From operable windows to frozen pipes and building forensics

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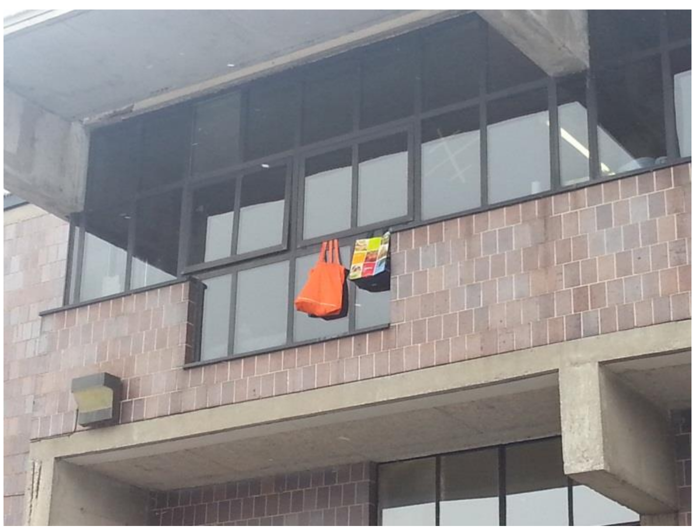
My European and Asian summertime visitors have often asked me why we don't rely on natural ventilation in Ottawa. After becoming accustomed to naturally ventilated buildings, my visitors are not shy about vocalizing their suffering in our cool and dry air-conditioned buildings. I, on the other hand, enjoy the reprise from my often-sweltering, west-facing, sun-exposed apartment. Regardless, my summertime meeting agendas and conference programs with international guests now have a standard note about bringing sweaters to stay warm in our academic buildings.

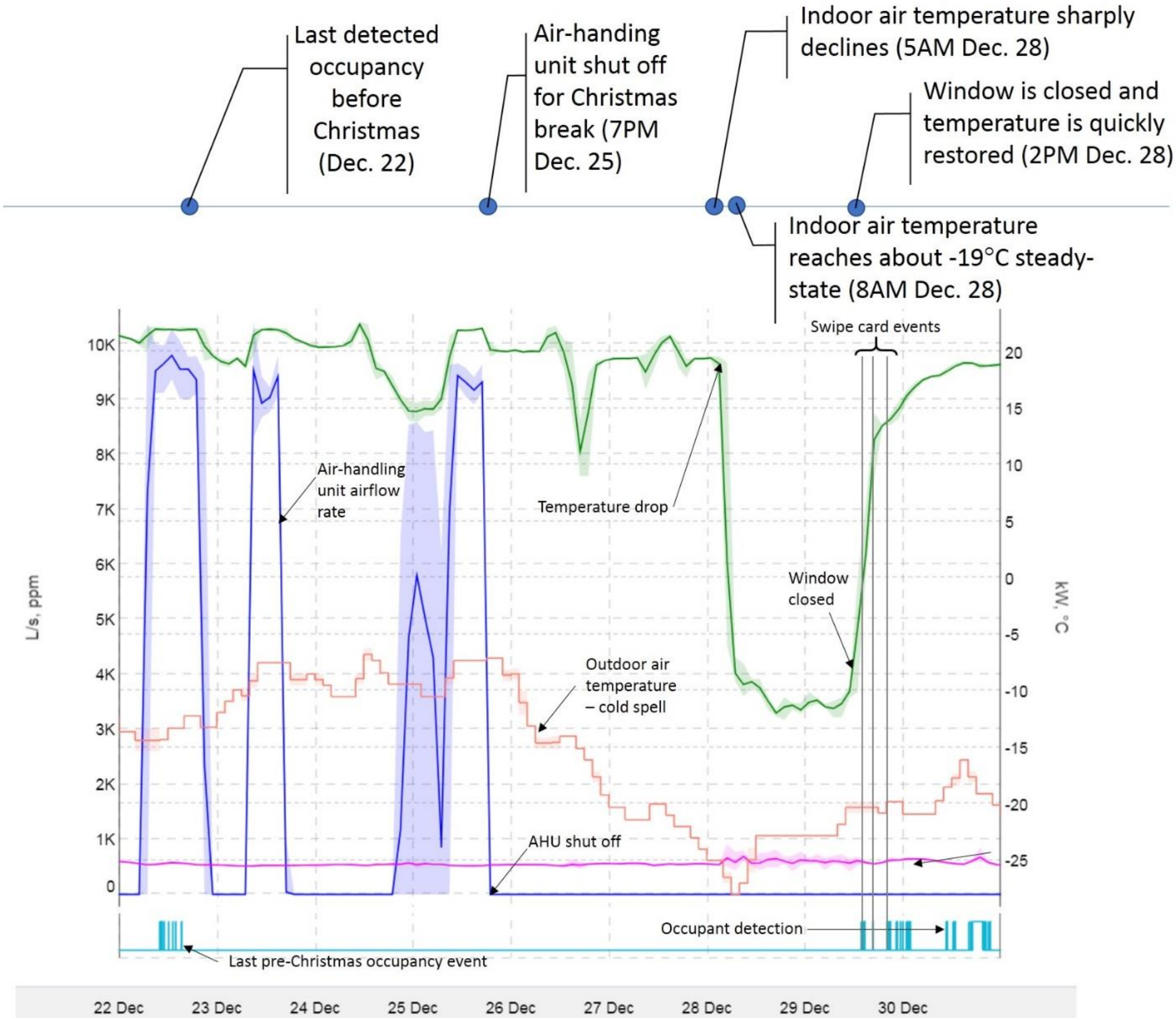
For the most part, Canadian commercial and academic buildings don't have operable windows[i]. I will admit that I haven't been able to give a good answer as to why. After all, there are about five months a year when the southern part of the country's mean outdoor temperature make it eligible for the adaptive comfort model (10 to 33.5°C) (ASHRAE Standard 55). Moreover, every Spring there's a week or two prior to switch-over to cooling mode when my office is hot enough to drive me out in search of a patio beer. Simply being able to open a window in my office would make it entirely comfortable, given that it's typically just 20°C outside. I have heard the irrefutable argument against operable windows that if students leave them open to keep their lunches cool (pictured below), there is not much point to upgrading them to double-glazing. I have also heard tales from building operators about how occupants leave the windows open in the winter and then they freeze open. But this remained a fairly abstract idea for me, until this winter.



