INVESTIGATING WINTERTIME THERMAL COMFORT OF POST-WAR MULTI-UNIT RESIDENTIAL BUILDINGS USING SURVEYS AND IN-SUITE MONITORING

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ABSTRACT

Multi-unit residential buildings (MURBs) provide nearly half of Toronto's housing and contribute significantly to energy consumption and greenhouse gas emissions in the city. Many residents, particularly in older, post-war MURBs, experience thermal discomfort in cold weather. The Atmospheric Fund (TAF) and a local social housing provider in Toronto, Canada, are undertaking retrofits in seven social housing buildings to address issues of both energy performance and thermal comfort. In order to design effective retrofit measures, baseline conditions for each building were established through resident surveys and data from one year of pre-retrofit in-suite monitoring. The surveys were used to investigate the residents' thermal comfort level, and how they control their indoor environmental conditions in the absence of an in-suite thermostat. In-suite sensor packages were used to collect data on air temperature, mean radiant temperature, and relative humidity data, which were then used to determine thermal comfort levels in each suite according to ASHRAE Standard 55-2013. The monitoring results were compared with the surveys by grouping the data by building site and floor to identify commonalities and differences. The results indicate that the residents' reported thermal comfort satisfaction does not consistently correspond with the results of the monitored conditions. Furthermore, the magnitude of this discrepancy varied between the study buildings. An analysis of the factors that contribute to these discrepancies is presented by comparing the results against building height, orientation, demographics and resident behavior. The analysis indicated that while resident perception is a major factor in the discrepancies, additional factors such as air leakage and window area likely also influence the results. The paper concludes by reflecting on the appropriateness and accuracy of the survey and monitoring results and identifies key areas for retrofit based on these findings.

BACKGROUND

Multi-unit residential buildings (MURBs) are an important source of housing in Southern Ontario. Providing nearly half of the housing in Toronto, many of these MURBs were constructed in the post-war era (Touchie et al, 2013). For a number of reasons including excessive air leakage, walls and windows with little thermal insulation and the lack of in-suite heating system controls, many residents in these buildings experience thermal discomfort during cold weather periods. With these operational issues and poor energy performance, post-war MURBs are excellent candidates for renewal as there is significant potential to improve both thermal comfort and energy performance through retrofits.

In North America, many older residential buildings are heated with hydronic or steam systems. These systems often led to building overheating in the winter months due to poor boiler control and uneven heat distribution (Dentz et al, 2013). These buildings are also typically bulk-metered which means that residents are not directly responsible for their energy costs (Burak et al, 2014). Without feedback on or responsibility for energy use, there is little incentive for residents to conserve energy (Burak et al, 2014). Furthermore, without in-suite thermostats, residents in these buildings typically resort to window operation to control indoor climate, which only increases energy consumption (Jian et al, 2011). One study showed that overheating results in an increase in surplus annual energy consumption of approximately 1.8% per degree Celsius over the desired temperature, for each eight hours of the day (U.S. DOE 2013). For the entire city, this translates into a large amount of energy that is needlessly wasted.

Overheating in wintertime poses different challenges when compared to summertime overheating. While overheating can adversely affect thermal comfort in both seasons, discomfort in winter is also related to low relative humidity levels (Dentz et al, 2013) and localized draught sensation. In addition, poor boiler controls and uneven heat distribution not only results in further discomfort, but also increases the space heating load in winter (Dentz et al, 2013). Therefore, addressing the overheating problem can improve both the thermal comfort and energy efficiency of a building.

Currently, there is very little research on wintertime thermal comfort in MURBs. To the authors' knowledge, there have been no studies that combine the use of continuous long-term in-suite monitoring of thermal comfort parameters with resident comfort surveys in the post-war MURB sector. The study described here which was funded and conducted by The Atmospheric Fund (TAF) and the University of Toronto, addresses this gap by exploring the correlation between monitored temperature data and data on occupant-perceived comfort. The goal of the study was to determine the most prevalent thermal comfort concerns and use these findings to prioritize appropriate retrofit measures for the buildings, as well as inform areas for future research. This paper presents a characterization of the wintertime thermal comfort conditions in these buildings and discusses whether survey responses can be a proxy for measured in-suite conditions.

METHODOLOGY

The analysis presented here is based on findings from a larger study, conducted by TAF and the University of Toronto, during which data were collected from resident surveys (approved by U of T's Research Ethics Board under protocol number 31142) and a multi-year in-suite monitoring program in seven post-war MURBs owned by a local social housing provider in Toronto. The resident participants were volunteers and received modest compensation for the inconvenience associated with study participation. The purpose of the study was to assess the pre- and post-retrofit energy performance and indoor environmental quality. The data referenced in this paper are from a one-year period (Dec 21, 2015 – Feb 29, 2016) prior to the start of the retrofit. A summary of the relevant building details is shown in Table 1. Building D was removed from this analysis due to its small sample size and relatively unique building configuration.

Table 1: Summary of Building Parameters

Bldg.	Const. Year	No. of stories	Floor Area (ft^2)	No. of Suites	No. of Suites Surveyed (% of total)	No. of Suites Monitored (% of total)	Type of Occupancy	Window to Wall Area Ratio (building)	Window to Wall Area Ratio (suite)
A	1972	4	113,580	213	30 (15%)	11 (5%)	Seniors	0.17	0.12
B	1972	4	97,920	184	25 (15%)	9 (5%)	Seniors	0.15	0.12
C	1965	7	126,540	217	33 (15%)	14 (6%)	Bachelor	0.26	0.24
D	1965	7	35,960	58	6 (10%)	3 (5%)	Seniors		
E	1965	11	116,820	196	31 (16%)	12 (6%)	Bachelor	0.25	0.24
F	1974	19	148,485	165	25 (15%)	11 (6%)	Family	0.24	0.47
G	1974	18	206,928	204	30 (15%)	13 (6%)	Family	0.16	0.47

In order to establish a pre-retrofit baseline for resident thermal comfort perceptions prior to the retrofit, surveys were conducted to determine residents' level of satisfaction with their indoor environment. The surveys included questions about demographics, occupant behaviors such as window, air conditioner and supplementary heater use as well as perceptions of thermal comfort and indoor air quality. At this time, an in-suite monitoring campaign was also initiated. Air temperature, relative humidity and a proxy for mean radiant temperature, among other parameters, were collected in 15-minute intervals over the monitoring period. The purpose of the monitoring was to collect objective data that could be compared across the study buildings and with other studies as well as with the results of the resident surveys. The survey results were also helpful for understanding variation in the suite-level monitoring data. A detailed description of the building envelope and HVAC system in each building as well as further information on the survey methods and in-suite monitoring is presented in Touchie et al., 2016.

