POST-OCCUPANCY EVALUATION OF A HIGH-DENSITY AFFORDABLE HOUSING COMPLEX WITH INNOVATIVE MECHANICAL HEATING AND VENTILATION SYSTEMS

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Abstract
This paper presents the results from a post-occupancy evaluation of Le Coteau vert housing cooperative, a multi-unit residential building situated in a dense neighbourhood in Montreal, Canada. The building has a highly insulated and air-tight envelope, and make-up air to the apartments is conditioned by an energy recovery ventilator operating in sequence with a heat exchanger coil supplied by ground source heat pumps. The study aimed to document performance of the building in terms of the energy consumed as well as the indoor environmental quality (IEQ) achieved inside the occupied units. Energy efficiency and IEQ were evaluated using quantitative data from on-site monitoring of the mechanical systems and of conditions inside the apartments. Qualitative IEQ data were obtained from interviews and surveys with occupants to gauge their subjective experience of the living spaces and to compare this with quantitative metrics (temperature, relative humidity, carbon dioxide). Results indicate an energy use intensity that is well below the Canadian average, and a high level of satisfaction among residents overall.

Keywords:
Multi-unit residential buildings; post-occupancy evaluation; indoor environmental quality; energy use intensity; energy-recovery ventilator; ground-source heat pump.

INTRODUCTION

Le Coteau vert housing cooperative, completed in 2010, is situated in the dense Rosemont-La-Petite-Patrie borough of Montreal, directly adjacent to the Rosemont subway station and 15 minutes from Montreal's downtown core by public transit [1]. The cooperative is a non-profit organization with a mandate of providing affordable and environmentally sustainable housing to its members, who collectively own and administer its building [2]. The complex was realized with support from the Québec AccèsLogis programme, which provided 60% of construction costs, with the goal of providing affordable housing to medium and low-income households [3]. Due to the AccèsLogis rental rate guidelines, the baseline construction budget was110-120$/sq.ft, with additional financial contributions from the City of Montreal, the Société d'Habitation du Québec, the Canada Housing and Mortgage Corporation (CMHC), the Caisse Populaire De Lorimier, and Hydro-Québec. Cooperative members invested large amounts of unpaid time and energy throughout the development, construction, optimization and operation phases of the building, which has been crucial to its ongoing success.

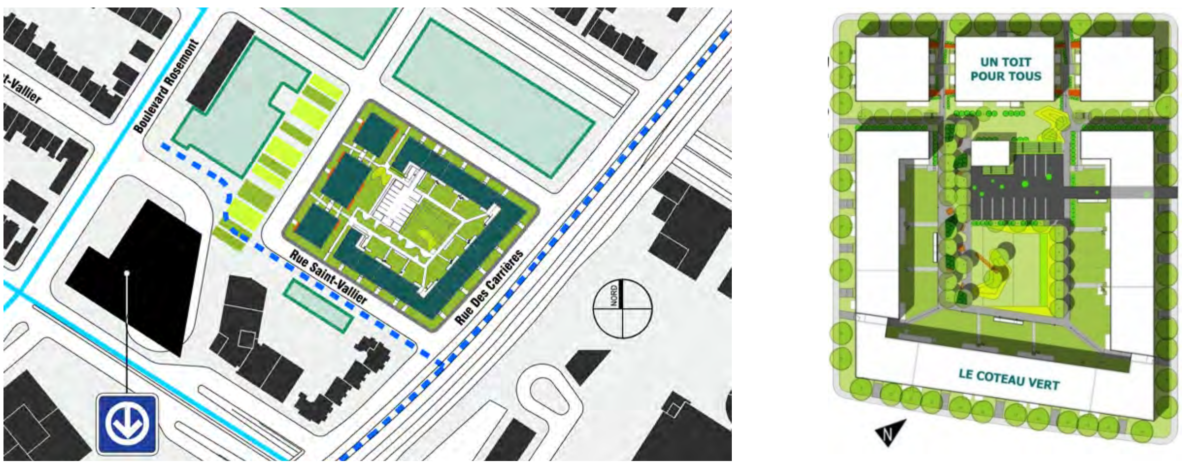

Fig. 1: The setting (left) and layout (right) of Coteau vert and neighbouring buildings (Credit: l'OEUF and NIP Paysage)

