THE EFFECT OF OCCUPANCY ON ELECTRICITY USE IN THREE CANADIAN SCHOOLS

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ABSTRACT

Through building performance simulations, previous studies showed the effect of occupants on buildings' energy consumption. To further demonstrate this effect using empirical evidence, this study analyzed the effect of occupancy on real-time electricity consumption in three case-study schools in Manitoba. Within each school, one classroom as well as the gymnasium were sub-metered to collect real-time electricity consumption data at half-hourly intervals. The study focused on electricity consumption for lighting and plug loads, which make up 30% of energy consumption in Canadian commercial and institutional buildings. A comprehensive method was developed to investigate energy-related occupant behaviour in the sub-metered spaces using four different tools simultaneously: 1) gymnasium bookings after school hours over a four-month period, 2) half-hourly observations of lighting and equipment use in the sub-metered spaces in each school over a two-week period, 3) a daily survey administered to teachers in the sub-metered classrooms over a two-week period, and 4) occupancy and light sensors to evaluate actual recorded occupancy and light use durations over a four-month period. Results showed that recorded occupancy durations over a 4-month period only explained less than 10% of the variations in classrooms' lighting electricity consumption, meaning that lights may have been used frequently while classrooms were unoccupied. Results also showed the differences in gymnasiums' electricity consumption were still statistically significant between the three schools, even after school hours and when the gymnasiums were not used or booked for other activities. This study is the first to provide in-depth evaluation of the effect of occupancy on electricity consumption in Canadian schools.

KEYWORDS

Occupancy; energy efficiency; school buildings; real-time electricity monitoring

1. INTRODUCTION

Previous studies suggest that building occupants can influence buildings' energy consumption by up to 150% [1]–[5]. However, only a few studies investigated their effect using actual, empirical data from existing buildings [6], [7], while others typically relied on building performance

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simulations [1]–[5]. Therefore, more research to investigate the effect of occupancy on real-time energy consumption in existing buildings is needed. Hoes et al. [8] provided a breakdown of the term 'occupancy' into two components: 1) occupants' presence in a building and 2) their behaviour which influences a building's energy consumption. Occupants' presence includes factors such as occupancy status at a given time, occupants' arrival and departure times, or the number of occupants at a given time [9]. On the other hand, occupant behaviour describes occupants' actions such as using windows, thermostats, plug-in equipment, lights, or other building components [10]. These actions can be quantified in terms of their frequency of occurrence, their durations, or by measuring their effect on building components (e.g. degree of window opening), which influences the different energy end-uses in buildings. In Canadian commercial and institutional buildings, space heating represents the largest energy end-use at 50%, followed by auxiliary equipment (i.e. plug loads) at 19%, and lighting at 11% [11].

This paper presented a method to evaluate the effect of energy-related occupant behaviour on the second and third largest energy end uses (lighting and plug loads) in three schools in Manitoba, Canada, between January and May 2015. These schools represented three different age-groups with an old school built in 1951, a middle-aged one built in 1968, and a new school built in 2009 to Leadership in Energy and Environmental Design (LEED) silver standards. Several tools were used to evaluate real-time energy-related occupant behaviour and study its effect on electricity consumption, namely space booking logs, occupancy and light sensors, observations, and daily surveys. To validate this method, specific objectives involved evaluating the following: 1) gymnasiums' electricity consumption after school hours and the effect of gymnasium bookings on that consumption, 2) occupant behaviour with regards to using lights and electricity consumption for lights, 3) occupant behaviour with regards to using equipment and electricity consumption for plug loads, and 4) occupants' self-reported energy-related behaviour and their electricity consumption.

2. BACKGROUND

Research on energy-efficient and green buildings' energy performance showed mixed results. Some studies found that green buildings' actual energy consumption exceeded forecasted consumption, raising concerns about the accuracy of energy model inputs used to predict consumption [12]–[14]. Other studies showed that while green school buildings saved on gas consumption, their electricity consumption was higher than conventional buildings', reinforcing the need to investigate increased electricity consumption and occupants' contribution [15], [16]. Although many factors may contribute to this increased energy consumption in new buildings, such as higher ventilation and air quality standards, the effect of occupant behaviour is rarely studied or documented.

Very few studies [17]–[20] investigated the relationship between building occupancy and energy performance, highlighting the need for more studies on the topic. They mostly focused on commercial buildings, reinforcing the need to study other types of buildings such as schools. These studies [3], [21] also primarily focused on occupant behaviour related to Heating Ventilation and Air Conditioning (HVAC) energy consumption, despite other end uses (e.g. lighting, plug loads) contributing up to 40% of total building energy consumption [22].

Studies that evaluated occupancy in relation to actual energy consumption typically relied on self-reporting surveys and interviews with building occupants and managers. For example, Huebner et al., [24] used an interview-style survey to investigate the extent to which different variables explained energy consumption in 924 households in the United Kingdom. The study found that building factors on their own explained approximately 39% of the variability in energy consumption whereas socio-demographic variables explained 24% of that variability. Heating behaviour factors explained 14% of these variations in energy consumption. The study argued for the need to investigate other occupant-related variables since the studied ones could not explain more than half of the variability in energy consumption. Similarly, Tetlow et al., [25] surveyed workstation users in two UK office buildings showing that their behaviour accounted for 11% of the variability in their workstations' energy consumption. Gill et al., [7] developed a survey of building occupants' usage of personal controls of HVAC and found that occupant behaviour explained a total of 51%, 37% and 11% of the variability in a building's heat, electricity and water consumption respectively. Al-Mumin et al., [6] also surveyed occupants in 30 residences and concluded that 21% of the variability in the electricity consumption of electrical appliances was due to their behaviour.

Instead of relying on actual energy performance data, some studies investigated the effect of occupancy on building energy use by modeling energy-related behaviour using building performance simulations. For example, Clevenger et al., [1] used parametric simulations and energy modelling to show that occupant behaviour can change annual energy usage by as much as 75% in residential buildings and 150% in commercial buildings. Similarly, Bonte et al., [27] used modelling of occupant behaviour to demonstrate that it can change energy consumption by up to 47%. Not only did these studies rely on energy models rather than actual data to make those conclusions, their models mostly focused on HVAC-related energy consumption, while over-looking typically unregulated plug loads. The models were developed with different assumptions on how occupants would use blinds, windows or change their clothing levels, then the changes in energy consumption due to these assumptions were investigated. These studies did not consider the effect of occupants on electricity consumption, thus ignoring occupant behaviour related to aspects such as light and plug loads.