For years, I've preached to students about the benefit of operable windows and natural ventilation. Aside from the pure physics that operable windows enhance air exchange with the outdoor and air movement such that there is the potential to improve thermal comfort and indoor air quality through enhanced air exchange with the outdoors and air movement, they also positively impact perceived occupant control and comfort. The result is that occupants in naturally ventilated buildings not only accept, but prefer, wider indoor air temperature ranges (Brager, Paliaga et al. 2004). For a long time, the latter notions were as foreign to me as my engineering students and I always feel a bit sheepish teaching about psychological concepts in an engineering course. Contrary to many technologically advanced building systems, operable windows are completely intuitive and yield nearly immediate benefits to occupants. There is plenty of scientific evidence to suggest that giving occupants immediate and intuitive adaptive opportunities greatly improves their tolerance of deviations from the classic comfortable temperature range. This is the basis for adaptive comfort model in ASHRAE Standard 55 and the European counterpart EN 15251.

But this winter, Ottawa (and much of North America suffered extreme cold temperatures). The period between Christmas and the New Year was reportedly the coldest since 1918, with little relief. This period unfortunately coincides with the time when commercial buildings are often partially shut-off and unoccupied. That means there's no one to directly suffer the consequences of open windows and there's often insufficient heating to compensate for the corresponding high level of heat losses. In my apartment, this meant frozen pipes, which was particularly unfortunate timing after I returned from my shower-less cabin after four days.

