observed frequencies to predicted frequencies (Field, 2009). The test found a statistically significant relationship between the two variables ($p<0.01$). Therefore, it is reasonable to say that in the greater population, an increase in ERV use would likely result from reading the training manual.

The cross tabulation results from Table 8 can be used to calculate an odds ratio, which indicates the odds of ERV use after reading the training manual (Field, 2009). Calculating the odds ratio yields the result that reading the training manual makes a resident 7.11 times more likely to be an ERV user.

It must be noted that occupants' knowledge about ventilation could have come from many other sources external to the formal training provided during building handover, including prior experience, conversations with neighbours, independent research, etc. A limitation of this chapter is that it did not systematically ask occupants to indicate how their ventilation learning has taken place.

Energy Data

Figure 3.4 shows that respondents in Towers A, B, and C who regularly or always use their ERV use more thermal energy (12% heating and 24% for cooling) than those who do not. This is assumed to be because ERV users are actively ventilating their dwelling, meaning that their ERV pre-conditions about 70% of incoming fresh air, with the rest being treated by the fan coil unit (from which the thermal meter reading is acquired). Non-users recycle air from their dwelling, meaning that they do not have to make up the temperature differential caused by bringing fresh air in. Similarly, it makes sense that the difference between ERV users and non-users is greater during the cooling season because the heat exchanger's maximum efficiency is 50% in cooling mode, compared to 70% in heating mode, meaning that only 50% of the energy is transferred from exhaust air into incoming fresh air.

Data for electricity and hot water has been included to suggest that ERV users and ERV non-users are otherwise generally alike in their energy use patterns and that a primary reason for their differing scores for heating and cooling is ventilation use (this will be explored in more detail in future work). It should be mentioned that an increase in electricity consumption would be hypothesized for ERV users as a result of electricity used to run the intake and exhaust fans. Calculations show that operating the ERV in intermittent mode (20 minutes/hour in low speed, 42 watts) would result in 121.0 kWh of electricity consumption over the course of a year; or 3.9% of the average electricity used by suites in Towers A, B, and C (3095.3 kWh/year).

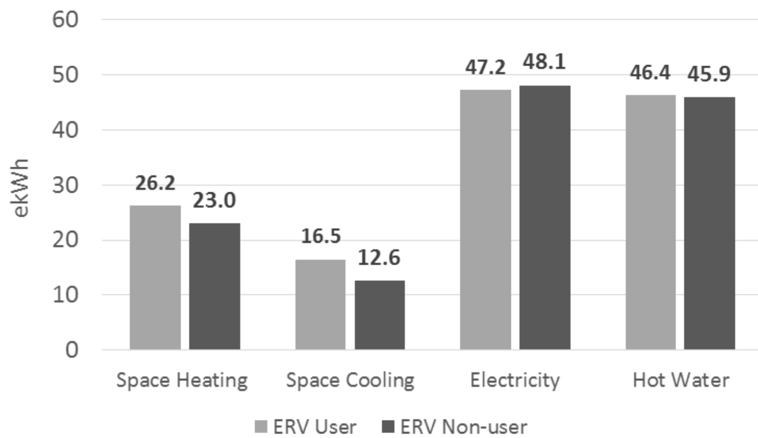

Figure 3.3: Energy and water use between ERV user and ERV non-users

As mentioned, there are no thermal submeters in Tower D, however there is still a way to explore the energy implications of ERV non-use. In addition to the in-suite ventilation, secondary ventilation is provided by a rooftop air handling unit that feeds treated air into the corridors and through the gap under dwelling entry doors. This has a capacity of 7,551 l/s and during the design phase it was predicted that the air handling unit would only have to work at this maximum capacity for a few hours each evening, when residents are cooking and the likelihood of odour-based complaints in commons areas is at its highest.

When a resident disconnects their bathroom exhaust/ERV fan (as 27% did), they immobilize their ERV (i.e., the intake fan turns off as well). This modifies the pressure differential between their suite and the corridor because a properly functioning ERV creates an 11.8 l/s pressure deficit in the suite, causing treated air to be drawn from the corridor.

Owing to the complaints about odours in corridors, building management now operate the air handling unit at 7,551 l/s (i.e., 100% capacity) for 24 hours per day, every day, resulting in increased electricity consumption. It must be noted that there are numerous causes for odors migrating into corridors, including exterior wind pressure, use of operable windows, stack effect, and use of other exhaust fans (e.g., dryer, range hood). Therefore it cannot be said that ERV non-use is driving all of the extra energy being consumed by the air handling unit in Tower D, though it is certainly a factor.

3.4 Discussion

The causes of ERV non-use will first be explored, followed by a discussion of the consequences of occupants choosing passive ventilation strategies instead of mechanical ones.

Control

The ERV control (Figure 3.1) can largely be ruled out as a major cause of ERV non-use. Though respondents indicated feeling the least amount of control over ventilation compared to heating and cooling, they ranked the usability of the ERV control slightly higher than the thermostat and produced zero complaints in open-ended questions, compared to twenty for the thermostat, even among ERV non-users. Baird (2010) found when using the *BUS questionnaire* that respondents were twice as likely to complain than to offer praise in open-ended questions. If the occupants of Towers A, B, or C had complaints about the ERV control, they likely would have offered these in the same way they had for the thermostat. Therefore, it is unlikely that the control is driving ERV underuse.

Filter Maintenance

For at least some of the respondents (16% of those who provided additional comments), difficulty maintaining the filter led to ERV non-use. This echoes some of the findings of Carmona-Andreu, Stevenson, and Hancock, (2013), in which participants were challenged by the task of maintaining the filter in their mechanical heat exchanger. Improving the accessibility of these systems should be a concern for designers if they are seeking to encourage stewardship over the system. In Tower D, building managers have tasked maintenance staff with cleaning and changing filters. Given the present findings, this management strategy seems appropriate for other towers as well and will be recommended to them in subsequent reporting.

HVAC Noise

Questionnaire scores, comments, and interviews reveal occupant dissatisfaction with the amount of noise caused by their HVAC systems. According to noise measurements taken of functioning HVAC systems, these complaints are largely warranted. This is especially true in Tower D where QAI values were high and where the noise caused by continuously running bathroom fans prompted 27% of respondents to disable their fan, negating their ERV entirely. As mentioned, in Tower D, 66% of residents reported being satisfied with the level of control they had over heating and cooling, compared to 40% for ventilation. It is reasonable to expect that this perceived lack of control has something to do with the quantifiable excess noise caused by the always running bathroom fan, and their inability to abate it via accessible controls (i.e., an 'off' switch).

ERV non-users in Towers A, B, and C reported in questionnaire comments that the noise caused by their HVAC system was a factor in their decision to abandon ERV usage; despite the fact that the manufacturer's sound rating for the ERV unit is only 3 sones (i.e., QAI < 5). It seems likely that their noise complaints stem from frustration with noise from the central fan coil heating and cooling system, which is responsible for delivering heated or cooled air through the suite, as well as fresh air from the ERV. In other words, these occupants have a very quiet ERV which delivers air via a relatively loud fan coil system. This has prompted at least some of the respondents to discontinue using their ERV as an acoustic coping strategy. These people likely never turned the ERV back on as it kept their HVAC system dormant and quiet in between calls for heating or cooling. Excessive noise, then, is another driver of ERV non-use in all four study towers.

Ventilation Preferences

Results presented above suggest a preference for passive ventilation, as the majority of respondents in all towers indicated that their windows and balcony doors were the primary means by which they ventilated their suites. It is clear that in some cases what could be perceived as a preference for passive ventilation is really just an occupant using their windows to ventilate because they are unaware of their ERV. As mentioned, there is a significant relationship between receiving training and ERV use. Only after being made aware of the benefits and functionality of the ERV could the preferences of these occupants properly emerge.

Other occupants appear to favour passive ventilation because they conceptualize ventilation as passive instead of mechanical. This is reminiscent of work done by Kempton (1986) which found that as many as 50% of Americans employed "folk logic" and operated their thermostat as if it were a valve, which is inconsistent with engineering knowledge and results in suboptimal operation. It could be said that some occupants (in particular the ones who were oblivious to their ERV) in the present study buildings were employing a sort of folk logic which led to them conceptualizing their ventilation options as passive instead of mixed-mode, resulting in the absence of mechanical ventilation behaviours.

However, there are also respondents who indicated on questionnaires and during interviews a clear preference for passive ventilation, praising operable windows and minimizing the role of the ERV in the 'ecosystem' of their suite. The fact that this preference emerged in a 'green' building which people bought into presumably in part because of its environmental controls, speaks to power of the preference for passive ventilation.

It should be noted that there are many reasons why this preference for passive ventilation could emerge, including connection with nature, familiarity, convenience, folk logic, a preference for unconditioned air; all of which are areas where more work is needed. Also, as mentioned, Leaman (in Yudelson & Meyer, 2013) asserts that some occupants may not be interested in having to operate complex buildings. It could be that the some of the respondents purchased their homes with the expectation that certain processes would not need to be managed, including ventilation. This is an area where further work is warranted. It should also be noted that though passively ventilating may seem simple (e.g., opening a window), an occupant who engages in this behaviour would ideally understand the role that wind pressure, stack effect, and pressurized corridors play on the consequences of drawing fresh air into their suites using their windows. This of course would require enhanced occupant training (and perhaps even building manager education), which will be discussed later.

Indoor Air Quality

Though only consisting of a sample of two units, the indoor air quality measurements taken in an ERV user suite are better than those of an ERV non-user, with lower levels of carbon dioxide, particulates (PM 2.5), and volatile organic compounds (Table 3.5). This is to be expected, as mechanical ventilation is more consistent than passive ventilation, and the ERV units are equipped with an air filter.

Interestingly, however, ERV non-users reported slightly higher overall satisfaction with indoor air quality in their dwellings. One possible explanation for this is that giving occupants access to effective environmental controls is a factor in their satisfaction (Baird, 2010; Leaman & Bordass, 2001, Combe et al., 2011). It is therefore likely that some of the higher satisfaction expressed by ERV non-users has to do with their being involved in managing their own ventilation passively, whether or not they are unaware of -or have abandoned using- their ERV.

It must also be noted that the IAQ measurements taken in the ERV non-user home were well within Health Canada guidelines, suggesting no major problems with IAQ in the passively ventilated suite. An area of further work involves collecting IAQ data from a greater number of suites in order to explore this.

The Ideal Ventilation Scheme?

It can be argued that ERV non-users are beneficial to building performance as they appear to be more satisfied with their IAQ , and are using less energy during the heating and cooling seasons; the latter being more important because of peak electricity demand concerns (see Figure 3.4). Clearly, energy efficiency which is driven by ERV non-use should not come at the expense of IAQ. However, the fact that ERV non-users are satisfied with their IAQ lends validity to the argument. Additional testing, including logged measurements instead of single ones, would be required in order to determine the extent to which ERV use contributes to enhanced IAQ.

It is also worth remembering that decentralized, in-suite ventilation schemes are seen as a significant energy efficiency design alternative to centralized (e.g., ‘roof-top’) ventilation schemes, which consume a great deal of energy in their effort to conform to ASHRAE guidelines. If occupants reject their mechanical ERV in favour of passive ventilation via operable windows, and are not suffering from inclement IAQ or high energy use, then decentralized mechanical ventilation becomes even more attractive. It is possible that it may be worth installing simple decentralized extract mechanical systems and allowing passive ventilation, rather than investing in more expensive ERV systems that are underused or unused.

It must be said, however, that the ideal occupant for a building is one who is familiar with the functioning and underlying logics of their home’s systems and utilizes them to achieve both comfort and energy efficiency. As mentioned above, this would require enhanced education on the part of building occupants, and would require managers to not only understand these phenomena, but also to procure outreach materials which effectively convey various building science principles. This discussion is carried on in greater detail in Chapter 5.

Implications for Design

There are numerous ways that the findings from this chapter can be of use to designers and managers of high-rise residential ventilation systems; for example the uncovering of a clash between designer expectations and occupant thinking and behaviours. In behavioural economics, individual behaviour is understood as not always being rational or reflective of an individual's best interest. A similar phenomenon could be said to be going on in these towers where occupants in search of fresh air overlook the most effective source (i.e., the ERV, which provides evenly dispersed, comfortable, filtered air) in favour of their operable windows and balcony doors. Designers need to remember that occupants are embedded in design decisions made long before they come to occupy a space and bring with them expectations, perceptions, capabilities and preferences, all of which combine to produce the achieved performance of their dwelling.

The provision of in-suite mechanical ventilation by designers has in part been undermined by a preference on the part of occupants for passive ventilation. In designing a mixed-mode building, it is unclear the extent to which designers of the study buildings wanted occupants to rely solely on mechanical ventilation, but it is likely that the relatively low usage rates would be considered undesirable by designers, especially during the extremes of summer and winter. Based on results above, if designers want higher ERV usage rates, then ongoing occupant training programs must be in place which alert occupants to the functionality and usefulness of their mechanical ventilation systems, while at the same time offering advice on how and when to exercise their preference for passive ventilation.

There should also be greater design team accountability around the uptake of design decisions. Whether through goal setting or monitoring, designers should be encouraged to track the success of innovative design strategies like the ones deployed in the study buildings. This does not appear to be the norm in the Canadian design and construction industries.

Designers also need to use resilient design in such a way that embraces the agency of occupants, giving them the ability to exercise their preferences in ways that do not short circuit the IAQ or energy performance of their suite or their building. Whether intentionally or not, Towers A, B, and C possess a resiliency that allows some occupants to exercise their preference for passive ventilation in a way that is neutral or even beneficial. In contrast, the disabling of loud ERV fans in Tower D caused problems in the ventilation ecosystem of the entire building. Results suggest that giving occupants full control over their

ERV (instead of the 'black-boxed' approach adopted by Tower D) is preferable because it allows them to modulate their ventilation needs alongside their complex and subjective IAQ expectations, saving energy in the process.

Despite this finding, however, in subsequent buildings the designers responsible for Towers A, B, and C have started to install ERVs which are integrated into the fan coil units, bypassing direct occupant control. The findings from this chapter will be fed forward to these designers in the hopes that future design decisions are well informed.

The final recommendation is that if mechanical ventilation systems are to be used, designers must ensure that their detail design does not alienate users. For example fan noise must be minimized. Designers need to specify HVAC equipment (e.g., fans) which produce very little noise. As was shown, the unacceptable acoustic quality of the ERV fan prompted Tower D occupants to manually disconnect them, thereby unintentionally altering the ventilation ecosystem of the entire building; affirming Yudelson & Meyer's (2013) claim that "wrong user behaviour can easily screw up the whole performance." Similarly, results from Towers A, B, and C highlighted that an ultra-quiet ERV which uses an acoustically objectionable fan coil system to distribute its air risks being rejected by users. An HVAC system is only as quiet as its loudest component.

3.5 Conclusions

The data collected and analyzed in these four buildings was useful in discovering how occupants interact with their ERVs and their controls. It was shown that the ERV control is likely not the reason that people avoid using their ERV. Rather, the following reasons were identified: acoustic dissatisfaction, difficulty with accessibility of filters, lack of ventilation knowledge, and engagement with training materials.

It was also found that ERV non-use had implications for IAQ and energy consumption. Specifically, ERV non-use does not seem to have a negative impact on IAQ from the occupants' perspective, and only marginally using quantitative measurements. Similarly, ERV non-users consume less heating and cooling energy that those who use their mechanical ventilation systems as designed. These unintended consequences are likely poorly understood by designers, occupants, and researchers alike, and are a valuable outcome of the current work.

As described above, multiple outcomes from this work ought to be applied by building designers and managers. It was discussed that ongoing occupant training is something which managers ought to consider, and which should happen alongside greater design team accountability. The use of resilient design and the provision of total control over ventilation are two strategies which were suggested for designers. It was also suggested that detail design be acoustically appropriate in order that it not alienate users. These findings will be shared with the design professionals, managers, and occupants involved in the study buildings, and also with the greater design community.

This chapter supports the need for the design and management industries to mandate the type of 'aftercare' advocated in the Soft Landings Framework (Usable Buildings Trust, n.d.). Without it, comprehensive, researcher led, post-occupancy evaluations in such buildings ensure the continued improvement in performance of this segment of the building sector.

In summary, Chapter 3 used quantitative and qualitative data to develop a complex explanation for ventilation behaviour within the study suites. In particular, it was found that:

1. 52% of respondents were found to not use their ERV;
2. This was due to: acoustic dissatisfaction, difficulty with accessibility of filters, occupant knowledge and preferences, a lack of engagement with training materials;
3. That occupants who engage with their training materials are 7 times more likely to use their ERV;
4. Results suggest that abandoning mechanical ventilation in favour of passive ventilation can actually lead to greater satisfaction with IAQ and to decreased energy consumption.

3.6 Bridging Section

As discussed above, Cole et al. (2008) suggest that the various systems and technologies in green buildings "may involve new responsibilities and require a commitment from occupants" (p. 326). Given the novelty of the ventilation design in the study buildings, this seems to be the case. Occupants in this building type had not been asked to manage their own mixed-mode ventilation scheme before, and their reactions were varied and unpredictable. As mentioned, the issue of how much control to give these occupants is complex, but given respondents' observed preference for passive ventilation, and their ability to exercise this preference, Chapter 3 seems to reaffirm the conventional wisdom that access to environmental controls increases satisfaction.

Leaman, Stevenson, and Bordass (2010) present a spectrum of situations ranging from those that require no intervention on the part of building occupants (e.g., the heating of water), to those that are entirely dependent on occupant behaviour (e.g., opening windows). It certainly seems that the designers of the study building misplaced ventilation along this spectrum. That is, they assumed that occupants would run the ventilator in intermittent mode, as designed, and did not account for "unanticipated operating modes for innovative technologies" (Leaman, Stevenson, & Bordass, 2010, p. 565).

This is problematic, as Leaman, Stevenson, and Bordass (2010) point out:

> Without adequate inputs of management and maintenance resources, buildings may quickly assume vicious circles of deterioration and dysfunctionality. This process usually starts with poorly executed handover and commissioning, so that chronic performance inefficiencies are built in from first occupancy. Once present, these can become embedded, and then quickly create conditions for chronic failures like occupant discomfort and poor energy performance (p. 572).

In uncovering and explaining ventilation behaviours in the study towers, Chapter 3 was able to use the drill-down method of inquiry espoused by Leaman, Stevenson, and Bordass (2010). That is, once the behaviour was uncovered, additional data was used to further understand why this behaviour was emerging in the present context, as well as the effect it was having on energy consumption, indoor air quality, and occupant satisfaction.

As mentioned, while Chapter 2 presented rigorous results, its focus was limited to defining and explaining energy use in the study buildings. Chapter 3, on the other hand, used most of the available data to rigorously explore a specific behaviour that pertained to satisfaction, IEQ, and energy use in the study buildings. Chapter 2 derived its success from being able to determine the extent to which occupant behaviour and demographics explained energy consumption, whereas the success of the third chapter comes from explaining and contextualizing why a specific behaviour emerged, and the various effects that it had. Taken together, the two chapters offer insight into how behaviour is shaping energy use in the study buildings as well as a strong justification that the collection of qualitative data from building occupants can yield very valuable insights into the effectiveness of building design and management decisions, as well as providing an enhanced understanding of energy and water consumption. In doing so, this chapter has further shown that real world research involving the combination of qualitative and quantitative data can yield valuable insights.

In order to complete this drilling-down process, Chapter 4 includes a systematic evaluation of user comments. Chapter 4 uses all available questionnaire comments to explore other possible behaviours, instead of just one (i.e., ventilation behaviour). Chapter 3 demonstrates the importance of understanding and contextualizing a specific behaviour, but is not able to explore *the range* of the behaviours which emerge in the study buildings. As Leaman, Stevenson, and Bordass (2010) point out: "buildings are self-evidently settings or 'contexts' for human activity and behaviour" (p. 571). Though this discussion has been substantially started in Chapter 3, the work presented in Chapter 4 represents its apex.

4. THE POWER OF QUALITATIVE DATA IN POST-OCCUPANCY EVALUATIONS[2] OF RESIDENTIAL HIGH-RISE BUILDINGS

4.1 Introduction

Evaluating buildings is important and academic work that benefits not only those who occupy the buildings, but society as well. Understanding the various discrepancies between predicted and actual performance (i.e., the performance gaps) is essential in delivering the best buildings possible. To do this, those involved in the design and management of buildings must collect feedback about their projects and ensure that past mistakes are not repeated (Leaman, Stevenson, & Bordass, 2010). As discussed in Section 1.3.1, feedback from residential building occupants in Canada is rarely carried out in a way that produces rigorous, publically available insights into performance and satisfaction. This chapter will address this shortcoming, and in doing so will demonstrate the methods, utility, and results of conducting qualitative research in Canadian high-rise residential buildings. The present chapter also strives to show the importance and utility of questionnaire comments in producing useful feedback for designers and building managers.

4.1.1 Literature Review

Post-occupancy evaluation involves gathering feedback about how buildings are being used and experienced in order to evaluate the extent to which they are meeting designers' and users' expectations. The majority of work in this area has been carried out in European buildings (e.g., Gupta & Chandiwala, 2010; Stevenson & Rijal, 2010; Williamson, Soebarto, & Radford, 2010; Shipworth et al., 2010; Gill, Tierney, Pegg, & Allan, 2010) with limited work being conducted in the North American context (e.g., Beauregard, Berkland, & Hoque, 2011; Bennet, O'Brien, & Gunay, 2014; Finch, Burnett, & Knowles, 2012; Binkley, Touchie, & Pressnail, 2013). This is important because of all North American cities, New York City is the only one with more buildings over 12 stories than Toronto (including office towers) (McClelland, 2011).

As discussed in Section 1.2 the desire to produce quantifiable results often leads to a lack of qualification in findings and that avoiding this misstep should be a priority for building evaluators. In the case of high-rise residential buildings, contextual elements include occupant behaviour and perceptions, design

[2] The phrase post-occupancy evaluation has been used here instead of building performance evaluation because the journal to which this manuscript was submitted prefers the term. Throughout this chapter, building evaluation will be used instead, in order to be consistent with the rest of the dissertation.

decisions, management strategies, and the like. Nicol and Humphreys (2002) show how contextual elements within a building (e.g., access to controls, outdoor climate, ventilation design) shape occupant comfort, and in doing so highlight the ways in which the context of a building can shape and influence occupant behaviour.

Case study research specializes in exploring specific contexts in detail. As mentioned, a full understanding of contextual elements, and how they relate to building performance and occupant satisfaction, has not been carried out in Canadian residential buildings. For example, when evaluating the performance of high-rise residential buildings (even those which have sought accreditation through the Leadership in Energy & Environmental Design [LEED] program) there is a tendency to simply report modeled predictions, or to superficially verify energy performance in relation to targets and benchmarks, instead of gathering useful feedback which can inform present management and future design practices.

Though this situation arises understandably in some part because of the quantitative-expertise of the building industry, another methodologically relevant explanation is that there are detrimental misunderstandings around mixed-method and case study research that prevent qualitative research from being undertaken (Flyvbjerg, 2006). One misunderstanding is that "general, theoretical (context-independent) knowledge is more valuable than concrete, practical (context-dependent) knowledge" (Flyvbjerg, 2006, p. 221). An example of this is the prevailing wisdom that occupant questionnaires are only useful in tracking occupant satisfaction with thermal comfort, lighting, and acoustics. This approach is exemplified in the ASHRAE Performance Measurement Protocols for Commercial Buildings where questionnaires are the first step in assessing indoor environmental quality [IEQ] in commercial buildings. However, a well-designed questionnaire can highlight complex issues that would not otherwise have been uncovered using a purely quantitative approach.

4.1.2 Objectives

In this chapter the comments received from occupants of four case study buildings are used to develop a rich contextual understanding of the study buildings to explore what are the design and performance challenges being faced by occupants of these buildings, and to what extent can qualitative research yield valuable insights into the design and performance of green residential buildings. Beyond measuring satisfaction with indoor environmental quality, this chapter explores how occupants are reacting to and behaving in this increasingly popular building type. It also considers what is the best way to work with questionnaire results in order to produce valuable feedback, as well as determining who stands to benefit from building evaluations in high-rise residential buildings.

4.2 Methods

Applying the POE methodology in residential buildings requires a range of research activities, and often constitutes mixed-method case study research. Yin (2009) defines case study research as “a strategy for doing research which involves an empirical investigation of a particular contemporary phenomenon within its real life context using multiple sources of evidence” (Robson, 2011, p. 136). In this case, the contemporary phenomenon is Toronto’s ubiquitous highly-glazed, high-rise residential towers, and the multiple sources of evidence include questionnaires, interviews, energy and water consumption data, and researcher observations; though the focus is on qualitative data, as is common in case study research (Robson 2011).

The present chapter is based on four case studies, conducted in four high-rise residential towers in Toronto (see Section 1.4.1 for a full description). Scores from the BUS questionnaire will be presented by providing a mean and standard deviation for all four buildings combined. As a result of using the Building Use Studies questionnaire, the results from the study buildings can be compared against benchmarks generated from the BUS database. As Baird (2010) points out the BUS benchmarks “are simply the mean of the scores for each individual [question], averaged over the last 50 buildings entered in to the BUS database.” Comparing the data from these buildings to the BUS benchmarks will help provide some context to the results, but should be considered with caution as the cases in the BUS database are all in Europe and there is no experimental control for building or occupancy characteristics. Nevertheless, the results are reported using **bold** text to indicate when the study mean is better than the BUS benchmark.

Questionnaire comments were processed using the statistical analysis software package NVivo to perform a content analysis, considered to be a quasi-statistical approach (Robson, 2011). To a certain extent, the content analysis was exploratory, with all comments being coded. However, due to familiarity with the data set, and with problems in buildings in general (e.g., acoustics), the thematic coding (organizing comments under specific labels) was confirmatory to a certain extent (Gibbs, 2007). Both semantic (i.e., literal) and latent (i.e., interpretive) coding were carried out (Braun & Clarke, 2006).

Some responses were useful in their literal form, whereas others yielded benefit only after being interpreted.

Within thematic elements (e.g., lighting, a sub-section of IEQ), comments were only coded as positive or negative; balanced categories, so-called, were not created. Some comments were coded into more than one theme. For example, extreme discomfort during shoulder seasons was put in “critical: heating” and “critical: cooling.” Zalejska-Jonsson (2012) writes that comments enabled the gathering of “inside information” and that “voluntary answers helped to capture some of the key problems and main reasons for occupants’ satisfaction and dissatisfaction” (p. 137). Zalejska-Jonsson (2012) also advocates using interviews with property managers to gather contextual information about a building.

Baird and Dykes (2012) reported a ratio of negative comments to positive comments and suggested that when “the ratio exceeds a value of 10:1… clearly there are issues requiring attention.” Similar ratios will be reported throughout the chapter, as well as analysis of the usefulness of this method.

Semi-structured interviews were carried out with nine residents, two property managers, and one superintendent. More interviews would have been conducted, but access proved to be difficult as the project proceeded. Results from these interviews have not been coded. This decision was made because the contextual information that this chapter seeks to provide was effectively generated without the need for coding.

4.3 Results

4.3.1 Response Rates

As shown in Table 1.3, an overall response rate of 17.9% (n=165) was achieved. This is far lower than Zalejska-Jonsson (2012) who received a response rate of 50% for a similar housing type, though with respondents in Sweden. In non-residential buildings response rates are generally around 35–50% for web-based surveys and 70–85% for paper ones (Dykes & Baird, 2013). Having said that, given that the rate was relatively stable across the four study buildings (see Table 2), 17.9% seems like an appropriate target for this building type in Canada.

Each of the 165 completed questionnaires contained 13 comment boxes. The maximum number of comments, therefore, is 2,145 (i.e., 165 x 13). Seven hundred comments were received, for an overall commenting rate of 32%. Almost all respondents offered at least one comment, with only 5.5% (n=9) offering no comments. For context, in commercial and institutional buildings 34% of people commented in Baird and Dykes (2012), suggesting that residential respondents are far more likely to comment. Of the 700 comments received, 255 offered praise while 445 offered criticism, for an overall ratio of 1.8:1. In commercial and institutional buildings, Baird and Dykes (2012) found that "the overall ratio of negative to positive comments was 2.23:1" (p. 38).

4.3.2 Qualitative Insights

Using NVivo, the main themes that emerged during coding were: building envelope, HVAC, hot water, IEQ, layout and design, and miscellaneous. As mentioned, these themes we largely exploratory, emerging during the coding process instead of existing *a priori*. Each theme is composed of certain thematic elements, which are not distinct enough to warrant their own theme.

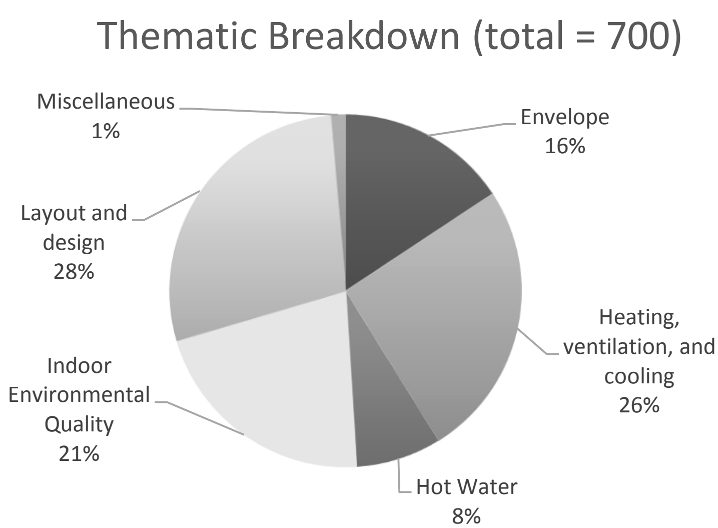

Figure 4.1: Breakdown of themes

Figure 4.1 shows the prevalence of each theme in respondents' comments. Layout and design received the most comments, which was echoed by Baird and Dykes (2012), though in the commercial/institutional setting. In the interest of conserving space, results for layout and design are only conveyed in Table 4.1 as they did not result in significant feedback for designers or managers. Each of the remaining themes will now be explored in order to determine the nature of the feedback that was given for each.

Table 4.1: Themes and thematic elements

Theme	Thematic Elements	Number	Ratio	Feedback to?
Envelope (n=110)	Praise - Balcony	22		Design
	Critical - Balcony	36	3.7:1	Design and Management
	Praise - Windows	15		Design
	Critical - Windows	37	1.6:1	Design
HVAC (n=178)	Praise - Heating	18		Design
	Critical - Heating	23	1.3:1	Design and Management
	Praise - Cooling	7		Design
	Critical - Cooling	31	4.4:1	Design and Management
	Praise - Ventilation	8		Design and Management
	Critical - Ventilation	64	8.0:1	Design and Management
	Praise - Thermostat	6		Design
	Critical - Thermostat	21	3.5:1	Design
Hot Water (n=55)	Praise - Water	22		Design and Management
	Critical - Water	33	1.5:1	Design and Management
IEQ (n=150)	Praise - Lighting	6		Design
	Critical - Lighting	44	7.3:1	Design
	Praise - Daylighting	14		Design
	Critical - Daylighting	8	0.6:1	Design
	Praise - Noise	8		Design and Management
	Critical - Noise	70	8.8:1	Design and Management
Layout and design (n=198)	Praise - Appliances	35		Design
	Critical - Appliances	23	0.7:1	Design
	Praise - Laundry	47		Design
	Critical - Laundry	14	0.3:1	Design
	Praise - Layout and Design	40		Design
	Critical - Layout and Design	37	0.9:1	Design
	Praise - Master Switch	2		Design
Misc. (n=9)	Praise - Security	5		Management
	Critical - Security	4	0.8:1	Management
	Praise	**255**	**Design**	**451**
	Complaint	**445**	**Design/man.**	**241**
			Total	**700**

4.3.2.1 Envelope

When asked to comment about their balcony, 38% of respondents (n=22) offered praise, while 62% (n=36) offered criticism. This resulted in a negative comment ratio of 3.7:1. The majority of complaints (69%) focused on the balcony being too small to be useful for respondents.