Other studies used statistics to investigate occupant behaviour in large building samples. For instance, Yu et al., [29] investigated energy consumption in 80 residential buildings over two years using cluster analysis and grey-relational techniques. The study found a large variability reaching up to four times the mean energy use intensity (EUI) which was induced by occupants' behavior. Nearly all identified studies correlated occupant behaviour to annual or monthly energy consumption instead of real-time consumption. The only exception was a study by Gul and Patidar, [17] which collected half-hourly electricity consumption data for a university building in the UK and used two-directional occupancy sensors to detect the number of occupants entering and exiting the building over half-hourly intervals. Furthermore, the study collected data on classroom schedules, administered an online survey to evaluate occupants' energy use and interviewed key management personnel. Surprisingly, results showed a weak correlation between energy use profiles and occupancy patterns. One of the reasons for this finding was the fact that the building was controlled by a building management system (BMS) where occupants had minimal access to the controls. The BMS also operated with a pre-defined schedule regardless of actual occupancy. These findings highlight the importance of investigating occupancy patterns to redesign and effectively control BMS which would ultimately decrease building energy use. However, the effect of using these automated systems on occupants' comfort must be considered. Although there has been a trend towards sophisticated building automation systems that theoretically improve occupants' comfort while maintaining low energy use, in reality they may do the opposite [30]. Future research should therefore assess the effect of limiting occupants' interaction with building systems on their comfort levels.

3. METHOD

This research entailed selecting three case-study schools as follows, 1) an old school built in 1951, 2) a middle-aged school built in 1968, and 3) a new school built in 2009 and certified as LEED silver. Selecting schools with different building ages was intended to investigate the differences in their electricity consumption patterns, and their relationship with occupancy. The new school, which was also certified as LEED silver, was expected to use less electricity. Table 1 provides more information about each school and the monitored spaces.

3.1 Electricity consumption data collection

The architectural and electrical drawings for each school were analyzed to identify spaces that would be sub-metered in order to measure real-time electricity consumption and occupancy. These spaces included one south-facing classroom (with students aged between 9 and 13), the gymnasium, and one space typically used outside regular school-hours within each school. The choice of south-facing classrooms helped minimize some of the variability between the three spaces where daylight patterns were expected to be consistent. School administrators were asked to identify spaces used outside regular school-hours, however, only two of the schools identified such spaces. These included a multi-purpose room used for community events such as town hall meetings and annual Christmas parties in the new school, and a music room typically used by a community choir on a regular basis in the old one.

Field visits to the three schools confirmed the circuit configurations obtained from electrical drawings to develop and finalize the electricity monitoring plan for each school. Sub-meters were then installed with the help of a technician from Manitoba Hydro to monitor all plug-load and light circuits for the selected spaces. Electricity consumption was then measured at half-hourly intervals. A RADIAN® RM-15-15 portable watthour meter was used to calibrate the different sub-metering equipment used to ensure consistency of the collected data. Measurement errors for the used equipment ranged between –0.95% and 2.02%, reflecting a high level of accuracy. Table 2 shows details of the monitoring plan used, including the number of circuits serving each space and the sub-metering equipment used for each circuit(s).

3.2 Occupancy data collection

In addition to collecting real-time electricity consumption data, this study entailed collecting occupancy data in the same sub-metered and monitored spaces in each school. Figure 1 shows the tools used to collect that data at the space level.

To evaluate energy-related occupancy after school hours, bookings of the three schools' gymnasiums after 15:30 were collected from each school for the period between January and May 2015. HOBO® UX90-006 light and occupancy sensors were also installed in the same classrooms that were sub-metered for electricity. These sensors aimed to monitor light use durations at half-hourly intervals over the four-month study period. They also aimed to monitor occupancy by detecting students and teachers' movements within the classroom at half-hourly intervals. Each sensor had a two-meter detection range and was installed in the center of each classroom. The sensors' sensitivities were adjusted for each classroom to eliminate the effect of

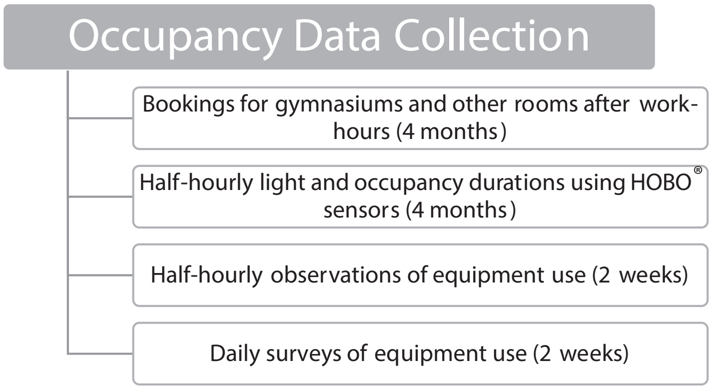
TABLE 1. Case-study schools' parameters.

Parameters	Old School	Middle Aged School	New School
Construction date	1951	1968	2009
Floor area	69,892 sq.ft.	37,000 sq.ft.	28,637 sq.ft.
Number of floors	2	1	1
Number of students (2014/15)	320	210	79
School type	K–8 (ages 6–14)	K–8 (ages 6–14)	K–12 (ages 6–18)
Floor area of monitored classroom	735 sq.ft.	745 sq.ft.	645 sq.ft.
Number of students in monitored classroom	24	19	22
Age range of students in monitored classroom	9–10	9–10	9–12
Floor area of monitored gymnasium	6500 sq.ft.	4000 sq.ft.	5000 sq.ft.
Lighting power density in classrooms	1.7 watts/sq.ft	1.1 watts/sq.ft	0.66 watts/sq.ft (*installed occupancy sensors*)
Power density of installed receptacles in classrooms	0.98 watts/sq.ft	0.96 watts/sq.ft	1.67 watts/sq.ft
Lighting power density in the gymnasium	0.9 watts /sq.ft	0.83 watts /sq.ft	1.1 watts/sq.ft
Power density of installed receptacles in the gymnasium	0.2 watts /sq.ft	0.36 watts / sq.ft	0.36 watts /sq.ft
Equipment in monitored classroom	Laptops Projector Stereo station (*with multiple headsets for students*) Sharpener Fans	Laptops A/V Station Stereo Microwaves Sharpener	Laptops Projector Stereo Sharpener
Equipment in monitored gymnasium	Laptops Scoreboard Speakers and control unit Projector Stereo Movable curtain Fans Coffee maker	Laptops Scoreboard Speakers and control unit A/V Station Stereo	Laptops Speakers and control unit A/V Station Stereo Movable screen Movable basketball hoops
Equipment in other monitored rooms	Laptops Digital piano Speakers and control unit Amplifiers Microphone charger	N/A	Digital piano Speakers and control unit Projector Microwaves Movable screen

TABLE 2. Electricity sub-metering plan.