The cooperative is a wood-frame construction composed of 95 apartment units organized in thirteen four-story blocks aligned as 8-plexes along three sides of a central courtyard, as shown in Figures 1 and 2. All the apartments in the cooperative are singly-loaded with operable windows on opposing facades to enable cross-ventilation [1]. The founding members were committed to providing housing to larger families, who face a shortage of affordable housing in the area. Nearly half the units therefore have three to five bedrooms, resulting in a high proportion of children and youth (roughly 35%) among the cooperative's 275 residents [4].

The buildings have an enhanced degree of insulation and air-tightness, in accordance with the Quebec Novoclimat energy-efficiency guidelines for buildings. The exterior walls are insulated to an RSI value of 4.3 (a nominal R value of 24.5). Blower-door tests completed during construction suggest that the buildings have a maximum air leakage rate of 1.5 air changes per hour at a 50 psi pressure differential, as required by Novoclimat. Conditioned make-up air is supplied to the apartments by seven centralized energy-recovery ventilators (ERV), each of which is followed by a heat-exchanger coil (HEC) through which a water-glycol solution circulates that is heated in winter and cooled in summer by ground-source heat pumps. The ground-source heat pumps exchange heat with the ground through 20 100-m deep vertical wells located in the inner courtyard. The system is designed to meet a significant proportion of the heating load in winter, the balance of which is met by electric resistance baseboard heaters in the apartments that are controlled by residents. The make-up air only undergoes a moderate level of cooling and dehumidification through the HEC in summer [4].

As shown in Figure 1, the north-western edge of the courtyard is delimited by three buildings owned and operated by the Un toit pour tous non-profit organization, containing 60 social housing units. These buildings were designed and constructed by the same team at the same time as the Coteau vert building. Un toit pour tous and Le Coteau vert share the use and operating expenses of the ground-source wells and pumps, whose main mechanical elements are housed in the basement of the one-story community building situated in the central courtyard [4].

METHODOLOGY

The goal of this study was to evaluate the energy performance of the building at Coteau vert and the quality of the indoor environment, as measured objectively and as experienced by the occupants, and to pass on lessons learned to building designers, developers and operators. To achieve this, quantitative and qualitative data were collected for a full year from February, 2014 to March, 2015 using diagnostic instrumentation, utility bills, surveys, and interviews with occupants. 26 households participated in various components of the study [5].

One eight-apartment block, referred to hereafter as the reference block, was monitored more closely and continuously over the full year to obtain a detailed portrait of the energy performance of the mechanical systems, energy usage patterns of occupants, and the measured and perceived IEQ levels. All eight apartments in the reference block have two bedrooms and identical layout and orientation. Indoor conditions in six other apartments of various sizes and orientations distributed throughout the complex were also monitored and surveyed for two to three weeks each season to verify that the results obtained in the reference block where representative of overall conditions.

Fig. 2 : Street (left) and courtyard (right) facades of Coteau vert. (Credit : L'ŒUF)

2.1 Energy assessment of the heating and cooling system

The contribution of the different mechanical elements to meeting heating and cooling loads was assessed by monitoring the increase (or decrease) in temperature undergone by fresh air drawn from outside as it passes first through the energy-recovery ventilator (ERV) and then through the heat-exchanger coil (HEC) supplied with the water-glycol solution. A temperature sensor connected to the building automation system (BAS) was installed directly downstream from the ERV and a second one was installed downstream from the HEC to measure the temperature differentials across each element and hence its respective contribution to heating or cooling. The fresh air temperature entering the ERV was approximated from the temperature measured by a sensor in the courtyard, which was validated with meteorological data from Environment Canada.

Temperatures measured by the sensors were recorded by the BAS every fifteen minutes. For each of the eight apartments of the reference block, total household electricity use and electricity used specifically by the baseboard heaters was monitored and logged every 5 minutes using current transformers, WattNode Pulse transducers and SmartReader data loggers installed on the apartment's electrical panel. The electricity consumed by the various central mechanical systems was estimated from bi-monthly utility bills.