When asked to comment about the windows in their suite, 23% (n=15) offered praise, while 77% (n=37) offered criticism. This resulted in a negative comment ratio of 1.6:1. On the questionnaire, windows received a mean score of 5.8 out of 7, with a standard deviation of 1.28.

The praise focused on the views that the large windows afforded respondents. Some criticisms arose as a result of respondents wanting more operable windows (n=2), or that windows were letting in too much light (n=2). The primary criticism, however, was that the windows negatively affected the thermal comfort of the occupants. Nineteen comments were received which reported that windows caused cold conditions during winter, and ten comments which indicated that windows were leading to overheating during the summer. Comments include:

- "The area near the windows gets very cold in the winter. They don't seem to provide very much insulation."
- "While floor to ceiling windows/walls are nice, they are a huge conductor of energy loss"
- "Very drafty near balcony door"
- "Draft by balcony door, can have ice buildup there"
- "Can get very hot in summer"

4.3.2.2 HVAC

The elements that make up the HVAC theme are: heating, cooling, ventilation, and thermostat. When asked to comment about their heating system, 38% of respondents (n=18) offered praise, while 62% (n=23) offered criticism. This resulted in a negative comment ratio of 1.3:1. The only questionnaire item pertaining to heating asked respondents to rate the amount of control they felt they had over heat. On this question respondents produced a mean score of 5.6 out of 7, with a standard deviation of 1.38.

Praise was often very simplistic. For example, when asked to comment on things which worked well in their suites, many respondents simply wrote "heat." Criticisms of the heating system focused on uneven heat distribution around the suite, and discomfort during shoulder seasons. Shoulder season complaints are common in buildings with two-pipe fan coil systems, as the suites can only be provided with either heat or cooling. The majority of comments though, reflect feedback for designers about the size and design of the heating system. Comments indicative of this include:

- "Needs more vents throughout the suite. Only two vents in common living space, none in bathroom or bedroom."
- "Heating system thermostats are not very responsive to temperature change"

When asked to comment about their cooling system, 38% of respondents (n=7) offered praise, while 62% (n=31) offered criticism. This resulted in a negative comment ratio of 4.4:1. This ratio is much higher than the ratio for heating, indicating a higher degree of dissatisfaction on the part of respondents. When asked to rate the amount of control they felt they had over cooling, respondents produced a mean score of 5.4 out of 7, with a standard deviation of 1.59.

Criticisms arise from dissatisfaction with shoulder season temperatures (n=5), uneven distribution throughout suite (n=7), and the system not being powerful enough (n=20). Comments on the latter include:

- "I feel sometimes that the unit isn't powerful enough. For example, summer setpoint of 21 bring temp only to 23 at the lowest."
- "The HVAC equipment location is poor and never really cools down my place."
- "A/C cannot cool the place down."

When asked to comment about their ventilation system, 38% of respondents (n=8) offered praise, while 62% (n=64) offered criticism. This resulted in a negative comment ratio of 8.0:1, which is significantly higher than heating or cooling, and which is close to the threshold of 10 which (Baird and Dykes, 2012) say indicates a major problem. A large proportion (38%, n=24) of these complaints were about the noise caused by the HVAC system in Towers A-C. This negative feedback about excessive noise is not specific to ventilation, but has been added under this thematic element.

The respondents have a very quiet mechanical ventilation system that delivers air via a relatively loud fan coil system. Noise measurements taken on site (see Chapter 3) indicate that the mechanical ventilation system is not the problem, but rather it is the fan coil system through which the ventilation system's air is delivered. As discussed in Chapter 3, this has led to some respondents abandoning usage of their mechanical ventilation system.

Tower D had a distinct problem with ventilation noise. Nineteen respondents indicated dissatisfaction with the amount of noise generated by the bathroom fan which constantly ran as a means of providing air to the mechanical ventilation system. This was confirmed during on-site acoustics measurements (for measurements and a complete discussion of the consequences of this design decision, see Chapter 3). Respondents from Tower D reported a mean score of 4.1 out of 7 with a standard deviation of 1.42 when asked to rate their satisfaction with the amount of noise from their ventilation system. These comments indicate a major problem in the both the design of the system, and the specification of the fans for the building.

The rest of the ventilation criticisms were about poor ventilation in corridors (n=7, all in Tower D), exhaust fans not working correctly (10), difficulty in changing ventilator filters (n=8), or were comments which displayed a lack of knowledge or being challenged by about the ventilation system (n=9). Comments indicative of a lack of knowledge about the mechanical ventilation system include:

- “Don't know how to use ventilation system.”
- “Should I be cleaning the ventilation system? I did not know this.”
- “Do not know anything about ventilation system.”

When asked to comment about their thermostat, 38% of respondents (n=6) offered praise, while 62% (n=21) offered criticism. This resulted in a negative comment ratio of 3.5:1. When asked to rate the usability of their thermostats, respondents produced a mean score of 5.3 out of 7 with a standard deviation of 1.86. The comments offering praise are fairly generic, for example “Thermostats are easy to use.” The comments which offer criticism tend to focus on incompatibility, or difficulty controlling.

- “Original thermostats were not compatible with HVAC system - we replaced them”
- “Thermostats needed replacing as originals were incompatible with HVAC units”
- “Thermostats hard to program.”
- “I find the programmable thermostat is difficult to set.”

Achieving thermal comfort is certainly a design priority in the study buildings which have received their LEED certification based on the fact that they will satisfy ASHRAE Standard 55 by having 80% of occupants satisfied with thermal comfort (CaGBC, 2013). Though it is difficult to precisely determine whether or not this standard has been achieved in the study buildings, the mean scores certainly indicate a higher level of satisfaction both in terms of the 7-point scale and in comparison to the BUS benchmarks (see Table 4.2).

Table 4.2: Thermal comfort scores

Season	Variable	Ideal Score	Mean	Standard Deviation
Winter	Comfort	7	**5.6**	1.27
Winter	Overall IAQ satisfaction	7	**5.4**	1.27
Summer	Comfort	7	**5.22**	1.58
Summer	Overall IAQ satisfaction	7	**5.4**	1.41
Overall	Indoor environment	7	**5.7**	1.20

4.3.2.3 Hot Water

When asked to comment about the water services in their suite, 40% of respondents (n=22) offered praise, while 60% (n=33) offered criticism. This resulted in a negative comment ratio of 1.5:1. The comments received are varied, indicating a range of experiences and conditions in the buildings. Some respondents praised the hot water delivery, for example: “Good water pressure, always hot.” While others indicated frustration with their hot water service:

- “Hot water takes quite a while to get it going in our shower stall”
- “Sometimes water pressure is weak”
- “The water pressure on the 4th floor is lacking I find a couple of times a week.”
- “Hot water takes too long.”

There was no questionnaire scale item which asked respondents to rate their satisfaction with their hot water services. See Section 3.3.1 for a more detailed description of comments and hot water consumption.

4.3.2.4 Indoor Environmental Quality

Typically, IEQ is comprised of acoustics, lighting, thermal environment, and air quality (ASHRAE, 2012). The present section will only deal with acoustics and lighting, as thermal comfort has been dealt with in Section 3.2.2, and air quality was explored in Chapter 3.

When asked to comment about the lighting conditions in their suite, 12% of respondents (n=6) offered praise, while 88% (n=44) offered criticism. This resulted in a negative comment ratio of 7.3:1. This is a relatively high ratio and suggests dissatisfaction with lighting conditions. Most of the criticisms (83%, n=24) were about the lack of lighting in the unit, especially the lack of overhead lighting. When asked to rate their satisfaction lighting conditions in their suite, respondents produced a mean score of 5.2 out of 7, with a standard deviation of 1.56.

When asked to comment about the daylighting conditions in their suite, 64% of respondents (n=14) offered praise, while 36% (n=8) offered criticism. This resulted in a negative comment ratio of 0.6:1. This ratio is far lower than for artificial lighting. This satisfaction is not surprising given the large number of windows. Of the criticisms received, the majority were about glare and excessive brightness, for example: “Too bright in summer.”

When asked to comment about the acoustic conditions in their suite, 10% of respondents (n=8) offered praise, while 90% (n=70) offered criticism. This resulted in a negative comment ratio of 8.8:1. This is a very high ratio and indicates that respondents are experiencing dissatisfaction in this area.

By looking at the sources of the acoustic criticisms, it is clear that there are two distinct noise issues going on, one in Tower D and one in Tower A-C. Nearly all of the noise criticisms in Tower D arose as a result of the loud bathroom exhaust fan (as was mentioned in Section 3.2.2). In Towers A-C the primary criticism (54% of comments in this theme, n=38) is overhearing noise caused by the respondent's upstairs neighbours (i.e., footsteps, talking, and using the bathroom). Only three such criticisms were received from respondents in Tower D, suggesting that Tower D is doing a much better job isolating suites from the noise of their neighbours.

Table 4.3: Acoustics and lighting scores

Satisfaction with…	Ideal Score	Mean	Standard Deviation
Control over lighting	7	5.4	1.61
Artificial lighting	4	**3.8**	1.22
Natural lighting	4	4.5	1.08
Lighting overall	7	5.3	1.59
Control over noise	7	3.1	1.78
Noise from neighbours*	7	**5.0/5.1**	1.92/1.83
Noise from outside	7	**4.8**	1.80
Noise overall*	7	**5.3/5.3**	1.77/1.66
*indicates scores from each Developer			

Table 4.3 shows that the level of control respondents' reported over noise is far lower than for lighting. Given the dissatisfaction observed in the noise comments, it is interesting to note that three of the four questions about noise had mean scores which were better than the BUS benchmarks.

4.3.3 Additional Insights

Aside from the specific thematic categories explored above, there were additional insights generated using the qualitative data collected during this study. These insights are drawn from respondents' comments, interviews with respondents and property managers, energy and water data, and researcher observations.

4.3.3.1 Hot water use

Figure 2.4 (Chapter 2) shows that the amount of hot water consumed by respondents varies widely between suites. The highest consuming suite used 163.8 m^3 of hot water per year, which is roughly equivalent to 600 bathtubs of hot water per year (U.S. Environmental Protection Agency, 2012). Though it could be true that this household simply took two baths per day, the comments received on the questionnaire suggest another potential cause of the problem. Consider the following comment: "In the morning I run all the taps, including shower, for 15-20 minutes (no exaggeration) before any hot water comes...we would actually set an alarm early to just turn on shower, then go back to bed, then wake up 15 minutes later." As all fifteen minutes worth of hot water would pass through the hot water meter, this clearly identifies an alternative explanation for why some of the suites in the study towers are consuming large amounts of hot water.

The number and nature of the criticisms received in the water theme suggests that this is not an isolated problem within the study towers. At the time of the study, a semi-structured interview was carried out with the superintendent of Towers A and B. This interview confirmed the presence of complaints, and highlighted that the design of the water distribution systems meant that some suites had excellent pressure, while others did not. The superintendent also reported that the buildings were preheating their water to 150^{o}F and then stepping it down to 135^{o}F for delivery to suites. It was not clear why this was being done, but it certainly points to an efficiency opportunity for these buildings.

4.3.3.2 Energy use

Comments received on questionnaires were useful in suggesting explanations for the observed variability in heating and cooling consumption shown in Figure 2.4. One trend that emerged in the comments was that some suites reported ideal conditions all winter long, while others complained that it was too hot, even with their heating system turned off. Consider the following indicative comments:

- "In winter we very rarely turn on heat. It's comfortable and we put the heat on manually when required. Our heating bill is extremely low. We keep our temperature between 65 ^{o}F and 70 ^{o}F degrees F."
- "Thermostat is completely off during winter months."

Meanwhile other suites in the same building indicated opposite conditions:

- "Always need heat in the winter."
- "Sometimes have to open balcony doors to cool the place down during winter."
- "Our unit is always hot in winter, at least 70-71. We installed overhead fans for cooling and black-out shades. We leave 2 windows open at all times, unless extremely cold out."

This is puzzling, given that the suites all have the same HVAC system and general construction attributes (e.g., same windows and fenestration ratio). Certainly the orientation of suites plays some role here (see Chapter 2) but additional comments point to uneven heating of corridors as another potential cause of general suite conditions.

- "Hallway is too warm in winter and too cool in summer"
- "Common areas are generally heated (or cooled) to extreme levels"

- “The staircases have heaters on bottom floor right by door which heats staircases, but no need to heat a staircase to 90 °F...in the winter I always have to take off my jacket before I climb up any stairs or I'll break out in a sweat.”

This could conceivably lead to less heat being used by suites which are on floors with overheated corridors, and could help to explain why some suites use no heating energy at all. The discussion of stack effect found in Chapter 2 is relevant once more here as the movement of air around the building certainly constitutes a significant unknown in the present study.

Similarly, negative comments involving balcony doors suggest that thermal bridging of balconies is not their only liability during the heating season. Rather, various respondents indicated that their drafty balcony door let a significant amount of cold air in during the winter (e.g., “draft by balcony door, can have ice buildup there”). This could help to explain why some suites use so much more heating energy than others.

Chapter 2 showed that occupant behaviour and demographics account for 57% of heating variability and 84% of cooling variability in the study buildings. Though difficult to determine the exact nature of behaviours causing this variability, an interview with a resident reveals that the type of user likely plays a role. Consider the following excerpt from the interview:

> “As the sun moves around the unit (we face east and south) the temperature varies in each season. In winter, we keep the unit at 67-68 degrees and rarely have to put the heat on during the day. At night, we keep it at 66 degrees and need little heat. In summer, we use the a/c to keep the unit a comfortable temperature. In the shoulder seasons, we use little heat or a/c.”

This interviewee mentioned that she was very diligent, and that she tried her hardest to understand her suite and operate it optimally. This is contrasted with the type of respondent who commented: “I know nothing about the ventilation system.”

Though explained more fully in Chapter 3, it is worth mentioning that the present study uncovered a lack of understanding about ventilation on the part of some respondents. For example, during a separate interview, an interviewee reported tolerating condensation on their windows because it was not as bad as the conventional tower they could see across the street, which is far worse. This family had ceased using their mechanical ventilation (which would have solved the condensation problem) because they viewed it as useless. This sentiment was echoed in other comments and is an important insight of the present study.

Chapter 3 showed that occupants who had read their training material for their suite were seven times more likely to use their mechanical ventilation system than those who had not. Comments analyzed in the present study support this. For example, the handover procedure for new owners and renters was criticized in the following ways:

- "Pre-move in walk through was too quick and ineffective."
- "Would like to be briefed by [developer] about how to optimize the energy saving facilities in my suite."
- "I am not aware of many of the things mentioned above, but would like to know more."

4.4 Discussion

In discussing the results above, the emphasis will be on how qualitative data reveals significant performance challenges and opportunities within this building type. As Table 4.3 shows, 38% (11 of 29) of thematic elements result in feedback which is considered relevant to current managers, while all 29 categories are relevant to designers. The result is 29 actionable items that those involved with these buildings could implement to improve the occupant experience, environmental sustainability, or both.

4.4.1 Envelope

The high glazing ratios used in this building type are criticized by those demanding greater sustainability. As Straube (2008) points out, "the size of a building's air-conditioning plant is almost always defined by the glazed area" (para. 4). This outlook is contrasted by developers who perceive that high window to wall ratios are desirable for sales, as well as by customers who are initially impressed with the great views they afford. However, as was shown above, some occupants struggle with the performance challenges that result from such high amounts of glazing (e.g., overheating in summer). These findings suggested that not only would the sustainability of these projects be increased by lower glazing ratios, but so too would occupant satisfaction and marketability. However, it must also be said that some occupants are benefiting from the large windows in their suites, using them for daylighting, natural ventilation, and enjoyment.

The thermal bridging caused by balconies is another sustainability impediment for this building type. It is generally acknowledged that Toronto's balconies are constructed in such a way that they are a major source of heat loss for this building type (RDH Building Engineering Ltd., 2013). The finding that balconies are rarely used if they are under a certain size is valuable as there is much concern that the thermal bridging caused by these balconies should be eliminated by not designing buildings with balconies. Based on this, it seems that designers should either design larger balconies that are more likely to get used, or none at all; in addition to considering using new thermally-broken balcony systems which reduce this problem.

It is also worth mentioning that the negative to positive comment ratios were 1.6:1 for balconies, and 3.4:1 windows. These do not surpass the “10:1” range that Baird and Dykes (2012) recommend, yet major problems were found in each of these thematic categories. This suggests that 10:1 is too high a threshold for indicating problems in this building type.

4.4.2 HVAC

Both the capacity/sizing of systems and vent locations have been suggested as problematic in the study buildings. HVAC professionals responsible for HVAC design in future buildings of this type should try to ensure better air flow and temperature distribution throughout the studies, and also increase the capacity of the cooling system so that it can effectively cool the suite during summer. Since window coverings were not included in the original sale of the study suites, managers should consider suggesting that occupants install them in order to reduce solar gain during summer.

Another source of dissatisfaction within the HVAC theme was the amount of noise generated by the fan coil systems. If a quieter product is available, it seems that designers should specify it instead of the current system. Similarly, the designers of Tower D need to be made aware that having always-running ventilation fans is problematic for occupants, especially is the fans which are specified are qualitatively and quantifiably unacceptable.

Results showed that some respondents are completely unaware of their ventilation system, and therefore do not use it. When this lack of knowledge is combined with the finding that some respondents struggle with ERV filter maintenance it seems that the responsibility for filter maintenance in Towers A-C should be assumed by managers, as it was in Tower D. This would serve as a reminder for occupants to use their ERV, and also ensure that the filter was clean when they decided to use it.

4.4.3 Hot Water

The content analysis of hot water comments indicates a negative comment ratio of 1.5:1. And yet, for at least 33 out of 165 respondents, hot water delivery was a problem. The comments received by these respondents indicate that the wait for hot water can be as long as fifteen minutes. This obviously leads to profligate water use, and helps explain some of the varied consumption observed in Figure 2. The interview with the superintendent of Towers A and B revealed that this problem was known to managers, but seemed to stem from the design of the system, detailed information of which is was not made available. Nevertheless, by collecting occupant feedback, a potentially major design problem has been highlighted. Addressing this problem would increase occupant satisfaction and decrease both energy and water use. Though management was aware of this problem, the present study provides them with an impartial assessment of the conditions in the buildings, which in the case of hot water is not favourable.

These results imply another form of action that ought to result from this work. Specifically, utility bills should be used as a venue for social benchmarking where residents can see how their energy and water consumption compare to their neighbours. This has proven effective in other work (Abrahamse et al., 2005). The occupant highlighted in Section 3.2.3 should be made aware that they are the highest consumer of hot water in their building, and that it is not typical for a suite to use 600 bathtubs of hot water per year.

The organizational structure of the buildings, however, does not facilitate the design, deployment, and evaluation of conservation programs however. At the time of study, the designer/developer demonstrated little interest in the consumption trends of these suites. Similarly, the metering company that provides residents with their utility bills has neither the mandate nor the capacity to rollout and measure a social benchmarking program. On a positive note, though, comments received suggest that the concierge and managers are held in high esteem, pointing to them as a possible facilitator of such a program. Consider the following comments:

- “Good and decent property management and security.”
- “Concierge is a great feature.”
- “Property Manager is amazing. Very attentive to all residence and always very helpful.”
- “The management and concierge are most obliging and friendly.”

4.4.4 Energy Use

Analysis of comments revealed that some suites have difficulty keeping their suite warm all winter while others have never need to use their heat. Chapter 2 showed that only 43% of the variability in heating can be explained by the orientation of the suite, even less for cooling. And therefore, the criticisms about corridors and balcony doors seem all the more relevant here as possible explanations for wildly varying conditions between similar suites. Designers need to assess the extent to which these conditions are a result of poor design, construction inconsistencies, or both.

4.4.5 IEQ

Comments received indicate numerous challenges with IEQ in the study buildings. Regarding acoustic complaints, there are things that management can do (e.g., asking neighbours to be quiet), but the problems were caused initially by a design decision that resulted in excessive noise transfer between suites. As was shown, the design and construction of Tower D was done in such a way that the noise complaints about upstairs neighbours received in Towers A-C were completely absent. Though beyond the purview of this study, this points to a major deficiency and customer satisfaction issue that designers ought to take into account in future buildings. This is a useful piece of feedback for designers of these towers, who ought to be producing better acoustic conditions for their customers. The same issue arises from the loud fans specified for Tower D. Somewhere in the specification and construction process, poorly performing fans were chosen, this had had serious consequences in the building (see Chapter 3).

The same phenomenon was observed with a lack of overhead lighting in the study suites. Respondents from all towers indicated that the lack of overhead lighting in their suites was a problem; especially since fixing it required major, and costly, renovations to their suites. This is an area of further study, as the design industry needs better information to act upon in design the lighting schemes for these dwellings.

Table 4.4: Specific feedback for each theme

Theme	Feedback	Audience
Envelope	- Highly glazed suites cause comfort problems for occupants.	Designers
	- Balconies need to be large enough to be perceived as useful.	Designers
	- Balcony doors can cause drafts during winter.	Designers and Managers
HVAC	- Less noisy systems ought to be specified.	Designers
	- Always-running fans are a problem for occupants.	Designers
	- Cooling capacity needs to reflect suite conditions.	Designers
	- More vents and more even distribution of heat are needed.	Designers
	- Residents should either be trained to use their mechanical ventilation system properly, or filter maintenance should be taken over by maintenance staff.	Designers and Managers
Hot Water	- Optimization of hot water delivery system ought to be investigated.	Designers and Managers
	- Residents ought to be made aware of their consumption via a social benchmarking program.	Managers
	- The study buildings are potentially overheating their water.	Designers
Energy	- Balcony doors and overheated corridors are a possible driver for the variability in energy use between suites.	Designers and Managers
	- Residents should be encouraged and educated about operating their suites efficiently.	Designers and Managers
IEQ	- Overhead lighting needs to be added to suites of this type	Designers
	-Tower A-C needs to re-consider its noise abatement strategies, looking to Tower D for inspiration.	Designers
Construction	- Tower D is much more soundproof that the other Towers.	Designers

4.5 Conclusion

This chapter has shown that questionnaire comments can be effective in illuminating large problems within this building type. The 'softest' qualitative items, open-ended comments and interviews, have been shown to be revelatory in the present setting. Though the findings do not diagnose performance problems with absolute certainty, they do highlight numerous challenges being faced in the study buildings. In doing so, they show that far from being unreliable anecdotes, occupant feedback in the form of questionnaire comments can be very value to researchers, designers, and managers.

Not only is work of this nature useful in a diagnostic sense, it is also useful in a practical sense and is significant to purchasers and renters of homes who upon move-in are confronted with various problems, many of which could have been avoided had the designers of their spaces learned from mistakes they had made in the past.

A final note on the theoretical underpinnings of the methodology used in this chapter is that real world research refers to "applied research projects which are typically small in scale and modest in scope.

They tend to be related to change and/or policy, often seeking to evaluate some initiative, service or whatever" (Robson, 2011, p. 3). The subject of evaluation of the present chapter was a hard to reach population in need of producing feedback for a rapidly progressing industry. As Sellers and Fiore (2013) write, "without a user-centered design, many sustainable products and features may either fail to be adopted or may not be used in a way that maximizes performance, thus limiting their utility and potential benefits" (p. 550). In the coming months this feedback will be systematically presented to relevant parties, in the hopes of remedying some of the criticisms outlined herein.

In summary content analysis was performed on 700 comments received on 165 questionnaires, identifying envelope, HVAC, hot water, indoor environmental quality, and layout and design as the primary themes for which comments were received. These highlighted:

1. 38% (11 of 29) of thematic elements result in feedback which is considered relevant to current managers, while all 29 categories are relevant to designers;
2. The noise containment between units is better in Tower D than in Towers A-C;
3. That high glazing ratios are resulting in summer and winter discomfort for some respondents;
4. That small balconies are rarely used; making their thermal bridging even more undesirable;
5. That ERV filter clearing and changing should be carried out by maintenance staff instead of occupants;
6. That the hot water system was designed in a way that did not ensure timely delivery to all suites, and that water was likely being needlessly over heated;
7. Utility bills should be used as a venue for social benchmarking where residents can see how their energy and water consumption compare to their neighbours;
8. If considered on their own, questionnaire scores could obscure the fact that very real problems exist for some of the respondents;
9. That the ratio of "10 to 1" between negative and positive occupant comments to indicate problems suggested by Baird and Dykes (2012) is not likely a useful tool for research in this setting. For example, the hot water ratio of 1.5:1 did not on its own indicate a problem, where clearly one existed;
10. Interview surveys could potentially increase the volume and quality of data collected from occupants in this building type.

5. Concluding Chapter

5.1 Summary of Dissertation Objectives

This dissertation reports on the outcomes of an interdisciplinary project which investigated the energy performance of, and occupant experience in, an increasingly popular housing type in Canada – the green high-rise residential tower. The objective was to substantiate that the collection of qualitative data from building occupants can yield valuable insights into the effectiveness of building design and management decisions, as well as providing an enhanced understanding of energy and water consumption. An additional objective was to study how occupants interacted with the buildings once constructed, and how the buildings performed as a result. The findings demonstrate some of the complexities and nuances of occupant behaviour in this building type and provide information by which to guide future designs.

5.2 Resolved Research Questions

Below, each of the research questions posed in Section 1.4 are discussed. Where appropriate, answers highlight specific contributions which have been made by the present work.

1. How is energy being used in individual suites within the study buildings?

1a. To what extent can trends be explained by physical factors, and by behavioural and demographic factors?

These two questions were answered in detail by the work presented in Chapter 2, and to a certain extent by work presented in Chapter 3.

The average suite-level energy use intensity was found to be 125.6 ekWh/m^2/year (not including heating, cooling and lighting for common spaces) and the average end-use breakdown is 35% for electricity (plug loads and lighting), 34% for hot water, 20% for heating, and 11% for cooling. This end-use breakdown differed significantly from the Ontario apartment average, with considerably less energy used for space conditioning. This is likely due in part to the compact nature of many of the suites, their better than average envelope and mechanical systems , all of which likely allowed some study occupants to use very little heating and cooling energy. It should be reiterated that there is very little data about how energy is used in suites within this building type, and therefore the production of these robust values is a major contribution of this work to both the research community and to the industry.

Energy use intensity differed by a factor of 7 between similar suites, electricity by a factor of 5, hot water by a factor of 13, cooling by a factor of 47, and heating by a factor of 67. These ranges suggest that occupant behavior differs widely between suites, though other unknowns such as stack effect and air tightness likely also play a role. To give some perspective, Kelsven (2103) compared gas and electricity use in thousands of similar single family homes and found the 5th and 95th percentile to differ by a factor of 4.3 for gas, and 5.7 for electricity. Though the results for electricity are similar, which is encouraging, the discrepancies between gas values are linked to building typology in ways that would take additional work to disentangle. For example, heating use varied so much more in the study buildings because some of the suites in the study building were able to use no heat at all during winter. Not only does this inflate the relationship between the 5th and 95th percentiles (hence the factor of 67 reported above), it is also something that would be very difficult to achieve in a single family home, which has much more external surface area and therefore a higher heating load. Notwithstanding this discussion, the results from the study buildings show that those studying and designing residential buildings should not assume a single type of occupant, as the performance they can achieve in their suites can vary so widely.

In order to add additional perspective to these findings, Chapter 2 separated the effect of physical building characteristics from behavioural and demographic ones in order to show that physical building characteristics explain 43% of the heating variability, 16% of the cooling variability, and 40% of electricity variability. It is suggested that behavior occupant behavior is the major contributor in explaining the remainder. Gill et al. (2010) found that occupant behaviours accounted for 51% of gas variability and 37% of electricity variability in low energy single family homes.

Findings of this nature have implications for the upper limits of performance that can be achieved through energy efficient design. Other than reducing the glazing ratio of the study buildings, they appear to be a relatively efficient building product (from an operating energy perspective). Given this, it is not surprising to see occupant behaviour being such a significant driver of the variability observed in energy and water consumption.

2. What insights are possible when qualitative and quantitative data from the study buildings are combined?

This discussion will begin with a literal account of the answers generated by this dissertation, and will proceed to a more analytical discussion of their importance.

Chapter 2 demonstrated that the combination of social science and building science enable interesting insights into the role of occupants in energy consumption, and served to demonstrate that real world research involving qualitative data can be rigorous. These findings were only possible after the creation of physical building variables as well as the collection of submetered data from each suite; both of which are quantitative. Using hierarchical regressions which included quantitative variables as well as qualitative ones led to findings about the drivers of energy and water use in the study buildings.

Similarly, Chapter 3 used questionnaire responses to create user categories (i.e., ERV users and non-users) whose energy use was then compared. Unless the ERV system had a logging function which tracked usage and was remotely accessible to researchers, the occupant questionnaire was necessary in both quantifying ERV usage, and exploring its energy consequences. But not only did the combination of qualitative and quantitative data enable an understanding of the implications of ERV non-use, it also enabled an understanding of the reasons behind this non-use. For example, using qualitative data it was shown that the noise generated during operation of the fan coil system was problematic for occupants. This complaint was then quantified using noise measurements which further corroborated the complaint, and produced much more valuable feedback about this aspect of suite design. Additionally, physical indoor air quality measurements were compared to questionnaire scores to paint a preliminary picture of the relationship between air quality and ERV use in the study suites.

Based on the findings presented in Chapter 3, it is reasonable to assert that the union of environmental logging instruments with submetered energy and water data and occupant questionnaires represents not only an exciting avenue for further research, but perhaps a necessary condition under which such research can generate truly valuable insights. Consider the work done by Gupta, Barnfield, and Hipwood (2014) in which these three types of data were used to evaluate the effectiveness of energy retrofits. Not only could the researchers quantify the energy and environmental quality improvements that resulted from the retrofits, they were also able to incorporate contextual insights relating to occupant behaviour and environmental conditions.

Adopting this approach makes it possible to answer complex questions like those posed by Cole et al. (2008): "are emerging high-performance buildings actually being designed with occupant engagement and intelligence in mind?" (p. 334). The results presented in this dissertation suggest that the study building type is not effectively leveraging occupant intelligence (e.g., by not training) and perhaps even generating occupant antagonism in some cases, and that designers have over-estimated occupant engagement (e.g., with the ERV).