School	Electrical configuration and monitoring plan	
Old School	Classroom Lights	Classroom Plugs
	3 circuits → 1 DENT® ElitePro XC meter	3 circuits → 1 DENT® ElitePro XC meter
	Gymnasium Lights	Gymnasium Plugs
	12 circuits → 2 Watt-Node® meters and Hobo® Data loggers	5 circuits → 1 Watt-Node® meter and Hobo® Data logger
	Music Room Lights	Music Room Plugs
	16 circuits → 2 Watt-Node® meters and Hobo® Data loggers	4 circuits → 1 DENT® ElitePro XC meter
Middle Aged School	Classroom Lights	Classroom Plugs
	1 circuit → 1 DENT® ElitePro XC meter	2 circuits → 1 DENT® ElitePro XC meter + 2 plug monitors to subtract plug loads from another classroom
	Gymnasium Lights	Gymnasium Plugs
	3 circuits → 1 K20® power meter + 1 light sensor to subtract lighting from another room	3 circuits → 1 K20® power meter
New School	Classroom Lights	Classroom Plugs
	1 circuit → 1 DENT® ElitePro XC meter + 1 light sensor to subtract lighting from another room	2 circuits → 1 DENT® ElitePro XC meter
	Gymnasium Lights	Gymnasium Plugs
	8 circuits → 1 K20® power meter	6 circuits → 1 K20® power meter
	MPR Lights	MPR Plugs
	3 circuits → 1 K20® power meter	4 circuits → 1 DENT® ElitePro XC meter

FIGURE 1. Occupancy data collection methods.



ambient light and improve the accuracy of the readings. Due to the limited range of each sensor and the size of the gymnasiums, no sensors were installed in the three schools' gymnasiums.

Teachers in the monitored classrooms in each school were asked to complete a daily, one-minute survey over the two-week observation period. This daily survey included open-ended questions that asked them to estimate at the end of each day the durations of light and equipment use in their classroom on that day, resulting in 10 data points. The survey was tailored to every classroom by only including the equipment available in each. It was paper-based to make it easier for them to fill out and thus ensure a higher response rate. Copies of the survey were left on each teacher's desk and collected at the end of the two-week observation period in each classroom. The three teachers responded to the survey; however, the teacher in the new school did not provide data on light use durations because she did not believe she could accurately estimate them in her classroom as lighting was sensor-controlled.

Point-in-time, half-hourly observations took place during work hours (8:30–15:30) every weekday (Monday to Friday) for two weeks in each school separately resulting in 140 data points for each classroom and gymnasium in each school. Given the periodical nature of school work, these data points helped identify some of the daily patterns of occupant behavior in these schools. For reasons beyond the researchers' control (e.g. exams or special events), less than ten observations in each school could not be made during this period. The University of Manitoba's Research Ethics Board did not allow direct monitoring of school children's behaviour without parental consent. Therefore, the observations focused on the frequency of equipment and light use, using them as indicators of energy-related occupant behaviour. The observations also aimed to determine whether the space was occupied or not in order to record light use in unoccupied spaces. Point-in-time observations were selected to minimize disruptions associated with other types of observations and to minimize the "Hawthorne Effect." Two research assistants conducted these observations through walk-throughs in the monitored spaces, in coordination with the teachers and staff in these spaces. In several cases, teachers agreed to leave the doors of the monitored classrooms and gymnasiums open to enable data collection from the outside to further minimize disruptions. A separate observation sheet was developed for each space in every school and filled out during the observations, with each one including a comprehensive list of the specific equipment available in every space. Every research assistant was required to determine the state of the monitored equipment by selecting from three existing states: "in-use," "idle," and "off." An equipment was considered "off" if it was unplugged and not being used, while it was "idle" when it was plugged in but not in use. Pilot observations were conducted for two days in a row in every school prior to the start of the actual observations to ensure inter-observer reliability. Discrepancies between the two observers were identified to refine the definitions of each equipment state during the pilot phase. During the two-week observation period in each school, the two research assistants conducted the observations simultaneously to identify discrepancies between them and correct them.

3.3 Data Analysis

Real-time electricity consumption data was collected and analyzed for the period between January and June 2015. The data collected from each circuit was used to calculate total plug load and light consumption in each space. For circuits serving more than one space, WattsUP® plug monitors were used to calculate and subtract plug load consumption in adjacent spaces served by the same circuit. Similarly, HOBO® light sensors were used to calculate and subtract light consumption in other spaces served by the same circuit.

The first objective of the research involved separating half-hour electricity consumption data for the gymnasiums between 15:30 and 24:00 into booked and non-booked half-hourly intervals based on booking data. The research involved determining the average half-hourly electricity consumption values for lighting and plug loads combined in the three schools' gymnasiums after school hours as well as for the booked and non-booked intervals after school hours. This data was then used to compare half-hourly electricity consumption during non-booked intervals between the three gymnasiums. Finally, electricity consumption was compared between booked and non-booked intervals for each gymnasium individually to determine the effect of occupancy on their electricity consumption.

The number of half-hourly observations where lights were on and spaces were unoccupied was compared between all monitored school spaces. The average half-hourly light consumption in classrooms was then compared between the three schools. Furthermore, a Spearman's rank-order correlation assessed the relationship between half-hourly occupancy durations recorded from occupancy sensors and half-hourly light consumption. The non-linear relationship between the two variables required a logarithmic transformation of the data prior to running the Spearman's rank-order correlation test.

The average half-hourly plug load consumption was compared between the three schools' classrooms and gymnasiums. In order to investigate the effect of equipment use on plug load consumption, observation data for each half-hourly interval indicated the number of equipment in use. The average number of equipment in use within a half-hour interval was then compared between the three schools' classrooms and gymnasiums. Afterwards, a Spearman's rank-order correlation assessed the relationship between the half-hourly number of equipment in use and half-hourly plug load consumption in school spaces

Since half-hourly electricity consumption did not follow a normal distribution as assessed by Shapiro-Wilk's test ($p < .05$), non-parametric tests were used to compare electricity consumption between the three schools. For example, non-parametric Kruskal-Wallis H tests were used to evaluate the statistical significance of differences between the three schools' electricity consumption for lighting or plug loads in each space. Whenever a statistically significant difference was found, pair-wise comparisons of the differences between every two schools were performed using Dunn's (1964) procedure with a Bonferroni correction. Similarly, a non-parametric Mann-Whitney U test was used to determine the statistical significance of differences in median half-hourly plug load and light consumption between booked and non-booked intervals after school hours. The non-parametric Spearman's rank-order correlation was also used to assess the relationships between variables which did not follow a normal distribution.