In this paper, first the survey and monitoring results are presented separately and then discussed. This is followed by a comparison of the survey and monitoring data on a suite-by-suite basis, as opposed to a comparison between aggregated data from these data sets. The results and comparisons were used to explore the various factors contributing to the different thermal comfort responses. These factors include building characteristics, such as height and orientation, and resident behavior, such as window operation and heater usage. In order to provide a meaningful comparison of the difference between the survey and monitoring results, only suites with both survey and monitoring data available are compared on a suite-by-suite basis. However, in the results section, all survey responses are included to take advantage of the larger sample size.

SURVEY RESULTS AND DISCUSSION

In this section, survey results relating to wintertime thermal comfort are presented with respect to building height and orientation. An analysis of window operation, and a comparison between perceived thermal comfort and supplementary space heater use are also shown.

Resident Survey

Residents were asked to rate their level of thermal comfort during the winter months as either "Too Cold", "Just Right" or "Too Warm". There was also an option to respond "Don't Know". These responses are

shown in Table 2, with the most common response in each building presented in boldface:

Table 2: Survey Responses for Residents' Winter Time Thermal Comfort Level

Site	1		2		3		
Building	**A**	**B**	**C**	**E**	**F**	**G**	**Total**
# of Respondents	**30**	**25**	**33**	**31**	**25**	**30**	**157**
Too Cold	**3%**	**0%**	**12%**	**42%**	**76%**	**70%**	**30%**
Just Right	**63%**	**76%**	**55%**	**32%**	**16%**	**17%**	**46%**
Too Warm	**33%**	**24%**	**27%**	**26%**	**8%**	**13%**	**23%**
Don't Know	**0%**	**0%**	**6%**	**0%**	**0%**	**0%**	**1%**

The totals show a somewhat even distribution of responses across the three comfort levels. However, at the building level, the responses vary as the majority of residents reported being "Too Cold" in Buildings E, F and G, while the majority reported being "Just Right" in Buildings A, B and C. In an attempt to explain this difference in response, the paper has identified several factors that can influence the thermal comfort between suites, floors and buildings. These include building related factors, such as building orientation, air leakage, window to wall area ratio, and occupant related factors, such as window operation, use of a supplementary heater, as well as comfort perception by different demographics. In this section, building height, orientation, window operation and supplementary heater use are explored.

Building Height

It was suspected that stack effect would play a significant role in the cause of thermal comfort issues therefore Figure 1 shows a plot of the percentage of respondents who reported being "Too Cold" against the building height which suggests a positive correlation between building height and cold thermal discomfort.

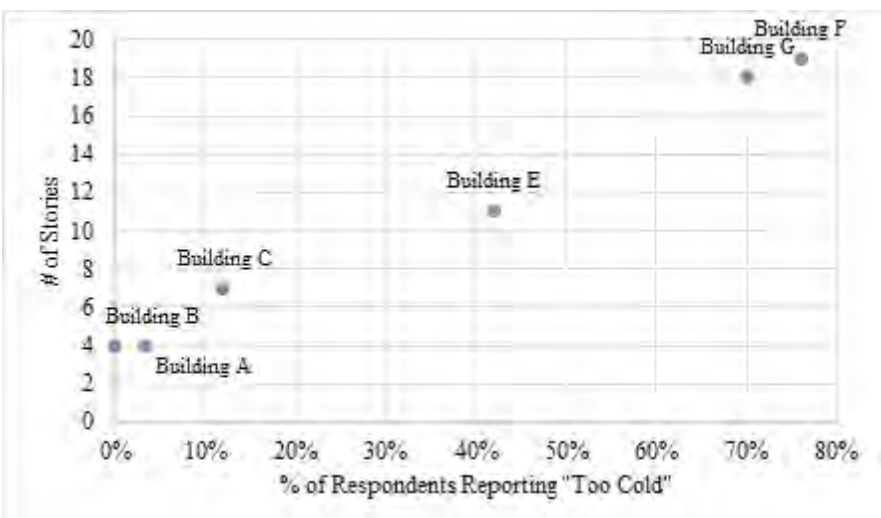

Figure 1: Relationship Between Building Height and the Percentage of "Too cold" Responses

While this may reflect the difficulty controlling conditions in taller buildings due to stack effect, a closer examination of the thermal comfort response on each floor is inconsistent with stack as many residents near the top of the buildings reporting conditions being too cold. This is contrary to expectation because stack

effect will result in a warmer temperature on the upper floors compared to the lower floors. As this is not the case, it suggests that there are other characteristics in these taller buildings that contributed to a higher proportion of cold discomfort.

Building Orientation

The orientation of each building is presented in Figure 2 along with the location of each of the monitored suites indicated by the numbered boxes. Numbers greater than one indicate that there are monitored suites in the same position but on different floors.