3. What insights are made possible by purely qualitative feedback from users?

Chapter 3 showed that questionnaires are not only useful in uncovering occupant behaviours, they are also crucial in beginning to explain them. Measured data can show "what" is happening, but qualitative data can provide explanations as to "why". For example, the insight that some respondents were avoiding using their ERV because accessing and maintaining the filter was too difficult would not be achievable without qualitative data collection. As was shown, this simple insight has wide ranging implications for the management of Towers A-C, where filter maintenance should probably be conducted by building staff instead of occupants.

The majority of answers to this research question, though, are found in Chapter 4. Beyond identifying major thematic categories (e.g., HVAC) and audiences (e.g., mangers) for feedback, Chapter 4 used comments from occupants to uncover performance challenges in the study buildings. Granted, it cannot do so with the same degree of certainty as quantitative tests, but it ought to be considered as a complementary diagnostic tool which is useful in improving the quality and sustainability of the built environment, as qualitative data provide better context and explanation about what is occurring and how it affects occupants.

Consider the insight about drafty balcony doors, which are certainly driving heating use to some extent in the study suites. This problem was uncovered with relative ease using comments from the questionnaire. To uncover this phenomenon quantitatively would have required access to suites and expensive tests. Though managers may still want to undergo these tests, they did not have to do so to identify this as a potential source of occupant dissatisfaction and driver of energy use. It should be noted that designers are likely aware that balcony doors are a poor design choice for building envelopes, but that prevailing customer desires force their hand. Nevertheless, the occupant questionnaire was still useful in uncovering this phenomenon, and could be used in further work which maps the complaints throughout the buildings and explores the role that wind pressure and stack effect are playing in creating drafty doors.

Another major insight which was made possible solely by qualitative data was the fact that noise containment between suites differed significantly between the two developers involved in the study. It is hard to imagine how this insight would have been generated another way. For example, a common complaint of hearing the upstairs neighbour using the bathroom would likely not register in a logged acoustic measurement, though it is obviously disturbing to occupants. It should also be noted that not only was qualitative research required to produce this insight, so too was an impartial real world researcher who could collect data from two separate companies and report without bias (albeit anonymously) what was found. This can be thought of as a contribution to this field of work as it affirms the methodological stance that a researcher ought to take in order to produce insights which stand to benefit the industry, and as a result building occupants and the greater society.

The high glazing ratios used in this building type are criticized by those demanding greater sustainability. This outlook is contrasted by developers who perceive that high window to wall ratios are desirable for sales, as well as by customers who are initially impressed with the great views they afford. However, as was shown in Chapter 4, some occupants struggle with the performance challenges that result from such high amounts of glazing (e.g., overheating in summer). The findings about window performance and balcony size were generated qualitatively and are of great importance as they suggest that not only would the sustainability of these projects be increased by lower glazing ratios, but so too would occupant satisfaction and marketability. Similarly, the insight that balconies are rarely used if they are under a certain size is important as there is much concern that the thermal bridging caused by these balconies should be eliminated by not designing buildings with balconies. The qualitative findings from Chapter 4 add some additional evidence to this position and contribute to this issue.

As mentioned in Section 1.2, the context within a building is something which ought to be explored, and not obscured by a propensity for quantitative results. Though subjective in nature, the questionnaire comments and interview results from Chapter 4 are particularly useful at creating preliminary feedback about furnishings, services, technologies, and environmental conditions within high-rise residential buildings. Though not a substitute for quantitative problem solving, they are a complimentary strategy in this pursuit. Flyvbjerg (2006) points out that a misunderstanding of case study research is that “one cannot generalize on the basis of an individual case; therefore, the case study cannot contribute to scientific development" (p. 221). The purpose of Chapter 4 was not to contribute objective and generalizable results to the academic canon. Instead, as was discussed in Section 1.2, this work was motivated to improve conditions in present and future buildings. This dissertation has shown repeatedly that a building's context is a source of valuable performance insights that can be gathered quickly and with relatively low expense. Though complex, understanding and leveraging a building's context holds much potential in better understanding occupants and their behaviour, as well as in diagnosing performance challenges and successes. This contribution is important for both those in the industry and those seeking to study it.

4. What design-related challenges have arisen in the study buildings?

Chapter 4 succeeded in using questionnaire data to highlight precise challenges being faced by occupants of the study buildings (see Table 4.4). These problems range from the banal, to the important. For example, some of the problems involve suite furnishing decisions made by designers which ought to be re-considered in future designs (e.g., perceived lack of overhead lighting, lack of storage); while other feedback indicated larger issues with building design. For example, the perceived uselessness of small balconies raises, or the lag time involved in hot water delivery. A more complete discussion of this question is found in Section 5.3.

5. How much control should these occupants have over their environment?

As was discussed in Section 1.3.5, determining the amount of control to give occupants over their environmental conditions can help or hinder their satisfaction with their space, as well as the amount of energy they cause it to consume. Chapter 3 demonstrates the importance of using the building evaluation methodology to understand how occupants interact with (new) technology in order to optimize performance and satisfaction in high-rise residential buildings. It was shown that having access to a relatively intuitive ERV system did not result in higher satisfaction. Instead, many respondents were satisfied simply by having operable windows and the perception that they had control over conditions in their suites (many of these respondents were unaware that their mechanical ERV would provide filtered air). In this case, giving occupants access to a mechanical ERV was not a sufficient design strategy in ensuring either their satisfaction, nor the optimal operation of their suites. However, if they had not had access to operable windows, and instead had to rely solely on the ERV for fresh air, it is likely that the results would be different. Finding a building type that fits this description and carrying out a similar study would help corroborate the findings from this dissertation.

As discussed above, Cole et al. (2008) suggest that the various systems and technologies in green buildings “may involve new responsibilities and require a commitment from occupants” (p. 326). Occupants in this building type had likely not been asked to manage their own mixed-mode ventilation scheme before, and their reactions were varied and unpredictable. The issue of how much control to give these occupants is complex, but given respondents’ observed preference for passive ventilation, and their ability to exercise this preference, Chapter 3 seems to reaffirm the conventional wisdom that the ability to control one’s environmental conditions increases their satisfaction therein.

5.3 Feedback for Designers and Developers

In answering the first research question above, it has become more clear that not only are occupants a contributor to the performance of the suite, but their contributions vary widely from person to person, irrespective of dwelling similarities. Both a building’s in-use performance and the merit of its certification (e.g., LEED) suffer when a building which was thought to be energy efficient is inhabited by occupants whose lifestyles contradict the assumptions made during design, resulting in higher energy use than predicted. To be clear, the implication here is that in addition to educating occupants, designers and building certifiers need to accommodate the variable performance which occupants can precipitate, and design with the assumption that there will be a variety of behaviours, adjusting their expectations and/or guarantees of performance accordingly. The ability of the present work to better inform the design and certification processes in this way is another contribution this work makes to the industry, though there is much additional work in identifying, creating, testing, and marketing resilient design strategies.

The items in Table 4.4 represent challenges and/or deficiencies which designers need to be aware of, as addressing these issues can result in buildings which are more energy and water efficient, and in which occupants are more satisfied. For example, the poor delivery of hot water for some suites has implications for both occupant satisfaction and energy efficiency. It is likely that a certain amount of lag is inevitable in this type of building, something which occupants ought to be made aware of during purchase and handover, and something which ought to be quantified via re-commissioning.

Chapter 3 demonstrates challenges that have arisen as a result of HVAC design in the study buildings. It was found that some occupants in the study buildings would prefer HVAC systems which were quieter, more powerful, with more vents, and that did not require any fans which had to run 24 hours per day. Beyond acknowledging these findings, designers need to remember that not all innovative technologies (e.g., ERV) will be embraced by occupants, who have varied capabilities and preferences. This is important since innovative technologies are often a component of energy and water efficient residential design. As the literature points out, occupants need to be properly trained, and their actions need to produce the desired responses in order for new technologies to create the efficiencies they are designed for. Moreover, as was the case with the respondents' preference for passive ventilation, occupants could end up abandoning novel technologies for something which they are more familiar and comfortable with.

Whether intentionally or not, Towers A, B, and C possessed a resiliency that allowed some occupants to exercise their preference for passive ventilation in a way that was neutral or even beneficial. In contrast, the disabling of loud ERV fans in Tower D caused problems in the ventilation ecosystem of the entire building. Results suggest that giving occupants full control over their ERV (instead of the 'black-boxed' approach adopted by Tower D) is preferable because it allows them to modulate their ventilation needs alongside their complex and subjective IAQ expectations, saving energy in the process.

It is recommended that designers and developers be mindful that just because somebody chooses to live in a green building they are necessarily going to act in a pro-environmental way at all times. Designers need to remember that occupants are embedded in design decisions made long before they come to occupy a space and bring with them expectations, perceptions, capabilities and preferences, all of which combine to produce the achieved performance of their dwelling. This was known to a certain extent before, but the present work adds contemporary and rigorous findings to this canon.

In summary, the following lessons for designers were uncovered:

- Highly glazed suites cause comfort problems for occupants;
- Balconies need to be large enough to be perceived as useful;
- Balcony doors can cause drafts during winter;
- Less noisy HVAC systems ought to be specified and installed;
- Always-running fans are a problem for occupants;

- Cooling capacity needs to reflect suite conditions;
- More vents and more even distribution of heat are needed;
- Residents should either be trained to use their mechanical ventilation system properly, or filter maintenance should be taken over by maintenance staff;
- Optimization of hot water delivery system ought to be investigated;
- Residents should be encouraged and educated about operating their suites efficiently;
- Overhead lighting needs to be added to suites of this
- Certain noise abatement strategies were more effective than others in preventing unwanted noise from neighbours. Given the importance and prevalence of this issue, it bears careful attention.

5.4 Feedback for Managers

5.4.1 Occupant Training

The results presented throughout this dissertation suggest that occupants of the study buildings have not been sufficiently educated about the operation of the technology in their suites. For example, a number of respondents reported not knowing anything about their ERV, which besides serving as the exhaust fan for their bathroom, is an innovative technology that contributes to the LEED certification of the building they chose to live it. The fact that this was not commonplace in the study towers speaks to a major gap in the building industry.

If higher ERV usage rates are to be achieved then managers need to be educated about the importance of the suite's systems so that they can procure and deliver outreach strategies aimed at increasing usage, and also to field questions from tenants that emerge. This outreach should be ongoing and should alert occupants to the functionality and usefulness of their mechanical ventilation systems, while at the same time offering advice on how and when to exercise their preference for passive ventilation.

Suite manuals which are given to the purchaser at handover are a good start; Chapter 3 showed that those who read them are 7 times more likely to be ERV users. A simple improvement in this training process would be for managers to ensure that each new tenant or purchaser is at the very least given access to the suite manual as they begin to learn how to operate their suite. Ideally, this process would include a walk-through of the suite with someone knowledgeable about efficient suite operation. This should likely be carried out by a third party in order that the walkthrough focus on suite operations, and not on aesthetics, or other issues at the suite or building level which are in the manager's purview.

It should be said though, that the above strategies are quite simplistic and could be improved upon. For example, with all of the technology available to designers (e.g., QR codes on control surfaces that lead to instructional videos) there is significant potential to address the poor level of training observed in the study buildings. Moreover, it is important to mention that there is a vast body of research and practice that involves innovative and effective techniques for encouraging household behaviours (e.g. McKenzie-Mohr, 2011). It is recommended that these and other strategies be employed in the study buildings in order to increase ERV usage, as well as other beneficial behaviours.

As mentioned, Cole et al. (2008) suggest that the various systems and technologies (e.g., ventilation switches) used in green buildings "may involve new responsibilities and require a commitment from occupants" (p. 326). Though some respondents in the present study seemed to welcome the responsibility that came with living in a green dwellings, results suggest that some occupants were not interested in managing their mechanical ventilation systems in the first place. One possible remedy for this is for building management to assume responsibility of ERV filter maintenance in order to remove barriers to use that exists for some respondents; thus helping with issues of condensation, and improving indoor air quality. In addition, this exercise may remind residents that they have an ERV and management could ensure its proper functioning should the occupant choose to use it.

But more importantly, the ERV filter seems to represent a level of control or responsibility that some occupants are not comfortable with. Moreover, this type of maintenance task is typical for homeownership. And so, it could be that occupants of the study suites purchased or rented these units with the expectation of not having to manage anything. This is somewhat worrisome, given the thoughts of Cole et al. (2008) presented above. Certainly a challenge for managers and third-party program designers is to engender an enlightened sense of stewardship for occupants in this building type.

In summary, the following are activities which managers should consider in order to improve the energy and water efficiency of the study buildings:

- Ensure that suite manuals are given to each new tenant/or owner;

- Hire an informed third party to perform a walkthrough which is focused on optimal suite operation;
- Use QR codes on control surfaces that lead to instructional videos;
- Hire a third party to deliver a well-informed outreach strategy (e.g., Community-based social marketing) aimed at remedying problems within the building;
- Create a social benchmarking initiative that shows how an individual suite's energy and water consumption compares to others' in the building;
- Use maintenance staff to clean and replace ERV filters.

5.5 Feedback for Researchers

Though real world research involving diverse datasets can be messy, it is nonetheless very valuable. What those in the industry might not know, and which has been demonstrated here, is that this approach holds a key to innovation in the building industry. Simultaneously considering submetered energy data, IEQ measurements, questionnaires, interviews, and observations enables one to diagnose and understand building conditions on a deeper and more meaningful level. As was shown, isolating a single type of data provides only a limited understanding of building performance and/or occupant behaviour.

This has implications for the type of insights which are considered valuable by those in the building performance community. It is commonly held that simply reporting the modeled assumptions of a building is not sufficient in demonstrating the success of a project. Similarly, simply showing the energy use intensity for the project begs all of the questions which were answered by Chapter 2 and discussed in the answer to the first research question. Namely, one needs to know whether this performance is coming at the expense of occupant comfort or satisfaction, as it was in the six LEED certified homes evaluated by Beauregard, Berkland, and Hoque (2011). Not only does one need a subjective account of the effects of performance on the occupants, but an objective account as well. Indoor environmental quality measurements, taken alongside qualitative inquiry and compared to energy and water data is an exciting research frontier that this work is proud to have contributed to.

As shown in Chapter 4, comments and interviews can be valuable additions to questionnaire scores, which though useful, do not always provide comprehensive insights into conditions within suites. It is difficult to say with certainty that qualitative insights are more valuable than quantitative ones, however, it can be said that as a preliminary diagnostic tool, qualitative data collection can reveal aspects of a building's performance, especially in the type of building studied herein. It must be acknowledged that there are dangers inherent in collecting this type of data. Occupants could offer faulty information (e.g., a draft where there is none), or could overwhelm a researcher with complaints about issues which are outside the purview of the study (e.g., interpersonal issues within a building).

As mentioned, the methodology used in this dissertation has been informed by the tenets of real world research, and as such there are some important lessons that have been learned. Conducting research in an unfamiliar setting means that certain things are going to be overlooked. There are also restrictions encountered in the real world which restrict access to information, as well as the ability to publicize results. In the real world, the researchers lacks the control mechanisms that are present in laboratory research, where interventions are meticulously designed based on trial and error. In the research presented in this dissertation, there was one chance to carry out this research, and many hard won lessons have been learned as a result.

For future researchers in this field it is recommended to do pilot testing of all methodological elements to the extent possible, before putting them into the field. This means testing the questionnaire, but it also means working with sample energy data to create the types of results that the study aims to produce. In the case of this dissertation, this would have meant carrying out statistical analysis beforehand in on sample datasets in order to determine exactly what types of behavioural variables were needed. However, even this process is difficult in the real world research setting, where exploratory work sees hypothesis emerge mid-project, instead of at the beginning, and where new research questions emerge during data analysis.

If this project were being carried out again in a new set of buildings, the following points would be emphasized:

- Determination of researchers goals; are they related to building performance, occupant satisfaction, community involvement, aesthetics, etc.? Determining this at the outset enables the researcher to resist making the project more complicated than it needs to be, especially as various stakeholders begin to offer their input.

- Walk-through interviews with property manager, designer representative, and then with at least a small sample of occupants. Even if the researcher does not know what to ask during these interviews, the process with be valuable during the creation of the research project.
- As mentioned above, the researcher should strive to become practically familiar with all data collection and analysis that will be used in the study to the extent possible. This will ensure that actual data collection is focused and leads to productive results.
- Interviews with occupants which are carried out by someone with near expert understanding of the building design and systems. This enables the researcher to not only clarify responses received from the occupants, but also to utilize the expert's observations during data analysis.

5.6 Strengths and Limitations

Using buildings that were very similar to one and other enabled a high degree of control between participants and led to some interesting results. This was compounded by the presence of monthly submetered, suite-level energy and water data, and resulted in figures and results which future researchers can use to do their work more effectively.

Robson (2011) defines evaluation research as "a study which has a distinctive purpose" (p. 176) and which experiences "issues of clearances and permissions, negotiations with 'gatekeepers', the political nature of an evaluation, ethics and the type of report" (p. 176). Many of these problems were faced during the present research project. The populations in the study buildings were difficult to access, with controlled entrances, hesitant condominium corporations and overworked property managers; and the results were difficult to share, with risk-averse, reticent developers. One of the major achievements of this work is that it successfully negotiated these barriers in order to shed light on to the performance and conditions within this building type.

It should be noted that work of this nature runs the risk of becoming too rigorous, too academic, too abstract. As Adrian Leaman says "coherent strategies for the future are what's required, not theories" (A. Leaman, personal communication, October 6, 2014). Despite the rigor required by a doctoral dissertation, this work did try to embody this approach to some degree, using a combination of statistically based insights, *and* subjective evidence to produce useful lessons for the designers, managers, and occupants associated with these buildings (e.g., insights into window area, balcony design, HVAC design, and noise containment). As Leaman, Stevenson, and Bordass (2010) write: "many of the conclusions from performance-in-use studies have profound implications for briefing, design, construction, commissioning and handover; and the associated products and services" (p. 567).

Additional limitations arise as a result of the design and delivery of questionnaire. As mentioned in Chapter 2, it is acknowledged as a limitation the fact that respondents were not asked about their window covering behaviour. This would have added immensely to the findings in Chapter 2 as it would have helped strengthen the understanding of how much insolation and irradiation were received by each suite. Similarly, better questions should have been designed to measure thermostat use (e.g., programs, setbacks, manual overrides, on/off operation), as these too would have resulted in enhancing the findings. It also would have been desirable to deliver the questionnaire in conventional (i.e., non-LEED certified) high-rise residential buildings in order to make comparisons between the two; for example, answering the question: are people in green buildings asked to manage their comfort in different ways that conventional dwellings?

It is recommended that a building evaluation methodology for this building type consider using what Robson (2011) calls interview surveys; where the researcher goes through the questions with the respondents. In the present building type, a researcher could set up in the lobby and ask people to stop for a few minutes as they entered the building. This could result in a higher response rate, and could also provide more in-depth understanding into contextual elements within the building and suite. A similar limitation in the present methodology was that separate interviews should have been conducted with buildings users before the delivery of the questionnaire. Interviewing some users before the questionnaire was designed (especially since the instrument was not pre-tested on a pilot sample) would have ensured that is was appropriate to the setting.

Another limitation of the questionnaire has to do with the potential for bias both in the sampling method and in the questions themselves. As Schwarz and Oyserman (2001) point out "participants' reports can be profoundly influenced by question wording, format, and context" (p. 127). To this end, it is somewhat unclear, for example, the extent to which the themes that emerged in Chapter 4 are the result of the questions which were asked. Did respondents get a chance to air all of their concerns, or only those which were prompted? There is likely some room for improvement in this area.

It is also possible that those who chose to respond to the questionnaire were more *engaged* occupants, with more interest in their dwelling's optimal operation, and in providing feedback. It is presently unclear the extent to which this was the case in the present study. Similarly, it is unclear the extent to which the results were plagued by "socially desirable responding" (Schwarz & Oyserman, 2001). Having acknowledged this, it should be said that, as mentioned in Chapter 2, the high R^2 values reported in the hot water section (i.e., .506) suggest a high level of criterion validity for those particular questionnaire items, and generally suggest that the questionnaires were answered truthfully by participants. This is corroborated by an unpublished finding that those with smaller windows in their suite rated their satisfaction with window area lower than those with larger windows. In other words, the questionnaire item asking respondents to rate their satisfaction with window area appears to correspond to the physical reality of actual window area, meaning that the respondents are answering truthfully, resulting in accurate measurements.

Two final limitations regarding the questionnaire include the fact that online questionnaires (as were used by most respondents) do not guarantee that questionnaires are displayed uniformly (due to display monitor sizes) to all participants in the way that a paper-printed postal survey does (Robson, 2011). Lastly, it is acknowledged that more interviews and IEQ testing should have taken place. This did not happen due to complicated logistics within the buildings, but nevertheless results in a limitation of the present work.

In the case of this dissertation, the study buildings had a mandate to lower energy use, and increase occupant satisfaction (see Section 1.4.1), and this formed part of the reason for their being evaluated the way they did. They could have been evaluated using other methods, and measuring other indicators. Though the findings presented appear comprehensive, it could be that other issues were not raised during the evaluation of the study buildings.

It is useful to point out that the developers involved in the present study would have ideally been more interested in the results. Not only was this lack of interest disheartening as a researcher, it also led to pieces of information about the buildings not being collected (e.g., predicted energy use of suites) that would have contributed significantly to the results. It is commonly espoused that building evaluation are a tough sell to designers of buildings because of the impact on their brand and their time (among other reasons), and unfortunately this study ended up being the rule, and not the exception in this regard.

5.7 Recommendations and Future Work

In order for developers (and their designers) to produce better buildings, feedback from current buildings needs to be incorporated into the best practices that inform future designs. This would have to be different from the customer satisfaction questionnaires that occupants of this building type often receive, in which they are asked to rate their enjoyment of amenities, the quality of finishes, and to highlight any deficiencies that resulted from the construction process. These instruments are largely for legal purposes, and not for producing feedback which can better inform future design.

Instead, developers need to collect the type of feedback that was presented in this dissertation, using a variety of methods to critically assess conditions in their buildings. This could be conducted in-house, by a University, or by the private sector (e.g., the Arup SPeAR® program). The use of a third party is preferable as it will lead to less biased reporting of conditions. To facilitate this, LEED certification could be expanded to include a mandatory feedback collection process which would certainly involve more than the verification of thermal comfort and would focus more on ensuring that developers and designers were learning from their past mistakes. It is even feasible that the City of Toronto could withhold development approvals until evidence of a robust feedback process is demonstrated by developers. It is also possible that trade associations like the OAA or RAIC could mandate that their licensees utilize established feedback mechanisms.

In order to gather feedback on an ongoing basis, detailed log books need to be maintained by building staff who are incentivized and empowered to report all performance challenges within the building. If a voluntary approach were unsuccessful, perhaps the Ontario Building Code could mandate such documents. By collecting this feedback, designers could begin to address some of the difficult challenges highlighted by this work (e.g., hot water delivery).

Internally, developers should encourage greater design team accountability around the uptake of design decisions. For example, following up on the deployment of innovate design strategies like the ERV is advisable. And so, through goal setting, monitoring, and measurement and verification, designers should be encouraged to track the success of innovative design strategies like the ones deployed in the study buildings. However, this needs to be done in such a way that design teams are not discouraged from experimenting and innovating.

The same is true for the energy performance of the building. The achieved performance of a building should be treated as more important than the predicted performance. Indeed, the USGBC/CaGBC's use of the Dynamic Plaque is a step in this direction, though only in the commercial space for the foreseeable future. It is conceivable that mandatory energy benchmarking in Toronto could spur the collection of performance data by developers, but in the meantime good practice suggests that verifying how one's creation is actually performing, and comparing to benchmarks, makes ethical and economic sense.

Further research in this area should involve carrying out similar evaluations in different seasons within the study buildings, as well as conducting an examination of the study buildings during which drafty balcony doors and over-heated corridors are measured in order to determine the precise extent to which they are driving heating use in some suites. This type of inquiry could be carried out in additional buildings using the methodology from this dissertation.

As mentioned above, an avenue of further research involves the union of environmental logging instruments with submetered energy and water data and occupant questionnaires. Consider the work done by Gupta, Barnfield, and Hipwood (2014) in which these three types of data were used to evaluate the effectiveness of energy retrofits. Collecting detailed IEQ data and comparing it to meter data and qualitative data would likely lead to insights about conditions in the study building type.

Perhaps the most important recommendation for researchers carrying out similar work in the future in this building type involves the systematic study of the energy and comfort implications of the high glazing ratios that dominate this industry. It is widely known that the large amount of windows used in these projects has negative energy consequences, but if further evidence can be generated which demonstrates negative implications for occupant comfort, then perhaps the industry can begin to shift away from these design decisions and towards more appropriate ones. The creation of a publically accessible database of performance problems in current buildings could be used to convince prospective customers that purchasing a suite with less windows is in their best interest, as well as being pro-environmental. Perhaps this could be done by including more Canadian building into the Building Use Studies database, in addition to the four contributed as part of this study.

In order to better understand the role that airtightness and the stack affect are playing in determining the heating and cooling consumption in the study buildings, researchers could estimate the neutral pressure plane and take measurements of heating and cooling consumption there, using these values as the most accurate indicators of heating and cooling use. In addition to this, temperature measurements in common corridor spaces could be taken and used in a heat gain calculation to determine the extent to which suites are benefitting/suffering from overheated corridors. Similarly, embedding logging IEQ measurements devices in suites which use very little and very high amounts of heating or cooling consumption would provide valuable insights in the environmental conditions in these suites and suggest additional explanations of their energy use.

Further work is also required to determine the extent to which the floors are compartmentalized from one another (Lstiburek, 2014). In other words, it would need to be determined the extent to which the buildings were designed such that air from one floor was blocked from migrating the another floor.

As mentioned in Chapter 4, questionnaire scores (reported as frequency, mean, and standard deviation) are useful in highlighting trends within buildings. The authors share the view that user performance benchmarks based on questionnaire scores can provide useful insight into the achieved performance of buildings (Baird, 2011). Researchers should also consider the use of a ‘summary index’ to test the correlation between it and the proportions of positive and negative comments. Baird and Dykes (2012) write that this approach “shows considerable promise as a tool for assessing building performance” (p. 45). Research in this area should proceed cautiously in order that questionnaire scores and their relationship to established benchmarks not cause the researcher to overlook relevant issues within the building being studied.

Another avenue for further work includes exploring the extent to which owners and renters purchased their suites with the expectation that certain processes would not need to be managed, including ventilation. In other words, what amount of control did they expect to have, what amount were they given, and what are the effects of this discrepancy on indoor environmental quality and energy efficiency. Similarly, further research ought to involve measuring occupants’ preferences for passive, mechanical, and mixed modes of ventilation and developing appropriate design and management strategies which reflect these. There are many reasons why this preference for passive ventilation could emerge, including connection with nature, familiarity, convenience, folk logic, a preference for unconditioned air; all of which are areas where more work is needed.

This ties into further work that needs to be conducted on the various aspects of the innovative technologies that occupants encounter in their suites. For example, a usability study of the various control surfaces would be useful in determining the extent to which control surfaces encourage appropriate use, as the findings presented in Chapter 3 suggest. Similarly, the use of Wi-Fi enabled, logging thermostats would enable a better understanding of how people are using their thermostats. Long-term logging of IEQ parameters in different types of suites (ERV users and non-users, etc.) would also strengthen the types of insights produced by a work of this nature.

It is worth elaborating on an insight produced in Chapter 4 that in order to produce the most high quality feedback about occupant satisfaction and/or building performance, a researcher ought to *triangulate* as much as possible. In the case of the present study, this meant starting by comparing questionnaire scores and comments with quantitative data (e.g., from energy meters) and then drilling-down using interviews with property managers and occupants, as well as indoor environmental quality measurements within suites. As mentioned, the research design was largely exploratory, so it made sense to start by collecting large amount of occupant and submetered data and seeing what issues emerged. Of course, a logical approach would entail starting with interviews and submetered data and only using the occupant questionnaire to explore specific issues that arise from those data. For exploratory case study research, as long as the researcher is collecting the data with intent, or it is warranted for drilling-down, it seems reasonable to collect as much data as possible in order to fully incorporate context into one's findings, and to produce the most comprehensive feedback possible. That being said, one needs to achieve a balance between collecting too much data at the risk of creating fatigue or upset among the participants, including designers and managers. In order to mitigate this, it is essential to have a well formulated research plan before starting the data collection process, while still leaving room for emergent issues and drilling down that will yield the most valuable feedback.

Brown (2009) makes it clear how difficult the task of truly understanding occupant behaviour can be: "there is little understanding of the cultural context within which buildings and users exist, where shared values and norms can influence…how users experience and engage with a building" (p. 2). The final recommendation is that future researchers not over-simply their endeavors because of their apparent complexity. Instead, design research agendas which embrace and leverage this complexity in order to make meaningful progress in this field.

5.8 Significance Of Work

The feedback produced by a study of this nature is significant in an academic sense, for example in understanding the relevance of occupant behaviour. In order for buildings of this type to achieve their various targets, occupant behaviour must be understood so that is can be optimized. As Janda (2011) writes, “buildings don’t use energy, people do” (p. 20).

It is also significant in a practical sense (e.g., informing future design decisions) and in a diagnostic sense (e.g., uncovering current problems within buildings). The work is significant to purchasers and renters of homes who upon move-in are confronted with various problems, many of which could have been avoided had the designers of their spaces learned from mistakes they had made in the past. Occupants deserve a place where they feel both comfortable and empowered. This work is significant to this community of people.

This work has made several contributions to both the academic research field, and to the building industry. These include:

- Calculating accurate end-use breakdowns for suites in this buildings type;
- Uncovering of a gap in occupants’ knowledge about their ERV;
- Suggesting important ways that managers can encourage beneficial occupant behaviours;
- Showing how occupant dissatisfaction can cause performance problems in the study building type;
- Demonstrating the importance and complexity of using real world research methods;
- Demonstrating the importance of understanding the contextual factors within a building;
- Providing results which can be used to better inform the design and certification processes for this building type.

There are challenges associated with doing largely qualitative work in a field dominated by quantitative professionals with financial obligations and propensities. One challenge is encouraging designers to learn from the work presented here. The extent to which the findings from this work will result in positive changes in both the lives of the study buildings’ current occupants, and the design of future buildings by these and other developers, will become clear in the time after which these results are actively disseminated. Of the many tenets of 'real world research' embodied by the present work, there is likely none more worthwhile than producing knowledge that affects some level of change in the world. Though rewarding to contribute to the academic canon, it is imperative that one contributes, to the extent possible, to improving conditions in society. Though the process is messy, complicated, and relies of sources of data and methods of analysis which could be considered less than academically rigorous, this type of research is nonetheless extremely important if real change in the quality and sustainability of the built environment is to be achieved. Furthering this research agenda in an understudied setting and an innovative and increasingly ubiquitous building type imbues further significance onto this work.

Having transcended the qualitative-quantitative incompatibility thesis espoused by Robson (2011), the volume and rigor of the findings presented in this dissertation should find a welcome home with those who seek to increase the satisfaction with -and sustainability of- their projects, be they designers, managers, or researchers. A significant conclusion of this work is the finding that combining qualitative and quantitative data can unlock potential in building evaluations, and can suggest complex performance challenges.