Data from the daily surveys (energy use diaries) was used to investigate the relationship between self-reported occupant behaviour and electricity consumption. Since the new school's teacher did not provide estimates of light use durations, the analysis mainly focused on the old and middle-aged schools. Half-hourly electricity consumption data was added between 8:30 and 15:30 in order to match the data collected using the daily surveys, thus calculating daily electricity consumption during school hours. These daily electricity consumption values, as well as self-reported light use durations were normally distributed as assessed by Shapiro-Wilk's test ($p > .05$). Therefore, independent-samples t-tests were run to determine statistically significant differences in light consumption, as well as self-reported and recorded light use durations between the old and middle-aged schools' classrooms. Afterwards, a Pearson's product-moment correlation assessed the relationship between self-reported light use durations and daily light consumption in each classroom. Another Pearson's product-moment correlation also assessed the relationship between recorded light use durations using occupancy sensors and daily light consumption in each classroom. Self-reported estimates of equipment use durations did not follow a normal distribution as assessed by Shapiro-Wilk's test ($p < .05$). Therefore, a non-parametric Kruskal-Wallis H test was used to identify statistically significant differences in median daily self-reported equipment use durations between the classrooms. A Spearman's rank-order correlation also assessed the relationship between daily self-reported equipment use durations and daily plug load consumption.

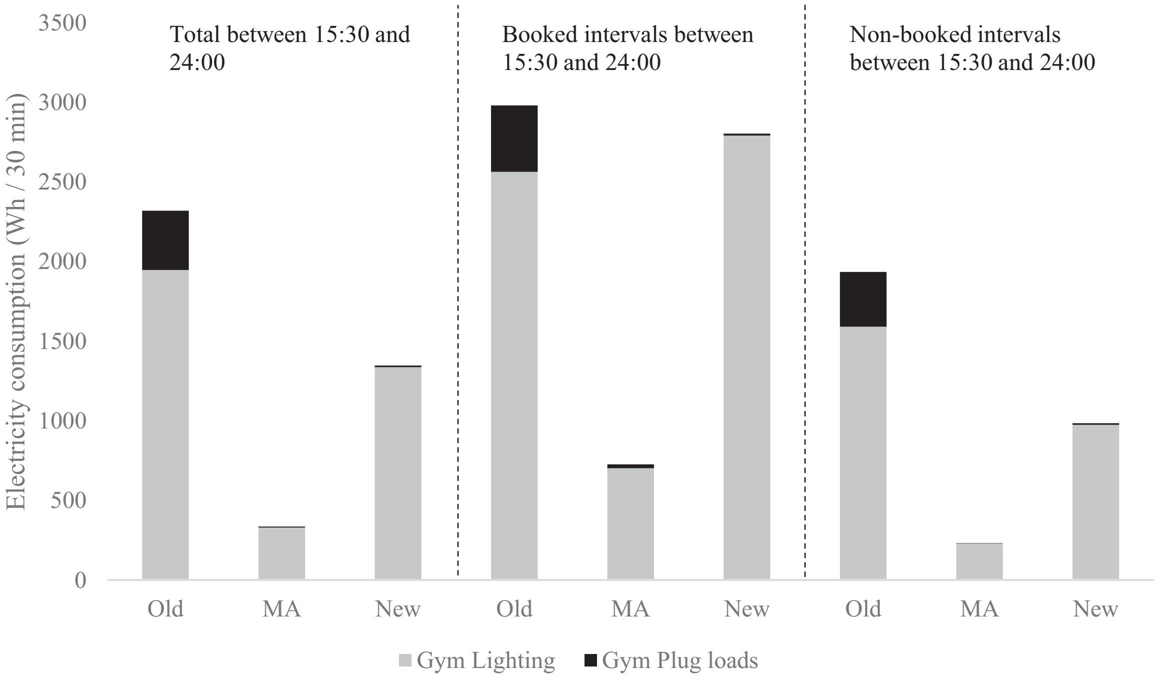
4. RESULTS

This section reports on the results of analyzing electricity consumption in relation to energy-related occupant behaviour in the three case-study schools. The analysis involved investigating 1) gymnasiums' electricity consumption after school hours, 2) occupant behaviour with regards to using lights and electricity consumption for lights, 3) occupant behaviour with regards to using equipment and electricity consumption for plug loads, and 4) occupants' self-reported energy-related behaviour and their electricity consumption.

4.1 Gymnasiums' electricity consumption after school hours

Figure 2 shows that the old school's gymnasium used on average 59% more electricity for lighting and plug loads combined per half-hour during non-booked intervals after school hours (1591 Wh/30 min for lighting, 344 Wh/30 min for plug loads) than the new school's gymnasium (1207 Wh/30 min for lighting, 8 Wh/30 min for plug loads). The new school's gymnasium used on average 424% more electricity for lighting and plug loads combined per half-hour during non-booked intervals after school hours than the middle-aged school's gymnasium

FIGURE 2. Gymnasiums' electricity consumption for lighting and plug loads between 15:30 and 24:00, during booked intervals, and during non-booked intervals.



(230 Wh/30 min for lighting, 2 Wh/30 min for plug loads). The Kruskal-Wallis H test showed these differences were statistically significant between the three schools' gymnasiums ($\chi 2(3)$ = 1658.47, 1105.34, p < .005). Post-hoc pairwise comparisons also revealed statistically significant differences between all pairs of gymnasiums.

Across the three schools' gymnasiums, Figure 2 also shows that electricity consumption for lighting and plug loads combined during booked intervals was higher than non-booked intervals after school hours. However, the relative increase in electricity consumption between booked and non-booked intervals was not consistent across all three gymnasiums. The old school's gymnasium used on average 54% more electricity for lighting and plug loads combined per half-hour during the booked intervals after school hours than during the non-booked intervals. The middle-aged school's gymnasium used on average 214% more electricity for lighting and plug loads combined per half-hour during the booked intervals than during the non-booked intervals. The new school's gymnasium used on average 185% more electricity for lighting and plug loads combined per half-hour during the booked intervals than during the non-booked intervals. Mann-Whitney U tests showed statistically significant differences in median half-hourly electricity consumption for lighting and plug loads between the booked and non-booked intervals in each gymnasium. These results demonstrate that school gymnasiums' bookings after school hours had a statistically significant effect on their electricity consumption for lighting and plug loads. Bookings of these gymnasiums for sports or community events usually took place in the early evening between 17:00 and 20:00. However, the gymnasium bookings extended till midnight in very few cases during school play rehearsals.

4.2 Relationship between light consumption and occupant behaviour

During the two-week observation period, there were approximately 140 half-hourly observations of each school space where observers noted when a space was unoccupied but lights were on. These occurrences were frequent in the old and middle-aged schools as shown in Figure 3 but less frequent in the new school, possibly due to the use of light sensors. They were also frequent in particular in offices attached to the schools' gymnasiums and the music room in the old school.

FIGURE 3. Observations of unoccupied spaces where lights were on.