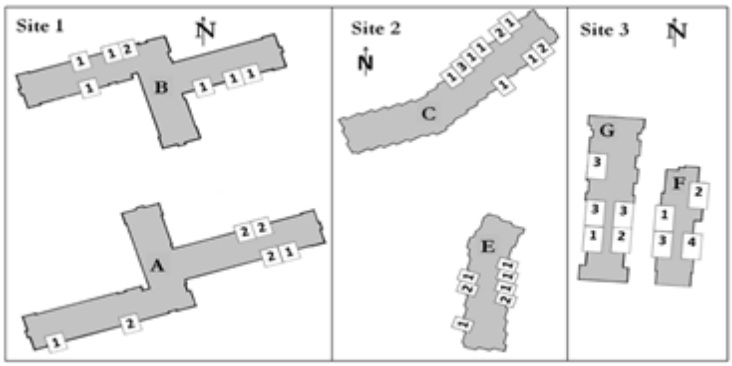

Figure 2: Building Orientations (reproduced from Touchie et al., 2016)

By comparing the suite orientation with the thermal comfort responses, it was observed that a higher proportion of residents living in the North and South facing buildings (A, B and C) report to being "Just Right" (65%), while the majority of residents living in the East and West facing buildings (E, F and G) report to being "Too Cold" (63%). The wind rose for each winter month, shown in Figure 3, indicates that the dominant direction of the winter wind is from the west and, to a lesser degree, from the east. These wind directions are normal to the broad face of the buildings with a larger proportion of respondents that report to being "Too cold".

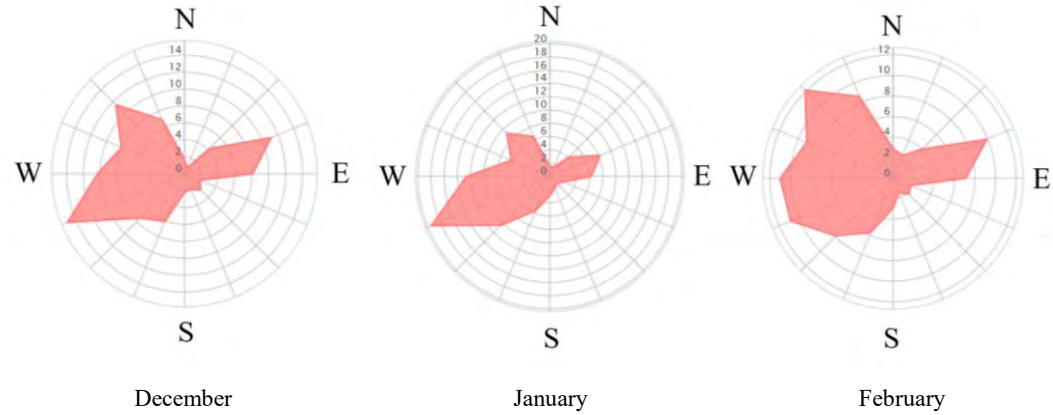

Figure 3: Toronto Wind Rose in December, January, and February ("Windfinder", 2015)

Given the age of these buildings and the airtightness of the building envelope, infiltration may be impacting the thermal comfort of residents living in the taller East and West facing buildings more than those in lower

North and South facing buildings. This is supported by the survey question about draughts, where 62% of residents in Site 3 (two tallest E-W facing buildings) reported experiencing draughty conditions around the window, compare to 10% of Site 1 and 2 (two shortest buildings). Coupled with this, taller buildings are exposed to higher wind pressures (Simmonds et al, 2013). Buildings E, F and G are taller than Buildings A, B and C which may expose them to higher wind pressures near the top of the buildings. This is also supported by the survey where 53% of the responses reporting draughty conditions in Site 3 were from suites located in the upper half of the building. When combined with stack effect, this could potentially explain the drastic difference in comfort level between Buildings A, B, C and Buildings E, G, F. However, envelope and inter-suite air leakage testing is needed to investigate this further.

Window and Balcony Door Operation

Figure 4 shows the proportion of residents who open their windows and balcony door, alongside reported smoking habits and detection of cooking and tobacco odours, presented by site. This plot reveals that Site 2 has a higher balcony door operation rate (69%) compared to 54% at Site 3 (only a small proportion of suites have balconies at Site 1 so these were excluded). Sites 1 and 3 have higher window operation rates (95% for Site 1, 65% for Site 2 and 86% for Site 3). The reason for the high balcony door operation at Site 2 may be due to a higher smoking population, as more residents "allow smoking" in their suites. On the other hand, high window operation rate at Site 3 may be attributed to odour detection, as more residents reported being affected by cooking odours from both themselves and neighbours. High window operation rate at Site 3 is noteworthy because Site 3 is also the site with the highest proportion of "Too Cold" responses. Visual observations on site also showed that some balcony doors at Site 3 would not close fully and some of the window sliders had missing lites which would contribute to uncontrolled air leakage. This could suggest that provision of adequate mechanical ventilation at Site 3 may also improve thermal comfort by lowering window opening rate.

Although Site 1 has the highest window opening rate, its residents are least affected by odours. Given the lack thermostatic controls in Site 1, window operation at Site 1 may instead be used to control the thermal comfort in the suite. This point is explored further in the monitoring section.

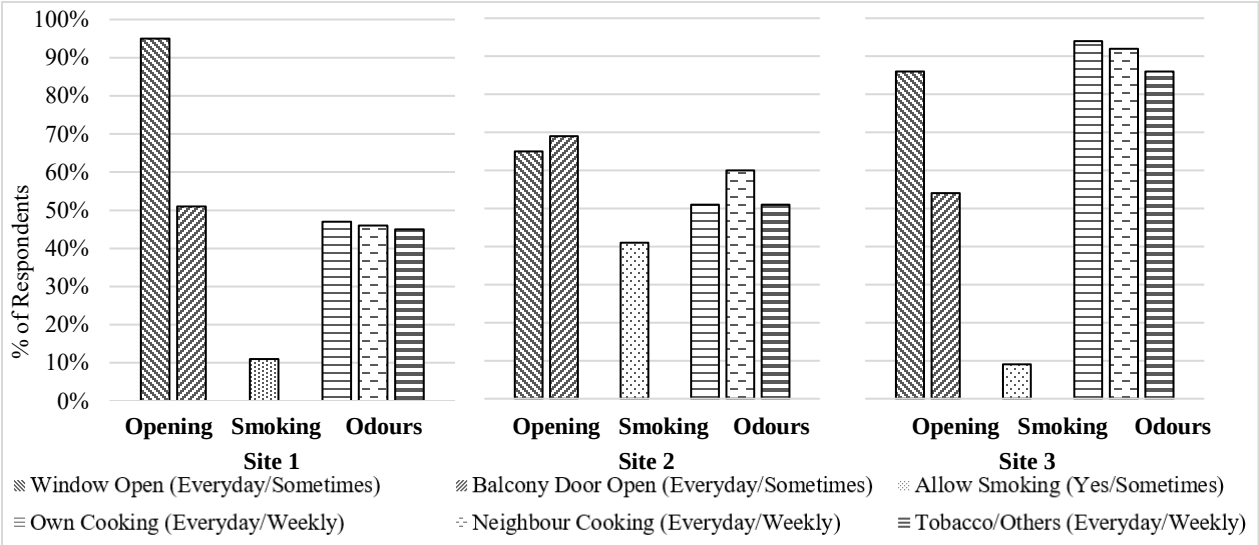

Figure 4: Relationship between Opening Frequency, Smoking Behaviour and Odour Detection