The present work has also shown the utility of case study research, and was successful in convincing funding agencies that this was valuable work. This is important, as Leaman, Stevenson, and Bordass (2010) write:

> Research funders need to recognize the incremental value of case studies for building-up effective data. A single case study will nearly always throw light on new issues (as well as reminding one of old ones still in need of attention!) and create hypotheses that can be tested in other ways, e.g. on other case studies; in discussions with design and building teams; and in helping to structure new research (p. 568).

As mentioned in Section 1.2, real world research applied to the evaluation of buildings calls forth the following difficult questions: "How best is the public interest served in the face of commercial self-interest? Where does duty of care to individual building users fit in, or indeed to the wider considerations of sustainable development?" (Leaman, Stevenson, & Bordass, 2010, p. 565). If Canada is to become a leader in both environmental sustainability and quality of life, then having buildings which embody these tenets is a crucial strategy. In critically evaluating green, high-rise residential towers in

Toronto, this dissertation has contributed in a small but hopefully significant way to these great and important aspirations.

6. Appendices

Appendix 1

Weather normalization is an important step in calculating EUIs because it takes into account changes in energy use caused by unusually hot or cold years. Essentially, it is the process of comparing a given year's cooling degree days (CDD) or heating degree days (HDD) to a 30 year average and adjusting the energy use data accordingly (BizEE Software Ltd., 2015). For Chapter 2,

1. Heating or cooling data (kWh) from each suite was divided by the number of degree days for that month (purchased from www.degreedays.net)
2. This new value (kWh/degree day) was then multiplied by the 30-year average for the month in question.

This new value was then used during data analysis instead of the original value form the submeter.

Appendix 2

Definitions

Questionnaire: The work produced by the Licensor

Territory : Canada

Period : Two years

Term: The full term of copyright and all renewals and extensions.

Rights: The non-exclusive right by licence, to utilise the questionnaire in the agreed material format for the purposes defined.

Study building : The building/s to which the licence applies, normally named in Further Details below.

Further details :

BUS project 1221

For postgraduate study of new build high rise or row house condominiums and single-family homes.

Invoices : If invoices apply they should be raised and paid to:
Building Use Studies Ltd.,
c/o Sprunt,
The Quadrangle,
180 Wardour Street,
London W1F 8FY
UK

Licence agreement

2/3/12

This is a questionnaire licence agreement between:

Adrian Leaman, Building Use Studies — *The Licensor*

and:

Craig Brown, ~~Centre for Urban Energy~~ Ryerson University — *The Licensee*

concerning the method/s:

BUS Methodology Domestic version Standard

The licensors as owners of the copyright of the title agree to grant the rights to the licensee subject to these terms and conditions.

1. The licensor as beneficial owner grants the licensee rights throughout the territory for the period.
2. The licensor warrants that they are the sole owners of the rights and have full power to enter the agreement.
3. The licensee undertakes that the following copyright notice is prominently displayed on all pages of the questionnaire and prominently in the report of survey, especially within data tables:

© Copyright: Building Use Studies Ltd 2012 Used under licence.

4. If a survey is undertaken, the licensee undertakes to lodge the data file of the survey with BUS Methodology subject to full confidentiality in agreed computer file format..
5. If a survey is undertaken. and data are supplied as in 4., BUS Methdology undertakes to supply the licensee with data analysis in the current formats.
6. If a survey is undertaken, the licensee undertakes to conduct the survey using agreed ethical principles such as those of the Market Research Society.
7. The licensee undertakes not to change any questionnaire or other formats without prior agreement of BUS Methodology.
8. The licensee undertakes not to publish or circulate details of questionnaires or benchmarks without prior agreement of BUS Methodology.
9. The licensor undertakes never to reveal details of individuals or to release details of building names without prior agreement of the licensee.
10. The licensor undertakes not to grant more than one licence for a particular study building during a defined period.
11. If a translation is undertaken, the licensee undertakes to carry out the translation under supervision from the licensor and to release the resulting translation file to BUS Methodology.

More details are available of the approach on:
www.usablebuildings.co.uk/WebGuideOSM/index.html

Signed: Adrian Leaman

Digitally signed by Adrian Leaman
DN: cn=Adrian Leaman, o, ou, email=adrianleaman@usablebuildings.co.uk, c=GB
Date: 2012.03.02 09:43:40 Z

Adrian Leaman, Building Use Studies

Signed:

Craig Brown, ~~Centre for Urban Energy~~, Ryerson University

VAT number: (GB) 371 1084 78 — Company number 1497266
Account Name: Building Use Studies Limited
Account No: 20207543
Bank Address: Barclays Bank, Barclays Business Centre, P O Box 32016, London NW1 2ZH
Bank Sort Code: 20-03-53 — Swift code: BARCGB22

Appendix 3

RYERSON UNIVERSITY
RESEARCH ETHICS BOARD

To: Craig Brown
Environmental Applied Science and Management

Re: REB 2012-240: Occupant Satisfaction and Behaviour in Green-intent Multi-Unit Residential Buildings and Office Settings

Date: September 29, 2014

Dear Craig Brown,

The review of your protocol REB File REB 2012-240 is now complete. This is a renewal for REB File . The project has been approved for a one year period. Please note that before proceeding with your project, compliance with other required University approvals/certifications, institutional requirements, or governmental authorizations may be required.

This approval may be extended after one year upon request. Please be advised that if the project is not renewed, approval will expire and no more research involving humans may take place. If this is a funded project, access to research funds may also be affected.

Please note that REB approval policies require that you adhere strictly to the protocol as last reviewed by the REB and that any modifications must be approved by the Board before they can be implemented. Adverse or unexpected events must be reported to the REB as soon as possible with an indication from the Principal Investigator as to how, in the view of the Principal Investigator, these events affect the continuation of the protocol.

Finally, if research subjects are in the care of a health facility, at a school, or other institution or community organization, it is the responsibility of the Principal Investigator to ensure that the ethical guidelines and approvals of those facilities or institutions are obtained and filed with the REB prior to the initiation of any research.

Please quote your REB file number (REB 2012-240) on future correspondence.

Congratulations and best of luck in conducting your research.

Lynn Lavallée, Ph.D.
Chair, Research Ethics Board

Appendix 4

Building Research & Information
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/rbri20

Understanding the role of inhabitants in innovative mechanical ventilation strategies

Craig Brown[a] & Mark Gorgolewski[b]

[a] Environmental Applied Science and Management, Ryerson University, 350 Victoria Street, Toronto, ON M5B 2K3, Canada. E-mail:

[b] Department of Architectural Science, Ryerson University, 350 Victoria Street, Toronto, ON M5B 2K3, Canada. E-mail:

Published online: 10 Oct 2014.

To cite this article: Craig Brown & Mark Gorgolewski (2014): Understanding the role of inhabitants in innovative mechanical ventilation strategies, Building Research & Information, DOI: 10.1080/09613218.2015.963350

To link to this article: http://dx.doi.org/10.1080/09613218.2015.963350

BRI Building Research & Information 2014
http://dx.doi.org/10.1080/09613218.2015.963350

Routledge Taylor & Francis Group

RESEARCH PAPER

Understanding the role of inhabitants in innovative mechanical ventilation strategies

Craig Brown[1] and Mark Gorgolewski[2]

[1]Environmental Applied Science and Management, Ryerson University, 350 Victoria Street, Toronto, ON M5B 2K3, Canada. E-mail: craig.brown@ryerson.ca

[2]Department of Architectural Science, Ryerson University, 350 Victoria Street, Toronto, ON M5B 2K3, Canada. E-mail: mgorgo@ryerson.ca

The causes and implications are explored for why some inhabitants choose to avoid or abandon usage of their mechanical ventilation system. Over half of respondents in four LEED-certified high-rise residential buildings in Toronto, Canada, were found not to use their heat recovery ventilators (HRV). Questionnaire scores, comments and interview results found the following reasons: acoustic dissatisfaction, difficulty with the accessibility of filters, inhabitant knowledge and preferences, and lack of engagement with training materials. A disconnect also exists between the expectations of designers and the thinking and behaviours of inhabitants. The implications of inhabitants' ventilation behaviours were also explored though metered energy data as well as noise and indoor air quality (IAQ) measurements within their dwellings. Results suggest that abandoning mechanical ventilation in favour of passive ventilation can actually lead to greater satisfaction with IAQ and to decreased energy consumption. It is recommended that designers employ resilient design strategies that allow for varied preferences (*e.g.*, for passive ventilation) to be exercised by inhabitants without undermining suite- or building-level performance. The study also highlights the importance of using post-occupancy evaluation methodology to understand how inhabitants interact with (new) technology in order to optimize performance and satisfaction in high-rise residential buildings.

Keywords: building performance, controls, heating, high-rise, housing, indoor air quality, inhabitant behaviour, usability, ventilation

Introduction

It is commonly accepted that good design and the latest new technologies on their own are not sufficient to create efficient and healthy buildings. Building inhabitants play an important role in affecting building performance (*e.g.*, Gill, Tierney, Pegg, & Allan, 2010; Gram-Hansson, 2010; Pilkington, Roach, & Perkins 2011; Stevenson, Carmona-Andreu, & Hancock, 2013). Despite this importance, there can be a disconnect between the intentions of designers and the expectations and capabilities of users which can affect performance (Hauge, Thomsen, & Berker, 2011). For example, Leaman (quoted in Bordass & Leaman, 1997; Yudelson & Meyer, 2013) claims that 'unmanageable complexity' can be a result of this disconnect and can lead to buildings being poorly operated.

Although giving inhabitants access to controls is an important factor in them being satisfied with their surroundings (Baird, 2010; Combe, Harrison, Dong, Craig, & Gill, 2011; Leaman & Bordass, 2001) there are often numerous ways in which an inhabitant can interact with a design strategy (Berker, 2011). This variability can be difficult to account for during the design and modelling phases of a project, but is nonetheless important.

There is also a certain amount of buy-in that must occur on the part of inhabitants if design strategies are to become successful. Leaman (cited in Yudelson & Meyer, 2013) asserts that inhabitants may not be interested in having to operate complex buildings. Cole, Robinson, Brown, and O'Shea (2008) similarly insist that a willingness on the part of occupants is crucial to the success of new systems and designs. This important relationship between the buy-in of inhabitants and building performance is sometimes articulated by referring to building occupants as inhabitants instead of occupants, implying an active role for both their integration and stewardship within buildings (Cole et al., 2008).

Though achieved performance is most often thought of in terms of energy use, inhabitants also play a crucial role in achieving high indoor environmental quality (IEQ) and can negate the expectations predicted (and certified) during design. This is especially true in buildings that give occupants a high degree of control over heating, cooling and ventilation (Yudelson & Meyer, 2013). The buildings in the present study use innovative, non-standard mechanical ventilation systems, something Yudelson and Meyer (2013) argue exacerbates the likelihood of so-called performance gaps in the indoor environment. However, the study buildings also provide passive ventilation, which gives inhabitants an opportunity to rectify IEQ performance gaps passively.

This paper explores the causes and implications of some inhabitants choosing to avoid or abandon usage of their mechanical ventilation system. Similar work in single-family homes found that fewer than 40% of the inhabitants of dwellings surveyed used their mechanical ventilation systems as they were designed to be operated (Gill et al., 2010). Similarly, Carmona-Andreu, Stevenson, and Hancock (2013) found that poor handover procedures led to poor understanding, control over, and maintenance of mechanical ventilation systems. This paper reinforces the idea that design-intent and advanced technologies do not guarantee performance, and that careful attention must be paid to the capabilities, preferences and satisfaction of occupants (Schweber and Leiringer, 2012).

Beyond exploring the importance of inhabitants in achieving energy and IEQ predictions, this paper serves to demonstrate that the post-occupancy evaluation methodology – which relies largely on occupant feedback – is useful in understanding the causes and implications of technology adoption by inhabitants of high-rise residential buildings. This paper also strives to address a common shortcoming with the post-occupancy evaluation of residential buildings. Stevenson and Leaman (2010, p. 437) point out that:

> traditionally, the evaluation of housing performance has consisted of either physical monitoring or occupancy satisfaction questionnaires, but quantitative and qualitative feedback are rarely related to each other as they span across the disciplines of building science and social science.

By combining various data sets (described below) this paper aims to address this gap and explore which high-rise residential design and management strategies are appropriate and effective.

Methods

Recent decades have seen the construction of a significant number of high-rise residential buildings in Toronto, Canada. Of all North American cities, New York City is the only one with more buildings over 12 stories (including office towers) (McClelland, Stewart, & Ord, 2011). Recently, some Toronto developers have pursued green strategies and Leadership in Energy and Environmental Design (LEED) green building certification for their high-rise residential projects (Nolan, 2013).

The buildings

This paper utilizes data collected in four high-rise residential towers in Toronto, all built between 2008 and 2010. All four buildings are centrally located within dense neighbourhoods in Toronto, with immediate access to transit and amenities. These buildings were suggested by contacts from the authors' networks, and consent was sought from the board of governors for each building. All four buildings were certified LEED Gold, indicating above-average design aspirations in the areas of energy and IEQ, among others (CaGBC, 2013). Although three of the towers (A–C) are by the same developer, and Tower D is by a different developer, the four towers are similar (*i.e.*, similar heating, cooling and water heating systems) with only small differences in the relationship of suite-level ventilation to building-wide ventilation, which will be discussed. All four buildings target the luxury end of the residential market and are rented or owned by people with a relatively high socio-economic status (Table 1).

Individual units

All four towers make for interesting sites in which to study inhabitant satisfaction and behaviour. Units in Towers A–C each contain operable windows, a balcony door, a master electricity switch that shuts down all lights and non-essential receptacles, a thermostat and, most salient to this study, an occupant-controlled heat recovery ventilator (HRV) and sub-metering for space-conditioning (not typical in such buildings in Canada). Tower D contains most of the above features, but units have a constantly running HRV that can only be turned up, not off, by the inhabitant. As will be discussed further, inhabitants in Towers A–C receive a monthly bill for heating/cooling, hot water and electricity. Inhabitants in Tower D receive a monthly bill for electricity, hot water and cold water, but not space-conditioning.

Table 1 Research site information

Site	LEED certification	Units in the building	Occupied (months)	Ventilation system	Thermal sub-meters	Electricity and water sub-meters
Tower A	Gold	248	34	In-suite	Yes	Yes
Tower B	Gold	172	34	In-suite	Yes	Yes
Tower C	Gold	305	20	In-suite	Yes	Yes
Tower D	Gold	198	34	In-suite/central	No	Yes

Note: LEED = Leadership in Energy and Environmental Design.

As there are no heating or cooling sub-meters in Tower D, its inhabitants pay indirectly for their heating and cooling energy usage in their monthly condominium fees. Therefore, they are not aware of their consumption.

Ventilation design

In conventional Canadian high-rise residential towers, centralized ventilation systems deliver heated or cooled air to corridors, pressurizing them and forcing the treated air under entry doors and into dwellings.[1] This method requires large air-handling units and can result in suboptimal indoor air quality (IAQ) within suites (indeed, it is pejoratively referred to as the 'carpet filter' method of ventilation). These buildings usually also have a centralized heating system with no thermal sub-metering.

Beginning in the early part of this century, some Toronto designers began designing buildings in which dwelling entry doors were entirely sealed from corridors, meaning that inhabitants were fully responsible for their heating, cooling and ventilation needs – a strategy aimed at improving energy efficiency, IAQ and occupant satisfaction. It should be noted that due to the Toronto climate, passive ventilation through windows is often not desirable. This is due to energy loss and humidity fluctuations during the extremes of summer and winter in particular.

In Towers A–C, inhabitants use a switch in their bathroom (Figure 1) to control their HRV, which then operates in low, high or recirculation mode; it can also be shut off entirely by the pushing the button an extra time. The system is intended so that at the very least it is left in intermittent (recirculation) mode, where it operates at low speed (approximately 23.6 l/s) for 20 min out of each hour; sending fresh air to the fan coil unit where it is heated or cooled as need and distributed throughout the suite. In Tower D there is no control for the HRV. Instead, a constantly running exhaust fan in the bathroom ceiling is ducted to the HRV. This fan delivers indoor air to the HRV where its energy is exchanged with outdoor fresh air and then delivered to the dwelling via the fan coil unit. In

Figure 1 Heat recovery ventilator (HRV) control (Towers A–C)

addition to this system, Tower D also utilizes a small gap under entry doors to deliver additional fresh, treated air from the central air-handling unit.

Data collection methods

This study utilizes multiple data sources, including questionnaires, interviews, metered energy data, noise and IAQ measurements, and appliance specifications. The *BUS Methodology Domestic Questionnaire* was used to collect information from building inhabitants. Core questions of the BUS questionnaire have been used in a variety of post-occupancy evaluations (*e.g.*, Baird, 2010) and explore the areas of IAQ, thermal comfort, acoustics, lighting, design, health and general satisfaction. Specific questions about control and usability were added for the present study in order to explore more fully how inhabitants interacted with their particular heating, ventilation and air-conditioning (HVAC) systems.

Questionnaires were delivered between January 2012 and May 2012, with the survey period lasting two

Table 2 Data collected from each site

Site	Units in the building	Questionnaire responses	Questionnaire delivery	Noise measurements	Individual interviews	Air quality measurements
Tower A	248	41 (16.5%)	January 2013	2	2	1
Tower B	172	27 (15.2%)	February 2013	0	3	1
Tower C	305	52 (17.1%)	March 2013	0	0	0
Tower D	198	45 (22.7%)	May 2013	6	6	0
Total	926	165 (17.8%)		8	9	2

weeks in each of the buildings (Table 2). Every unit in each building was asked to participate in the survey. This non-probability sampling method was chosen in order to maximize participation. It should be noted that respondents to the questionnaire are likely to be more engaged inhabitants, with more interest in their dwelling's optimal operation and in providing feedback.

The majority of questions ask the respondents to rate some aspect of the building (*e.g.*, satisfaction with acoustics) on a seven-point scale where '1' indicates dissatisfaction and '7' indicates a high degree of satisfaction. The seven points on the scale are assigned a numerical value which is used to generate a mean value for relevant variables. This is useful because it allows comparisons with similar work (*e.g.*, Baird, 2010) and to *BUS Methodology* benchmarks. In addition to this approach, results are also reported using the categories 'percentage satisfied' and 'percentage dissatisfied'. 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).[2] This level of categorical resolution provides context for the mean values, and is the most granularity that can be offered given that the original questionnaire items did not include text labels.

In addition to questionnaires, a small number (Table 2) of semi-structured interviews were conducted in the home of consenting participants and focused on gaining insight into how they operate their ventilation system using the same questions for each participant. Eligible participants indicated on their questionnaire that they would be willing to participate in a follow-up interview, but only a relatively small number of interviews were conducted due to difficulty scheduling time with people.

Quantitative data collection

For Towers A–C, data were collected from thermal meters in each dwelling unit which measure flow rate and temperature change in order produce monthly kWh values for heating and cooling energy use. Data from these meters were acquired from the building's energy management contractor from the beginning of each respondent's tenancy. These kWh values were normalized using the floor area of each dwelling (m^2), which was derived from scale floor plans and can therefore be assumed to be fairly accurate. Heating and cooling data were then further normalized for weather using local heating- and cooling-degree days (reference temperature of 18°C), based on a 30-year average to complete the normalization process and provide an energy-use intensity ($kWh/m^2/year$) for each respondent. Thermal sub-meter data were not available in Tower D.

Acoustic measurements were carried out using a class 2 integrating sound-level meter and real-time octave-band spectrum-band analyser (CESVA SC-160). Various noise ratings (*e.g.*, Sones, QAI, RC Mark II) can be generated from the data collected by the equipment. IAQ measurements were taken using a 3M EVM 7 Environmental Monitor, and included CO_2, air temperature, humidity, particulates (*i.e.*, PM 2.5) and volatile organic compounds (VOC). It should be noted that these were indicative spot measurements and not long-term logged measurements, and a full indoor environment survey was not carried out. Therefore, these measurements should be treated as supplementary to some of the more comprehensive data presented in this paper. Certainly, further research should involve logging IAQ parameters and noise measurements in all different types of suites.

Results

Table 2 summarizes the data collected for this study. Thermal sub-meter data were collected for all participants who completed a questionnaire in Towers A–C. Questionnaire data for all four towers were analysed using the statistical analysis software package SPSS[3] to generate frequency and mean for relevant items. It should be noted that there were no expectations for response rates in any of the buildings. The only research done in Canadian high-rises has been performed in rental towers with largely different socio-economic makeups and different challenges (*e.g.*, language barriers). Given the results from the present study, responses rates between 15% and 20% seem reasonable for future work in similar buildings.

Of the 165 respondents, 75% were over 30 years old, 64% were female, 11% of dwellings had children living in them, and 39% of dwellings were occupied by only one person. The majority of respondents (59%) owned their dwelling, while the remainder were renters. Data related to occupancy patterns suggest that 59% of people are typically home only during evenings and weekends, whereas 33% of people reported being home most of the time. Finally, 38% of respondents had previously owned single-family house.

On the questionnaire, inhabitants were asked to report whether or not they use their HRV, as well as how often they use it in winter. These responses were used to create a dichotomous variable (HRV user and HRV non-user) into which respondents were grouped. Over half of respondents from Towers A–C (53%, $n = 56$) were grouped as HRV non-users, indicating on the questionnaire that either they did not know about their HRV or that they use it either rarely or never. Comments from HRV non-users range from 'Not sure about ventilator – I believe building operates' to 'I don't know anything about the HRV'. An unpublished internal study conducted in 2009 by the developer of Towers A–C found that 49% of respondents did not know if their dwelling had an HRV, supporting the grouping used in the current study. In Tower D, at least 27% of respondents are HRV non-users, this number having immobilized their HRV by disconnecting their bathroom fan.

Table 3 Questionnaire scores for heating, ventilation and air-conditioning (HVAC) system control and usability

	Mean (ideal = 7)	Per cent dissatisfied	Per cent satisfied
Towers A–C			
Control over heating	5.63	9	83
Control over cooling	5.42	12	77
Control over ventilation	4.51	27	52
Usability of thermostat	5.26	21	68
Usability of heat recovery ventilator (HRV) control	5.38	8	49
Tower D			
Control over heating	5.66	20	76
Control over cooling	5.32	15	65
Control over ventilation	4.02	41	40

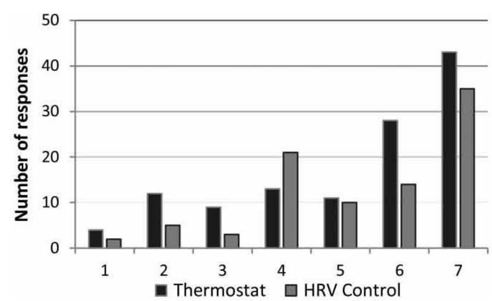

Figure 2 Questionnaire scores for satisfaction with heating, ventilation and air-conditioning (HVAC) controls

Control and usability

Table 3 shows the results of several questions relating to usability and control of the HVAC systems. A higher mean score expresses greater satisfaction. Table 3 indicates that respondents from Towers A–C felt the least amount of control over ventilation (with a mean score of 4.51) compared with the amount of control they feel they have over heating and cooling (with mean scores of 5.63 and 5.42 respectively). Satisfaction percentages similarly show that inhabitants feel the least amount of control over the ventilation in their suites. This trend was also observed in Tower D.

Despite poor satisfaction with the control over ventilation, respondents rated the usability of their HRV control (5.38) marginally higher than thermostats (5.26); though it should be noted that a similar range of responses was received (Figure 2). On open-ended questionnaire items (*i.e.*, comments), complaints about thermostat usability outnumbered those for the HRV control 20 to zero. This suggests that the usability of the HRV control is not a likely cause of dissatisfaction with control over ventilation.

Inhabitants in Towers A–C are required to clean and change their own HRV filter to ensure optimal operation. On the questionnaire, 39% of respondents ($n = 41$) reported that they had never done this, and of those who provided comments on their questionnaires, 16% said that the filter was too difficult to clean. For example, one respondent commented: 'tried to clean HRV filter, way too difficult, did not bother.' Maintenance of the HRV filter is a usability parameter with which inhabitants appear to be challenged.

Acoustics

Unwanted noise is a potential factor in inhabitants abandoning usage of their HRV. Only inhabitants in

Table 4 Acoustic satisfaction

Satisfaction with ...	Mean	Per cent dissatisfied	Per cent satisfied
Noise from heating, ventilation and air-conditioning (HVAC) equipment	4.14	39	48
Overall acoustic conditions	5.56	9	78

Tower D were asked specifically to rate their satisfaction with the amount of noise generated by their HVAC systems. Their scores (Table 4) suggest dissatisfaction with the noise caused by their ventilation system. Additionally, all 27% of respondents who had disabled their HRV did so because of its objectionable noise.

Respondents from all four towers used open-ended questionnaire items to complain about, or praise, the acoustic conditions in their suites. There were three main areas of acoustic complaints: noise from neighbours, noise from common areas and noise from the HVAC system. As was the case with controls, these comments were largely negative and the majority focused on the noise caused by the HVAC system, suggesting that HVAC noise is something with which respondents are dissatisfied.

Table 5 shows the results of noise measurements taken in eight different units in Towers A and D. Results from the octave-band analyser were entered into a spreadsheet calculator that calculated quality assessment index (QAI) and predicted objectionable noise qualities. To give these results context, the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) guidelines for noise caused by residential ventilation equipment state that:

> a QAI that exceeds 5 dB but is less than 10 dB represents a marginal situation, in which acceptance by an occupant is questionable. However, a QAI greater than 10 dB will likely be objectionable to the average occupant.
> (ASHRAE, 2011)

Table 5 Noise measurements

Location	Quality assessment index (QAI) (dB)	Predicted objectionable qualities
Tower D: Bathroom fan	10	Hiss
Tower D: Bathroom fan	7	Slight hiss
Tower D: All fans	13	Mid-frequency roar
Tower D: All fans	8	Rattle
Tower D: Bathroom fan on high	20	Mid-frequency roar
Tower D: Bathroom fan on high	13	Hiss, rattle
Tower A: All fans	7	Slight hiss
Tower A: Bathroom	5	None predicted

ASHRAE also prescribes that ventilation systems be free from 'fluctuations in level such as throbbing or pulsing'.

The QAI results for Tower D show significant variation, but overall the readings confirm respondents' questionnaire responses that HVAC noise is a source of dissatisfaction. The results from the two measurements taken in Tower A are in the ASHRAE marginal category, indicating that dissatisfaction could be justified.

Indoor air quality (IAQ) measurements

Table 6 shows data collected by the IAQ monitoring device and indicates better IAQ in the suite belonging to an HRV user. Both suites were measured on the same day in March 2014, and both had the same thermostat set-point, with inhabitants who had been away at work all day and had not showered or cooked since they returned home. One had their HRV running in intermittent mode all day; the other had it switched off for the last three months. It should be noted, however, that the IAQ measurements in the HRV non-user suite are within the guidelines recommended by Health Canada (2013).

Table 7 shows the results from questions that asked inhabitants to rate their satisfaction with IAQ. Results for overall satisfaction are shown graphically

Table 6 Indoor air quality (IAQ) measurements

	CO_2 (ppm, average)	Humidity (average)	PM 2.5 (average mg/m^3)	VOC (ppb, average)
Heat recovery ventilator (HRV) user	572	24.2%	0.003	552
HRV non-user	673	21.7%	0.014	617

Note: VOC = volatile organic compound.

Table 7 Indoor air quality (IAQ) satisfaction in heat recovery ventilator (HRV) users and non-users

	Mean	Per cent dissatisfied	Per cent satisfied
Overall IAQ satisfaction (ideal = 7)			
HRV user	5.27	6	67
HRV non-user	5.87	13	87
Freshness of air (Ideal = 1)			
HRV user	3.29	10	37
HRV non-user	3.42	21	48

(Figure 3) in order to represent further the range of responses received. Interestingly, HRV non-users reported higher satisfaction with overall IAQ, but slightly lower satisfaction with the freshness of their air.

Knowledge and preferences

The majority of respondents (76%) from Towers A–C indicated that either the balcony door or their operable windows were the primary means by which they provided fresh air into their suite during winter (15% responded that they primarily use their HRV). In Tower D, 63% of respondents reported using their balcony door or windows (19% responded that they use their HRV). These results clearly suggest a preference for passive ventilation, which will be discussed.

Though this study was not explicitly designed to understand the ventilation knowledge of inhabitants, interviews with two HRV non-users revealed that ventilation for them meant getting fresh air into the suites via operable windows (*i.e.*, passively). One respondent

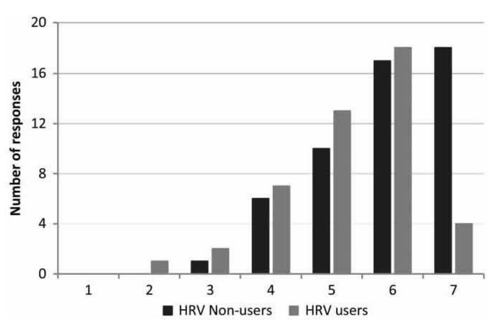

Figure 3 Questionnaire scores for satisfaction with overall indoor air quality (IAQ)

indicated how great it was finally to have a balcony door that she could use to get more air into the suite, instead of only having windows.

There is also evidence that respondents do not know how to use their HRV to rectify IEQ problems in their suites. For example, an HRV non-user reported during an interview that condensation occurs on the inside of windows during winter. This would occur because of excess moisture from cooking, bathing and breathing which was not exhausted sufficiently. This respondent had abandoned use of their HRV because of perceived ineffectiveness, despite it being able to improve the conditions in their suite (*i.e.*, the HRV can regulate humidity in winter). Passive ventilation would not work well in such conditions because it would be letting in too much cold winter air. Interestingly, this family rationalized their condensation problem by saying that it was not as bad as the condensation they observed on the windows in the conventional residential tower they could see from their 'green' dwelling.

Learning

Over half of the respondents from Tower D (52%) said that it became easier over time to control the indoor environment of their suites, suggesting that achieving IEQ satisfaction is an iterative process which improves over time. In Towers A–C, HRV use appears to be positively related to length of tenancy. Fifty-seven per cent of people who have lived there for longer than a year were HRV users, whereas only 25% of those who have lived there for less than a year used their HRV. One possible reason for this is that respondents who have been in their suite for over a year were more likely to have been involved in the initial handover process, which included a training manual.

To explore this, Table 8 shows the cross-tabulation results between reading the training manual and using the HRV. It should be noted that aside from the training manual presented during the initial handover, no further training about the HRV or any other systems in the dwellings has been carried out.

Table 8 Cross-tabulation results involving training materials

	Did you read the training manual? (%)	
	Yes	No
Heat recovery ventilator (HRV) user	74	29
HRV non-user	25	71

Even at first glance, Table 8 suggests a positive relationship between reading the training manual and using the HRV. In order to explore this further, Pearson's chi-square statistic was used to determine whether or not a statistically significant relationship exists between the two variables. SPSS conducts this test by comparing the observed frequencies to predicted frequencies (Field, 2009). The test found a statistically significant relationship between the two variables ($p < 0.001$). Therefore, it is reasonable to say that in the greater population, an increase in HRV use would result from reading the training manual.

