Air Temperature and CO_2 Variations in a Naturally Ventilated Classroom under a Nordic Climate

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ABSTRACT: The aim of this study is to assess the effectiveness of window operation in controlling a classroom thermal environment and indoor air quality. Field measurements and questionnaires were collected in the fall of 2008 in a naturally ventilated single sided classroom of a primary school located in Ste-Marie-de-Beauce, Québec, Canada. Data presented and analysed are part of an ongoing pre-refurbishment evaluation of passive cooling and natural ventilation feasibility study through the use of personal operable windows in a Nordic climate. Feasibility is evaluated in a multi-scale approach: (1) the surrounding school microclimate qualities (2) the envelope performance and (3) the thermal environment and indoor air quality according to window operation by the occupants. A systemic approach integrating acoustic, thermal, visual and olfactory ambiences is proposed.
Keywords: thermal comfort, indoor air quality, passive cooling, natural ventilation, operable windows, personal control

INTRODUCTION

Naturally conditioned spaces are conventionally defined as those spaces where the thermal conditions of the space are regulated primarily by the occupant through opening and closing of windows [1]. When occupants open or close a window, they modify the indoor air movement producing a variation on the thermal and olfactory (air quality) environments. Access to windows can potentially improve the thermal and psychological comfort of the occupants and the air quality [2,3]. However, the design of a naturally conditioned space requires an integrated approach in which the operable window scheme is a fundamental component of the whole passive cooling system. Figure 1 summarizes the five fundamental elements of a passive cooling strategy: 1) cooling of the immediate outdoor environment of the building; 2) protection against solar heat gains; 3) protection against conductive heat gains; 4) reduction of internal heat; and (5) dissipation of heat gains by convective forces [4]. In figure 1the outdoor environment affects the air properties (temperature, humidity and pollutants) that go into the building. The shading device protects the indoor environment from external heat gains. The internal heat gains (e.g. electrical lighting) are reduced and stored into the building's thermal mass. Finally, the heat excess is evacuated through the window to the surrounding environment which acts as a heat and pollutant sink and fresh air source. In naturally ventilated buildings with operable windows, occupants' behaviour is also an important variable of the passive cooling system performance.

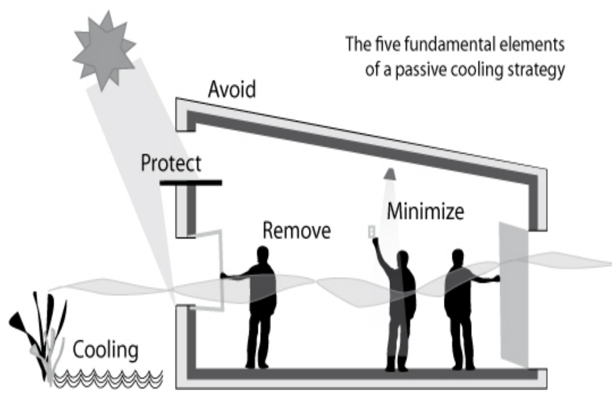


Figure 1: Main elements of a naturally conditioned space.

This paper presents preliminary results of the first stage of an ongoing passive cooling pre-design evaluation for the Feuiltault Primary School refurbishment project. The design team inherited a 1950's building without any sort of mechanical systems apart from the central hot-water heating system. The narrow floor plate, high ceilings and the high inertia of the concrete slab structure were all part of a responsible passive cooling strategy. However, the blocking of the upper wall operable windows and 1990's envelope alterations contributed to a significant decrease in the original passive cooling and IAQ performances.

Therefore, the common objective of the owner and design team consists of using mechanical systems (HVCA and electric lighting) only at the final stage of fine-tuning the environmental capability of the proposed natural control strategies by architectural variables. Recent surveys also reveal the positive influence of natural learning environments on children's health and school performance [5,6]. Such learning environments can also play an educational role by teaching students the interdependence between the individuals, the community and nature [7]. Passive control systems and active occupants can also potentially reduce operational energy consumption and the related greenhouse gases emission [8].

The viability of passive cooling and natural ventilation was evaluated answering the following three questions:

1) Are the surrounding outside conditions favourable to passive cooling and natural ventilation?

2) Is the building envelope optimized to minimize solar gain into the space?

3) How do the thermal environment and the indoor air quality respond to occupant's windows use?

THE FEUILTAULT PRIMARY SCHOOL

The Feuiltault Primary School is located in Sainte-Marie de-Beauce, Québec, Canada at 46,3°NLat. Figure 2 shows the urban context of the school at the crossing of two main city roads. The school is orientated 45° along the north-south axis and perpendicular to prevailing SW winds. The SW façade has no shading mask, even under low winter sun exposure.