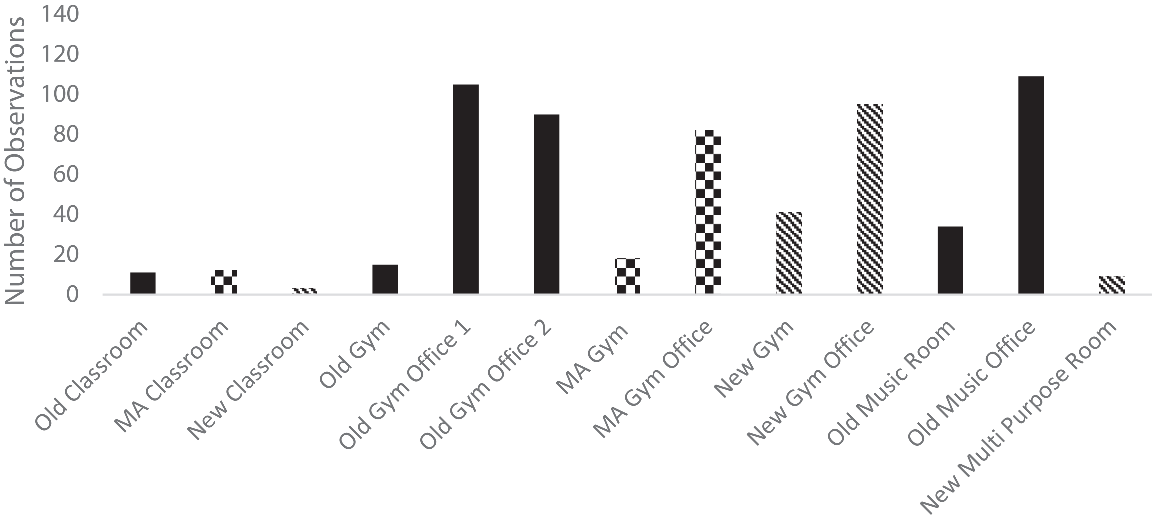
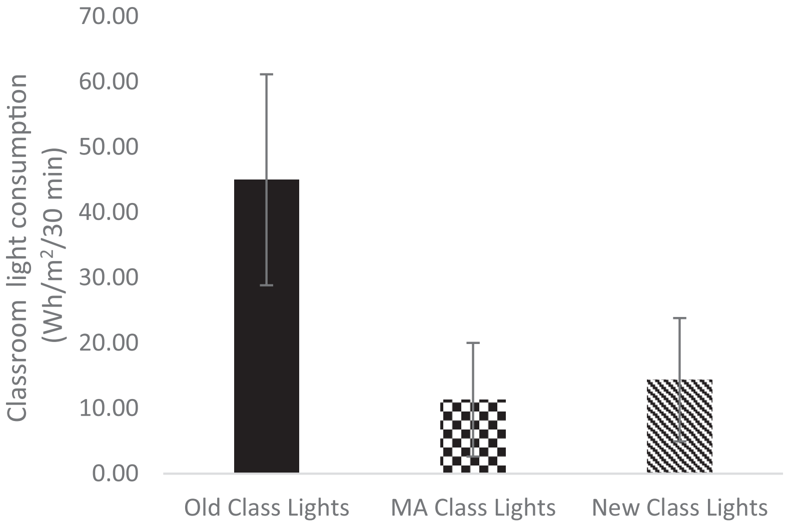


FIGURE 4. Average half-hourly light consumption in classrooms.



The average half-hourly classrooms' light consumption was highest in the old school classroom (44.9 Wh/m^2/30 min), and lowest in the middle-aged one (11.3 Wh/m^2/30 min) as shown in Figure 4. The Kruskal-Wallis H test showed the differences in median half-hourly light consumption between the three schools' classrooms were statistically significant ($\chi2(3) = 600.3$, $p < .005$). Subsequent pairwise comparisons revealed statistically significant differences in classrooms' light consumption between all pairs of classrooms.

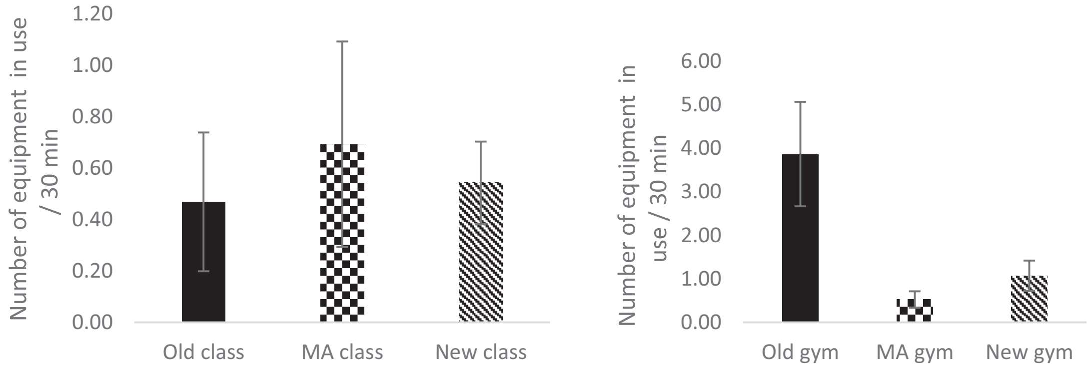
The Spearman's rank-order correlation test showed statistically significant, but weak positive correlations between half-hourly occupancy durations, obtained from occupancy sensors, and half-hourly light consumption in the old and new school classrooms only (r = 0.149, 0.281 respectively, $P < 0.0005$). These results indicated occupancy duration only explained 2.2% and 7.9% of the variation in light consumption in the old and new schools' classrooms, respectively.

4.3 Relationship between plug load consumption and occupant behaviour

Based on observations, the average half-hourly number of equipment in use also varied between the three schools as shown in Figure 5. It was highest in the old school gymnasium (3.87) and lowest in the middle-aged gymnasium (0.52), while it was highest in the middle-aged classroom (0.69) and lowest in the old one (0.47). The Kruskal-Wallis H test only showed statistically significant differences in median half-hourly number of equipment in use between the three gymnasiums ($\chi2(3) = 100.47$, $p < .005$). Subsequent pairwise comparisons showed statistically significant differences in the number of equipment in use between all pairs of gymnasiums.

The average half-hourly plug load consumption was highest in the old school classroom (11.72 Wh/m^2/30 min) and gymnasium (264.62 Wh/m^2/30 min), while it was lowest in the new classroom (4.16 Wh/m^2/30 min) and the middle-aged gymnasium (4.8 Wh/m^2/30 min), as shown in Figure 6. The Kruskal-Wallis H test showed the differences in median half-hourly plug load consumption between the three classrooms and gymnasiums were statistically significant ($\chi2(3) = 83.2, 201.69$ respectively, $p < .005$). Subsequent, pairwise comparisons also showed statistically significant differences in plug load consumption between all pairs of classrooms and gymnasiums.