The cross-tabulation results from Table 8 can be used to calculate an odds ratio, which indicates the odds of HRV use after reading the training manual (Field, 2009). Calculating the odds ratio yields the result that reading the training manual makes a resident 7.11 times more likely to be an HRV user.

It must be noted that inhabitants' knowledge about ventilation could have come from many other sources external to the formal training provided during building handover, including prior experience, conversations with neighbours, independent research, etc. A limitation of this study is that it did not systematically ask inhabitants to indicate how their ventilation learning has taken place.

Energy data

Figure 4 shows that respondents in Towers A–C who regularly or always use their HRV use more thermal energy (12% heating and 24% for cooling) than those who do not. This is assumed to be because HRV users are actively ventilating their dwelling, meaning that their HRV preconditions about 70% of incoming fresh air, with the rest being treated by the fan coil unit (from which the thermal meter reading is acquired). Non-users recycle air from their dwelling, meaning that they do not have to make up the temperature differential caused by bringing fresh air in. Similarly, it makes sense that the difference between HRV users and non-users is greater during the cooling season because the heat exchanger's maximum efficiency is 50% in cooling mode, compared with 70% in heating mode, meaning that only 50% of the energy is transferred from exhaust air into incoming fresh air.

Data for electricity and hot water have been included to suggest that HRV users and HRV non-users are otherwise generally alike in their energy use patterns and that a primary reason for their differing scores for heating and cooling is ventilation use (this will be explored in more detail in future work). It should be mentioned that an increase in electricity consumption would be hypothesized for HRV users as a result of

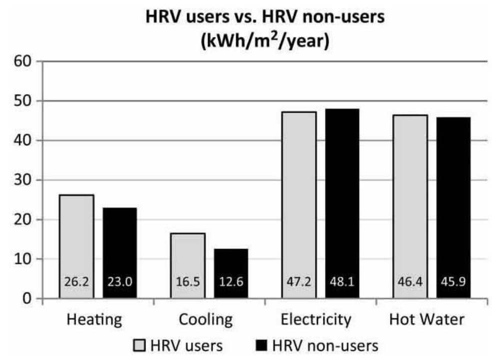

Figure 4 Energy and water user between heat recovery ventilator (HRV) users and HRV non-users

electricity used to run the intake and exhaust fans. Operating in intermitted mode (20 min per hour in low speed, 42 W) would result in 120.96 kWh of electricity consumption over the course of a year; or 3.9% of the average electricity used by suites in Towers A–C (3095.3 kWh/year). As above, this will be explored in future work with this data set.

As mentioned, there are no thermal sub-meters in Tower D, however there is still a way to explore the energy implications of HRV non-use. In addition to the in-suite ventilation, secondary ventilation is provided by a rooftop air-handling unit that feeds treated air into the corridors and through the gap under dwelling entry doors. This has a capacity of 7551 l/s and during the design phase it was predicted that the air-handling unit would only have to work at this maximum capacity for a few hours each evening, when residents are cooking and the likelihood of odour-based complaints in commons areas is at its highest.

When a resident disconnects their bathroom exhaust/HRV fan (as 27% did), they immobilize their HRV (*i.e.*, the intake fan turns off as well). This modifies the pressure differential between their suite and the corridor because a properly functioning HRV creates an 11.8 l/s pressure deficit in the suite, causing treated air to be drawn from the corridor.

Owing to the complaints about odours in corridors, building management now operate the air-handling unit at 7551 l/s (*i.e.*, 100% capacity) for 24 h per day, every day, resulting in increased electricity consumption. It must be noted that there are numerous causes for odours migrating into corridors, including exterior wind pressure, use of operable windows, stack effect and use of other exhaust fans (*e.g.*, dryer, range hood). Therefore, it cannot be said that HRV non-use is driving all the extra energy being consumed by the air-handling unit in Tower D, though it is certainly a factor.

Discussion

The causes of HRV non-use will first be explored, followed by a discussion of the consequences of inhabitants choosing passive ventilation strategies instead of mechanical ones.

Control

The HRV control (Figure 1) can largely been ruled out as a major cause of HRV non-use. Though respondents indicated feeling the least amount of control over ventilation compared with heating and cooling, they ranked the usability of the HRV control slightly higher than the thermostat and produced zero complaints in open-ended questions, compared with 20 for the thermostat. Baird (2010) found when using the *BUS questionnaire* that respondents were twice as likely to complain than to offer praise in open-ended questions. If the inhabitants of Towers A, B or C had complaints about the HRV control, they likely would have offered these in the same way they had for the thermostat. Therefore, it is unlikely that the control is driving HRV underuse.

Filter maintenance

For at least some of the respondents (16% of those who provided additional comments), difficulty maintaining the filter led to HRV non-use. This echoes some of the findings of Carmona-Andreu et al. (2013), in which participants were challenged by the task of maintaining the filter in their mechanical heat exchanger. Improving the accessibility of these systems should be a concern for designers if they are seeking to encourage stewardship over the system. In Tower D, building managers have tasked maintenance staff with cleaning and changing filters. Given the present findings, this management strategy seems appropriate for other towers as well and will be recommended to them in subsequent reporting.

Heating, ventilation and air-conditioning (HVAC) noise

Questionnaire scores, comments and interviews reveal occupant dissatisfaction with the amount of noise caused by their HVAC systems. According to noise measurements taken of functioning HVAC systems, these complaints are largely warranted. This is especially true in Tower D where QAI values were high and where the noise caused by continuously running bathroom fans prompted 27% of respondents to disable their fan, negating their HRV entirely. As mentioned, in Tower D, 66% of residents reported being satisfied with the level of control they had over heating and cooling, compared with 40% for ventilation. It is reasonable to expect that this perceived lack of control has something to do with the quantifiable excess noise caused by the always running bathroom fan, and their inability to abate it via accessible controls (*i.e.*, an 'off' switch).

HRV non-users in Towers A–C reported in questionnaire comments that the noise caused by their HVAC system was a factor in their decision to abandon HRV usage, despite the fact that the manufacturer's sound rating for the HRV unit is only 3 sones (*i.e.*, QAI < 5). It seems likely that their noise complaints stem from frustration with noise from the central fan coil heating and cooling system, which is responsible for delivering heated or cooled air through the suite, as well as fresh air from the HRV. In other words, these inhabitants have a very quiet HRV that delivers air via a relatively loud fan coil system. This has prompted at least some of the respondents to discontinue using their HRV as an acoustic coping strategy. These people likely never turned the HRV back on as it kept their HVAC system dormant and quiet in between calls for heating or cooling. Excessive noise, then, is another driver of HRV non-use in all four study towers.

Ventilation preferences

Results presented above suggest a preference for passive ventilation, as the majority of respondents in all towers indicated that their windows and balcony doors were the primary means by which they ventilated their suites. It is clear that in some cases what could be perceived as a preference for passive ventilation is really just an inhabitant using their windows to ventilate because they are unaware of their HRV. As mentioned, there is a significant relationship between receiving training and HRV use. Only after being made aware of the benefits and functionality of the HRV could the preferences of these inhabitants properly emerge.

Other inhabitants appear to favour passive ventilation because they conceptualize ventilation as passive instead of mechanical. This is reminiscent of work done by Kempton (1986) which found that as many as 50% of Americans employed 'folk logic' and operated their thermostat as if it were a valve, which is inconsistent with engineering knowledge and results in suboptimal operation. It could be said that some inhabitants (in particular those who were oblivious to their HRV) in the present study buildings were employing a sort of folk logic that led to them to conceptualize their ventilation options as passive instead of mixed mode, resulting in the absence of mechanical ventilation behaviours.

However, there are also respondents who indicated on questionnaires and during interviews a clear preference for passive ventilation, praising operable windows and minimizing the role of the HRV in the 'ecosystem' of their suite. The fact that this preference emerged in a 'green' building that people bought into presumably in part because of its environmental controls speaks to the power of the preference for passive ventilation.

It should be noted that there are many reasons why this preference for passive ventilation could emerge, including connection with nature, familiarity, convenience, folk logic, a preference for unconditioned air – all of which are areas where more work is needed. Also, as mentioned, Leaman (cited in Yudelson & Meyer, 2013) asserts that some inhabitants may not be interested in having to operate complex buildings. It could be that the some of the respondents purchased their homes with the expectation that certain processes would not need to be managed, including ventilation. This is an area where further work is warranted.

Indoor air quality (IAQ)

Though only consisting of a sample of two units, the IAQ measurements taken in an HRV-user suite are better than those of an HRV non-user, with lower levels of CO_2, particulates (PM 2.5) and VOC (Table 6). This is to be expected, as mechanical ventilation is more consistent than passive ventilation, and the HRV units are equipped with an air filter.

Interestingly, however, HRV non-users reported higher overall satisfaction with IAQ in their dwellings. One possible explanation for this is that giving occupants access to effective environmental controls is an important factor in their satisfaction (Baird, 2010; Combe et al., 2011; Leaman & Bordass, 2001). It is therefore likely that some of the higher satisfaction expressed by HRV non-users has to do with their being involved in managing their own ventilation passively, whether or not they are unaware of – or have abandoned using – their HRV.

It must also be noted that the IAQ measurements taken in the HRV non-user home were well within Health Canada guidelines, suggesting no major problems with IAQ in the passively ventilated suite. In other words, from an IAQ perspective, results from the current study suggest that inhabitants exercising their preference for passive ventilation could be a benign choice. An important area of further work involves collecting IAQ data from a greater number of suites in order to explore this more fully.

The ideal ventilation scheme?

It can be argued that HRV non-users are actually the ideal user type for these buildings as they appear to be more satisfied with their IAQ, and are using less energy during the heating and cooling seasons; the latter being more important because of peak electricity demand concerns (Figure 2). Clearly, energy efficiency that is driven by HRV non-use should not come at the expense of IAQ. However, the fact that HRV non-users are satisfied with their IAQ and that the limited measurements suggest that their indoor environment meets Health Canada guidelines lends validity to the argument that HRV non-users are pursuing a valid strategy.

It is also worth remembering that decentralized, in-suite ventilation schemes are seen as a significant energy-efficiency design alternative to centralized (*e.g.*, 'roof-top') ventilation schemes, which consume a great deal of energy in their effort to conform to ASHRAE guidelines. If inhabitants reject their mechanical HRV in favour of passive ventilation via operable windows, and are not suffering from inclement IAQ or high energy use, then decentralized mechanical ventilation becomes even more attractive. It is possible that it may be worth installing simple decentralized extract mechanical systems and allowing passive ventilation, rather than investing in more expensive HRV systems that are underused or unused.

Implications for design

There are numerous ways that the findings from this paper can be of use to designers and managers of high-rise residential ventilation systems. An important finding is the uncovering of a clash between designer expectations and inhabitant thinking and behaviours. In behavioural economics, individual behaviour is understood as not always being rational or reflective of an individual's best interest. A similar phenomenon could be said to be going on in these towers where inhabitants in search of fresh air overlook the most effective source (*i.e.*, the HRV, which provides evenly dispersed, comfortable, filtered air) in favour of their operable windows and balcony doors. Designers need to remember that inhabitants are embedded in design decisions made long before they come to occupy a space and bring with them expectations, perceptions, capabilities and preferences, all of which combine to produce the achieved performance of their dwelling.

The provision of in-suite mechanical ventilation by designers has in part been undermined by a preference on the part of inhabitants for passive ventilation. In designing a mixed-mode building, it is unclear the extent to which designers of the study buildings wanted inhabitants to rely solely on mechanical ventilation, but it is likely that the relatively low usage rates would be considered undesirable by designers, especially during the extremes of summer and winter. Based on the above results, if designers want higher HRV usage rates, then ongoing occupant training programmes must be in place that alert inhabitants to the functionality and usefulness of their mechanical ventilation systems, while at the same time offering advice on how and when to exercise their preference for passive ventilation.

There should also be greater design team accountability around the uptake of important design decisions. Whether through goal setting or monitoring, designers should be encouraged to track the success of innovative design strategies like the ones deployed in the study buildings. This does not appear to be the norm in the Canadian design and construction industries.

Designers also need to use resilient design in such a way that embraces the agency of inhabitants, giving them the ability to exercise their preferences in ways that do not short circuit the IAQ or energy performance of their suite or their building. Whether intentionally or not, Towers A–C possess a resiliency that allows some inhabitants to exercise their preference for passive ventilation in a way that is neutral or even beneficial. In contrast, the disabling of loud HRV fans in Tower D caused problems in the ventilation ecosystem of the entire building. Results suggest that giving occupants full control over their HRV (instead of the 'black-boxed' approach adopted by Tower D) is preferable because it allows them to modulate their ventilation needs alongside their complex and subjective IAQ expectations, saving energy in the process.

Despite this finding, however, in subsequent buildings the designers responsible for Towers A–C have started to install HRV that are integrated into the fan coil units, bypassing direct occupant control. The findings from this study will be fed forward to these designers in the hopes that future design decisions are well informed.

The final recommendation is that if mechanical systems are to be used, designers must ensure that their detail design does not alienate user. For example, fan noise must be minimized. Designers need to specify HVAC equipment (*e.g.*, fans) that produce very little noise. As was shown, the unacceptable acoustic quality of the HRV fan prompted Tower D inhabitants to disconnect them manually, thereby unintentionally altering the ventilation ecosystem of the entire building; affirming Yudelson and Meyer's (2013) claim that 'wrong user behaviour can easily screw up the whole performance' (p. 27). Similarly, results from Towers A–C highlighted that an ultra-quiet HRV that uses an acoustically objectionable fan coil system to distribute its air risks being rejected by users. An HVAC system is only as quiet as its loudest component.

Further work in this area should involve measuring inhabitants' preferences for passive, mechanical, and mixed modes of ventilation and develop appropriate design and management strategies which reflect these. Second, a study in which a greater number of IAQ and noise measurements are conducted in HRV user and non-user suites would address what was a major limitation with this paper. Additional key questions raised in this paper will be explored in further work that involves this data set.

Conclusions

The post-occupancy evaluation approach used in these four buildings was useful in discovering how inhabitants interact with their HRV and their controls. It was shown that the HRV control is likely not the reason that people avoid using their HRV. Rather, the following reasons were identified as important: acoustic dissatisfaction, difficulty with accessibility of filters, lack of ventilation knowledge and engagement with training materials.

It was also found that HRV non-use had implications for IAQ and energy consumption. Specifically, HRV non-use does not seem to have a negative impact on IAQ from the inhabitants' perspective, and only marginally using real measurements. Similarly, HRV non-users consume less heating and cooling energy that those who use their mechanical ventilation systems as designed. These unintended consequences are poorly understood by designers, inhabitants and researchers alike, and are a valuable outcome of the current work.

As described above, multiple outcomes from this work ought to be applied by building designers and managers. It was discussed that ongoing occupant training is something that managers ought to consider, and which should happen alongside greater design team accountability. The use of resilient design and the provision of total control over ventilation are two strategies that were suggested for designers. It was also suggested that detail design needs to be acoustically appropriate in order that it not alienate users. These findings will be shared with the design professionals, managers and inhabitants involved in the study buildings, and also with the greater design community.

This study supports the need for the design and management industries to mandate the type of 'aftercare' advocated in the Soft Landings framework.[4] Without it, comprehensive, researcher led, post-occupancy evaluations in such buildings will be important to ensure the continued improvement in performance of this segment of the building sector. High-rise residential populations can be difficult to access, with controlled entrances, hesitant condominium corporations and overworked property managers; and the results can be difficult to share, with risk-averse, reticent developers. Despite this, it is important that post-occupancy evaluations be undertaken in this building type, otherwise innovative residential building strategies risk failing to achieve their potential.

Acknowledgements

The authors would like to thank Adrian Leaman of BUS Methodology, the two development partners, condominium boards, property managers and inhabitants who facilitated this important work. Any views expressed in this paper are those of the authors alone and do not necessarily represent the views of the funders.

Funding

This research was supported by the Social Sciences and Humanities Research Council (SSHRC) and by the Federal Economic Development Agency for Southern Ontario's Applied Research and Commercialization Initiative.

References

ASHRAE, (2011). *2011 ASHRAE Handbook – HVAC Applications; Chapter 48: Noise and Vibration Control*. Atlanta, GA: ASHRAE.

Baird, G. (2010). *Sustainable buildings in practice; what the users think*. New York: Routledge.

Berker, T. (2011). Domesticating spaces: Sociotechnical studies and the built environment. *Space and Culture*, *14*(3), 259–268.

Bordass, W., & Leaman, A. (1997). Design for manageability. *Building Research & Information*, *25*(3), 148–157.

Canada Green Building Council. (2013). *LEED Project Profiles search page*. Retrieved November 2013, from http://www.cagbc.org/leed/projectprofile_EN.aspx

Carmona-Andreu, I., Stevenson, F., & Hancock, M. (2013). Low carbon housing: Understanding occupant guidance and training. *Smart Innovation, Systems and Technologies*, *22*, 545–554.

Cole, R. J., Robinson, J., Brown, Z., & O'Shea, M. (2008). Re-contextualizing the notion of comfort. *Building Research & Information*, *36*(4), 323–336.

Combe, N., Harrison, D., Dong, H., Craig, S., & Gill, Z. (2011). Assessing the number of users who are excluded by domestic heating controls. *International Journal of Sustainable Engineering*, *4*(1), 84–92.

Field, A. (2009). *Discovering statistics using SPSS* (3rd ed.). Thousand Oaks, CA: SAGE Publications Inc.

Gill, Z., Tierney, M., Pegg, I., & Allan, N. (2010). Low-energy dwellings: The contribution of behaviours to actual performance. *Building Research & Information*, *38*(5), 491–508.

Gram-Hanssen, K. (2010). Residential heat comfort practices: Understanding users. *Building Research & Information*, *38*(2), 175–186.

Hauge, A., Thomsen, J., & Berker, T. (2011). User evaluations of energy efficient buildings: Literature review and further research. *Advances in Building Energy Research*, *5*(1), 109–127.

Health Canada. (2013). *Exposure Guidelines for Residential Indoor Air Quality*. Retrieved May 2014, from http://www.hc-sc.gc.ca/ewh-semt/pubs/air/exposure-exposition/index-eng.php#appa

Kempton, (1986). Two theories of home heat control. *Cognitive Science*, *10*, 75–90.

Leaman, A., & Bordass, B. (2001). Assessing building performance in use 4: The Probe occupant surveys and their implications. *Building Research & Information*, *29*(2), 129–143.

McClelland, M., Stewart, G., & Ord, A. (2011). Reassessing the recent past: Tower neighborhood renewal in Toronto. *APT Bulletin*, *42*(2/3), 9–14.

Nolan, C. (2013). A living laboratory for high-rise innovation. *Sustainable Architecture and Building Magazine (Issue 39)*.

Pilkington, B., Roach, R., & Perkins, J. (2011). Relative benefits of technology and occupant behaviour in moving towards a more energy efficient, sustainable housing paradigm. *Energy Policy*, *39*(9), 4962–4970.

Schweber, L., & Leiringer, R. (2012). Beyond the technical: A snapshot of energy and buildings research. *Building Research & Information*, *40*(4), 481–492.

Stevenson, F., Carmona-Andreu, I., & Hancock, M. (2013). The usability of control interfaces in low-carbon housing. *Architectural Science Review*, *56*(1), 1–13.

Stevenson, F., & Leaman, A. (2010). Evaluating housing performance in relation to human behaviour: New challenges. *Building Research & Information*, *38*(5), 437–441.

Yudelson, J., & Meyer, U. (2013). *The world's greenest buildings: Promise versus performance in sustainable design*. New York: Routledge.

Endnotes

[1]This ventilation strategy is often accompanied by electric baseboard heaters and rarely involves delivering conditioned air in summer. As a result, variable temperatures in winter can result in some suites having their windows open, while some suites are too cold. Overheating in summer is also a very common problem in these buildings: it is most commonly addressed with the use of window air-conditioning units (where allowed).

[2]Per cent (dis)satisfied values have been rounded to the nearest whole number. The accuracy implied by rounding these values to the nearest 10th is inappropriate given the relatively small sample size.

[3]See http://www.spss.com/.

[4]See https://www.bsria.co.uk/services/design/soft-landings/.

Appendix 5

Building and Environment 89 (2015) 308–317

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Using physical, behavioral, and demographic variables to explain suite-level energy use in multiresidential buildings

Craig Brown [a,*], Mark Gorgolewski [b], Alasdair Goodwill [c]

[a] Environmental Applied Science and Management, Ryerson University, Toronto, Ontario M5B 2K3, Canada
[b] Department of Architectural Science, Ryerson University, Toronto, Ontario M5B 2K3, Canada
[c] Department of Psychology, Ryerson University, Toronto, Ontario M5B 2K3, Canada

ARTICLE INFO

Article history:
Received 20 December 2014
Received in revised form
18 February 2015
Accepted 27 February 2015
Available online 10 March 2015

Keywords:
Occupant behavior
High-rise residential
Energy use
Water use
Survey research

ABSTRACT

Highly glazed high-rise residential towers are becoming increasingly popular across Canada, especially in Toronto. The present study explores energy use trends in these buildings, investigating the extent to which physical, behavioral, and demographic variables explain suite-level energy and water consumption. The study relies on data collected in four recently built towers, in Ontario, Canada, and involves submeter data from participating suites, questionnaire responses, and physical data relating to the each suite (e.g., exterior wall area). The average suite-level energy use intensity was found to be 125.6 ekWh/m^2/year (not including heating, cooling and lighting for common spaces). The average end-use breakdown is 35% for electricity (plug loads and lighting), 34% for hot water, 20% for heating, and 11% for cooling. Energy use intensity differed by a factor of 7 between similar suites, electricity by a factor of 5, hot water by a factor of 13, cooling by a factor of 47, and heating by a factor of 67. Results suggest that occupant behavior and demographics account for 57% of the heating variability, 84% of the cooling variability, and 60% of electricity variability. For hot water, 51% of variability was explained by self-reported behaviors, with the rest of the variability being explained by behaviors which were not measured. Combining quantitative and qualitative datasets was an effective approach to understanding energy use in this understudied building type.

1. Introduction

As buildings become better designed and constructed, the effect of occupant behavior on performance increases [1]. Various researchers have sought to understand the extent to which occupant behavior explains variability in energy and water consumption between similar dwellings. For example, Kelsven [2] compared gas and electricity use in similar single family homes and found the 5th and 95th percentile to differ by a factor of 4.3 for gas, and 5.7 for electricity. Gill et al. [3] found that occupant behaviors account for "51%, 37%, and 11% of the variability in heat, electricity, and water consumption, respectively, between dwellings." Verhallen and Van Raaij [4] found that household behavior explained 26% of the variability in household energy use, and building characteristics explained 24%.

* Corresponding author. 245 Saint Helens Avenue, Toronto, Ontario M6H 4A2, Canada. Tel.: +1 647 341 0409.
E-mail address: craig.brown@ryerson.ca (C. Brown).

http://dx.doi.org/10.1016/j.buildenv.2015.02.039
0360-1323/© 2015 Elsevier Ltd. All rights reserved.

Using recently built, highly glazed high-rise residential towers in Ontario, Canada, this paper has the following objectives:

1. Determine the extent to which heating, cooling, electricity, and hot water use vary between suites;
2. Determine the extent to which this variability can be explained by physical building characteristics, and by behavioral and demographic determinants.

Though these objectives have been addressed to certain extents in previous work [5,6,1] the present study is novel in that the suites from which data was collected are within four very similar high-rise residential towers (described in detail below). This provides additional opportunities to explore energy use patterns.

A review of past work has shown that various determinants have been explored in relation to energy and water consumption in the residential setting. These include dwelling type, its configuration and size, how it is heated [7,8,1], the number and age of occupants [10,9,1,11], and their income level [11–14,5]. Beyond these demographics, individual characteristics have been studied including the role of repeated patterns of behavior and thought [14,15], preferences, upbringing, culture [16], and the role of occupant perception, as exemplified by the rebound effect [17] and the prebound effect [18]. There has also been work conducted into the role of feedback [19], the presence of submeters [20], and the willingness of occupants to pay additionally for green design features [21]. NRCan [22] found that low-rise apartments where occupants do not pay for their utilities used 2.4 times as much energy as those who did. Finally, window opening behavior and the way in which occupants relate to control surfaces [23], thermostat use [6,3], and ventilation behavior [24] have all been studied.

Due to constraints on the availability of data and resources, only some of the determinants above could be explored. The present study will explore the extent to which the variables in Table 1 explain variability in heating, cooling, electricity, and hot water consumption in the study buildings.

2. Methods

This paper relies on three types of data: submeter data from participating suites, questionnaire responses, and physical data relating to the each suite (e.g., floor area). In the following sections, the methods by which this data was collected and analyzed will be discussed.

Table 1
Study variables.

Variable	Reason for inclusion
Floor area (m^2)	Hypothesized to affect heating, cooling, and electricity use.
Balcony width (m)	Hypothesized that as the number of linear meters of balcony increases, so too does heating consumption as a result of thermal bridging, which is as an increasing concern in Toronto due to poor balcony design.
Exterior wall area (m^2)	Hypothesized to affect heating and cooling loads.
Insolation (kWh/m^2)	Hypothesized that as insolation increases, heating use declines and cooling use increases.
Irradiation (W/m^2)	Hypothesized that as irradiation increases, heating use declines and cooling use increases.
Fenestration ratio	A constant fenestration ratio of 70% has been assumed for all buildings.
Suite orientation	Using insolation and irradiation values specific to each orientation will allow for an exploration of the role of orientation in heating and cooling.
Storey	This variable has been included to explore if hot air rising in the building (i.e., the stack effect) is affecting heating consumption.
Number of occupants	Hypothesized to be a driver of heating, cooling, electricity, and hot water consumption.
Renter or owner	Though 97% of renters and owners in the study building pay for their own utilities, renters and owners may have different levels of stewardship over their suite.
Time spent at home (e.g., evenings and weekends)	Hypothesized to be a driver of heating, cooling, electricity, and hot water
Age of occupants	Older occupants may have different occupancy and consumption patterns than younger ones (e.g., less domestic hot water use).
Thermostat setpoint	Hypothesized to be a driver of heating and cooling consumption.
Hot water behaviors (e.g., showers per week)	To test to the ability of questionnaire responses to explain variability, and to meet objective two.
Electricity behaviors (e.g., use of master switch)	To test to the ability of questionnaire responses to explain variability, and to meet objective two.

Table 2
General building information.

Site	Size (m^2)	Units	Average suite size (m^2)	Age of building when studied (months)
Tower A	29,322	248	91.1	34
Tower B	18,964	172	73.8	34
Tower C	22,144	305	47.1	20
Tower D	18,691	198	88.4	34

2.1. The study buildings

Data was collected in four high-rise residential towers in Toronto, all built between 2008 and 2010 (Table 2). All four towers are centrally located within dense neighborhoods and are rented or owned by people with a relatively high socio-economic status. These towers were suggested by contacts from the authors' networks, and consent was sought from the management board of each tower.

Although three of the towers (A–C) are by the same developer, and Tower D is by a different developer, the four towers are similar. All four towers were certified LEED Gold, seeking 9 of 15 IEQ credits, and 10 of 17 energy credits, thus indicating performance aspirations in the areas of energy and IEQ [25]. As well, all four towers are concrete slab construction, have suites which use fan coil systems to provide heating and cooling, and are equipped with an energy recovery ventilator (ERV). Fig. 1 demonstrates the range of suite sizes in the study buildings.

Towers A–C were built by the same developer in the same time period, and certain design and construction attributes have been assumed to be similar across these three towers (Tower D is not used in the analysis of heating and cooling data). Table 3 shows exactly what was assumed to be constant across the three towers. It is acknowledged that these assumptions might not be 100% accurate, ideally each of the assumptions would have been physically measured (e.g., fenestration ratio) and included in the regression models alongside the physical variables from Table 1. However,

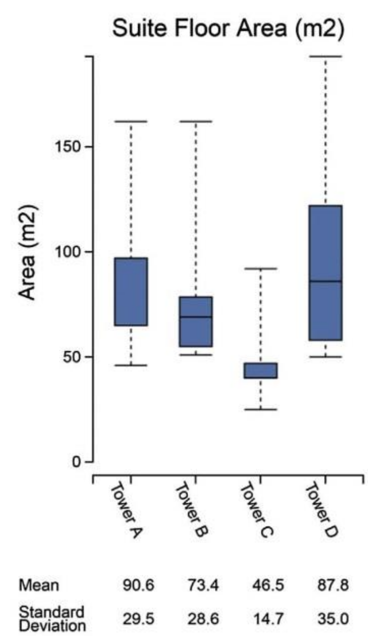

Fig. 1. Floor area.

Table 3
Physical constants.

Constants	Explanation
Wall height	Each suite was assumed to have an exterior wall height of 2.4 m.
Window type	Towers A–C have thermally broken aluminum window frames with low-E coated, argon gas filled, double pane, sealed glazing units, with operable awning windows. The exact SHGC for these windows is not known, but is assumed constant across the towers.
Fenestration ratio	Estimated to be above 70% in all three towers based on researcher observations.
Heating and cooling system	All four towers use a two-pipe fan coil systems to deliver heating or cooling to the suites.
Envelope construction	Envelope construction (e.g., R-value, air tightness) is held constant based on being of a similar age, construction type and built to satisfy the same building codes.

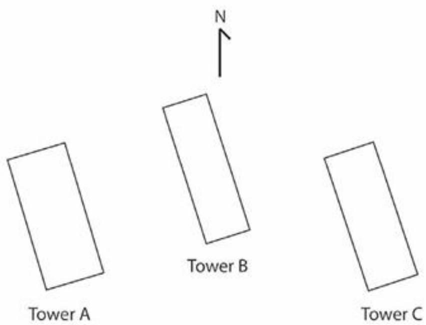

Fig. 2. Actual tower orientations taken from Google maps.

given the similarity of the towers based on researcher observations, and the fact that they were designed and built by the same developer, the assumption of similarity is not a significant impediment to accomplishing the objective of precisely determining the extent to which consumption data variability can be explained by physical building characteristics.

Towers A–C share the exact same orientation, despite being located in different parts of Toronto (Tower D was not used in heating and cooling analysis). Fig. 2 shows the actual orientations of the buildings, which are slightly askew to true north due to Toronto's grid pattern. At the time of study, a visual inspection revealed no tall buildings around Towers A, B, or C that would result in shading during a typical day.

The orientation of the study buildings is important, as Robertson and Athienitis [26] point out, "buildings with east-and west-facing orientations have greater potential for overheating in the non-heating season and get little solar gain in winter" and "north-facing windows provide consistent indirect light with minimal heat gains, but can also create heat loss and comfort problems during the heating season." The extent to which these phenomena are occurring in the study building will be explored using the orientation-specific insolation and irradiation variables described below.

2.2. Questionnaire and meter data

Table 4 shows the data collected for this study. The focus was on energy delivered (in kWh or ekWh) to the suites and not source (or primary) energy. Heating and cooling data for Towers A–C was collected from thermal metering systems in each suite which measure flow rate and temperature change in order produce monthly ekWh values, which are used for billing. Heating and cooling data were weather normalized using the ratio method, which adjusts raw data according to the relationship between heating- and cooling-degree day data from the study period and a 30-year average. The Canadian Climate Normals 30-year average (1981–2010) for an 18 °C reference temperature at Toronto's Pearson Airport was used (3873 HDD and 306 CDD).