Use of Supplementary Heaters

The use of supplementary heaters was examined to assess the popularity and effectiveness of this strategy for dealing with thermal discomfort during cold weather. The relationship between frequency of use and thermal comfort response is presented for each site in Figure 5.

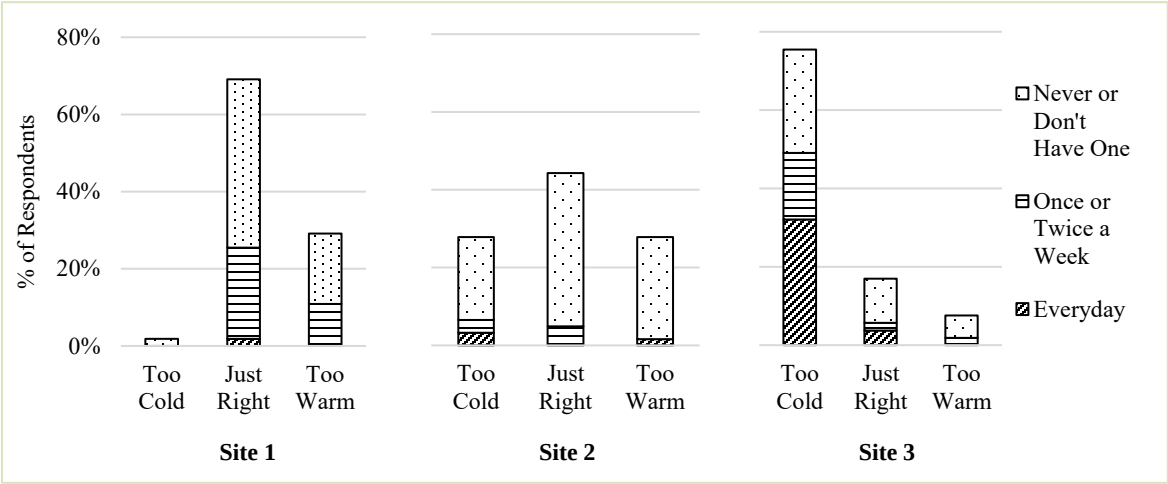

Figure 5: Frequency of Supplementary Heater Use

Most residents in the study do not use or do not own a supplementary heater (66%). Not surprisingly, the majority of supplementary heater use occurred at Site 3, which also had the greatest number respondents reporting conditions were "Too Cold". In other words, the interior conditions at Site 3 may have prompted the residents to use indoor heaters more frequently, yet this action still did not achieve an acceptable thermal comfort level. One of the issues could be that suites at different sites have different volumes of indoor space, which could impact the effectiveness of the supplementary heaters. This may explain the high heating

demand in Site 3 as they are also the largest suites of the three sites. Additionally, the fact that the mean radiant temperatures were consistently lower than the air temperatures at all three sites (0.56°C, 0.54°C and 0.61°C lower in Site 1, 2 and 3, respectively) suggests that radiant heat loss to the window could also have contributed to cold thermal discomfort.

MONITORING RESULTS AND DISCUSSION

In this section, suite air temperature results are summarized and discussed in the context of stack effect, window operation, and supplementary heater use.

Suite Air Temperature

In order to compare the survey results to objective data, in-suite monitoring of temperature, mean radiant temperature, and relative humidity, among other parameters, was conducted in 15-minute intervals. Figure 6 summarizes the suite air temperature distribution for each building including the median, interquartile range and minimum and maximum values. Each data point represents a suite temperature collected in a 15-min time interval in order to reflect the temperature fluctuation within each suite in the winter months, therefore there are tens of thousands of data points in each box plot below. The number of distinct suites monitored in each building can be found in Table 1.