2.2 Measured and perceived indoor environmental quality and comfort

The research team invested substantial effort into collecting both quantitative and qualitative data about the experience of occupants living in Coteau vert, to determine whether high energy performance was achieved while also providing a high quality indoor environment for the occupants. Information about IEQ, occupant satisfaction and comfort was collected using a combination of environmental sensors, written questionnaires and in-person interviews.

At the beginning of the study, a six-page building evaluation questionnaire was completed by residents from 26 households who had lived for one to three years in the cooperative [6]. The questionnaire surveyed residents' assessment of the level of sustainability of various elements of the building, site and management strategies. It also inquired into global and specific aspects of comfort and quality of environment in the apartments, such as temperature, day-lighting and sound quality, and adaptive strategies used by occupants to improve their comfort [5].

IEQ was evaluated quantitatively in occupied apartments throughout the year by measuring and recording ambient air temperature, black bulb temperature, relative humidity and CO_2 using portable CAN2GO data loggers. Monitoring was conducted continuously over the full year in four apartments of the reference block, and for two- to three-week periods during each season in six other apartments of different sizes distributed throughout the cooperative. During this period, residents in each of the monitored units were asked to fill out a short comfort survey twice a day, every day, during the same weeks where IEQ quantitative data was recorded in their home. Survey respondents rated their current level of comfort in terms of temperature, perceived air 'freshness', air flow, and their current level of activity and of clothing. At the end of each day, they were asked to record whether or not they had made use of adaptive strategies to increase their comfort.

To gain greater understanding of the factors affecting comfort and satisfaction in the buildings, semi-directed face-to-face interviews were conducted with three residents who had reported high levels of comfort and three who had reported the lowest levels of comfort in the building assessment questionnaire. During the 1 to 1.5 hour interviews, these residents were asked to describe the significance of residing in a cooperative for them and to elaborate on sources of comfort/discomfort or satisfaction/dissatisfaction in the cooperative [6].

RESULTS AND DISCUSSION

Given the large volume of rich data collected over the course of the monitoring project, only a sample of results can be presented here. Further details are provided in the final project report [5]. First, the performance of the ERV/HEC system in winter is discussed to provide insight into its behaviour in heating mode. The energy use intensity is estimated from the ERV/HEC thermal data combined with electricity monitoring data and utility bills. A sample of IEQ results follows, concluding with common themes that emerged from the interviews.

3.1 Energy performance of the building

After the full year of data collection was completed in March 2015, one week was selected for energy and IEQ analysis for each of the four seasons. The weeks were selected based on meteorological and on-site temperature data so as to capture typical conditions for spring and fall, and peak-demand conditions for summer and winter. For each analysed week during which heating occurs (winter, spring and fall), the amount of thermal energy supplied to the make-up air by the ERV/HEC unit system was calculated hourly from the temperature differential measured across the ERV and HEC and the total airflow specified for the unit. For the summer season, the amount of energy withdrawn from the air through cooling was assessed in the same manner. On average, the HEC provides roughly 60% of the energy to the air and the ERV provides 40% during heating months, with a greater contribution from the HEC during colder periods.

Figure 2 shows the airflow temperature measured at different locations in the ERV/HEC unit during the week of January 18 to 24, 2015. The graph provides an example of more typical behaviour as well as some operational problems that tend to develop when outside temperatures fall below -15 °C for several hours. The blue curve in the graph (T_ext) shows the outside air temperature entering the ERV, while the grey and red curves show the temperature of the air after it has passed through first the ERV (T_ERV) and then the HEC (T_HEC), respectively.