Sub-metered suite level electricity data was available for all four towers and does not include energy used for hot water, heating or cooling. Instead, it in includes fan coil and ventilation fans, lighting, receptacles, cooking (electric stoves in all suites), and appliances. Suite-level electricity data do not need to be weather normalized because they do not include cooling or heating energy.

Hot water data was metered separately from cold water in Towers A–D. Hot water data was provided in cubic meters per month and was converted to a monthly ekWh value using gas consumption data for central domestic hot water boilers in Towers A–D. The gas consumed by domestic hot water boilers was divided by the number of cubic meters consumed by all suites to establish that 8.5 cubic meters of gas is needed to produce one cubic meter of hot water. Using a conversion factor of 10.33 [27], this equals 87.8 ekWh/m^3 of hot water.

The energy and water meter data have been carefully checked. First, suites with extremely high usage were checked to make sure that high usage was consistent from month to month. These suite numbers were then submitted to the data provider to ensure the high values were not the result of a malfunctioning meter. If both of these conditions were not met, the suite was removed from the study.

Next, suites with very low cooling or heating data (e.g., certain suites used no heating at all during winter) would only be included in analysis if they had consumed hot water during the same period. A value other than zero for hot water use led to the assumption that suite was occupied during the period for which little or no heating or cooling was used, and that low values should be used in analysis.

The *BUS Methodology Domestic Questionnaire* was used (under license) to collect information from building inhabitants. Core questions of the BUS questionnaire have been used in a variety of post-occupancy evaluations [28] and explore the areas of IAQ, thermal comfort, acoustics, lighting, design, health and general satisfaction. Specific questions were added which asked about energy and water related behaviors. It is from the questionnaire responses that the demographic and behavioral variables were created.

Table 4
Data collected.

Building	Months of data	# Of suites	Thermal metering system?	Electricity meter?	Hot water meter?	Questionnaires (response rate)
Tower A	24	36	Yes	Yes	Yes	41 (16.5%)
Tower B	24	23	Yes	Yes	Yes	27 (15.2%)
Tower C	18	47	Yes	Yes	Yes	52 (17.1%)
Tower D	24	41	No	Yes	Yes	45 (22.7%)
		Total# of suites for each meter type	**106**	**147**	**127**	**165 (17.8%)**

2.3. Physical variables

Scaled floorplans for Towers A–D were used to calculate accurate interior floor area as well as linear meters of balcony for each participating suite. Next, floorplans were used to determine the number of linear meters of exterior envelope for each suite in Towers A–C. This number was multiplied by the wall height (2.4 m) to produce a value for exterior wall area, which was used as a discrete predictor variable for heating and cooling consumption.

In order to analyze the role that orientation and window area played in determining heating and cooling consumption, EnergyPlus v8.2 was used to determine solar exposure on each of the exterior faces of the building. A shell model was created using the geometry and orientation of Tower A (the orientation of which is identical to Towers B and C) and an hourly simulation was performed using Canadian Weather year for Energy Calculation (CWEC) weather data for Toronto, ON (Lester B. Pearson International Airport station) (see Table 5).

Average values for the whole year, the heating season, and the cooling season were calculated for the incident solar radiation rate (i.e., insolation, kWh/m^2) and summed values were calculated for the radiation heat gain (i.e., irradiation, W/m^2) for the same time bins to create discrete variables for use in regression analysis [29]. The number of months included in the heating and cooling seasons does not need to equal 12; rather the relationship between them is what is important. To calculate values for a corner unit, the insolation values for each orientation were summed, reflecting the fact that a corner unit has more exterior wall. This value was multiplied by the fenestration area to give an average amount of insolation (kWh) for each season, specific to each suite.

For irradiation, the irradiation values for each face were averaged and then multiplied by the fenestration area to give an average amount of irradiance received in watts, for each season, specific to each suite. Both insolation and irradiation have been included in the regression analysis, though only the one with the strongest relationship was included in hierarchical regressions (described in Section 2.4).

2.4. Data analysis procedures

Inferential statistical analyses are required to meet the second objective of the paper (the first requires only simple arithmetic). Some initial data preparation was required because the consumption data was positively skewed, with the majority of consumption values on the lower end of the scale, and a few high consumers creating large upper quartiles (see Fig. 3).

Outliers were identified and removed as a first step in addressing this skewness, and in order to minimize their effect on statistics such as the mean. Outliers were identified by converting raw data into z-scores and excluding those that were less than 2.58 [30]. In a normal distribution, 99% of all z-scores are less than 2.58. Using this value to exclude outliers, then, removes scores which deviate very significantly from the mean. This ensures that extremely high scores did not bias the results. It should be noted that though excluded during statistical analysis, these outliers have been included in the work for objective one, which seeks to report the extent to which energy and water use vary between similar suites.

Because the data were skewed, they did not pass tests for normality, which tested the extent to which the study distributions differed from a normal (i.e., Gaussian) distribution. Data which is not normally distributed – as was the case in the present study - is generally thought to be less fit for use in linear regression models [30]. In similar work, Steemers [5] and Santin [6] performed square root transformations (i.e., taking the square root of each score) on their data in order to increase the normality of their distributions. Though useful in preparing data for use in regression models, transforming data suffers from the drawback that the results demonstrate the relationship between a predictor variable and the square root of the outcome variable, not the outcome variable itself.

For the purposes of this paper, square root transformations were performed on the data and regressions involving transformed and non-transformed data will be reported, focusing on the R^2 value. Field [30] points out that "the coefficient of determination, R^2, is a measure of the amount of variability in one variable that is shared by the other." Where relevant, hierarchical regression models will be used. These models use multiple predictor variables, entered sequentially into the model based on a logic determined by the researcher. The results demonstrate the combined effect of all predictor variables on the output variable.

Independent samples t-tests have been performed on demographic data, with results indicating whether the mean consumption values of two groups (e.g., renters and owners) differ significantly from one and other. Correlations have also been performed. Since directionality can be assumed (e.g., as linear meters of balcony increases, so too does heating consumption) one-tailed tests for significance are used. When a correlation is found to be significant (e.g., $p < 0.05$) it means that 95% of the relationships in the correlations are not a result of a chance occurrence. Cohen [31] suggests the following interpretations for correlations: $r = .1$ indicates a small effect, $r = .3$ a medium effect, and $r = .5$ a large effect. In the present study, significant correlations are used to qualify a variable for use in a regression model.

Table 5
Discrete insolation values for each orientation.

	North	East	South	West
Insolation (kWh/m^2)				
Yearly	275.0	546.8	708.2	554.6
Heating season (Oct.–Mar.)	76.3	148.4	321.1	178.2
Cooling season (May–Aug.)	151.0	291.8	249.4	268.8
Irradiation (W/m^2/month)				
Yearly	44.8	89.0	115.6	90.4
Heating season (Oct.–Mar.)	25.0	48.5	105.2	58.4
Cooling season (May–Aug.)	73.2	141.2	120.6	130.2

3. Results and discussion

3.1. Energy use intensity and end-uses

Table 6 presents suite-level energy consumption values for each of the study buildings using both area-normalized values, as well as gross (i.e., non-normalized) values. Results from all towers were used to produce a global average energy use intensity of 125.6 ekWh/m^2/year. This figure includes energy used in suites for heating, cooling, electricity, and hot water and is 27% less than the Ontario average for apartment dwellings, which is 172.2 kWh/m^2/year [32]. Unfortunately, the overall EUI of the study buildings cannot be accurately determined due to a lack of data about the energy used in common areas. It should also be noted that this study is quoting delivered energy to the suite and that ekWh of heating, cooling, and hot water are being compared on a 1:1 basis with suite level electricity, despite there being various upstream inputs in generating these secondary sources of energy.

The results from Table 6 were used to produce the end-use breakdown in Fig. 3. These results can be compared to the end-use breakdown for all Ontario apartments in Fig. 4. Though Fig. 4 uses non-normalized energy use values in PJ, the percentages allow a point of comparison.

Hot water consumption is the only value which could be considered to be similar on a percentage basis, and is 4% higher in

Table 6
Energy and water data.

Building	Yearly suite average in kWh/year (Standard deviation)	ekWh/m²/year	ekWh/month/suite
	Electricity (kWh)		
Tower A	3507.4 (1582.2)	38.8	292.3
Tower B	3283.4 (1305.3)	46.3	273.6
Tower C	2391.8 (893.5)	51.9	187.1
Tower D	3311.1 (1462.3)	39.4	275.9
Average	**3243.4 (1301.8)**	**44.1**	**257.3**
	Heating (ekWh)		
Tower A	1897.4 (1654.7)	22.4	164.3
Tower B	2001.1 (1653.2)	25.6	157.4
Tower C	1253.9 (1271.0)	26.9	115.1
Average	**1717.5 (1499.6)**	**25.0**	**145.6**
	Cooling (ekWh)		
Tower A	1249.7 (1281.9)	12.8	104.1
Tower B	1026.2 (975.0)	13.4	85.5
Tower C	789.0 (692.1)	16.3	65.8
Average	**1021.6 (983.0)**	**14.2**	**85.1**

	m³/year	m³/year/occupant	ekWh/m²/year	ekWh/year/suite
		Hot water		
Tower A	38.0 (24.9)	22.0	37.5	3337.6
Tower B	38.8 (23.7)	19.7	48.4	3410.5
Tower C	25.5 (15.0)	17.0	48.8	2242.1
Tower D	30.9 (16.2)	18.9	34.4	2714.6
Average	**33.3 (20.0)**	**19.4**	**42.3**	**2926.2**
		Energy use		
Total		**8909 ekWh/year**		**125.6 ekWh/m²/year**

the study buildings. Fig. 3 indicates that the suites in the study buildings use considerably less heating and considerably more cooling than the Canadian average. The cooling finding is not surprising as the study buildings are tall, highly-glazed towers with large east and west façades, and that cooling is not present in all of the apartments used in the Ontario data. Part of the large discrepancy in heating loads could be a result of the Ontario average being generated by dividing the total energy used in the building by the number of suites, whereas the study EUI is generate using submeter data.

Figs. 3 and 4 also show that electricity comprises a higher percentage within the study suites than in the Ontario average. Though the reasons for this are complex, it is worth mentioning that the study building has electric, and not gas, ovens and ranges. An additional point of context is that the electricity used for suite plug loads and lighting in the study buildings is 22% higher than the 36.2 kWh/m²/year measured in 39 high-rise multi-residential buildings in the Lower Mainland of BC, and Victoria, BC [34].

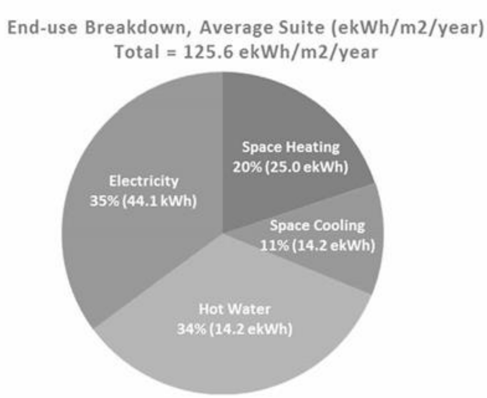

Fig. 3. End-use breakdown for study suites.

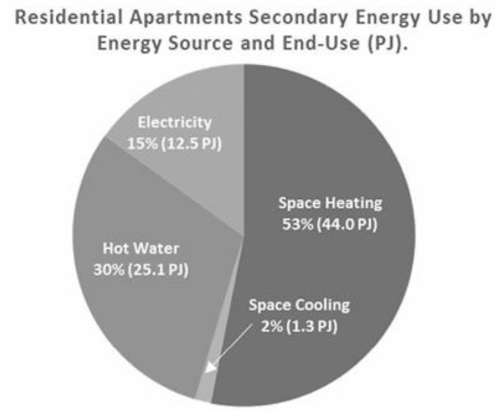

Fig. 4. Ontario apartment end-use breakdown [33].

3.1.1. Variation between suites

This section will report the extent to which area-normalized heating, cooling, electricity, and hot water consumption vary between suites. Fig. 4 graphically represents the variability for each end-use across all towers. Hot water is widely distributed, and differs by a factor of 13 from the lowest to the highest consumer. Electricity, which is also widely distributed, differs by a factor of 5. The variability in electricity consumption is caused largely by occupant behavior; either directly (e.g., watching a lot of TV) or indirectly (e.g., installed lighting).

Because some respondents used zero ekWh per year for heating and cooling, the minimum score has been raised from zero to one in order to make a factor calculation possible. In doing so, it was found that normalized heating consumption differs by a factor of 66, and normalized cooling by a factor of 47 (contextualization of these results is provided in Section 3.2.1.5). Using the 5th and 95th percentile results in a factor of 65 for heating and 38 for cooling. These large ranges are likely to be unique to high-rises, where heated corridors and party walls enable some suites to go all winter using very little or no heating energy. Notwithstanding this, it still signifies very high variability between the highest and lowest consumers.

Total energy use intensity was found to differ by a factor of 7.3 between suites. This is an important finding because it arose in a research setting in which accurate area-normalized data was used to compare between dwellings which are very similar to one and other (see Table 3). Next, physical, behavioral, and demographic variables will be used to explore the observed variability (Fig. 5).

3.2. Exploring variability

3.2.1. Space conditioning

3.2.1.1. Physical characteristics. The following section will use physical variables to explain the variability in heating and cooling consumption, which account for 20% and 11% of suite-level energy use intensity, respectively. In doing so, the amount of variability *not* explained by physical variables will be assumed and reported to be caused by demographics and behavior. In order to accomplish this, gross (i.e., non-normalized) data will be used as the outcome variable in regression models which explore the role of physical building characteristics in determining heating and cooling consumption.

Table 7 shows linear regression results involving six physical variables (labeled "a"–"f") and gross heating energy use. Results

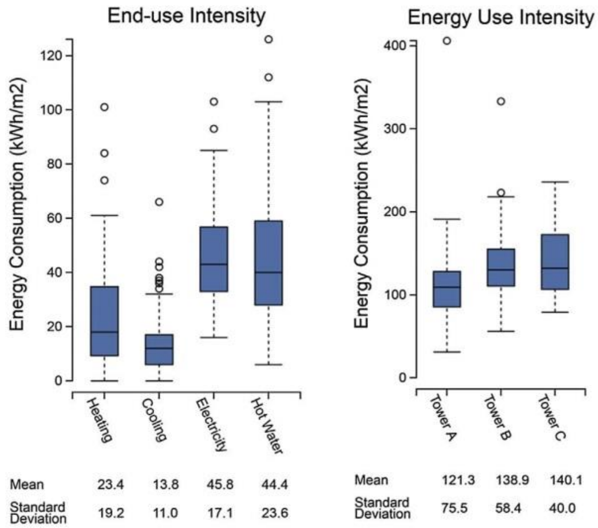

Fig. 5. End-use, and energy use intensity.

generated using transformed data indicate that exterior wall area is the most effective variable at explaining heating consumption, explaining 39.0% of the variability in the transformed data. As the results for 'Hierarchy 1' show, there is no R^2 change when floor area is added to a model containing exterior wall area. This is because exterior wall area is highly correlated to floor area (.833, $p < 0.01$) and therefore floor area becomes redundant in the model. Also, heat loss is dominated by the exterior wall area.

Insolation (kWh/m^2) explains 32.2% of variability in the transformed heating data and when added to a hierarchical regression with exterior wall area, together explain 43.2% of variability. This represents the strongest relationship between physical variables and transformed heating data. Table 7 also shows that storey and balcony are not very useful predictors of heating consumption. It should be mentioned, though, that as will be described (Section 3.2.1.4), drafty balcony doors, as reported by occupants, are likely driving heating loads in some of the suites, though not enough to contribute meaningfully in a regression model.

Table 7
Gross heating regressions, all towers.

	Variable(s)	Unstandardized beta	Standardized beta	R^2
Original data				
a	Exterior Wall Area	55.5	.618	.382
b	Floor Area	26.6	.506	.256
c	Insolation	592.5	.582	.338
d	Irradiation	670.8	.550	.302
e	Balcony Width	10.0	.246	.061
f	Storey	46.1	.195	.038
a + b	Hierarchy 1	58.3	.649	.382
a + c	Hierarchy 2	46.4	.547	.449
a + c + b	Hierarchy 3	47.0	.553	.449
Transformed data				
a	Exterior wall area (a)	n/a	.625	.390
b	Floor area (b)	n/a	.522	.272
c	Insolation (c)	n/a	.567	.322
d	Irradiation	n/a	.544	.296
e	Balcony width (d)	n/a	.265	.070
f	Storey	n/a	.195	.038
a + b	Hierarchy 1	n/a	.627	.390
a + c	Hierarchy 2	n/a	.538	.432
a + c + b	Hierarchy 3	n/a	.496	.433

Table 8 shows similar data for cooling. It shows that the strongest model explains 15.7% of transformed cooling variability and resulted from a hierarchical regression with exterior wall area as the first entry, floor area as the second, and irradiation. This is only slightly higher than the R^2 value for floor area (.14). Irradiation was found to be more effective than insolation, explaining 6.2% of transformed cooling variability. On the one hand this suggests that cooling is not highly determined by solar gain, and it may be more related to humidity which is high in the summer in Toronto. On the other hand, as was shown earlier, these suites use more cooling than the Ontario average, suggesting that high glazing ratios *are* increasing cooling loads.

Because of this, the use of windows blinds is likely a factor in producing these relatively weak regression relationships. The study buildings did not come with blinds installed; instead, it was an option people could choose during move-in. Laouadi [35] found a 9% reduction in on-peak cooling demand in houses where shades were added. The lack of data about the installation and use of blinds in the study buildings is a limitation of the present study.

3.2.1.2. Thermostat use. Unfortunately, there was not enough data collected to understand the effect of thermostat behaviors (e.g., programs, setbacks, manual overrides, on/off operation) on heating and cooling consumption. Even understanding on/off behavior would have been useful; Steemers and Yun [5] found that "the reported frequency of air-conditioning use accounts for 47% of the variation in cooling energy." Wi-fi enabled, logging thermostats would be required for this type of analysis, and certainly this is an avenue for further work given the increasing popularity of these thermostats.

3.2.1.3. Demographic determinants. In order to explore the role of demographics in heating and cooling consumption, results will be presented from independent samples t-tests. As discussed in Section 2.4, these results indicate whether the mean consumption values of two groups (e.g., renters and owners) differ significantly from one and other. If a significant result is found, it indicates that 95% of the time the two means do not differ as a result of chance. The column "Mean difference" shows the differences in the two mean scores regardless of significance.

Table 9 shows that the only demographic variable which causes a significant difference in heating consumption is whether the suite has one occupant, or more than one occupant. It is somewhat unclear as to why this relationship exists. After all, a single-occupied suite still needs to be heated all winter long. It could be that

Table 8
Gross cooling regressions, all towers.

	Variable(s)	Unstandardized beta	Standardized beta	R^2
Original data				
a	Exterior wall area	38.8	.232	.054
b	Floor area	25.1	.273	.075
c	Insolation	682.4	.199	.039
d	Irradiation	530.6	.297	.088
a + b	Hierarchy 1	24.4	.262	.075
a + d	Hierarchy 2	500.7	.662	.115
a + b + d	Hierarchy 3	13.8	.500	.192
Transformed data				
a	Exterior wall area	n/a	.301	.091
b	Floor area	n/a	.374	.140
c	Insolation	n/a	.163	.027
d	Irradiation	n/a	.250	.062
a + b	Hierarchy 1	n/a	.402	.141
a + d	Hierarchy 2	n/a	.767	.096
a + b + d	Hierarchy 3	n/a	.446	.157

Table 9
Heating and demographics.

Factors	Mean heating (ekWh/m²)	SD	t	df	Sig.* (2-tailed)	Mean difference
Single occupied	20.3	16.7	1.734	89	.086	.35
More than one occupant	27.3	21.8				
Home all the time	25.0	15.2	-.324	77	.747	.07
Evenings and weekends	26.8	21.8				
Under 30	23.3	20.0	-.421	89	.675	.08
Over 30	25.1	20.3				
Renters	22.6	20.5	−1.006	88	.317	.19
Owners	26.9	19.9				

*$p < 0.05$.

suites with one or more occupant experience more manual overrides to thermostat programs, but this was not measured. It is also perhaps surprising that those that who are home all day do not seem to use significantly more energy than those who are home only evenings and weekends. We can speculate that this is because occupants do not use thermostat setbacks for non-occupied periods. There also seems to be little impact of age on the amount of heating used, but this could be a function of the questionnaire items being too simplistic. There is not a large difference between renters and owners in the study buildings, perhaps because 97% of participants paid for their own utilities, regardless of whether they owned or rented.

Table 10 shows that the only significant demographic factor determining cooling use is whether people are home all the time or only on weekends. This suggests that respondents are setting back or disabling their cooling while away from home. This is surprising considering the observation above about heating. One explanation for this is that since cooling costs more (approximately $.06/ekWh, compared to $.04/ekWh for heating), residents are incentivized to setback or disable cooling when not at home. Another explanation may be that heating is expected, but cooling is optional.

Overall, it seems sufficient to say that these types of demographics and analyses are not very useful in explaining the remaining heating (57%) and cooling (84%) variability not accounted for by the physical variables.

3.2.1.4. Occupant context. Comments received on questionnaires were useful in suggesting additional explanations for the variability in heating and cooling consumption. For example, comments indicated that some corridors were overheated during winter (e.g., "hallway is too warm in winter and too cool in summer"). This could conceivably lead to less heat being used by suites which are on floors with overheated corridors and could help to explain why some suites use no heating energy at all. For example, one respondent who used very little heating energy reported that their suite "is always hot in winter, at least 70–71. We installed overhead fans for cooling and black-out shades and leave two windows open at all times, unless extremely cold out." A similar complaint was received from their neighbor: "sometimes have to open balcony doors to cool the place down during winter." Meanwhile other suites in the same building indicate that they "always need heat in the winter." Overheating of some corridors could be a factor in excessively low heating consumption.

Similarly, negative comments involving balcony doors suggest that thermal bridging of balconies is not their only liability during the heating season. Rather, various respondents indicated that their drafty balcony door let a significant amount of cold air in during the winter (e.g., "draft by balcony door, can have ice buildup there"). As mentioned in Section 3.2.1.1 this is likely driving heating use in some suites, though not enough to register in the regression modeling. Neither of these phenomenon were measured in the present study, but are important insights gathered via occupant feedback and are areas for further research in similar buildings. Similarly, further work in underway that involves coding of comments in order to more rigorously examine them.

Table 10
Cooling and demographics.

Factors	Mean cooling (ekWh/m²)	SD	t	df	Sig.* (2-tailed)	Mean difference
Single occupied	19.3	39.5	.916	103	.916	.32
More than one occupant	14.6	10.6				
Home all the time	26.8	47.3	2.305	90	.019*	2.16
Evenings and weekends	12.4	9.4				
Under 30	13.4	10.4	.792	103	.430	.32
Over 30	17.7	29.9				
Renters	15.5	13.0	-.319	102	.750	.10
Owners	17.1	34.1				

*$p < 0.05$.

3.2.1.5. Summary of space conditioning findings. Heating differed by a factor of 67, with physical factors accounting for 43.2% of the variability. This number may seem high, but other researchers have found that heating consumption resulting from occupant behavior in similar dwellings varied by a factor as low as 10 and as high as 37 [36,8,37]. Cooling in the study buildings differed by a factor of 47, with physical variables explaining 15.7% of the variability. To provide context, Parker [38] found cooling loads differing by a factor 21 in a study of cooling loads in 204 Florida homes. Pratt et al. [39], found that heating and cooling were the first and second most distributed residential end-uses, respectively.

This leaves 56.8% of the heating variation, and 84.3% of the cooling variation being caused by something other than building type, floor area, heating/cooling type, exterior wall area, glazing ratio, insolation, balcony width, and orientation. It is interesting to point out that Gill et al. [3], found that 51% of variability in heating consumption could be explained by occupant behavior. The analysis above seems to support this or even a higher % due to occupant behavior and demographics, though this was difficult to explore with the data available for the present study. Though behavioral and demographic determinants were not very useful in explaining the remaining variability in heating and cooling consumption data, anomalies were better understood through questionnaire comments, which highlighted corridor temperature and drafty balcony doors as potential physical determinants. Understanding these two physical phenomenon are pieces of further work to be conducted in the study buildings.

As mentioned, another limitation of the present study is the lack of insight about thermostat use. As Meier et al. [40] point out, "residential thermostats control 9% of the total energy use in the United States and similar amounts in most developed countries." More detailed questionnaires and Wi-Fi-enabled thermostats would help to overcome this limitation in further work.

3.2.2. Electricity

As shown in Fig. 3, electricity is the largest contributor to suite-level energy use intensity at 35%. Normalized electricity consumption differs by a factor of 5 from the lowest to the highest consumer (see Fig. 6).

Table 11 shows that non-normalized electricity use and floor area are correlated (.632, $p < 0.01$), indicating a strong relationships and justifying inclusion in a regression analysis. When floor area is used to predict electricity, the resulting $R^2 = .394$, indicating that

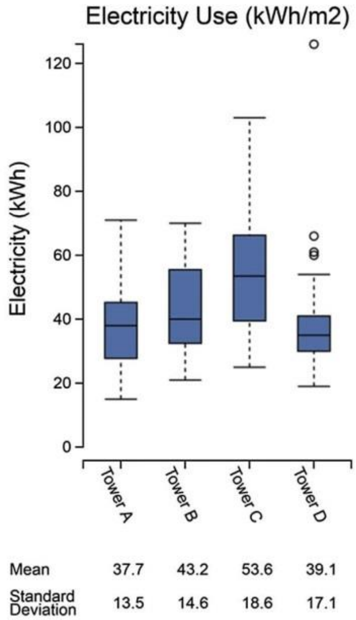

Fig. 6. Normalized electricity use.

Table 11
Electricity and floor area correlations.

	r	p-Value
Tower A	.548	<.01
Tower B	.489	<.05
Tower C	.289	n.s
Tower D	.716	<.01
All towers	.632	<.01

n.s. = non-significant.

floor area accounts for 39.4% of the variability in normalized electricity consumption. This suggests that as floor area is a relevant factor in electricity use in the study buildings. Since the essential appliances in each suite are the same (e.g., dishwasher, fridge, washer, and dryer) this variability is likely caused by the amount and type of personal electronic appliances, lighting choices, and other behavioral and demographic determinants.

Respondents in Tower D (Towers A–C were unfortunately not asked) were asked to rate the number of electronic appliances in their suite on a 7-point scale ranging from less than average to more than average. They were also asked to report the number of times per week that they used their clothes dryer. Table 12 shows how results from these questions are correlated to area-normalized electricity use. The number of times a person uses their dryer per week is not correlated to normalized electricity use, but a significant correlation was found between number of electronic appliances and normalized electricity consumption. Though only a medium strength relationship, this offers some suggestion for why electricity consumption varies as it does. Unfortunately, this item cannot be used in a regression due to questionnaire responses not being a continuous variable.

Table 12
Electricity behavior correlations.

	R	p-Value
Dryer/week	-.065	n/a
Number of electronic appliances	.359	<.05

Another electricity-related behavior which was measured on the questionnaire was respondents' use of the master electricity switch. This switch is located in the suite near the entry door and turns off all lights and the majority of receptacles, with the intention of reducing phantom loads and unnecessary electricity consumption. Table 13 shows that people who use the master switch in their suite do not use a significantly different amount of electricity that those who do. Indeed the mean values only differ by 3%.

Table 13 shows that all four of the demographic questions result in significantly different means. It should also be noted that on an absolute basis, the means differ by as much as 37%. Some of these relationships are interrelated, for example younger people use less electricity than those over 30 because they are 4.2 times more likely to be home only on weekends and evenings. For context, Binkley, Touchie, and Pressnail [9] found that buildings "designated as seniors' homes tend to exhibit lower energy use."

In summary, electricity use differed by a factor of 5 and floor area accounted for 39.4% of the variability. Neither weekly dryer use nor use of a master kill switch were found to be significant predictors of electricity use. Demographic determinants appear to be more effective than behavioral variables at explaining the 60% of variability in electricity consumption not explained by floor area.

3.2.3. Hot water

Hot water is the second largest component of suite-level energy use intensity, at 34%, and was found to vary by a factor of 13 from the lowest to the highest user. This section aims to explore the reasons for this high variability, which is entirely driven by occupant behavior.

All suites were sold furnished with low flow showerheads and sink aerators. Though some of these low flow fixtures have likely been replaced with higher flow ones, we assume that the majority are still in place. Aside from this possibility, there are no other physical characteristics that could be thought to drive hot water use. This section will begin by using demographic and hot water-behavior questionnaire items to explore variability.

Table 14 uses the same four demographic questions used in Sections 3.2.1.3 and 3.2.2 to perform t-tests with hot water consumption data. The only significant relationship exists between suites with one occupant and suites with more than one occupant. This is intuitive as water use is driven by occupancy. It was also found by Binkley, Touchie, and Pressnail [9] who found that "domestic hot water energy is a function of the number of occupants." To illustrate this using data from the present study, questionnaire

Table 13
Electricity and demographics.

Factors	Mean electricity (kWh)	SD	t	df	Sig. (2-tailed)	Mean difference
Single occupied	2443.2	1095.3	−4.418	142	.000	.37
More than one occupant	3345.9	1331.6				
Home all the time	3554.4	1534.8	3.060	129	.003	.29
Evenings and weekends	2762.7	1157.0				
Under 30	2597.3	940.2	−2.979	145	.004	.24
Over 30	3221.7	1484.8				
Renters	2734.0	952.0	−2.274	129	.025	.17
Owners	3206.8	1522.1				
Use master switch	3097.6	1367.6	.425	144	.672	.03
Don't use master switch	3000.2	1387.7				

averages. Unfortunately, understanding cooling behavior has proved to be illusive. Specifically, the study buildings use more cooling than the Ontario average, yet this usage could not be sufficiently explained using physical or behavioral variables. One reason for this is that the use of window coverings was not measured.

One of the major merits of this study is that the above insights were gathered in suites with a high degree of similarity. Those there may be slight differences which were not accounted for, it can be said that they are much more similar to one and other than single family homes, and afforded a higher degree of control compared to previous work done in this area. It is hoped that this work will provide reliable values for modelers, researchers, and managers to use as they consider how to make buildings more efficient, and better at reducing peak demand.

Acknowledgments

The authors would like to thank Adrian Leaman of BUS Methodology, Adrian Turcato and Matthew Tokarik of Ryerson University, the two development partners, condominium boards, property managers and inhabitants who facilitated this important work.