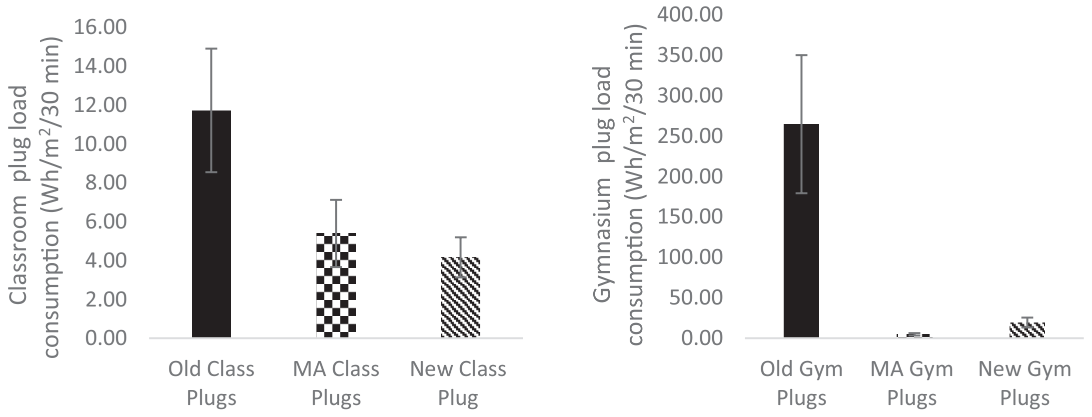
FIGURE 5. Average half-hourly number of equipment in use in a) classrooms and b) gymnasiums.



a

b

FIGURE 6. Average half-hourly plug load consumption in a) classrooms and b) gymnasiums



a

b

The Spearman's rank-order correlation showed statistically significant weak to moderate positive correlations between half-hourly numbers of equipment in use and half-hourly plug load consumption in some school spaces identified in Table 3. These results indicated the number of equipment in use explained 11–26% of the variation in plug load consumption.

4.4 Relationship between occupants' perception of their energy-related behaviour and their electricity consumption.

Daily light consumption during school hours (8:30–15:30) was higher in the old school's classroom (2706.3 Wh/m^2/day) than in the middle aged one (327.2 Wh/m^2/day) as shown in Figure 7. Independent-samples t-tests showed a statistically significant difference between the average light consumption in both classrooms (95% CI, 1134.4 to 3623.8, t(9) = 4.32, p =

TABLE 3. Spearman correlation coefficient between the number of equipment in use and plug load consumption.

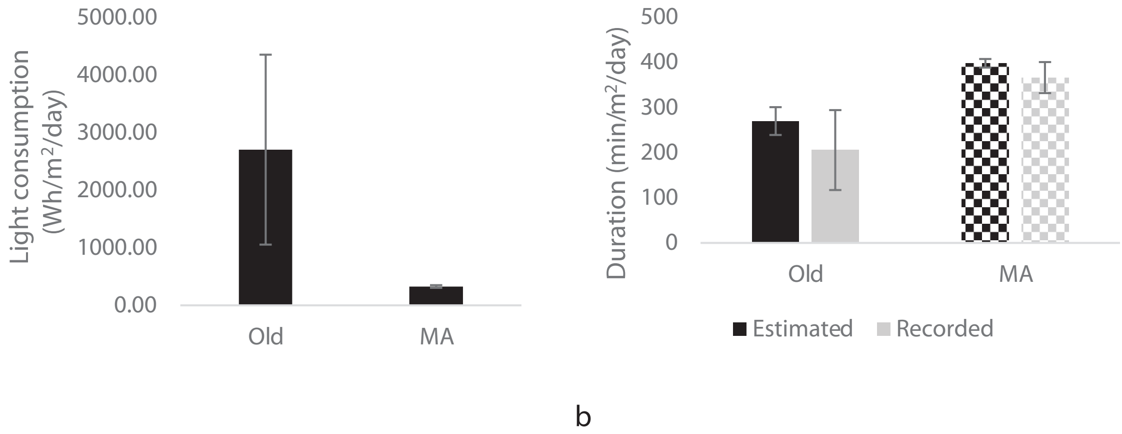
School space	Spearman Correlation Coefficient (r_s)	P (Sig. 2-tailed)
Old Gymnasium	0.176	0.049
MA Gymnasium	**0.478**	**<0.0005**
New Gymnasium	0.182	0.041
Old Classroom	**0.489**	**<0.0005**
MA Classroom	–0.097	0.212
New Classroom	**0.509**	**<0.0005**

Note: Results in bold are statistically significant (P<0.05)

.002). In contrast, self-reported and recorded light use durations were higher in the middle aged school's classroom (396.8, 366.3 minutes, respectively) than in the old one (270, 205.7 minutes, respectively), with a statistically significant difference of 126.8 minutes for self-reported light use durations (95% CI, –152.1 to –101.6, t(9.65) = –5.35, p < .005), and 160.6 minutes for recorded light use durations (95% CI, –227.9 to –93.4, t(8.52) = –11.46, p < .005). Figure 7 shows light consumption, as well as self-reported and recorded light use durations for the old and middle aged classrooms during school hours.

The Pearson's product-moment correlation showed a statistically significant strong positive correlation between self-reported light use duration and light consumption during school hours in the middle aged classroom only (r = 0.789, P = 0.012). This result indicated occupant estimates of light use duration explained 62.3% of the variation in light consumption in this classroom. However, self-reported light use duration in the old classroom did not show a statistically significant correlation with light consumption (r = 0.214, P = 0.364).

FIGURE 7. Average a) light consumption and b) self-reported and recorded light use durations during school hours (8:30–15:30).



Pearson's product-moment correlation showed a strong, statistically significant positive correlation between recorded light use durations using occupancy sensors and light consumption during school hours in the old and new school's classroom (r = 0.826, r = 0.785 respectively, P<0.005). There was also a statistically significant moderate positive correlation between both variables in the middle aged school's classroom (r = 0.411, P = 0.009). These results indicated that recorded light use durations explained 68.2%, 16.9% and 61.6% of the variations in light consumption in the old, middle aged and new school classrooms, respectively. These percentages are based on the coefficient of determination which is a measure of how close the data are to the fitted regression line.

The Spearman's rank-order correlation showed no statistically significant correlations between self-reported equipment use durations and plug load consumption during school hours in all three classrooms. The Kruskal-Wallis H test revealed differences in median half-hourly plug load consumption were statistically significant between the three classrooms, as shown in the previous section. However, no statistically significant differences in median self-reported equipment use durations during school hours were found between the three classrooms.

5. DISCUSSION

Electricity consumption after school hours during non-booked intervals was expected to be similar across the three schools' gymnasiums since they were unoccupied during those times. Instead, statistically significant differences were found between those gymnasiums' electricity consumption which suggests that factors other than gymnasiums' bookings may also be at play and affecting that consumption. These other factors may be occupant or non-occupant related. Non-occupant related factors include equipment types and their power ratings. These factors may have affected the phantom loads consumed by every equipment which may explain the statistically significant differences in that consumption during non-booked intervals. Occupant-related factors may include the number of off versus idle equipment in every gymnasium. This number is directly related to occupant behaviour since occupants are the ones who chose to turn off equipment and unplug it. Therefore, their behaviour directly affects the phantom loads consumed by the equipment in every gymnasium, which in turn affects every gymnasium's electricity consumption after school hours.