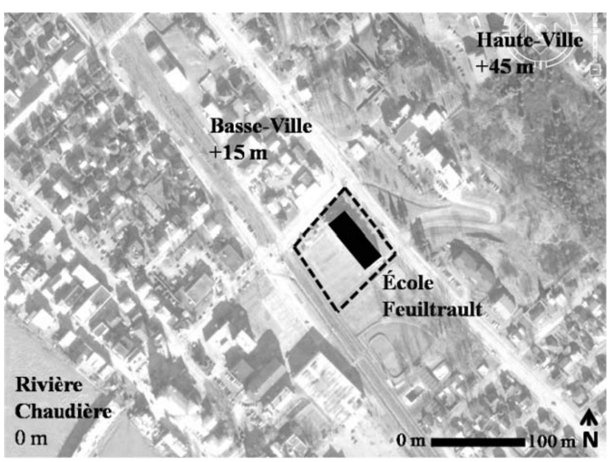


Figure 2: Feuiltault primary school location.

Figure 3 shows the classroom's environmental control systems. Classrooms are oriented SW or NE along a double-sided circulation corridor. On average, classrooms are occupied on a daily basis by 24 pupils and one teacher. Occupants can adjust the thermal environment by manipulating seven operable windows, blinds, and two ceiling-fans. The front door and its top operable window favour cross ventilation. The exterior building skin does not have any external shading devices and was even renovated using dark brown clay bricks. Fluorescent tubes provide electrical lighting when daylight is not sufficient. Occupants do not have control on the central heating system. The concrete mass of the floor and ceiling are non-exposed.

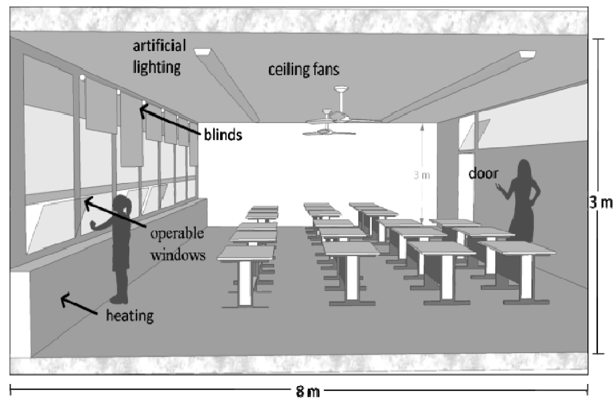


Figure 3: Classroom environmental control systems.

The climate of the region is of the "wet continental type": hot summers, cold winters and plentiful precipitation. The maximum (30°C) and minimum (-27°C) temperatures appears in July and January respectively. According to Boivin [9], 24 % of Quebec's weather conditions are favourable for natural ventilation and buildings must be heated 71 % of typical occupancy hours. Figure 4 presents the natural ventilation applicability according to dry-bulb temperature and humidity ratios. Overheated periods tend to appear during the July-August period where classrooms are vacated for summer holiday.

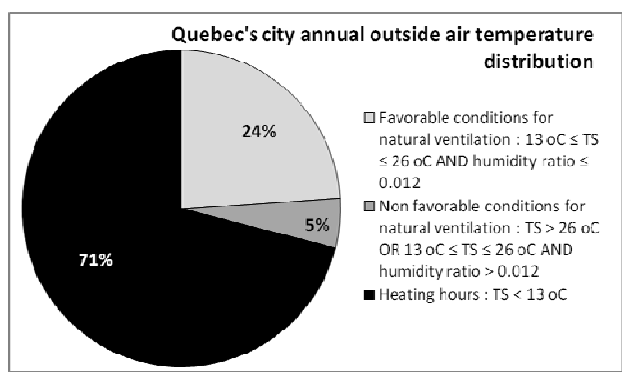


Figure 4: Natural ventilation applicability in Québec.

METHODOLOGY

Two survey methods were used during the 7 days in situ survey: quantitative physical data collection (fixed workstation, hand-held sensors and infrared thermograph) and qualitative questionnaires.

The RNCan fixed workstation is designed in compliance with ASHRAE standard 113-2005 [10] to collect continuous measurements of thermal environment and indoor air quality. The air temperature, air velocity and CO_2 concentrations were measured at specific heights (0.1m, 0.6m, 1.1m and 1.7m), under Fall conditions, in a SW orientated classroom. An infrared thermograph camera (FLIR systems) surveyed the surface temperatures of the SW glazed wall. Figure 5 shows the location of the measuring devices in the classroom.