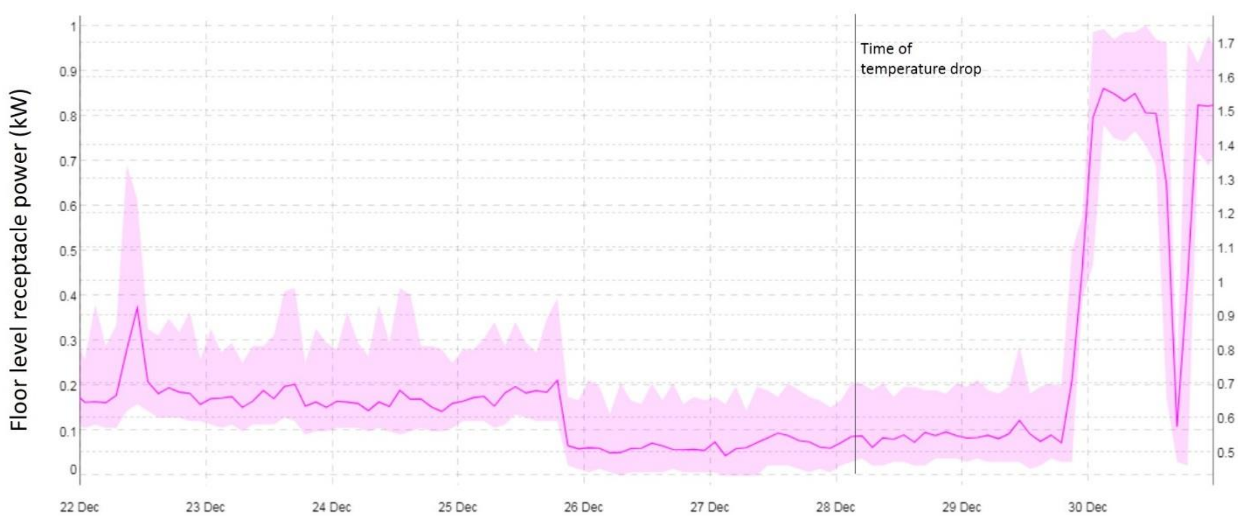
In the university building where my office is located, this perfect storm hit significantly harder and we've got concrete forensic evidence to interpret an unfortunate series of events, thanks to a suite of building automation system and access technologies. A window was left open, a pipe burst on December 28, and the result was 3 inches (7.5 cm) of water on the top floor and 1 inch from water leaked down to the floor below. But what events and circumstances led to this point? The timeline below is inferred from the building automation system data archive.



In the days that followed the window opening event (assumed to be on or before December 22, when the last occupant was present), the outdoor temperature remained *mild* at around -10°C. With the air-handling unit (AHU) on, the room was pressurized and warm air was delivered such that the indoor temperature didn't drop below 15°C. However, at between 5AM and 8AM on December 28, the temperature in the space (as measured at the thermostat) dropped by 30°C from 19°C to -9°C. Remarkably, the first 20°C of this occurred in just 30 minutes. Of course, this does not mean the air around the pipes in the plenum got this cold as fast. During this time, the outdoor temperature was hovering around -30°C. The ceiling-mounted radiant panels remained on full capacity for this entire duration, but they were never sized to compensate for open windows and a corresponding ΔT between indoors and out of 50°C. The data show that someone arrived at 1PM the next day and presumably shut the window, given the relatively fast response of five hours back to normal. However, the damage was done.

The data leave one key mystery, however. The occupancy data do not indicate that anyone was in the space in the five days before the window was opened. Three hypotheses were formed by my grad students, myself, and anyone how was willing to listen to my pondering:

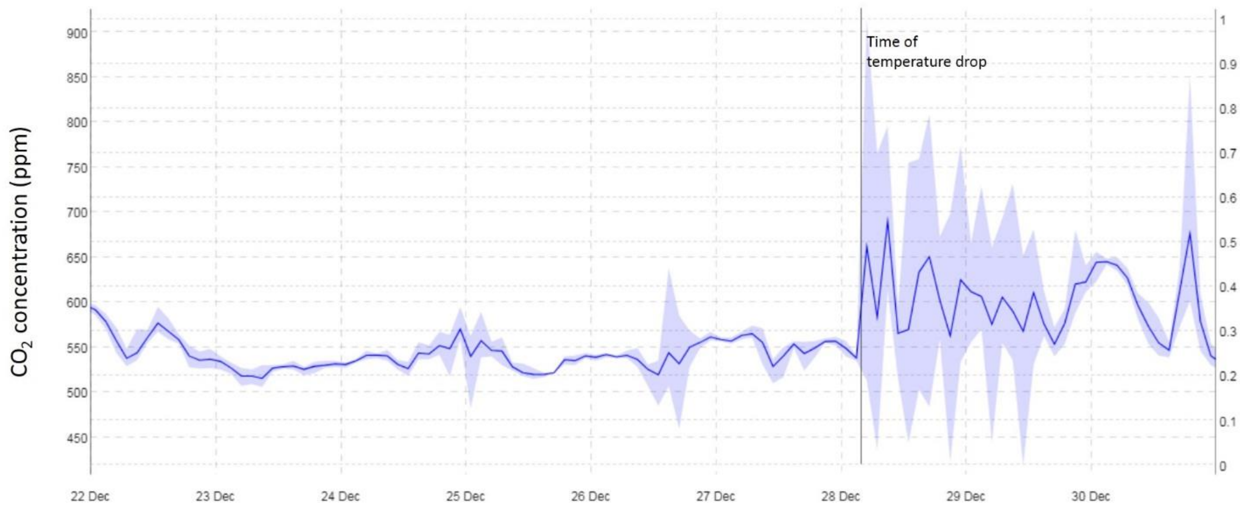
1. **The motion sensor failed to detect them, but someone entered the space undetected and opened the windows right before the big temperature drop.** After all, it is possible that an occupant slipped into the space without being detected by the wall-mounted motion sensor; just as such sensors sometimes result in lights spontaneously turning off. However, campus safety was kind enough to dig up the swipe-card access log for the rom. That new data source verified the motion sensor data.
2. **The window was open since December 22, but the supply air, which was warm enough to compensate for heat loss through the open window and the space was pressurized to mostly keep cold air from entering, was turned off on Dec. 28.** A log of the air-handling unit serving the space suggests that it had been turned off two days before the temperature dropped. So the air-handling unit being off may have been a contributing problem, but it was not the cause of a sudden temperature drop.
3. **Some major source of internal heat gains that was previously offsetting heat losses from the open window turned off on Dec. 28.** Informal discussion with a graduate student at the campus pub suggested that the room was full of heavy laboratory equipment. Therefore, this hypothesis seemed plausible, though the equipment did a remarkably good job of maintaining comfortable conditions up until the major temperature drop. However, the floor-level power meter data (figure below) does not show any anomalies (i.e., a major drop in power from the lab equipment being turned off) around the time of the major temperature drop.



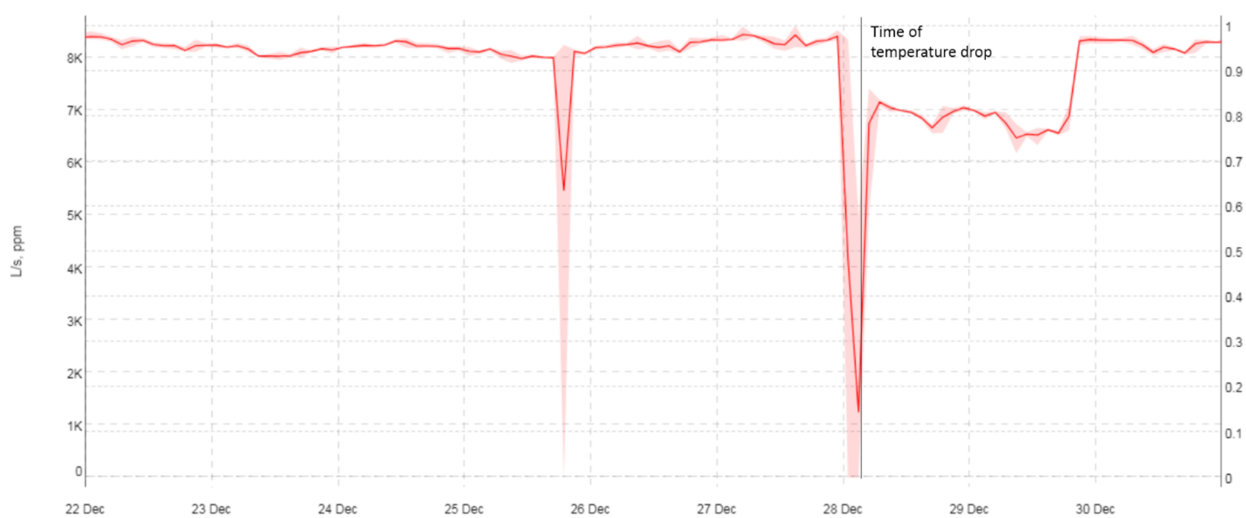
Thus, a mystery remains: what caused the temperature to rapidly when no one was present to open the window? Comments are welcome!