References

[1] de Meester T, Marique A-F, De Herde A, Reiter S. Impacts of occupant behaviours on residential heating consumption for detached houses in a temperate climate in the northern part of Europe. Energy Build 2013;57:313–23.
[2] Kelsven P. One of these homes is not like the other: residential consumption variability. In: UC Berkeley: behavior, energy and climate change conference; 2013. Retrieved from: http://escholarship.org/uc/item/4z68561x [accessed 17 12.14].
[3] Gill Z, Tierney M, Pegg I, Allan N. Low-energy dwellings: the contribution of behaviours to actual performance. Build Res Inform 2010;38(5):491–508.
[4] Verhallen T, Van Raaij W. Household behavior and the use of natural gas for home heating. J Consum Res 1981;8(3):253–7.
[5] Steemers K, Young Yun G. Household energy consumption: a study of the role of occupants. Build Res Inform 2009;37(5–6):625–37.
[6] Santin OG. Behavioural patterns and user profiles related to energy consumption for heating. Energy Build 2011;43(10):2662–72.
[7] Guerra-Santin O, Itard O, Visscher H. The effect of occupancy and building characteristics on energy use for space and water heating in Dutch residential stock. Energy Build 2009;41:1223–32.
[8] Gram-Hanssen K. Residential heat comfort practices: understanding users. Build Res Inform 2010;38(2):175–86.
[9] Binkley C, Touchie M, Pressnail K. Energy consumption trends of multi-unit residential buildings in the city of Toronto. 2013. Retrieved from, http://www.towerwise.ca/wp-content/uploads/2013/07/TAF-MURB-Energy-Performance-Report-Phase-II.pdf [accessed 17.01.15].
[10] Liao H, Chang T. Space-heating and water-heating energy demands of the aged in the U.S. Energy Econ 2002;24:267–84.
[11] De Groot E, Spiekman M, Opostein I. Dutch research into user behaviour in relation to energy use of residences. In: PLEA 2008 – 25th conference on passive and low energy architecture. Dublin, October 22–24th, 2008; 2008.
[12] Vringer C. Analysis of the requirements for household consumption [Unpublished doctoral dissertation]. Netherlands Environmental Assessment Agency. Retrieved from: http://www.vringer.nl/VRINGER-140805.pdf [accessed 04.02.15].
[13] Biesiot W, Noorman K. Energy requirements of household consumption: a case study of NL. Ecol Econ 1999;28:367–83.
[14] Lutzenhiser L. Social and behavioural aspects of energy use. Annu Rev Energy Environ 1993;18:247–89.
[15] Stern P. Towards a coherent theory of environmentally significant behaviour. J Soc Issues 2000;56:407–24.
[16] Schweiker M, Shukuya M. Comparison of theoretical and statistical models of air-conditioning-unit usage behaviour in a residential setting under Japanese climatic conditions. Build Environ 2009;44:2137–49.
[17] Haas R, Biermayr P. The rebound effect for space heating: empirical evidence from Austria. Energy Policy 2000;28:403–10.
[18] Sunikka-Blank M, Galvin G. Introducing the prebound effect: the gap between performance and actual energy consumption. Build Res Inform 2012;40(3):260–73.
[19] Brown Z, Dowlatabadi H, Cole R. Feedback and adaptive behaviour in green buildings. Intell Build Int 2009;1:296–315.
[20] Gunay H, O'Brien W, Beausoleil-Morrison I, Perna A. On the behavioral effects of residential electricity submetering in a heating season. Build Environ 2014;81:396–403.
[21] Chau C, Tse M, Chung K. A choice experiment to estimate the effect of green experience on preferences and willingness-to-pay for green building attributes. Build Environ 2010;45:2553–61.
[22] NRCan. Survey of household energy use 2005: summary report. 2006. http://oee.rncan.gc.ca/Publications/statistics/sheu-summary07/pdf/sheu-summary07.pdf [accessed on 30.01.15].
[23] Fabi V, Andersen R, Corgnati S, Olesen B. Occupants' window opening behaviour: a literature review of factors influencing occupant behaviour and models. Build Environ 2012;58:188–98.
[24] Brown C, Gorgolewski M. Understanding the role of inhabitants in innovative mechanical ventilation strategies. Build Res Inform 2014;43(2):210–21. http://dx.doi.org/10.1080/09613218.2015.963350.
[25] Canada Green Building Council. LEED project profiles search page. 2013. Retrieved from: http://www.cagbc.org/leed/projectprofile_EN.aspx [accessed 12.11.14].
[26] Robertson K, Athienitis A. Solar energy for buildings. 2009. Retrieved from: http://www.cmhc-schl.gc.ca/en/inpr/bude/himu/coedar/upload/OAA_En_aug10.pdf [accessed on 04.02.2014].
[27] NRCan. Energy efficiency in buildings. 2015. http://www.nrcan.gc.ca/energy/publications/efficiency/buildings/5985 [accessed on 30.01.15].
[28] Baird G. Sustainable buildings in practice; what the users think. New York: Routledge; 2010.
[29] Vyas J. Irradiance vs. insolation. 2012. Retrieved from: http://sargosis.com/articles/science/intro-guide/irradiance-vs-insolation/ [accessed on 12.02.15].
[30] Field A. Discovering statistics using SPSS. 3rd ed. Thousand Oaks, CA: SAGE Publications Inc; 2009.
[31] Cohen J. Statistical power analysis for the behavioral sciences. 2nd ed. Hillsdale, NJ: Erlbaum; 1988.
[32] NRCan. Comprehensive energy use database: residential sector Ontario table 38: apartments secondary energy use and GHG emissions by energy source. 2014. Retrieved from: http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/showTable.cfm?type=CP&sector=res&juris=on&rn=38&page=4&CFID=35631024&CFTOKEN=476d1a5df9129462-747EB201-DB8D-C8F1-5F20EF65146F2B3E [accessed 12.02.15].
[33] NRCan. Comprehensive energy use database: residential sector Ontario table 39: apartments secondary energy use and GHG emissions by end-use. 2014. Retrieved from: http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/showTable.cfm?type=CP&sector=res&juris=on&rn=39&page=4&CFID=35647257&CFTOKEN=8a346c2b3661f791-7DEBB05C-02CC-7C2C-CD78DAF676B71559 [accessed 12.02.15].
[34] RDH Building Engineering Limited. Energy consumption and conservation in mid and high-rise residential buildings in British Columbia. 2012. http://www.hpo.bc.ca/sites/www.hpo.bc.ca/files/download/Report/MURB-Energy-Study-Report.pdf [accessed on 30.01.15].
[35] Laouadi A. Guidelines for effective residential solar shading devices. NRC Institute for Research in Construction; National Research Council Canada; 2010. Retrieved from: http://www.ccht-cctr.gc.ca/eng/projects/solar_shadings.html [accessed 04.12.14].
[36] Urban B. Improving programmable thermostat usage with less aggressive default setbacks. In: Presented at behaviour energy and climate change, Sacramento, November 2013; 2013.
[37] Pilkington B, Roach R, Perkins J. Relative benefits of technology and occupant behaviour in moving towards a more energy efficient, sustainable housing paradigm. Energy Policy 2011;39(9):4962–70.
[38] Parker DS. Research highlights from a large scale residential monitoring study in a hot climate. In: Proceedings from international symposium on highly efficient use of energy and reduction of its environmental impact, Japan; 2002. p. 108–16. http://www.fsec.ucf.edu/en/publications/html/FSEC-PF-369-02/ [accessed on 30.01.15].
[39] Pratt R, Conner C, Cooke B, Richman E. Metered end-use consumption and load shapes from the ELCAP residential sample of existing homes in the Pacific Northwest. Energy Build 1993;19:179–93.
[40] Meier A, Aragon C, Peffer T, Perry T, Pritoni M. Usability of residential thermostats: preliminary investigations. Build Environ 2011;46:1891–8.
[41] U.S. Environmental Protection Agency. Bathroom. 2012. http://www.epa.gov/greenhomes/bathroom.htm [accessed on 30.01.15].
[42] Straube J. Can highly glazed building façades Be Green?. Building Science Corporation; 2008. http://www.buildingscience.com/documents/insights/bsi-006-can-fully-glazed-curtainwalls-be-green [accessed 17.12.14].

Appendix 6

Assessing occupant satisfaction and energy behaviours in Toronto's LEED gold high-rise residential buildings

Craig Brown
Environmental Applied Science and Management, Ryerson University, Toronto, Canada, and
Mark Gorgolewski
Department of Architectural Science, Ryerson University, Toronto, Canada

Abstract

Purpose – This paper aims to present four purposes: to assess occupant satisfaction with indoor environmental quality (IEQ); to determine if occupants appear to be operating their dwellings in an energy efficient manner; to suggest ways that occupant satisfaction and behaviour can help or hinder energy efficiency; and to show that the post-occupancy evaluation approach is an effective tool in diagnosing and improving satisfaction and energy efficiency in high-rise residential buildings.

Design/methodology/approach – Beyond measuring occupant satisfaction with IEQ, this paper uses scores and user comments from occupant questionnaires to identify success and indicate frustration and/or confusion with particular building technologies. It also extrapolates the energy efficiency implications of these responses in four Leadership in Energy and Environmental Design Gold residential towers.

Findings – The research highlights where problems occur, particularly with the adoption of new technologies which may not be well understood by the occupants. It also identifies behaviour patterns that may negate energy efficiency strategies.

Research limitations/implications – The lack of dwelling metre data prevents this research from making causal links between behaviours and their energy implications. Also, the lack of Canadian benchmarks for satisfaction of occupants means that comparisons can only be made to cases from the UK, which is less robust.

Originality/value – This type of work has never been done in Canadian residential high rise towers before. It helps to better understand the process of ensuring that occupants successfully adopt innovation that can lead to energy savings.

Keywords Construction, Mail questionnaires, Energy conservation, Occupant behaviour, Post-occupancy evaluation, Occupant satisfaction

Paper type Research paper

International Journal of Energy Sector Management
Vol. 8 No. 4, 2014
pp. 492-505

1750-6220
DOI 10.1108/IJESM-11-2013-0007

The authors would like to acknowledge the support of the Adrian Leaman at BUS Methodology for his support with this project. Funding for this project was, in part, provided by the Government of Canada's *FedDev Ontario Applied Research and Commercialization Initiative*. The Government of Canada provided no additional research support for this project.

1. Background

The building sector in Canada accounts for over 30 per cent of the total secondary energy use (Natural Resources Canada, 2012) and is responsible for about 35 per cent of greenhouse gas emissions (Environment Canada, 2012). Rating buildings during their design is one of many strategies created to decrease the amount of energy used in buildings, and to decrease the extent to which this sector exacerbates climate change. The *Leadership in Energy and Environmental Design* (LEED) is currently the most popular green building rating system in Canada, awarding credits in seven areas including energy efficiency, where points are awarded for performance below ASHRAE 90.1 requirements, and indoor environmental quality, where occupant satisfaction with noise, lighting, air quality and thermal comfort is prioritized. By late 2013, the Canada Green Building Council (CaGBC) had certified over 800 buildings with the LEED NC designation; and over 4,000 Canadian projects have been registered to date (Canada Green Building Council, CaGBC, 2013). This includes many high-rise residential buildings, particularly in Toronto.

Despite best intentions, buildings that are LEED certified do not always meet their targets in one or more of the seven performance areas (Newsham *et al.*, 2009). Building owners are increasingly observing that there can be a "performance gap" between design predictions and actual performance (ASHRAE, 2012). This not only happens in terms of energy and water use; there are also performance gaps associated with the quality of the indoor environmental (ASHRAE, 2012).

To uncover and understand these performance gaps, researchers have created various ways of evaluating the actual performance of green buildings. These approaches can be purely technical, for example Energy Star's Portfolio Manager program which compares the energy use intensities of buildings. However, there is a widespread recognition that evaluations which are purely technical omit very important feedback about actual performance from occupants (Stevenson and Leaman, 2010; ASHRAE, 2012).

2. Post-occupancy evaluation

The landmark *PROBE* studies (Post-occupancy Review of Buildings and their Engineering) in the UK in the 1990s were a formative use of the post-occupancy evaluation (POE) approach. The POE approach relies heavily on the use of occupant questionnaires (along with other sources of information) to highlight areas in which buildings are succeeding and failing. This occupant feedback can help identify and avoid many chronic problems and repeated mistakes, and can also engender an appreciation by the designer towards the on-going life of the building, an area where the designer may have little input. The *PROBE* studies combined occupant questionnaires with technical assessments of building performance to gain a better understanding of successes and failures.

Other studies, such as that of Baird (2010), put even more emphasis on questionnaires. Though it may seem impractical or incomplete to evaluate buildings using only data gathered via occupant questionnaires, this has been done recently with very insightful results (Baird, 2010). Despite the success of this work, there currently exists a dearth of publically available data from post-occupancy evaluations of Canadian buildings, especially in the residential sector. Indeed, as of June 2013, the largest database of POE results in North America which includes data on over 600 buildings (i.e. UC Berkeley's Centre for Built Environment) had only 28 Canadian cases, none of which were high-rise residential. This research aims to address this knowledge gap.

The reluctance of designers to make their findings publically available certainly accounts for part of this dearth, as does the difficulty of carrying out these evaluations. Abbaszadeh *et al.* (2006, p. 365) highlight that:

> [...] most POE studies of green buildings have focused on more easily quantifiable criteria such as energy use and physical measurements of environmental conditions, which at best give an indirect assessment of how the building is affecting the occupants.

It is well established that post-occupancy evaluations produce valuable feedback about occupant satisfaction and behaviour but they can also provide valuable insights into how energy is being consumed in buildings. The way that occupants experience, use and control buildings partially determines energy performance (Birt and Newsham, 2009; Dietz *et al.*, 2009; Gill *et al.*, 2010). As Cole (2003, p. 57) points out: "buildings designed with excellent 'green' performance standards can be severely compromised because the specification and technical performance fail adequately to account for the inhabitants' needs, expectations and behaviour".

POE is also useful for determining occupant satisfaction with indoor environmental quality (IEQ). IEQ comprises four key factors: thermal comfort, indoor air quality, lighting and noise (ASHRAE, 2012) and is one of the design areas for which LEED buildings are rated. LEED Canada NC 2009 includes eight credits for indoor environment and a total of fifteen points are available, as well as two required prerequisites (CaGBC, 2010). Points can be scored for thermal comfort, indoor air quality and lighting, but not acoustics (which is being integrated in the most recent version of LEED). The buildings involved in this study all received either 9 or 10 points out of the 15 possible (CaGBC, 2013).

Occupant satisfaction with IEQ is not only important for occupants – and for such buildings to be successful in the real estate market – it also has energy use implications. ASHRAE (2012, p. 36) points out that "people are not passive receptors of their environment rather, they interact continuously with it". ASHRAE (2012) uses the following as one of many possible examples that make a direct link between IEQ dissatisfaction and increased energy use:

> [...] if occupants are experiencing glare from the daylighting, they may choose to keep the blinds closed continuously, thereby eliminating any potential energy savings that could be provided by the daylight though the reduced use of electric lighting (ASHRAE, 2012, p. 36).

Finally, it is widely acknowledged that building occupants need to be given a certain amount of control over their indoor environments to feel satisfied (Leaman and Bordass, 2000). ASHRAE (2012) points out that "problems associated with the indoor environmental factors can sometimes be circumvented by providing the occupants suitable control over their environment" (ASHRAE, 2012, p. 37). There exists a delicate balance where occupants need to be given sufficient levels of control to ensure their satisfaction and comfort, but not so much that their incorrect operation can seriously jeopardize the operation and efficiency of the building overall.

3. Aims

A primary aim of this paper is to demonstrate the usefulness of the POE approach in assessing occupant satisfaction and energy behaviours in LEED-certified multi-unit residential buildings. This building type is understudied and is an ideal candidate for the POE approach. To show this, the present paper will suggest the energy use implications of occupant satisfaction and behaviour in this particular building type. Another aim of the paper is to consider the extent to which designers of green buildings are producing a product which is likely to be successful in creating a market transition towards energy efficient high-rise housing in Canada. In other words, by measuring satisfaction and behaviour in these four towers this work will be implicitly assessing the effectiveness of energy efficient high-rise towers in meeting consumer's and operator's needs, two important factors in encouraging widespread market adoption. Residential building design is seen as an important contributor in reducing Canadian carbon emissions; however, if a subpar product is being delivered, this strategy is likely to fail.

4. Methodology

Four high-rise residential towers in Toronto, Ontario, Canada, identified through local networks of the researcher, were chosen for this research. All four towers met the criteria of being LEED Gold certified and aim to perform better than typical residential construction in Toronto. The buildings had been occupied for at least 18 months at the time of surveying (this ranged from 20 to 34 months). The towers range from 14 to 24 stories, and contain between 178 and 305 units each. Three of the towers were built by one developer, the fourth building by a different developer. Results from this study indicate that roughly the same number of suites are occupied by owners compared to rental units owned by investors.

Due to their ambition to perform better than typical buildings, the study buildings use various features which make them attractive research sites. One feature which is explicitly explored in the questionnaire is the provision of in-dwelling energy-recovery ventilation (ERV) systems which are entirely controlled by the occupants. In traditional high-rise residential towers in Toronto, centralized ventilation delivers treated air to pressurized corridors, forcing air under unit doors and into dwellings. In the study buildings, dwelling entry doors are either entirely or partially weather-stripped, forcing occupants to take care of their own ventilation using either an in-suite energy-recovery ventilator (which exchanges heat from exhaust air into incoming outdoor air) or by using operable windows, which can undermine energy efficiency. Additionally, each dwelling has at least one thermostat which controls a fan-coil system that delivers either heating or cooling, giving the occupants ample ability to control thermal conditions in their dwellings.

Throughout 2013, an augmented version of the *BUS Methodology Domestic Questionnaire* (BUS, 2013) was delivered to building occupants. This questionnaire was selected because of its track record as an effective measurement tool in this building type in the UK. There is a prevailing wisdom that researchers should avoid "reinventing the wheel" and should strive, where possible, to use questionnaires which have been used successfully in other work. The ability to compare current data to benchmarking from the BUS Database (discussed shortly) is another reason that this instrument was chosen. Core questions of the BUS questionnaire have been used in a variety of post-occupancy evaluations (Baird, 2010) and explore the areas of indoor air quality, thermal comfort, noise, lighting, design, health and general satisfaction. Questions about control and usability were added to more fully explore how residents interacted with the particular heating, ventilating and air conditioning (HVAC) systems in these dwellings.

The majority of questions ask the respondents to rate some aspect of the building on a 7-point scale "typically from 'unsatisfactory' to 'satisfactory' or from 'uncomfortable' to 'comfortable', where a '7' would be the best score". Note, however, that in several instances, a "4" would be the best score, while in others a "1" would be best (Baird, 2010, p. 3). As with similar studies in this field (Baird, 2010), results below will be presented using the mean score and standard deviation for select questions. Standard deviation is useful to report because it helps to give the reader some sense of the variability in responses, especially when compared to studies which have used the same questionnaire.

Generally, results will be presented by providing a mean and standard deviation for all four buildings combined. If comparisons between buildings are not offered, the reader can assume that the responses from each building are close enough to the four-building-mean that it makes comparisons redundant. It should also be noted that as a result of using the BUS questionnaire, the results from the study buildings can be compared against benchmarks generated from the BUS database. As Baird (2010, p. 12) points out the BUS benchmarks "are simply the mean of the scores for each individual [question], averaged over the last 50 buildings entered in to the BUS database". Comparing the data from these buildings to the BUS benchmarks will help provide some context to the results, but should be considered with caution as the cases in the BUS database are all in Europe and there is no experimental control for building or occupancy characteristics. For example, we may be comparing noise satisfaction scores in our Canadian high-rises to scores from semi-rural row houses in a different climate. Nevertheless, the results are reported using **bold** text to indicate when the study mean is better than the BUS benchmark.

Aside from giving scores on various questions, respondents were also asked to comment on the following areas of building performance: thermal comfort, indoor air quality, noise, light, design and lifestyle. Where appropriate, these comments will be used to add robustness to questionnaire scores.

Paper or online questionnaires were delivered to 953 dwellings in four towers, with 165 residents responding (17.3 per cent). Data were collected between February and May of 2013, and was done either be delivering a paper copy directly to their dwelling door, or by having the property manager use the building's emailing system to send a URL for the questionnaire to all residents. The decision of whether to use a paper or an online questionnaire rested with the property manager and the condominium board. Both versions of the questionnaire were identical.

5. Findings

Of the 165 respondents in 953 dwellings, the majority (75.3 per cent) were over 30 years old, 63.9 per cent were female, and only 10.9 per cent of dwellings had children living in them. The majority of respondents (59.4 per cent) owned their dwelling, while the remainder were renters. Data related to occupancy patterns suggest that 58.8 per cent of people are home only on evening and weekends, whereas 32.5 per cent of people reported being home most of the time. Finally, only 38 per cent of respondents had previously owned a home. Though it is beyond the purview of the current paper, this demographic information will prove useful in trying to undercover the variability in energy consumption data that has been observed across the participating dwellings.

5.1 Indoor environmental quality

5.1.1 Lighting. Table I shows that respondents in the study buildings were generally satisfied with the amount of artificial lighting in their dwellings, with scores that were better than the BUS benchmark. Satisfaction scores for natural lighting and control over lighting were slightly lower than the BUS benchmark, suggesting that residents are struggling with the amount of daylighting let in by the large amounts of glazing (estimated at well over 50 per cent on exterior walls) that each dwelling is furnished with. Lower satisfaction with natural lighting is likely the result of inconvenient glare in the dwelling which may result in excessive use of blinds during sunny days, a behaviour which would limit solar heat gains in winter and lead to increased energy use.

5.1.2 Noise. Table I shows that the level of control respondents' reported over noise is far lower than for lighting. This trend is supported by respondents' comments in which dissatisfaction was expressed primarily with noise from neighbours. Many respondents expressed that they could hearing talking, music, televisions and other undesirable activities from their neighbouring dwellings, especially those above their own dwelling.

Given the dissatisfaction observed in the noise comments, it is interesting to note that three of the four questions about noise had mean scores which were better than the BUS benchmarks (Table I). On the one hand, this suggests that noise is a common problem in residential buildings. It also suggests that Canadian buildings may be performing better in this regard than European buildings, although this cannot be said definitively. Relative success in this area could have positive implications for the uptake of this building product in the Canadian market.

Dissatisfaction with noise also arose from the noise produced by the HVAC equipment in the dwellings. As discussed in Section 5.2, respondents' dissatisfaction with HVAC noise has led to decreased usage of ventilation systems, something which is certainly resulting in increased heating and cooling energy use.

5.1.3 Indoor air quality. Aside from numerous questions about thermal comfort, the BUS questionnaire has four questions which are particularly useful for understanding satisfaction levels with indoor air quality (i.e. freshness of air and presence of odours in summer and winter). Table II shows that the study buildings performed better than the BUS benchmarks on each of these four questions. As with noise, relative success in the

Satisfaction with [. . .]	Ideal score	Mean	*SD*	BUS benchmark
Control over lighting	7	5.44	1.613	5.55
Artificial lighting	4	**3.80**	1.223	4.24
Natural lighting	4	4.47	1.080	4.10
Lighting overall	7	5.25	1.595	5.37
Control over noise	7	3.12	1.778	3.66
Noise from neighbours*	7	**4.95/5.11**	1.923/1.830	3.99
Noise from outside	7	**4.82**	1.803	4.23
Noise overall*	7	**5.26/5.34**	1.773/1.661	5.18

Note: *Indicates scores from each developer

Table I. Noise and lighting scores

area of IAQ could have positive implications for the uptake of this building product in the Canadian market.

One likely reason for respondents' satisfaction with IAQ is their high degree of control over ventilation in their dwellings. The comments seem to support this, with few respondents complaining about the freshness of the air in their dwellings during either winter or summer. However, as will be discussed later, it appears that residents are acquiring their IAQ satisfaction at the expense of energy efficiency by bypassing their ERV and using windows and balcony doors for fresh intake instead. This shows how satisfaction scores can be used to identify potential areas of profligate energy use within green buildings, and also highlights the usefulness of the integrated POE approach in this building type.

5.1.4 Thermal comfort. Achieving thermal comfort is certainly a design priority in any building, and especially in the study buildings which have received their LEED certification based on the fact that they will satisfy ASHRAE Standard 55 by having 80 per cent of occupants satisfied with thermal comfort (CaGBC, 2013). Though it is difficult to precisely determine whether or not this standard has been achieved in the study buildings, the mean scores certainly indicate a higher level of satisfaction both in terms of the seven-point scale and in comparison to the BUS benchmarks (Table III).

Negative comments received about thermal comfort are clustered heavily around dissatisfaction with control of heating or cooling during shoulder seasons. This is to be expected given that the dwellings use a two-pipe fan coil system which can provide only heating or cooling, thus preventing respondents from coping easily with hot days in the early spring and cool days in the early fall.

5.2 Control/usability

When discussing usability and control, it is important to remember that occupants of the study buildings have a high degree of control opportunities in their dwellings (compared to typical dwellings in Toronto residential towers), with operable windows, in-dwelling ventilation and, at least, one thermostat (Table IV).

When looking at the scores for how respondents rated their level of control over their HVAC components, it is clear that they felt the least amount of control over ventilation

Table II.
Indoor air quality scores

Season	Variable	Ideal score	Mean	*SD*	BUS benchmark
Winter	Freshness of air	1	**3.5**	1.509	3.58
Summer	Freshness of air	1	**3.19**	1.514	3.74
Winter	Odours in air	1	**2.43**	1.409	2.99
Summer	Odours in air	1	**2.51**	1.383	2.91

Table III.
Thermal comfort scores

Season	Variable	Ideal score	Mean	*SD*	BUS benchmark
Winter	Comfort	7	**5.64**	1.274	5.43
Winter	Overall IAQ satisfaction	7	**5.44**	1.269	5.32
Summer	Comfort	7	**5.22**	1.577	4.91
Summer	Overall IAQ satisfaction	7	**5.4**	1.411	5.21
Overall	Indoor environment	7	**5.66**	1.192	5.69

in their dwellings. This is surprising considering that the dwelling-based systems allow more control than in typical buildings. Despite this, as shown in previous sections, respondents appear to be generally satisfied with air quality and thermal comfort in their dwellings. It should be noted that this effect could be attributed to excessive air infiltration due to poor air-tightness.

As mentioned, another hypothesis is that during winter, respondents are using their windows and balcony doors to get fresh air into their dwellings and compensating for the change in temperature by using their heating system, instead of using their ERV for their fresh air needs. Indeed, only 52.9 per cent of respondents ($n = 87$) reported using their ERV system daily in the winter, and 17.9 per cent ($n = 30$) indicated that their ERV was the primary means by which they actively got fresh air into their dwellings during winter. These scores indicate an alarmingly low usage rate for ventilation systems, and suggest that heating energy consumption values may be higher than were predicted during the design phase. Further work is underway to quantify the exact effect the apparent under-usage of in-dwelling ERVs is having on heating energy consumption. It should also be noted that due to the overall high level of energy efficiency of these projects, heating loads are generally low and so occupants may be willing to accept an increase in energy cost if it gives them improved comfort by compensating for open windows in winter.

The occupant questionnaire proves a powerful tool in beginning to explain this under-usage and also to highlight the interplay between usability, occupant behaviour and energy efficiency. In two questions that were exclusive to this study (and therefore not compared to the BUS database) occupants were asked to indicate how easy or difficult it was to make changes to indoor environmental conditions, and also to rate the usability of their HVAC systems. The mean score for HVAC usability is 4.94, which is relatively close to the scale midpoint of 4.00, suggesting that respondents are challenged by some aspect of their HVAC system. Given that they scored so highly on rating the level of control over heating and cooling, it is likely that the ventilation system is the problem (Table V).

When asked to rate the usability of their thermostats, respondents produced a mean score of 5.28, suggesting again that ventilation is the primary source of their usability challenges, and that the way the ERVs are being operated needs to be addressed. A logical place to look for this usability challenge would be to the control surface used to change the ERV settings (Figure 1). This does not appear to be the case, although, as

Variable	Ideal score	Mean	*SD*	BUS benchmark
Control overheating	7	**5.64**	1.431	4.97
Control overcooling	7	**5.39**	1.596	4.33
Control overventilation	7	4.38	1.772	4.87

Table IV. Satisfaction with access to HVAC controls

Variable	Ideal score	Mean	*SD*	BUS benchmark
Easy/difficult to make changes	7	5.15	1.734	n/a
HVAC usability	7	4.94	1.847	n/a

Table V. Usability scores

Figure 1.
Primary ERV control surface

respondents produced a mean score of 5.38 when asked how easy or difficult it was to operate their ERV. Moreover, the comments about the ERV do not indicate the control surface as being a significant problem.

So why are only 52.9 per cent of respondents reporting using their ERV system daily in the winter? This is where comments from occupants can be useful. Table VI shows that a lack of knowledge is part of the reason for ERV under-use. The rate of ERV usage is slightly higher than the number of occupants who had read the instruction manual that came with their dwelling (42.1 per cent). This suggests that those who do not know about the ERV do not use it. Indeed, a number of comments make it clear that some respondents simply do not know about their ERV. In this case, re-education is advisable and would likely result in increasing the energy efficiency of many of the dwellings within the study buildings, and in similar buildings outside of the study. Again, this important insight was gained via the POE methodology.

However, there is more going on here than simple lack of information. First, occupants are made aware of the ERV system from building management in the form of a twice yearly email about owner-performed ERV filter maintenance. They are also confronted with the control surface every time they walk into the bathroom. It is

HVAC control comments
"Do not know anything about ERV"
"Do not know how to use ERV"
"Not sure about ventilator–I believe building changes and operates"
"Instructions for cleaning ERV need to be clearer"
"Tried to clean, way too difficult, did not bother"
"Very difficult to clean ERV, located too high"
"ERV system–marginal benefit, hard to clean"
"ERV–sometimes wonder if it works at all; no effect when it is on/off"
"HVAC too noisy"
"HVAC fans make loud noise"
"The ventilation is really loud"
"Noisy fan, have to adjust TV when it comes on in winter"
"Need better thermostats. Fans are too loud all year long while running"
"Constantly have to adjust thermostat depending on which room I am in"

Table VI.
HVAC comments

interesting to point out that there was no difference in the usage rate between renters and owners in the study buildings, both had similar use patterns of their ERV system; suggesting that the building handover and education procedure which owners underwent when acquiring their dwellings did not produce a higher rate of usage. This indicates that occupant training is not a silver bullet solution for increasing usage of this important appliance, and the energy efficiency of these dwellings.

Negative comments about the ERV system in Table VI provide substantial guidance in understanding underuse of ERV systems. One trend in the comments echoes Carmona-Andreu *et al.* (2013, p. 5), who found that "there was no demonstration of how to get into [ERV] unit for cleaning the heat exchanger filter". Comments 3-7 (Table VI) clearly show that occupants are either unaware or unduly challenged by the task of cleaning the ERV filter, which could lead to outright abandonment of its operation (i.e. comment 5).

As mentioned earlier, the noise created by the ERV systems represents another barrier to their use. Respondents' comments clearly show dissatisfaction with the noise level during operation, which is likely a factor in ERV underuse. Thus, the logical explanations for ERV underuse, though varied, seem to centre around perceived ineffectiveness (frustration), lack of knowledge (confusion) and the noise caused by the fans themselves (inconvenience). It is important to understand this phenomenon, as it helps to begin to answer the complex questions: how much control should be given to occupants of residential green buildings? and How much complexity and responsibility can they effectively manage? Clearly the provision of in-dwelling ventilation warrants continued attention by designers and managers.

6. Discussion

This paper has shown that despite the best intentions of building certification systems, buildings do not always perform as designed. In this case, giving occupants access to controls was not a sufficient design strategy. Though it should be said that respondents appear to be generally satisfied with the various aspects of their dwelling's performance, there are problems that emerge from design decisions which negatively impact both energy efficiency indoor environmental quality.