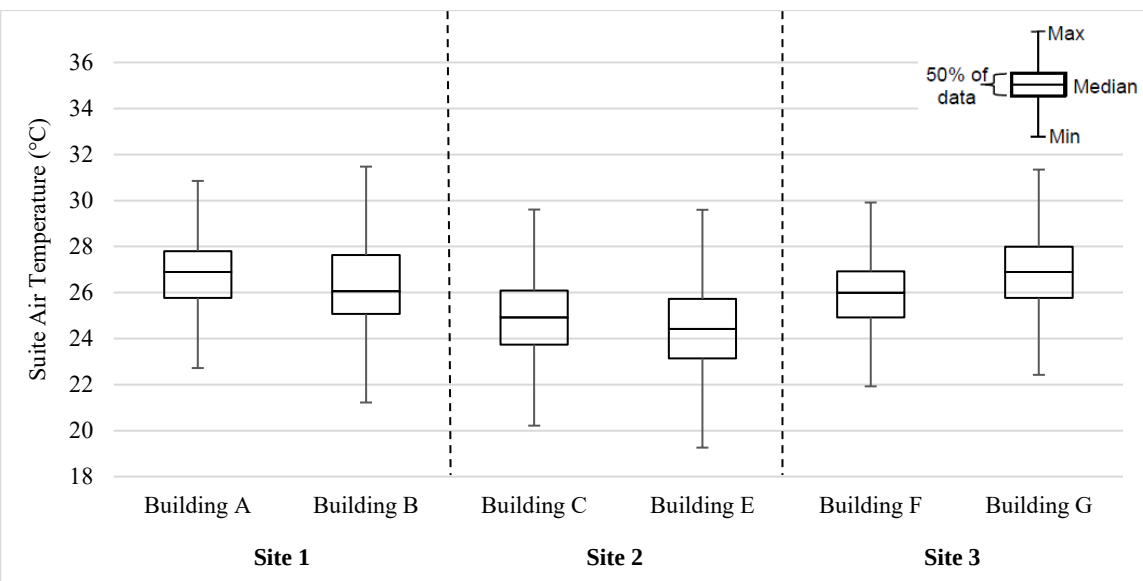

Figure 6: Winter Suite Temperature Distribution for Each Building

The distribution of suite temperature in winter reveals a general trend of overheating. In particular, Sites 1 and 3 experienced a median temperature above 26.5°C, which exceeds ASHRAE's recommended winter indoor temperature range of 22.4 – 26.1 °C (ASHRAE 55, 2013). At Sites 1 and 3, the air temperature was above the 26.1°C threshold for 61 % and 59% of the time, respectively. Additionally, Site 1 showed a higher average temperature than Site 3, which may suggest that suites in Site 1 not only experience higher temperature extremes, but are also exposed to longer periods of overheating. In comparison, air

temperatures at Site 2 were above 26.1°C for only 22% of the time while also experiencing lower extremes of indoor temperature. The differences between these buildings may be a result of resident behavior, such as window operation and supplementary heater usage, as discussed, as well as other suite-specific conditions.

In a few instances, extremely high and low temperatures were recorded. The maximum suite temperature of 39.2°C is found in Building B, while the minimum of 13.8°C is found in Building E. For the high temperature case, the suite was found to be consistently more overheated as it had an average suite air temperature of 29.7°C, the highest in the building. On the other hand, the low temperature case seems to be an outlier as the average suite temperature of 23.9°C was close to the median. These extremes, whether they are the result of suite conditions or occupant behavior, are explored in the next section.

Stack Effect

To understand what drives the temperature distribution within a building, stack effect was analyzed by examining the difference between the temperatures in the upper and lower half of the building. These differences between the upper and lower half mean temperatures were determined to be statistically significant using an ANOVA test ($p<0.001$ in all cases). Table 3 shows the suite temperatures in the upper and lower half of the buildings on each site.

Table 3: Suite Temperature Comparison between Upper and Lower Half Floors

Site	1	2	3
Upper Half Floors	**26.1 °C**	**25.0 °C**	**26.7 °C**
Lower Half Floors	**27.2 °C**	**24.4 °C**	**25.9 °C**

Contrary to the survey results, the analysis revealed observable stack effect in the buildings on Sites 2 and 3 where suites in the upper half are warmer by an average of 0.88°C and 1.23°C, respectively. On the other hand, no stack effect was observed in Site 1, where upper floors are, on average, slightly cooler than the lower floors with greater temperature variance. The difference in the magnitude of stack effect may be attributed to the building heights. Site 2 and 3, with building heights of 7, 11 and 18, 19 stories, respectively, showed stronger stack effect than Site 1, where the buildings are 4 stories.

Window and Balcony Door Operation

In addition to stack effect, human factors may contribute to the temperature difference between suites. The average indoor air temperatures of the suites were compared to the frequency of balcony door operation: daily, weekly, or never. The result showed that suites with balcony doors opened daily or weekly are on average colder than those who never opened by 0.79°C, 0.96°C and 1.27°C at Sites 1, 2 and 3, respectively. Furthermore, at the site level, Figure 6 demonstrated that Site 2 has lower average indoor temperatures, both in the upper and lower half of the building, when compared with Site 1 and 3. This corresponds with the frequency of balcony door operation where 68% of Site 2 residents reported opening the door daily or weekly, compared to 54% in Site 3. Although Site 2 has a lower window operation frequency than Site 1 and 3, it was assumed that opening balcony door brings in higher volume of cold air than opening windows. In contrast to Site 2 and 3 whose high balcony door and window operation rates were attributed to odour

control, it is suspected that residents at Site 1 use window operation to control their thermal environment. As the highest average temperature is found at Site 1, the monitoring result supports this theory.

Use of Supplementary Heater

The relationship between supplementary heater use and indoor temperature is shown in Figure 7. The purpose of this analysis was to identify whether different rates of supplementary heater use contributed to indoor temperature differences between the buildings. The effectiveness of supplementary heaters in controlling suite temperature in each of the buildings is also discussed. In Figure 7, each point corresponds to the average temperature of a suite over winter.

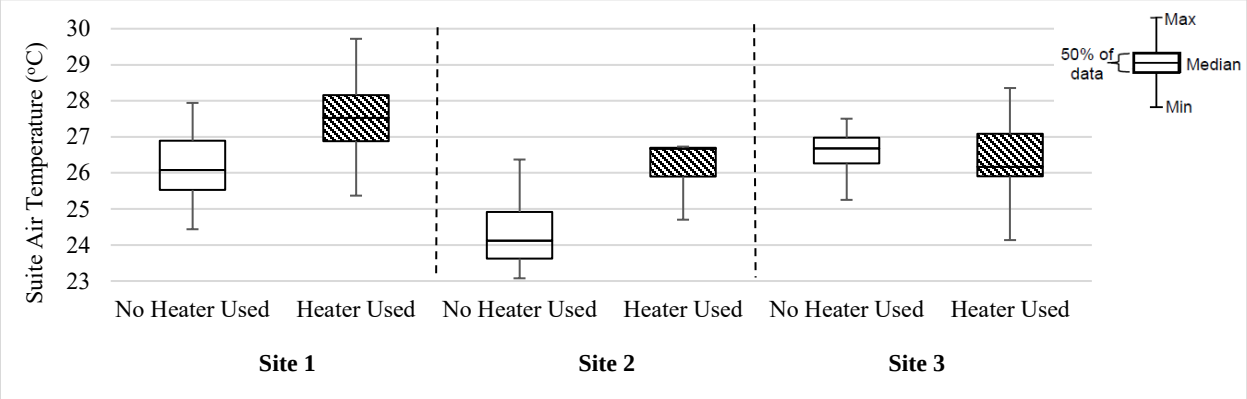

Figure 7: Average Suite Temperature for Suites That Use and Do Not Use Supplementary Heaters