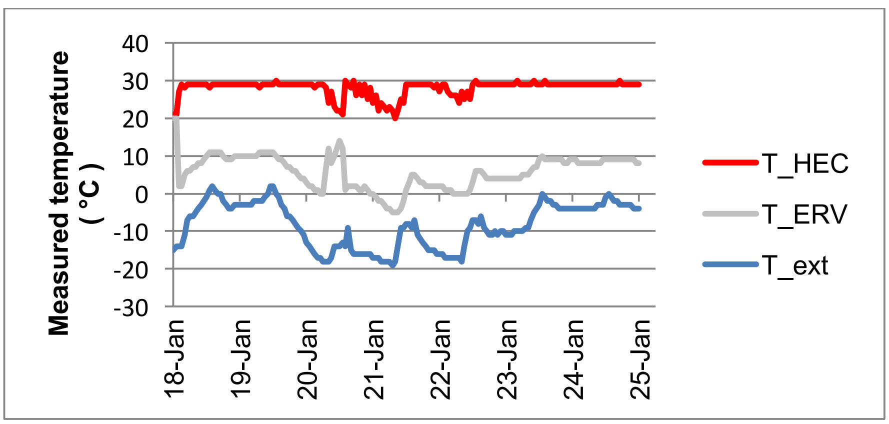

Fig. 2 : Temperature data downstream from the ERV and HEC for January 18 to 24, 2015.

During periods of moderate cold, the ERV produces a 10 to 15 °C increase in temperature to the fresh air, while the HEC supplies the rest of the energy needed to reach the set point of 29 °C for the make-up air that is then supplied to the apartments (red curve). During periods of more intense cold (January 20-22 on the graph), frost accumulation on the heat-exchanger core of the ERV significantly reduces its effectiveness, and the HEC does not have the capacity to compensate, resulting in a drop in the air temperature T_HEC supplied to the apartments. This problem has since been largely resolved by rewiring the controls for the defrost system on the ERV.

The energy use intensity of the building associated with heating, cooling and plug loads is estimated for each season from the sum of the average daily electricity consumption measured in the monitored apartments (which includes plug loads and electric baseboard heaters), the thermal energy supplied (or withdrawn) by the ERV and HEC, and the electricity used to operate the fans, circulating pumps and the heat pumps, excluding the energy from gas used to heat the domestic hot water. The EUI values calculated for the sample week of each season are given in Table 1.

Table 1: Estimated energy use intensity (EUI) by season

Season	EUI (kWh/m^2)
Spring	22
Summer	15
Fall	18
Winter	34

During heating seasons, electric consumption for electric baseboard heating is up to four times greater on the lower floors of the reference block than on the top floors, resulting in a higher EUI for these floors. This would appear to confirm reports by ground floor residents in the building assessment questionnaire that they must make greater use of their baseboard heaters (as manifested by higher household electricity bills) than upper-floor apartments to achieve equivalent comfort levels. Ground floor units also house a greater proportion of families with young children, which may influence this assessment. However it is also likely that greater heating loads on ground floors are caused by the stack effect and heat losses to the ground, through the foundation walls and between apartments. Make-up air entering the apartments on the ground floor was found to be 1 to 1.5 °C cooler than the air entering the top two floors during the coldest part of the winter, which may also contribute.

3.2 IEQ and indoor comfort

Quantitative IEQ measurements recorded in the apartments were statistically analysed to evaluate what proportion of the readings correspond to comfortable temperature, relative humidity and CO_2 levels, as defined by ASHRAE's season-specific comfort standards [7]. The result of this analysis is compared to the proportion of responses or 'votes' in the daily comfort surveys that qualify conditions as 'comfortable'. Figure 3 shows the results for thermal comfort, with the measured, ASHRAE-categorized, results on the left and the distribution of occupants' survey responses on the right. The figure suggests a good correlation between measured and reported comfort levels, with what appears to be a slightly wider range of conditions deemed comfortable by occupants than what is predicted by ASHRAE. The majority of the recorded CO_2 levels fall below 700 ppm, significantly below the maximum recommended value of 1000 ppm above outside air levels.