Though the connection to actual energy consumption is only hypothetical in the present study, there are insights which are highly suggestive of deficiencies. For example, the use of floor-to-ceiling windows as a selling feature can create increased cooling loads in the summer, which is when Ontario's power generation systems are most strained. The fact that residents do not appear to be experiencing overheating during the summer, and that they are likely keeping their blinds open to enjoy their views (as supported by their questionnaire scores) means that they are likely contributing to increased electricity use for cooling, contributing to this serious problem in Ontario.

Obviously the strategic use of window coverings would result in lower cooling energy use during summer, making it the preferable control strategy. Though not asked about this on the questionnaire, further work will involve interviewing residents to determine their use of window coverings. These results will be compared to dwelling energy meter data to identify the effect that window coverings are having on energy consumption during heating and cooling seasons. The findings from the current research are fundamental to this deeper exploration, and again help to show the power of the POE approach in uncovering performance issues in high-rise residential buildings.

The use of questionnaire scores and comments to uncover and understand underuse of the in-dwelling ventilations systems should be considered a salient part of this work. It is commonly held that you cannot manage what you do not measure and in this case, the present study has managed to measure something which has been previously illusive, but which is nonetheless crucial to the energy efficiency and indoor environmental quality of the study buildings, and the building type in general.

The POE approach was particularly useful here because the underuse of ventilation arises from issues which could only be uncovered by asking people about how they actually perceive and interact with their device. That is, complaints centering around noise, perceived ineffectiveness, lack of awareness and confusion are best understood in practice, as opposed to in a laboratory or modeling program. Comments clearly show that respondents are disappointed and/or frustrated with their ERV system. This "perceived ineffectiveness" taps into an important idea in the usability/control literature. Baird (2010, p. 21) writes that "the occupant also appreciated being able to see or feel the effect of their operating of any of the control systems to which they had access". That is, respondents were likely not seeing the results they had expected from their ERV systems (e.g. quick steam removal after showers), and stopped using them.

Respondents' dissatisfaction with their novel ventilation system is very likely, resulting in higher than predicted heating energy consumption. The ventilation systems in the respondents' dwellings recover approximately 74 per cent of the heat from exhaust air when operated in low speed mode with an incoming air temperature of 0 Celsius (Venmar, 2013). Bypassing this system is obviously going to result in increased energy use by the fan coil system, which now must deliver heated air to the dwelling without having it preheated by the ERV beforehand. This suggests that performance gaps can be intricately linked to occupant satisfaction and behaviour within buildings. As Janda (2011, p. 17) said: "buildings don't use energy, people do".

It is also important to note that underuse of the ventilation systems could, if not remedied, represent a large waste of capital investment in this novel technology. The design, procurement and construction costs associated with this ventilation strategy surely only yield ideal returns when the systems are used appropriately.

One aim of this paper was to assess occupant satisfaction with IEQ. It should be clear from the discussion above that respondents appear to be satisfied with the air quality, access to controls and lighting levels in their suites. They appear to be generally dissatisfied with noise levels in their suites, especially noise from neighbours. Noise has become somewhat of a persistent issue in green buildings, and it appears that Towers A, B and C in particular are no different. Given the increased performance of Tower D in this regard, a further avenue of inquiry involves comparing the two developers' approaches to noise containment in the design and construction of their buildings.

Another aim of this paper was to determine if inhabitants are operating their dwellings in an energy efficient manner, and to suggest ways that their satisfaction and behaviour can help or hinder energy efficiency. The discussion on the underuse of in-dwelling ventilation systems clearly suggests that inhabitants are disappointed in, confused about, or oblivious to their ventilation systems and that this underuse is likely hindering the efficiency of both their dwelling and the overall building. This study also suggests that inhabitants are going to find strategies to ensure their satisfaction with their IAQ. For example, if the ventilation system is not working for them (or they do not know about it), they will open windows until they are satisfied that their air is not stuffy, fresh and the like. In other words, it is important to remedy the issues surrounding the ventilation systems (in these and future buildings) to eliminate profligate adaptive behaviours that can emerge if not.

7. Conclusions

The POE approach can be an effective tool in diagnosing and improving occupant satisfaction and energy efficiency in high-rise residential buildings. The above discussions have highlighted the importance and usefulness of both questionnaire scores and comments in better understanding occupant satisfaction and behaviour within a relatively hard to reach population who often reside behind a risk adverse property management team, a sceptical and stressed condominium board of directors and a controlled entrance. This, in part, has lead to this population being understudied, something this paper addresses.

The results from this study highlight strategies that can be used by designers and operators to lower both the greenhouse gas emissions and the operating costs of this ambitiously green building type. The POE approach used herein is a fundamental step in giving designers and operators the information they need to make buildings which more perfectly dovetail with occupant's perceptions, preferences and capabilities. It is also an important component in ensuring that people who purchase these units receive the return on investment that they expect and that this important green building product continue to be an important part of the real estate development in Canada. This paper helps to bridge the gap between theory and practice by showing the real world, in situ, consequences of innovative design decisions and assumptions (e.g. to give residents control over ventilation).

The litigious climate surrounding high-rise residential developments mean that asking too many questions about performance gaps is unduly risky on the part of the developer, who's primary aim after construction seems to be avoiding liability issues. It takes an impartial, and committed, research team to properly assess the usage patterns of this important technology so that useful feedback can be produced for the designers who are pushing ahead with innovative design strategy and for the building managers and customer support staff who are tasked with encouraging proper use. Despite the apparent "softness" of the approach, the use of occupant questionnaires is an important tool in understanding energy use, indoor environmental quality and overall satisfaction in these buildings.

References

Abbaszadeh, S., Zagreus, L., Lehrer, D. and Huizenga, C. (2006), "Occupant satisfaction with indoor environmental quality in green buildings", *Proceedings of Healthy Buildings 2006, Lisbon*, Vol. III, pp. 365-370.

ASHRAE (2012), *Performance Measurement Protocols for Commercial Buildings: Best Practices Guide*, ASHRAE, Atlanta, GA.

Baird, G. (2010), *Sustainable Buildings in Practice; What the Users Think*, Routledge, New York, NY.

Birt, B. and Newsham, G. (2009), "Post-occupancy evaluation of energy and indoor environment quality in green buildings: a review", in *Proceedings of the 3rd International Conference on Smart and Sustainable Built Environments in Delft*, The Netherlands, pp. 1-7.

Canada green building council (2010), "LEED Canada for new construction and major renovations 2009", available at: www.cagbc.org/AM/PDF/LEED_Canada_NC_CS_2009_Rating_System-En-Jun2010.pdf (accessed 25 February 2014).

Canada green building council (2013), "LEED project profiles search page", available at: www.cagbc.org/leed/projectprofile_EN.aspx (accessed 12 November 2013).

Carmona-Andreu, I., Stevenson, F. and Hancock, M. (2013), "Low carbon housing: understanding occupant guidance and training", in *Proceedings of 4th International Conference in Sustainability in Energy and Buildings*, Stockholm, pp. 545-554.

Cole, R.J. (2003), "Green buildings – reconciling technological change and occupant expectations" in Cole, R.J. and Lorch, R. (Eds), *Buildings, Culture, and Environment*, Blackwell, Oxford, pp. 57-82.

Dietz, T., Gerald, G., Gilligan, J., Stern, P. and Vandenbergh, M. (2009), "Household actions can provide a behavioral wedge to rapidly reduce US carbon emissions", *Proceedings of the National Academy of Sciences*, Vol. 106 No. 44, pp. 18452-18456.

Environment Canada (2012), "Greenhouse gas emissions data", available at: www.ec.gc.ca/indicateurs-indicators/default.asp?lang=enandn=BFB1B398-1#ghg3 (accessed 12 November 2013).

Gill, Z., Tierney, M., Pegg, I. and Allan, N. (2010), "Low-energy dwellings: the contribution of behaviours to actual performance", *Building Research and Information*, Vol. 38 No. 5, pp. 491-508.

Janda, K. (2011), "Buildings don't use energy: people do", *Architectural Science Review*, Vol. 54 No. 1, pp. 15-22.

Leaman, A. and Bordass, B. (2000), "Keeping occupants satisficed", *Energy and Environmental Management*, Second Quarter, Vol. 2, pp. 23-27.

Natural Resources Canada (2012), "Energy efficiency trends in Canada 1990-2009", available at: http://oee.nrcan.gc.ca/publications/statistics/trends11/pdf/trends.pdf (accessed on 12 November 2013).

Newsham, G., Mancini, S. and Birt, B. (2009), "Do LEED-certified buildings save energy? Yes, but", *Energy and Buildings*, Vol. 41 No. 8, pp. 897-905.

Stevenson, F. and Leaman, A. (2010), "Evaluating housing performance in relation to human behaviour: new challenges", *Building Research and Information*, Vol. 38 No. 5, pp. 437-441.

Venmar, (2013), "Indoor air quality product brochure", available at: www.venmar.ca/DATA/DOCUMENT/111_2_en~v~Brochure.pdf (accessed on 26 November 2013).

About the authors

Craig Brown is a PhD candidate in Ryerson University's Environmental Applied Science and Management program. His research interests include post-occupancy evaluation of residential, institutional and commercial buildings as well as energy benchmarking in the high-rise residential sector. Craig Brown is the corresponding author and can be contacted at: craig.brown@ryerson.ca

Mark Gorgolewski's interest is in the area of closed-loop systems applied to the built environment. This includes strategies to enhance the sustainability performance of construction materials, building products, buildings as well as urban environments. His work addresses the integration of energy, water, materials and urban food systems.

References

Abbaszadeh, S., Zagreus. L., Lehrer, D., & Huizenga, C. (2006). *Occupant satisfaction with indoor environmental quality in green buildings*. Proceedings of Healthy Buildings 2006, Lisbon, Vol. III, 365-370.

Abrahamse, W., Steg, L., Vlek, C., & Rothengatter, T. (2005). A review of intervention studies aimed at household energy conservation. *Journal of Environmental Psychology, 25*, 273–291.

ASHRAE. (2012). *Performance measurement protocols for commercial buildings: Best practices guide*, Atlanta, GA: ASHRAE.

Baird, G. (2010). *Sustainable buildings in practice; what the users think.* New York: Routledge.

Baird, G. (2011). Did that building feel good for you? Or – isn't it just as important to assess and benchmark users' perceptions of buildings as it is to audit their energy efficiency? *Intelligent Building International, 3*, 124-130.

Baird, G., & Dykes, C. (2012). The potential for the use of the occupants' comments in the analysis and prediction of building performance. *Buildings, 2*, 33-47.

Bartlett, K., Brown, C., Chu, A.M., Ebrahimi, G., Gorgolewski, M., Hodgson, M., Issa, M., Mallory-Hill, S., Ouf, M., Scannell, K., & Turcato, A. (2014, October). *Do our building perform as intended?* Paper presented at the World Sustainable Building 2014 Conference, Barcelona, Spain. Retrieved from http://iisbecanada.ca/umedia/cms_files/Conference_Paper_1.pdf

Beauregard, S., Berkland, S., & Hoque, S. (2011). Ever-green: A post-occupancy building performance analysis of LEED certified homes in New England. *Journal of Green Building, 6*(4), 138-145.

Bennet, I., O'Brien, W., & Gunay, B. (2014). *Effect of Window Blind Use in Residential Buildings Observation and Simulation Study.* Paper presented at eSIM 2014, Ottawa, ON. Retrieved from http://www.ibpsa.org/proceedings/eSimPapers/2014/3A.3.pdf

Berker, T. (2011). Domesticating spaces: sociotechnical studies and the built environment. *Space and Culture, 14*(3), 259-268.

Biesiot, W., & Noorman, K. (1999). Energy requirements of household consumption: a case study of NL, *Ecological Economics, 28,* 367–383.

Binkley, C., Touchie, M., & Pressnail, K. (2013). Energy consumption trends of multi-unit residential buildings in the city of Toronto. Retrieved from http://www.towerwise.ca/wp-content/uploads/2013/07/TAF-MURB-Energy-Performance-Report-Phase-II.pdf

Birt, B., & Newsham, G. (2009). Post-occupancy evaluation of energy and indoor environment quality in green buildings: a review. *National Research Council of Canada*. Retrieved from http://archive.nrc-cnrc.gc.ca/obj/irc/doc/pubs/nrcc51211.pdf

BizEE Software Limited. (2015). Degree days - Handle with care. Retrieved from: http://www.energylens.com/articles/degree-days

Bordass, W. & Leaman, A. (1997). Design for manageability. *Building Research & Information, 25*(3), 148-157.

Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology, 3*(2), 77-101.

Brown, C., & Gorgolewski, M. (2014). Assessing occupant satisfaction and energy behaviours in Toronto's LEED Gold high-rise residential buildings. *International Journal of Energy Sector Management, 8*(4), 492-505.

Brown, C., & Gorgolewski, M. (2015a). Understanding the role of occupants in innovative mechanical ventilation strategies. *Building Research & Information, 43*(2), 210-221.

Brown, C., & Gorgolewski, M. (2015b). Using physical, behavioural, and demographic variables to explain suite-level energy use in multi-residential buildings. *Energy and Buildings, 89*, 308-317.

Brown, Z. (2009). *Occupant comfort and engagement in green buildings: Examining the effects of knowledge, feedback and workplace culture* (Doctoral Dissertation, University of British Columbia). Retrieved from https://circle.ubc.ca/handle/2429/17490

Brown, Z., Dowlatabadi, H., & Cole, R. (2009). Feedback and adaptive behaviour in green buildings. *Intelligent Buildings International, 1*, 296–315.

Building Use Studies. (n.d.). BUS occupant survey methodology. Retrieved from: http://www.usablebuildings.co.uk/WebGuideOSM/

Canada Green Building Council. (2015). *LEED project profiles.* Retrieved from http://www.cagbc.org/leed/projectprofile_EN.aspx

Canadian Building Energy End-use Data and Analysis Centre. (2010). Energy use in Canadian multi-family dwellings. Retrieved from http://www.cbeedac.com/publications/documents/multifamilydwellingsreport_FINAL.pdf

Carmona-Andreu, I., Stevenson, F., & Hancock, M. (2013). Low carbon housing: understanding occupant guidance and training. *Smart Innovation, Systems and Technologies, 22*, 545-554.

Chau, C., Tse, M., & Chung, K. (2010). A choice experiment to estimate the effect of green experience on preferences and willingness-to-pay for green building attributes. Building and Environment, 45, 2553-2561

City Of Toronto. (2012). *2011 Census: Population and Dwelling Counts*. Retrieved from: http://www1.toronto.ca/city_of_toronto/social_development_finance__administration/files/pdf/2011-census-backgrounder.pdf

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences (2nd ed.)*. Hillsdale, NJ: Erlbaum.

Cole, R. (2003). Green buildings – Reconciling technological change and occupant expectations (p. 57-82). In *Buildings, Culture and Environment*, Cole, R. and Lorch, R. (Eds), Oxford: Blackwell.

Cole, R.J., Brown, Z., & McKay, S. (2010). Building human agency: a timely manifesto. *Building Research & Information, 38*(3), 339–350.

Cole, R., Robinson, J., Brown, Z., & O'Shea, M. (2008). Re-contextualizing the notion of comfort. *Building Research & Information, 36*(4), 323–336.

Combe, N., Harrison, D., Dong, H., Craig S., & Gill, Z. (2011). Assessing the number of users who are excluded by domestic heating controls. *International Journal of Sustainable Engineering, 4*(1), 84-92.

De Groot, E., Spiekman, M., & Opostein, I. (2008). Dutch research into user behaviour in relation to energy use of residences. PLEA 2008 – 25th Conference on Passive and Low Energy Architecture. Dublin, October 22-24th, 2008.

de Meester, T., Marique, A-F., De Herde, A., & Reiter, S. (2013). Impacts of occupant behaviours on residential heating consumption for detached houses in a temperate climate in the northern part of Europe. *Energy and Buildings, 57*, 313-323.

Dietz, T., Gerald, G., Gilligan, J., Stern, P., & Vandenbergh, M. (2009). Household actions can provide a behavioral wedge to rapidly reduce US carbon emissions. *Proceedings of the National Academy of Sciences, 106*(44), 18452-18456.

Dykes, C., & Baird, G. (2013). A review of questionnaire-based methods used for assessing and benchmarking indoor environmental quality. *Intelligent Buildings International, 5*(3), 135–149.

Dykes, C., & Baird, G. (2014). Performance benchmarks for non-domestic buildings: towards user perception benchmarks. *Building Research & Information, 42*(1), 62–71.

Environment Canada. (2012). *Greenhouse gas emissions data.* Retrieved from http://www.ec.gc.ca/indicateurs-indicators/default.asp?lang=enandn=BFB1B398-1#ghg3

Fabi, V., Andersen, R., Corgnati, S., & Olesen, B. (2012). Occupants' window opening behaviour: A literature review of factors influencing occupant behaviour and models. *Building and Environment, 58*, 188-198.

Field, A. (2009). *Discovering statistics using* SPSS (Third Edition). Thousand Oaks, CA: SAGE Publications Inc.

Finch, G., Burnett, E., & Knowles, W. (2012). Energy consumption in mid and high rise residential buildings in British Columbia. Retrieved from https://www.hpo.bc.ca/sites/www.hpo.bc.ca/files/download/Report/MURB-EnergyStudy-Report.pdf

Flyvbjerg, B. (2006). Five misunderstandings about case-study research. *Qualitative Inquiry, 12*(2), 219-245.

Forouharmajd, F., Nassiri, P., Monazzam, M., & Yazdchi, M. (2012). Estimating occupant satisfaction of HVAC system noise using quality assessment index. Noise Health, 14(59). 1463-1741.

Gibbs, G. (2007). *Analyzing qualitative data*. London: Sage.

Gill, Z., Tierney, M., Pegg, I., & Allan, N. (2010). Low-energy dwellings: the contribution of behaviours to actual performance. *Building Research & Information, 38*(5), 491-508.

Government of Ontario. (2014). Ontario Population Projections. Retrieved from http://www.fin.gov.on.ca/en/economy/demographics/projections/

Gram-Hanssen, K. (2010). Residential heat comfort practices: understanding users. *Building Research & Information, 38*(2), 175-186.

Guerra-Santin, O., Itard, O., & Visscher, H. (2009). The effect of occupancy and building characteristics on energy use for space and water heating in Dutch residential stock. *Energy and Buildings, 41*, 1223–1232.

Guerra-Santin, O.(2011). Behavioural patterns and user profiles related to energy consumption for heating, *Energy and Buildings, 43*(10), 2662–2672.

Gupta, R. and Chandiwala, S. (2010). Understanding occupants: feedback techniques for large-scale low-carbon domestic refurbishments, *Building Research & Information*, *38*(5), 530–548.

Gupta, R., Barnfield, L., & Hipwood, T. (2014). Impacts of community-led energy retrofitting of owner-occupied dwellings. *Building Research & Information, 42*(4), 446–461.

Gunay, H., O'Brien, W., Beausoleil-Morrison, I., & Perna, A. (2014). On the behavioral effects of residential electricity submetering in a heating season. *Building and Environment, 81*, 396-403.

Haas, R., & Biermayr, P. (2000). The rebound effect for space heating: empirical evidence from Austria. *Energy Policy, 28*, 403–410.

Hauge, A., Thomsen, J, & Berker, T. (2011). User evaluations of energy efficient buildings: literature review and further research. *Advances in Building Energy Research, 5*(1), 109-127.

Health Canada. (2013). *Exposure guidelines for residential indoor air quality.* Retrieved from http://www.hc-sc.gc.ca/ewh-semt/air/in/res-in/index-eng.php

Hewitt, E., Andrews, C., Senick, J., Wener, R., Krogmann, U., & Allaccia, M. (2015). Distinguishing between green building occupants' reasoned and unplanned behaviours. *Building Research & Information, in press*, DOI: 10.1080/09613218.2015.1015854

Janda, K. (2011). Buildings don't use energy: people do. *Architectural Science Review, 54*, 15-22.

Kelsven, P. (2013). One of these homes is not like the other: Residential consumption variability. UC Berkeley: Behavior, Energy and Climate Change Conference. Retrieved from http://escholarship.org/uc/item/4z68561x

Kempton, (1986). Two theories of home heat control. *Cognitive Science, 10*, 75-90.

Kim, M., Oh, M., & Kim, J. (2013). A method for evaluating the performance of green buildings with a focus on user experience. *Energy and Buildings, 66*, 203-210.

Laouadi, A. (2010). *Guidelines for effective residential solar shading devices* (NRC Institute for Research in Construction; National Research Council Canada). Retrieved from http://www.ccht-cctr.gc.ca/eng/projects/solar_shadings.html

Leaman, A. (2000). Usability in Building: The Cinderella Subject. *Building Research & Information, 28*(4), 296-300.

Leaman, A., & Bordass, B. (2001). Assessing building performance in use 4: the Probe occupant surveys and their implications. *Building Research & Information, 29*(2), 129–143.

Leaman, A., & Bordass, B. (2007). Are users more tolerant of 'green' buildings? *Building Research & Information, 35*(6), 662-673.

Leaman, A., Stevenson, F., & Bordass, B. (2010). Building evaluation: practice and principles. *Building Research & Information, 38*(5), 564-577.

Liao, H., & Chang, T. (2002). Space-heating and water-heating energy demands of the aged in the U.S., *Energy Economics, 24*, 267–284.

Lstiburek, J. (2014). How do building stack up? Retrieved from: http://www.buildingscience.com/documents/insights/bsi-075-how-do-buildings-stack-up

Lutzenhiser, L. (1993). Social and behavioural aspects of energy use. *Annual Review of Energy* and the *Environment, 18,* 247-89.

Mallory-Hill, S., Preiser, W., & Watson, C. (2012). Introduction to building performance evaluation: Milestones in evolution. In S. Mallory-Hill, W. Preiser, & C. Watson (Eds.), *Enhancing building performance* (pp. 3-18). UK: John Wiley & Sons.

McClelland, M., Stewart, G., & Ord, A. (2011). Reassessing the recent past: tower neighborhood renewal in Toronto. *APT Bulletin, 42*(2/3), 9-14.

McKenzie-Mohr (2011). *Fostering sustainable behavior: An introduction to community-based social marketing*. Gabriola Island, B.C.: New Society Publishers.

Meier, A., Aragon, C., Peffer, T., Perry, T., & Pritoni, M. (2011). Usability of residential thermostats: Preliminary investigations, *Building and Environment, 46*, 1891-1898.

Miles, M., & Huberman, A. (1984). *Qualitative data analysis: A sourcebook of new methods.* Newbury Park, CA: Sage.

National Council of Architectural Registration Boards (NCARB). (2003). *Improving building performance.* Washington, D.C.: NCARB.

Nicol, J., and Humphreys, M. (2002). Adaptive thermal comfort and sustainable thermal standards for buildings. *Energy and Buildings, 32*(6), 563–572.

Nolan, C. (2013). A living laboratory for high-rise innovation. *Sustainable Architecture and building magazine (Issue 39).*

NRCan. (2012). *Energy efficiency trends in Canada 1990-2009*. Retrieved from http://oee.nrcan.gc.ca/publications/statistics/trends11/pdf/trends.pdf

NRCan. (2014a). *Comprehensive energy use database: Residential sector Ontario table 38: Apartments secondary energy use and GHG emissions by energy source*. Retrieved from http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/menus/trends/comprehensive/trends_res_on.cfm

NRCan. (2014b). *Comprehensive energy use database: Residential sector Ontario table 39: Apartments secondary energy use and GHG emissions by end-use.* Retrieved from http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/menus/trends/comprehensive/trends_res_on.cfm

NRCan. (2015). Energy efficiency in buildings. http://www.nrcan.gc.ca/energy/publications/efficiency/buildings/5985

Parker, D. (2002, January). *Research highlights from a large scale residential monitoring study in a hot climate.* Paper presented at the International Symposium on Highly Efficient Use of Energy and Reduction of its Environmental Impact, Osaka, Japan. Retrieved from: http://www.fsec.ucf.edu/en/publications/html/FSEC-PF-369-02/

Peretti, C., & Stefano, S. (2011, June). Indoor environmental quality surveys—A brief literature review. Paper presented at Indoor Air, Dallas, TX. Retrieved from: https://escholarship.org/uc/item/0wb1v0ss

Pilkington, B., R. Roach, & Perkins, J. (2011). Relative benefits of technology and occupant behaviour in moving towards a more energy efficient, sustainable housing paradigm. *Energy Policy, 39*(9), 4962–4970.

Pratt, R., Conner, C., Cooke, B., & Richman, E. (1993). Metered end-use consumption and load shapes from the ELCAP residential sample of existing homes in the Pacific Northwest. *Energy and Buildings, 19*, 179-193.

Preiser, W., & Schramm. U. (1997). Building performance evaluation. In M. Crosbie, & D. Watson (Eds.) Time saver standards, 7th ed. New York: McGraw-Hill.

RDH Building Engineering Limited (2012). Energy consumption and conservation in mid and high-rise residential buildings in British Columbia. Retrieved from: http://www.hpo.bc.ca/sites/www.hpo.bc.ca/files/download/Report/MURB-EnergyStudy-Report.pdf

RDH Building Engineering Ltd. (2013). The Importance of Slab Edge & Balcony Thermal Bridges. Retrieved from: http://rdh.com/wp-content/uploads/2014/07/Part-1-The-Importance-of-Slab-Edge-Balcony-Thermal-Bridges.pdf

RDH Engineering Ltd. (2013). Air leakage control in multi-unit residential buildings. Retrieved from: http://rdh.com/wp-content/uploads/2014/04/Air-Leakage-Control-in-Multi-Unit-Residential-Buildings.pdf

Robertson, K., & Athienitis, A. (2009). Solar energy for buildings. Retrieved from: http://www.cmhc-schl.gc.ca/en/inpr/bude/himu/coedar/upload/OAA_En_aug10.pdf

Robson, C. (2011). *Real world research (3rd ed.)*. UK: John Wiley & Sons Ltd.

Samimi M., & Shoaeioskouei, S. (2013). *Best strategies to reduce internal energy loads in multi-unit residential buildings.* Retrieved from: http://sbsp2.sites.olt.ubc.ca/files/2013/07/SBSP-final-report-SabaMina-130420.pdf

Schwarz, N., & Oyserman, D. (2001). Asking questions about behavior: Cognition, communication, and questionnaire construction. *American Journal of Evaluation, 22*(2), 127–160.

Schweber, L., & Leiringer, R. (2012). Beyond the technical: A snapshot of energy and buildings research. *Building Research & Information, 40*(4), 481-492.

Schweiker, M., & Shukuya, M. (2009). Comparison of theoretical and statistical models of air-conditioning-unit usage behaviour in a residential setting under Japanese climatic conditions. *Building and Environment, 44*, 2137–2149.

Sellers, B., & Fiore, S. (2013). Sustainable and user-centered: Applying human factors solutions towards improving the effectiveness of “green” buildings. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 57*(1), 550-554.

Shipworth, M., Firth, S., Gentry, M., Wright, A., Shipworth, D., & Lomas, K. (2010). Central heating thermostat settings and timing: building demographics. *Building Research & Information, 38*(1), 50–69.

Slob, A., & Verbeek, P.P. (Eds.). (2006). *User behavior and technology development: Shaping sustainable relations between consumers and technologies. 1st ed*. Dordrecht, The Netherlands: Springer.

Socolow, R. (1978). The Twin Rivers Program on Energy Conservation. *Energy and Buildings, 1*, 207-242.

Steemers, K., & Young Yun, G. (2009). Household energy consumption: A study of the role of occupants, *Building Research & Information, 37*(5-6), 625-637.

Stern, P. (2000). Towards a coherent theory of environmentally significant behaviour. *Journal of Social Issues, 56*, 407–424.

Stevenson, A. (Ed.). (2010). *Oxford dictionary of English (3rd ed.)*. UK: Oxford University Press.

Stevenson, F. & Leaman, A. (2010). Evaluating housing performance in relation to human behaviour: New challenges, *Building Research & Information, 38(*5), 437-441.

Stevenson, F., & Rijal, H. (2010). Developing occupancy feedback from a prototype to improve housing production. *Building Research & Information, 38*(5). 549-563.

Stevenson, F., Carmona-Andreu, I., & Hancock, M. (2013). The usability of control interfaces in low-carbon housing. *Architectural Science Review, 56*(1), 1-13.

Straube, J. (2008). *Can highly glazed building façades be green?* (Building Science Corporation). Retrieved from: http://www.buildingscience.com/documents/insights/bsi-006-can-fully-glazed-curtainwalls-be-green

Sunikka-Blank, M. & Galvin, G. (2012). Introducing the prebound effect: The gap between performance and actual energy consumption, *Building Research & Information, 40*(3), 260-273.

U.S. Environmental Protection Agency. (2012). Bathroom. Retrieved from: http://www.epa.gov/greenhomes/bathroom.htm

Urban, B. (2013, November). *Improving programmable thermostat usage with less aggressive default setbacks.* Paper presented at Behaviour Energy and Climate Change, Sacramento, CA.

Usable Buildings Trust. (n.d.). Soft Landings. Retrieved from: http://www.usablebuildings.co.uk/

Wingfield, J., Bell, M., Miles-Shenton, D., South, T., & Lowe, R. (2009). *Evaluating the Impact of an Enhanced Energy Performance Standard on Load-Bearing Masonry Construction – Final Report: Lessons from Stamford Brook – Understanding the Gap between Designed and Real Performance.* PII Project No. CI39/3/663, Leeds Metropolitan University, Leeds. Retrieved from: http://www.leedsbeckett.ac.uk/as/cebe/projects/stamford/pdfs/stambrk-final-pre-pub.pdf

Vale, B., & Vale, R. (2010). Domestic energy use, lifestyles and POE: Past lessons for current problems. *Building Research & Information, 38*(5). 578-588.

Verhallen, T., & Van Raaij, W. (1981). Household behavior and the use of natural gas for home heating, *Journal of Consumer Research, 8*(3), 253–257.

Vringer, C. (2005). Analysis of the requirements for household consumption (Unpublished doctoral dissertation). Netherlands Environmental Assessment Agency. Retrieved from http://www.vringer.nl/VRINGER-140805.pdf

Vyas, J. (2012). *Irradiance vs. insolation.* Retrieved from: http://sargosis.com/articles/science/intro-guide/irradiance-vs-insolation/

Williamson, T., Soebarto, V., & Radford, A. (2010). Comfort and energy use in five Australian award-winning houses: regulated, measured and perceived. *Building Research & Information, 38*(5). 509-529.

Yin, R. (2009). *Case study research: Design and methods (4^{th} ed)*. Thousand Oaks, CA: Sage.

Yudelson, J., & Meyer, U. (2013). *The world's greenest buildings: Promise versus performance in sustainable design*. New York: Routledge.

Zalejska-Jonsson, A. (2012). Evaluation of low-energy and conventional residential buildings from occupants' perspective. *Building and Environment*, *58*, 135–144.

Zimmerman, A., & Martin, M. (2001). Post-occupancy evaluation: Benefits and barriers. *Building Research & Information, 29*(2), 168-174.