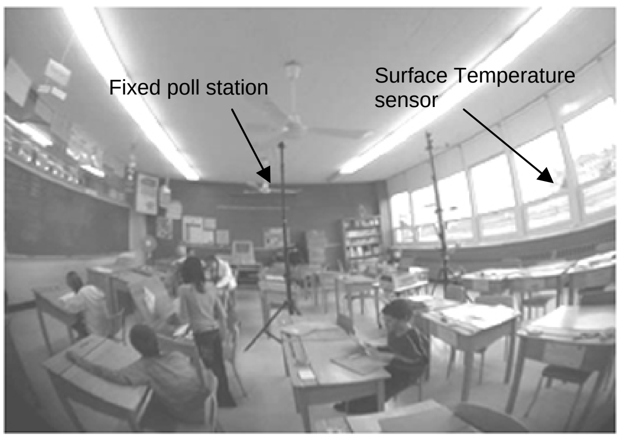


Figure 5: Classroom with measurement equipment.

In the questionnaire, the teacher was asked to indicate the times when she interacted with the windows and blinds and to specify if the manipulation was intended to improve thermal, acoustical, visual or olfactory comfort. These data were gathered for 7 days from September 26th to October 2nd, 2008.

WINDOW OPERATION, INDOOR AIR QUALITY AND THERMAL ENVIRONMENT

Figure 6 presents the overall thermal behavior of the classroom for the entire survey. The survey comprised three clear and three overcast days. The sixth day went missing in mid-morning when a pupil accidentally unplugged the acquisition logger. Air temperature never exceeded 24°C but surface temperature of the SW windows systematically reached 32°C on the three clear sky days suggesting a major impact on occupants' perception of comfort and operative temperature. Figure 7 presents the justifications for window operation by the teacher. The main reason for using the window was to improve thermal comfort (81 %) and indoor air quality (19 %). Outdoor acoustic environment seems not to be a problem in this classroom facing the playground. Surprisingly, blinds were essentially used to avoid glare and improve visual comfort (67 %).

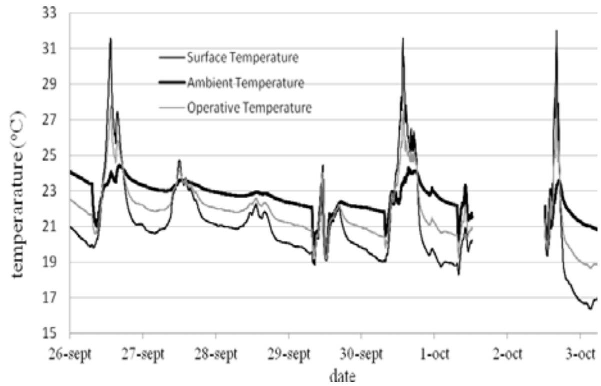


Figure 6: Evolution of Air, Radiative and Operative Temperatures from 26 September to 3 October 2008.

The aim of the survey was to discover how the classroom's thermal environment and indoor air quality perform according to window operation. Figures 8 and 9 respectively show the air temperature and carbon dioxide concentrations measured on a typical overcast school day (29 September) whereas figures 10 and 11 show these two parameters on a typical clear sky day (30 September). Grey bars represent the percentage of open windows from 0 to 100%. The classroom was fully occupied by 24 pupils and their teacher between 8h00 and 15h30. These two comparative days clearly illustrate the incidence of external heat loads by direct solar radiation and the impact of different window adjustment over the day on the indoor temperature and CO_2 concentration in the classroom. Outdoor average temperature was 13°C on both days.

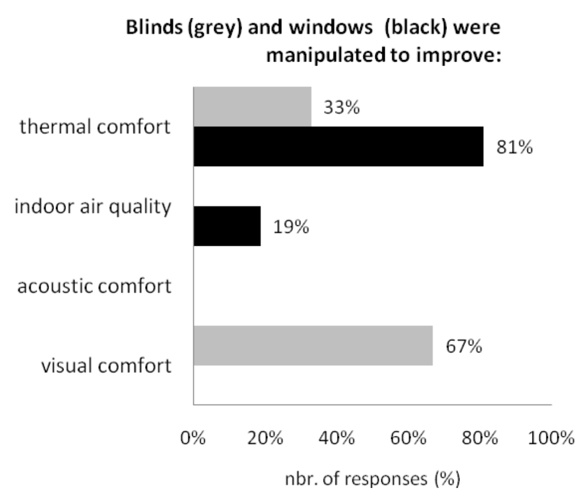


Figure 7: Justification for windows (black) and blinds (gray) manipulations.