Firstly, for Site 1 and 2, a higher average temperature is observed for suites that use supplementary heaters. However, this is not the case for Site 3, where no clear differentiation is observed between suites that use heaters and suites that do not. In addition, while Site 2 showed a similarly low rate of heater usage compared to Site 1, the average suite temperature in Site 2 is lower by 2°C. Site 3, on the other hand, showed a much higher rate of heater use than Site 1, while still experiencing lower average suite temperatures. This corresponds with the survey results which showed the ineffectiveness of heaters in producing satisfactory thermal comfort at Site 3. As discussed, supplementary heater effectiveness may be influenced by a larger room volume, WWR and the associated draughts (air movement measurements were not taken in the suites). The larger WWR at Site 3 (0.47) may explain why there are significantly more residents at Site 3 who reported to being too cold compared to Site 1 (WWR=0.12), even though the monitored average temperature in both sites are within 0.3 °C.

COMPARISON ANALYSIS

This section examines the agreements and discrepancies between the survey responses and monitored data. Where agreements are observed, they can be used to inform and prioritize appropriate retrofit measures. Where discrepancies are found, they can used to reveal shortcomings in the survey and monitoring programs, and inform areas for future studies and research. In order to provide meaningful comparisons between surveys and monitor results, only suites with both survey and monitoring data available are investigated in this section. Figure 8 shows residents' reported comfort level from the survey compared

with the monitored indoor air temperature on a per suite basis. Each data point represents a suite temperature collected in a 15-min time interval during the winter months which yields tens of thousands of data points per box plot. The number of unique suites in each category are listed at the bottom of Figure 8.

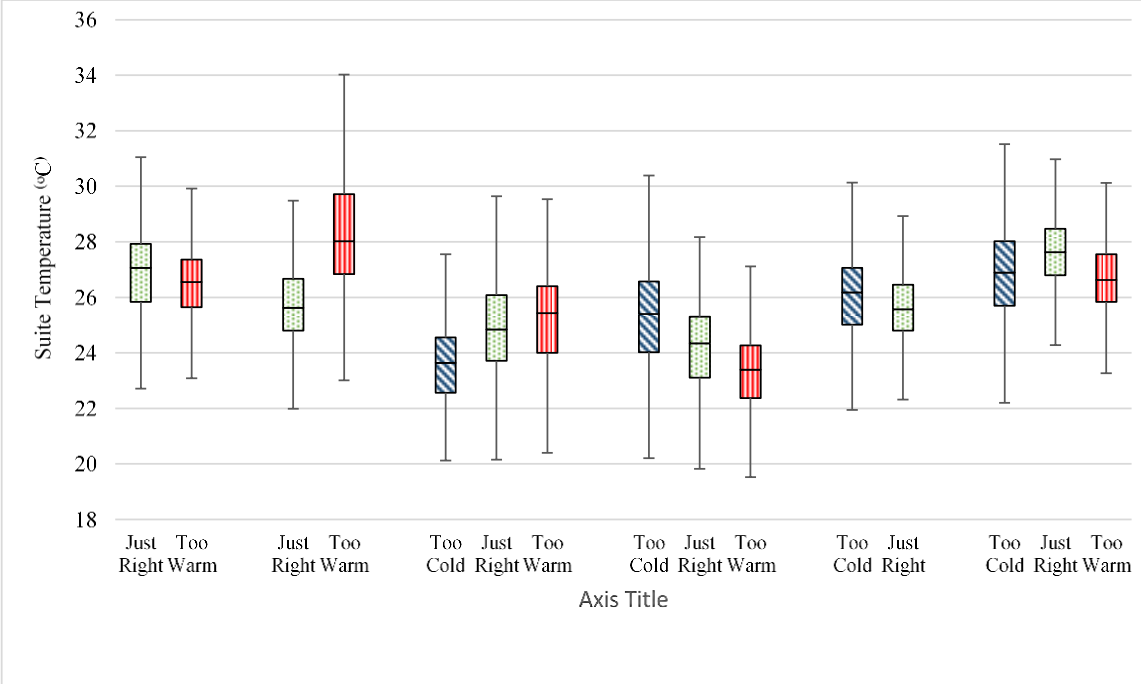

Figure 8: Comparison between Suite Air Temperature and Survey Comfort Level

From Sites 1 to 3, there is no consistent agreement observed between suite temperature and residents' thermal comfort. For example, suites that report to being "Too Cold" do not, generally, have lower indoor temperatures than suites that report to being "Too Hot" or "Just Right" in the same building. This discrepancy is further observed between different buildings, where no consensus is reached on which temperature is "Just Right". This is problematic because it makes it difficult to find a set point temperature that will be able to satisfy the majority of residents (Touchie et al, 2016).

The difference in the comfort responses is especially prevalent between Sites 1 and 3. Although the average suite air temperature difference between the two sites is negligible (0.3 °C which is within the temperature sensor error of 0.35°C for the Onset HOBO U12-13), 79% of residents at Site 3 report to being "Too Cold" compared to none at Site 1. In addition, while Site 2 is on average 1.7 °C colder than Site 3, only 23% of residents report being "Too Cold". Thus, Site 3 shows the largest proportion of residents who feel that their suites are too cold, even though the monitored data shows similar average suite temperatures compared to the other sites.

Thermal Comfort

Due to the level of discrepancy in thermal comfort, indoor air temperature alone was determined to be an insufficient basis for comparison. To create a more complete picture of thermal comfort for each suite, the Thermal Comfort Calculator developed by The Atmospheric Fund (TAF) was used to compute the thermal comfort for each suite according to ASHRAE 55-2013. The model incorporates the monitored mean radiant

temperature and relative humidity in each suite. Due to lack of on-site measurements, air speed in the suites is assumed to be 0.15 m/s, while resident's clothing level and metabolic rate are 1.0 clo and 1.0 met, respectively. The clothing level corresponds to typical winter indoor clothing, while the metabolic rate corresponds to a sedentary person. The results are shown in Figure 9. Similar to Figure 8, each data point represents a suite temperature collected in a 15-min time interval during the winter months and the number of suites in the each box are shown at the bottom of the figure.