Two potentially relevant hints:

1. The CO_2 sensor in the room fluctuated wildly when the window was open. One would expect that all the fresh air would bring it closer to outdoor levels (around 400 ppm), but this did not happen.



2. The other main air-handling unit in the other wing of the building seems to have temporarily been throttled down to near-zero airflow right before the event. Conceivably, that air-handling unit was helping to pressurize the room with the open window. The wings of the building are connected by a hallway, though the door to the problematic room was almost certainly closed during this time. I cannot think of a way to confirm this without trying to repeat the sequence of events.



Most of my research (e.g., Gunay, O'Brien et al. 2014) has suggested that occupants are remarkably attuned to gearing their behaviour towards energy savings and improving comfort. However, this time, they did not anticipate the dire consequences of leaving the windows open before Christmas break. Until now I also had the impression that occupants of office buildings had less sense of ownership than in their own home. But a series of anecdotes around the table the local ASHRAE dinner immediately after the cold spell suggest otherwise – or at least that residential occupants are not any better. One of my dinner companions mentioned a homeowner who left his window open over the Christmas break and came home to a solidly frozen toilet.

Starting now, I am not so sure I can blindly advocate for operable windows in Canada. The benefits are irrefutable, but the consequences of misuse are graver than I previously understood. That said, there are plenty of technological solutions that we can and should pursue, including:

- Fault detection and diagnostics (either looking at the thermal response or inferred or sensed window state) linked to alarms. A simple black-box or grey-box thermal model implanted into the building automation system for the space would be able to detect an anomaly in heating load or temperature drop without the need for a window sensor.
- Window-state based temperature setpoints. Something we are advocating for in newer buildings with window contact sensors is to lower heating setpoints and raise cooling setpoints for spaces with open windows. Had this been implemented in the current building, it may have trained occupants not to leave the window open.
- Occupant feedback. Along the line of the signalling systems recommended by Ackerly and Brager (2011), occupants could be warned about open windows. This could be achieved through stand-alone signals, backlighting on thermostats, or even through email or text message.
- Motorized windows that close during extreme conditions – much like the exterior shades that retract with high wind speeds that can be spotted throughout Europe.

On the qualitative research front, I have learned that its good practice to ask why occupants are behaving in energy-intensive ways. I don't believe occupants enjoy wasting energy or building causing faults, nor are they as naïve about their energy use. Thus, there's a lot we can learn from occupants –by talking to them or studying building automation system data—for the sake of immediate controls tweaks or for future designs. I am an advocate of sharing lessons learned as much as success stories – hence this article.

References

Ackerly, K. C. and G. Brager (2011). Occupant response to window control signaling systems. University of California, Berkeley, Center for the Built Environment.

Brager, G., G. Paliaga, et al. (2004). "Operable windows, personal control and occupant comfort." ASHRAE Transactions **110**(2).

Gunay, H. B., W. O'Brien, et al. (2014). "On behavioral effects of residential electricity submetering." Building and Environment **81**: 396–403.

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[i] Let us not confuse presence of operable windows with natural ventilation. Operable windows are a necessary condition for a naturally ventilated building, but are not enough to make it naturally ventilated. The whole design and operating strategy must embrace the idea of relying on operable windows for cooling and fresh air and providing occupants with personal control to open and close windows. A fully-conditioned building with operable windows is just that: a fully-conditioned building with operable windows. According to ASHRAE Standard 55-2017,

the adaptive comfort model only applies if no mechanical air-conditioning system is installed and there is not currently mechanical heating.