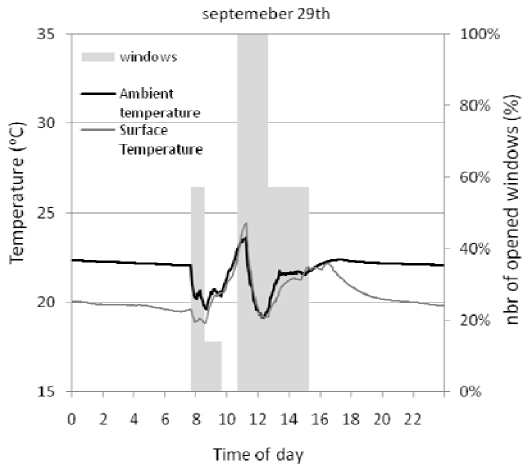


Figure 8: Temperatures and percentage of open windows.

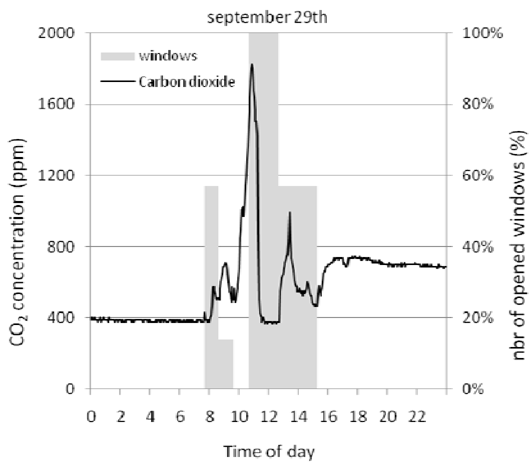


Figure 9: CO_2 and percentage of open windows.

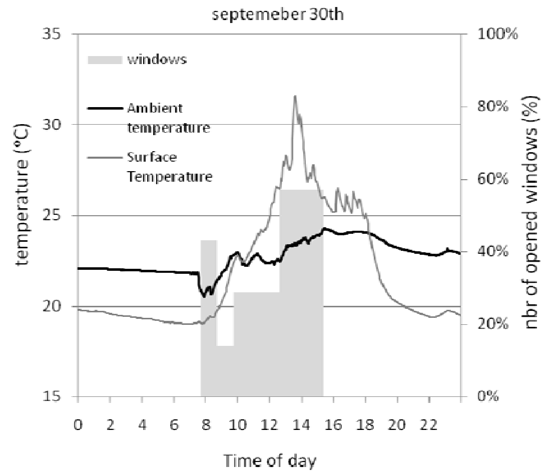


Figure 10: Temperatures and percentage of open windows.

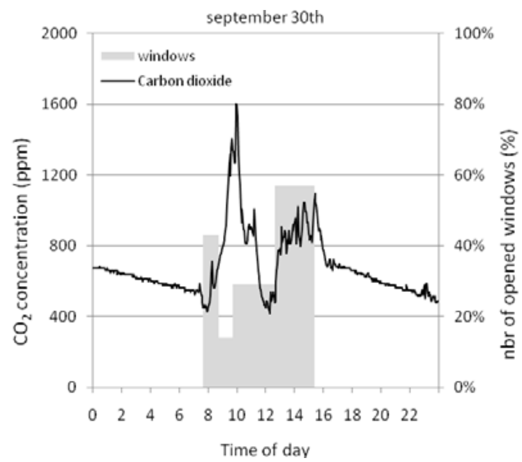
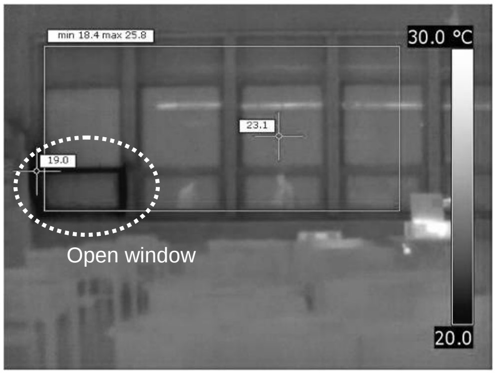


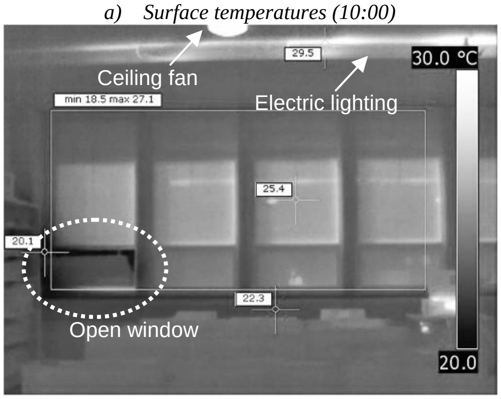
Figure 11: CO_2 and percentage of open windows.