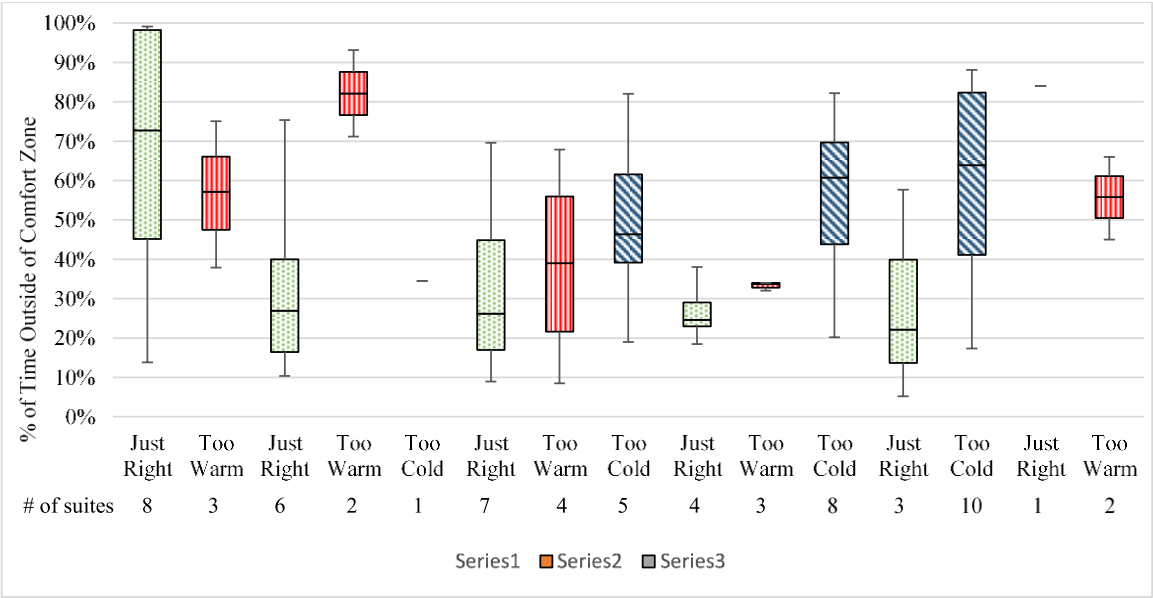

Figure 9: Percentage of Time When Suite Comfort Level Falls Out of ASHRAE 55-2013 Comfort Zone

The analysis shows a stronger agreement between monitored results and survey responses. In Buildings B, C, E and F, suites that are reported to being "Too Cold" or "Too Warm" are outside of ASHRAE 55-2013 defined comfort zone 45%, 8%, 16% and 29%, of the time respectively. In contrast, Buildings A and G showed the opposite trend. In Building G, this may be due to the small sample size where only one suite reported to being just right. In Building A, however, this discrepancy may be caused by a combination of other factor such as different perception of comfort.

When comparing by sites, Site 1, 2 and 3 are outside of comfort zone by an average of 57%, 37% and 57%, respectively. While the comfort zone analysis reveals Site 2 to be 20% more comfortable, this figure does not align with the dramatic difference in the survey's perceived comfort level, where Site 1, 2 and 3 each has 20%, 58% and 81% of suites who reported feeling "Too Cold" or "Too Warm". In particular, while monitored results show that Site 2 is 20% more comfortable than Site 1, there are 38% less suites in Site 2 who reported being "Just Right". This discrepancy may be caused by residents' personal comfort perception or the assumptions made about air speed, clothing and metabolic rate when determining the time spent within the comfort zone. Another possibility is that the suspected air leakage and colder temperatures near the window are having an impact on comfort.

Comfort Perception

A comparison between occupancy type and comfort level, as determined by both the surveys and the

monitoring, is summarized in Figure 10. The goal of the analysis was to identify whether different demographics have different perceptions of comfort and if this is may, in part, explain the disagreements between survey and monitoring results.