The weak, albeit statistically significant correlations between half-hourly occupancy durations and electricity consumption for lighting in two of three classrooms suggest that lights were used when classrooms were unoccupied. This suggestion may have been especially true in the middle-aged school's classroom, where no statistically significant correlation was found between these two variables. School visits confirmed teachers in the middle-aged school usually left the lights on at the end of the school day. Those were usually switched off by custodial staff at the end of their night shifts around 22:00. These results were in line with the results of analyzing electricity consumption for lighting in these three classrooms and described in Ouf et al. [31]. This analysis had shown that electricity consumption for lighting in the middle-aged school's classroom typically dropped on an average day around 22:30 unlike the other two classrooms' where it dropped around 16:30. The analysis had also shown that electricity consumption for lighting during non-work hours made up 15.3% of total electricity consumption for lighting in the middle-aged school's classroom compared to 2.4% and 0.5% in the old and new classrooms, respectively. These findings reinforce the need to improve lighting controls by using for instance sensor-controlled lighting to ensure that lights are on only when a space is occupied.

Sensor-controlled lighting was in fact used in the new school's classroom, which may explain the stronger statistically significant correlation between its electricity consumption for lighting and its occupancy durations. Ouf et al. [31] had also shown that the new school's classroom used only 2.2% of its lighting electricity when it was unoccupied, which further demonstrated the energy-efficiency of these sensors. It is important to note that while increasing building automation may reduce energy consumption, it may have an adverse effect on occupants' comfort. For example, automatically controlled window blinds may not address immediate occupant comfort needs or improve views, but instead be controlled to reduce adverse solar heat gains [30].

The correlation tests showed statistically significant positive relationships between recorded light use durations and electricity consumption for lighting during the school day in all three classrooms. However, they only showed a strong and statistically significant positive relationship between self-reported light use durations and electricity consumption for lighting during the school day in the middle-aged school's classroom. These results demonstrate that light use duration and electricity consumption for lighting are tightly related. However, they also show that recorded light use durations were more effective than self-reported ones at explaining electricity consumption for lighting. Self-reported light use duration explained 62.3% of the variation in lighting electricity consumption in the middle-aged school's classroom only whereas recorded light use durations explained 68.2%, 16.9% and 61.6% of the variation in lighting electricity consumption in the old, middle-aged and new school classrooms, respectively. This could be due to the subjective nature of self-reported durations which rely on the respondent's ability to recall them. This ability differs from one respondent to another, thus the strong and statistically significant correlation in the middle-aged school's classroom only. The inability of one of the teachers to report their estimated light use durations represented another limitation which further highlights the benefits of using sensors to record this aspect of occupant behaviour. Recorded light use durations were more objective and measured actual durations, thus the consistently positive and statistically significant correlations in the three schools' classrooms. These results show that lighting and occupancy sensors were more effective than surveys at determining actual light use durations and should therefore be used for that purpose.

The correlation tests also showed only moderate positive relationships between the observed number of equipment per half-hour and electricity consumption for plug loads in three of the six analyzed classrooms and gymnasiums. These moderate correlations showed point-in-time observations could only explain up to 26% of the variations in electricity consumption for plug loads. This may have been due to nature of the tool used to determine those numbers. Point-in-time observations were used to determine the number of equipment in every state (i.e. off, idle or in-use) at half-hour intervals. Because of that, the state of a piece of equipment may have changed more than once during the half-hour interval, either before or after an observation. This change in equipment state would not have been captured by the observations because it would have lasted less than half an hour, thus these moderate correlations in some of the spaces. Continuous observations whereby the observers would be present in the monitored space at all times may be more accurate and appropriate than point-in-time observations in this case. These moderate correlations may also be due to electricity consumption for plug loads being related to factors other than the number of equipment in-use. As per the results of analyzing the effect of gymnasium bookings on electricity consumption for plug loads, these factors may be occupant or non-occupant related and may include factors such as equipment power ratings, equipment types, and equipment use durations.

6. CONCLUSION

This study provides several important contributions to the literature as it is one of the first to investigate and quantify the effect of energy-related occupant behaviour on electricity consumption in Canadian schools. The study presented and validated a new comprehensive method for evaluating energy-related occupant behaviour at the building and space levels using several tools other than building performance simulations and occupant surveys. Findings helped identify some occupant-related factors with a significant impact on electricity consumption, making this study relevant to school building managers and operators looking to improve their existing schools' energy-efficiency. With the shift towards more stringent energy codes, and net-zero energy buildings, identifying and improving such factors becomes a necessity. This energy savings goal is to decrease the electricity consumption of existing buildings, which would by extension decrease their overall energy consumption.

Future research should focus on evaluating energy-related occupant behaviour in relation to school buildings' real-time electricity consumption in more than three-case study buildings and in more than one classroom per building. Future research should also address technical problems with the sub-metering equipment as soon as they arise to ensure those do not affect the results. Human errors that may occur due to discrepancies in the way the observations are conducted need to also be addressed to ensure those do not have any effect on the results. More needs to be done to minimize and if possible eliminate the "Hawthorne Effect" that may occur as a result of occupants realizing they are being observed. Longer observation periods are recommended to collect a larger amount of data on occupant behaviour. These limitations can be addressed by automating the data collection process using sensors or video monitoring, although these tools may also present other limitations such as privacy concerns. Future research should also consider the effect of a number of factors such as the power ratings of different equipment and their types, as well as lighting power densities on real-time electricity consumption for lighting and plug loads respectively. Furthermore, the relationship between decreasing energy consumption in buildings and maintaining or increasing occupant comfort must also be addressed in future research. If building controls do not provide comfortable indoor environmental conditions, occupants may opt to take adaptive actions that could be disruptive to building operations and ultimately result in an unintended increase in energy consumption.

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REFERENCES

[1] C. M. Clevenger, J. R. Haymaker, and M. Jalili, "Demonstrating the Impact of the Occupant on Building Performance," *J. Comput. Civ. Eng.*, vol. 28, no. February, pp. 99–102, 2014.

[2] E. Azar and C. C. Menassa, "A comprehensive analysis of the impact of occupancy parameters in energy simulation of office buildings," *Energy Build.*, vol. 55, pp. 841–853, 2012.

[3] F. Haldi and D. Robinson, "The impact of occupants' behaviour on building energy demand," *J. Build. Perform. Simul.*, vol. 4, no. October 2014, pp. 323–338, 2011.