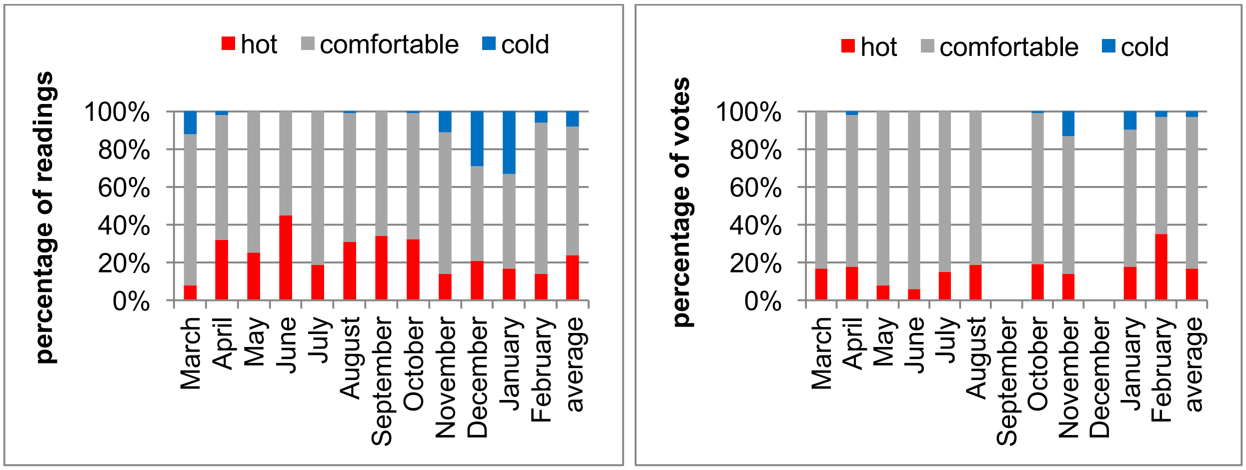

Fig. 3: Thermal comfort as measured (left) and as reported by occupants (right) in daily surveys.

Residents generally reported a high level of comfort. Reported levels of discomfort in summer due to overheating were significantly higher in the retrospective questionnaire completed by residents at the beginning of the study than in the daily surveys completed during the monitoring period. This is likely due in part to the cooler summer that occurred during the year where monitoring took place: 2014 had 23% fewer cooling degree days than the first 2 summers (2011 and 2012) of occupation in the coop [8]. 2014 was also the first year where the ground-source heat pumps provided cooling over the full summer, following three summers of operational problems. In winter, overheating was reported in certain upper floor apartments while some ground floor residents reported cold temperatures. Other commonly cited sources of discomfort include the propagation of smells (especially tobacco) between units, and vibration and mechanical noise heard by residents living directly below certain ERV and HEC units.

Common themes evoked in the interviews include the importance of the social and support networks that the cooperative structure allows residents to develop and strengthen, including opportunities to voice their concerns and have input into decisions that affect their quality of life in the building complex. The inner courtyard is widely cited as a positive element, despite occasional irritation for some linked to higher levels of noise and reduced privacy that result from the intensive use children and youth make of this central space. Most of the residents interviewed also mentioned that living in the cooperative gives them a greater sense of security and control over their lives, due to the fact that they co-own the building as members. Easy access to public transit and services are cited by all respondents as a major contributor to their quality of life and all study participants expressed a desire to continue residing at the cooperative for many years [6].

CONCLUSION

Results from data collected at Coteau vert housing cooperative over the course of a full year reveal that high levels of performance are achieved, including high occupant comfort on average during the monitoring period, and an estimated average energy use intensity that is substantially below the Canadian average.

Lessons learned from Coteau vert have informed design decisions for the 166-unit Bois Ellen Cooperative, another multi-residential social housing building currently nearing completion in Laval, near Montreal. Compared to Coteau vert, the designers prioritized investments in a higher-performance envelope at Bois Ellen (up to 50% more air-tight), with reduced thermal bridging to further reduce heating loads and increase comfort. Heating and cooling are provided by simpler, more decentralized mechanical systems to reduce the logistical burden of optimizing and maintaining these systems for building owners. The decentralized systems should also allow greater individual control over indoor temperature and energy use by occupants [1,4]. In accordance with the concept of 'future-proofing' applied at Coteau vert, key infrastructure has been incorporated into the building as an investment to render future installation of additional environmental elements easier and less costly once funds and evolving technology make them accessible. Sensors for detailed performance monitoring have also been installed.

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