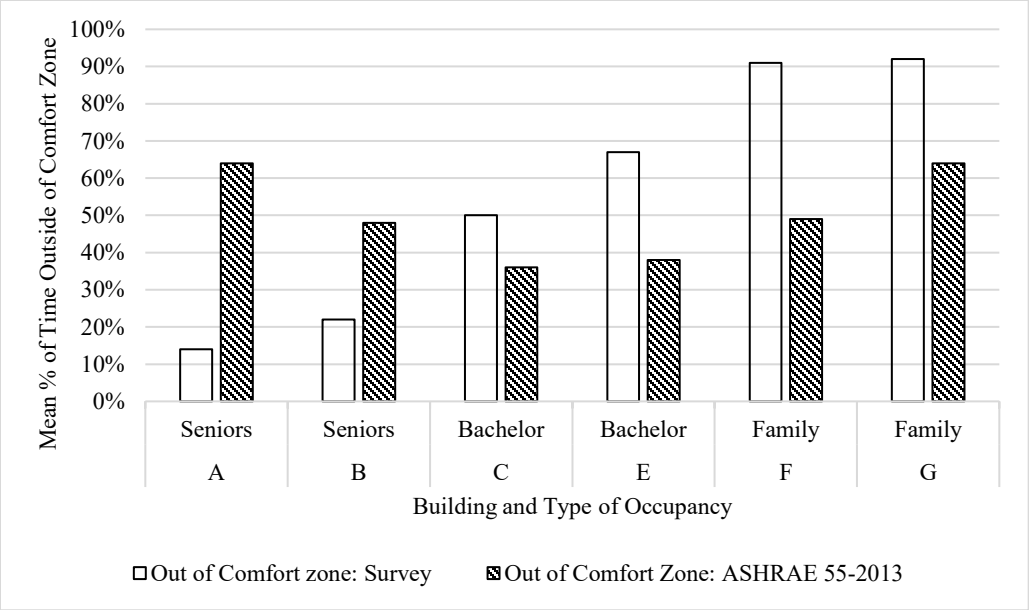

Figure 10: Occupancy Type and Surveyed and Monitored Comfort Level

Although difficult to quantify, studies have found that elderly people and non-elderly, in the same environment, experience the indoor climate differently (Roelofsen, 2015). The difference can be explained by the elderly having a slower thermoregulatory response when compared to their younger counterparts (Gonzalez, 1977), and therefore have a slower reaction when it comes to changes in the thermal environment. Furthermore, even though the elderly are less tolerant of uncomfortable environments and are more prone to health hazards (Roelofsen, 2014), they often under-report pain because they believe it is part of the normal aging process (Jones et al, 2016). This may explain why thermal discomfort seems to be under-reported in Site 1 which is predominantly occupied by seniors.

From Figure 10, there is agreement between both survey and comfort zone data showing that Site 2 has higher comfort level than Site 3. On the other hand, while Site 1 is most frequently outside of ASHRAE 55-2013's defined comfort zone, it has the highest reported level of comfort in the surveys. Although comfort perception may vary from one person to another, this discrepancy at Site 1 may be partially explained by the subjective thermal comfort perceptions of the elderly residents.

CONCLUSIONS AND IMPLICATION FOR RETROFITS

In this paper, the indoor thermal comfort of six buildings on three different sites were compared. After analyzing data from resident surveys and a year-long monitoring program, discrepancies were found between the perceived and monitored thermal comfort between the buildings.

The survey results:

- showed that residents in taller, East-West facing, family-occupied (as opposed to bachelor or senior) buildings most frequently reported to being "Too Cold";

- did not show any indication of stack effect so it is suspected that the impact of air infiltration due to the increased exposure of tall buildings to the dominant Easterly and Westerly wind in Toronto influences the thermal comfort response more than stack effect; and,

- showed a high reported frequency of window and balcony door operation at all three sites throughout winter period.

The monitoring data showed that:

- there was a noticeable stack effect in Site 2 and 3, where upper half of the floors were warmer by an average of 0.88°C and 1.23°C, respectively;

- the lowest suite temperatures were observed in the mid-rise building (Site 2), where average temperature is 1.64°C lower than the buildings on the other sites.

A comparison of the survey and monitored data showed:

- That the lower suite temperatures on Site 2 were likely due in part to the fact that Site 2 has more residents who smoke, and therefore open balcony doors more often;

- The suspected motivation for window and balcony door operation at the various sites: it is suspected that residents at Site 2 and 3 open balcony door and windows due to odours and residents at Site 1 likely use windows to control their thermal environment;

- Despite the fact that the average suite temperature of the high-rises (Site 3) is only 0.3°C lower than the low-rises (Site 1), a significantly higher proportion of the Site 3 population reported being "Too Cold" in Site 3 indicating that there are other factors besides air temperature that are impacting thermal comfort, such as air movement, that was not monitored.

- An estimate of the time each suite was within the comfort zone as defined by ASHRAE 55-2013 was determined from the monitored air temperature, mean radiant temperature and relative humidity data as well as assumed, constant values for air velocity, clothing level and metabolic rates. These data were compared to occupant-related factors, including window operation, heater usage and personal perceptions. This analysis showed that:

- Suites on Sites 1 and 3 are out of comfort zone similarly by an average of 57% of the time, which is significantly different from the comfort level reported in the survey where 92% of residents in Site 3 report to being "Too Hot" or "Too Cold" compared to the 19% in Site 1. Assuming a higher rate of air leakage in taller, East-West facing buildings due to greater window-to-wall ratio and resulting indoor air movement, then the considerably higher rate of "Too Cold" responses at Site 3 may be explained. However, as these data were not collected in the monitoring and future studies involving in-suite air movement will be required to confirm this theory;

- Residents who do not own or never used heaters have higher comfort satisfaction, likely because the central heating system is sufficient to meet their needs. However, Site 3, which has the highest usage rate for heaters, had 30% more residents who reported being "Too Cold" that use heaters than those who do not. This indicates that there are large differences between suite conditions across different buildings, and that the effectiveness of supplementary heaters in controlling indoor environment is dependent on suite characteristics. This theory is further supported by the monitored results, which found no clear difference in indoor temperature in Site 3 between suites who use and do not use heater. This suggests that suites with larger volume and window to wall ratio, such as Site 3, may have a more difficult time achieving adequate thermal comfort. This may also indicate a higher rate of infiltration in taller buildings, as the heat loss may be too much to be compensated for by supplementary heaters.

- That the elderly residents at Site 1 reported the highest levels of thermal comfort while being outside of ASHRAE 55-2013's comfort zone more than any other site. This may be due to elderly residents' under-reporting discomfort due to reasons mentioned in the previous section.

In conclusion, in-suite monitoring showed a trend of overheating, in some cases extreme overheating, at all three building sites throughout winter. However, as the survey and in-suite monitoring showed, the circumstances differ between the three sites. At Site 1, high frequency of window operation was found. Given the lack of thermostatic control, the residents likely resorted to window operation to control their indoor thermal environment. At Site 2 and 3, high frequency of balcony door and window operation was found, which was likely done to remove odours due to smoking and cooking. This suggests that a more effective mechanical ventilation system may reduce the need to open windows or balcony doors, and could, in turn, prevent the building from overheating to compensate for the cold draughts.

Lastly, the analysis of suite temperature and satisfaction level indicated no clear consensus as to which temperature range is "Just Right". This may indicate that adjusting the building set temperature alone is insufficient to solve the overheating and thermal comfort issues. As there are currently no in-suite heating controls in any of the three building sites, installing thermostats at all three building sites, in addition to adding/improving suite-based ventilation at Sites 2 and 3, might significantly improve resident thermal comfort while improving energy savings by reducing window and door operation in the winter.

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