[4] G. Y. Yun, H. Kim, and J. T. Kim, "Effects of occupancy and lighting use patterns on lighting energy consumption," *Energy Build.*, vol. 46, pp. 152–158, 2012.

[5] H. Burak Gunay, W. O'Brien, I. Beausoleil-Morrison, and A. Perna, "On the behavioral effects of residential electricity submetering in a heating season," *Build. Environ.*, vol. 81, pp. 396–403, 2014.

[6] A. Al-Mumin, O. Khattab, and G. Sridhar, "Occupants' behavior and activity patterns influencing the energy consumption in the Kuwaiti residences," *Energy Build.*, vol. 35, pp. 549–559, 2003.

[7] Z. M. Gill, M. J. Tierney, I. M. Pegg, and N. Allan, "Low-energy dwellings: the contribution of behaviours to actual performance," *Build. Res. Inf.*, vol. 38, no. 5, pp. 491–508, Oct. 2010.

[8] P. Hoes, J. L. M. Hensen, M. G. L. C. Loomans, B. de Vries, and D. Bourgeois, "User behavior in whole building simulation," *Energy Build.*, vol. 41, pp. 295–302, 2009.

[9] F. Haldi and D. Robinson, "The impact of occupants' behaviour on building energy demand," *J. Build. Perform. Simul.*, vol. 4, no. 4, pp. 323–338, 2011.

[10] O. Guerra-Santin and L. Itard, "Occupants' behaviour: determinants and effects on residential heating consumption," *Build. Res. Inf.*, vol. 38, no. 3, pp. 318–338, 2010.

[11] NRCan, "Survey of Commercial and Institutional Energy Use: Buildings 2009," 2012.

[12] C. Menassa, S. Mangasarian, M. Asmar, and C. Kirar, "Energy Consumption Evaluation of United States Navy Leed Certified Buildings," *J. Perform. Constr. Facil.*, vol. 26, no. February, pp. 46–53, 2012.

[13] D. Oates and K. Sullivan, "Postoccupancy Energy Consumption Survey of Arizona's LEED New Construction Population," *J. Constr. Eng. Manag.*, vol. 138, no. June, pp. 742–750, 2012.

[14] O. Guerra Santin, "Behavioural Patterns and User Profiles related to energy consumption for heating," *Energy Build.*, vol. 43, no. 10, pp. 2662–2672, Oct. 2011.

[15] M. H. Issa, M. Attalla, J. H. Rankin, and a. J. Christian, "Energy consumption in conventional, energy- retrofitted and green LEED Toronto schools," *Constr. Manag. Econ.*, vol. 29, no. 4, pp. 383–395, Apr. 2011.

[16] P. Taylor, D. K. Robertson, and M. W. Higgins, "Do Older Schools Use Less Energy? Results of Calibrated Simulations and Post-occupancy Evaluations Do Older Schools Use Less Energy? Results of Calibrated Simulations and Post-occupancy Evaluations," no. November, pp. 37–41, 2012.

[17] M. S. Gul and S. Patidar, "Understanding the energy consumption and occupancy of a multi-purpose academic building," *Energy Build.*, vol. 87, pp. 155–165, 2015.

[18] K. Steemers and G. Y. Yun, "Household energy consumption: a study of the role of occupants," *Build. Res. Inf.*, vol. 37, no. March 2013, pp. 625–637, 2009.

[19] E. Azar and C. Menassa, "Agent-based modeling of occupants and their impact on energy use in commercial buildings," *J. Comput. Civ. Eng.*, vol. 26, no. August, pp. 506–518, 2011.

[20] H. B. Gunay, W. O'Brien, and I. Beausoleil-Morrison, "A critical review of observation studies, modeling, and simulation of adaptive occupant behaviors in offices," *Build. Environ.*, vol. 70, pp. 31–47, 2013.

[21] C. M. Clevenger, J. R. Haymaker, and M. Jalili, "Demonstrating the Impact of the Occupant on Building Performance," *J. Comput. Civ. Eng.*, vol. 28, no. 1, pp. 99–102, 2014.

[22] D. Kaneda and B. Jacobson, "Plug Load Reduction: The Next Big Hurdle for Net Zero Energy Building Design," *ACEEE Summer Study on Energy Efficiency in Buildings*, 2010. [Online]. Available: http://wtgzik.pairserver.com/courses/632f14/plugloads-rumsey.pdf. [Accessed: 20-Jan-2016].

[23] G. M. Huebner, M. Mcmichael, D. Shipworth, M. Shipworth, M. Durand-daubin, and A. Summer, "Heating patterns in English homes: Comparing results from a national survey against common model assumptions q," vol. 70, pp. 298–305, 2013.

[24] G. M. Huebner, M. McMichael, D. Shipworth, M. Shipworth, M. Durand-Daubin, and A. Summerfield, "The reality of English living rooms—A comparison of internal temperatures against common model assumptions," *Energy Build.*, vol. 66, pp. 688–696, Nov. 2013.

[25] R. M. Tetlow, C. van Dronkelaar, C. P. Beaman, A. a. Elmualim, and K. Couling, "Identifying behavioural predictors of small power electricity consumption in office buildings," *Build. Environ.*, vol. 92, pp. 75–85, 2015.

[26] Z. M. Gill, M. J. Tierney, I. M. Pegg, and N. Allan, "Low-energy dwellings: the contribution of behaviours to actual performance," *Build. Res. Inf.*, vol. 38, no. March 2013, pp. 491–508, 2010.

[27] M. Bonte, F. Thellier, and B. Lartigue, "Impact of occupant's actions on energy building performance and thermal sensation," *Energy Build.*, vol. 76, pp. 219–227, 2014.

[28] Z. Yu, B. C. M. Fung, F. Haghighat, H. Yoshino, and E. Morofsky, "A systematic procedure to study the influence of occupant behavior on building energy consumption," *Energy Build.*, vol. 43, no. 6, pp. 1409–1417, Jun. 2011.

[29] Z. J. Yu Zhun Jerry, F. Haghighat, B. C. M. Fung, E. Morofsky, and H. Yoshino, "A methodology for identifying and improving occupant behavior in residential buildings," *Energy*, vol. 36, no. 11, pp. 6596–6608, 2011.

[30] W. O'Brien and H. B. Gunay, "The contextual factors contributing to occupants' adaptive comfort behaviors in offices—A review and proposed modeling framework," *Build. Environ.*, vol. 77, pp. 77–88, 2014.

[31] M. Ouf, M. Issa, and P. Merkel, "Analysis of real-time electricity consumption in Canadian school buildings," *Energy Build.*, vol. 128, pp. 530–539, 2016.

[32] D. Schwartz, B. Fischhoff, T. Krishnamurti, and F. Sowell, "The Hawthorne effect and energy awareness.," *Proc. Natl. Acad. Sci. U. S. A.*, vol. 110, no. 38, pp. 15242–6, 2013.