The teacher commented that she usually opens some windows on her arrival (7h30) in order to purge the nighttime stagnant air whatever the season. This behavior is clearly illustrated in figures 8 and 10 where the air temperature quickly dropped from 22°C to 20°C. On the overcast day, figures 8 and 9 also show that from 9h30 to lunch time (11h30) all windows were closed, increasing air temperature to 24°C and carbon dioxide concentration to 1800ppm which exceeds the 1000ppm ASHRAE [11] and 1500ppm CIBSE [12] threshold daily recommendations. At lunch time (11h30 - 12h30), the temperature and CO_2 concentration quickly decreased due to a drastic 100% window opening during the absence of occupants dropping air temperature to 19°C. Upon the pupils return, the teacher maintains 56 % of the windows open leading to a steep then gradual temperature increase until the end of the afternoon. The CO_2 concentration also intensifies quickly during the first hour and drops afterwards. This day is marked by very important variation in the percentage of window openings.

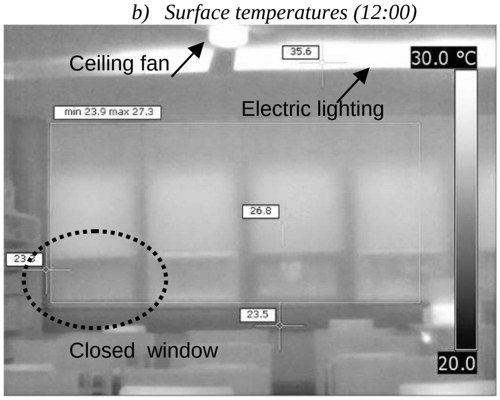
On the clear sky day, window manipulations were less drastic. Probably due to the fact that wind speed, air temperature and CO_2 differentials were accordingly more closely controlled. Figure 10 suggests that increasing window opening from 30% to 56% was just enough to offset this radiative heat gain even if air temperature kept rising until the end of the afternoon but remained under 24°C. A window opening of 56% also kept CO_2 concentration below 1000ppm. However, the surface temperature of the SW windows reached a 32°C peak at 13:30 due to direct solar gain and poor window shading coefficient creating a 9°C temperature differential between air temperature and surface temperature. Figure 12 shows the indoor SW façade surface temperature variability during a typical clear day. Infrared thermograph images were taken at (a) morning break (10:00), (b) lunch time (12:00), and (c) right after pupils left the classroom (15:45). In image (a), blinds are fully retracted and only one window was open; in image (b) electrical lighting is switched on and the teacher has activated the ceiling fan in order to improve thermal comfort; and in image (c) left window has been shut, blinds are fully drawn and artificial light and fans are switched on. From image (a) to image (c), the average surface temperature (glass and blinds) increased from 23 °C to 26.8°C.



a) Surface temperatures (10:00)



b) Surface temperatures (12:00)



c) Surface temperatures (15:45)

Figure 12: Evolution of SW façade surface temperatures.

During the day, the left window was maintained open and the adjacent surface temperature clearly shows the cooling effect of air passing throught the window. When the window is open (images a, b) the adjacent surface temperature is 3^{o}C lower than average surface temperature. In the afternoon (image c), the teacher closed the blinds in order to reduce the overheating caused by solar radiation and to control glare from windows. To compensate for the lack of light, the artificial lighting was maintained on. When pupils left the classroom, the lighting fixture and the ceiling fan surface temperatures had reached 35.6^{o}C and the blinds surface temperature reached 26.8^{o}C, clearly increasing internal heat loads and perceived temperature. This rapid evolution of radiative heat gain from the SW façade demonstrated by infrared images remains a major parameter that should be taken into account in the future development of the project.

The last figures show that classrooms' indoor air quality and air temperature are very sensitive to window operation. They demonstrate that on these specific days, maximum air temperature and CO_2 concentration could be controlled within accepted standards for naturally ventilated buildings. Nevertheless, for a better performance, building users should be informed of the impact of their behavior (window status) on environmental variations to avoid important temperature and/or CO_2 concentration differentials. For example, if the percentage of opening had remained low but constant along the overcast day, the reached level of CO_2 prior to the lunch time would probably have not be so high as gathered in the clear day survey. This behavior supports Cole & al. [8] assertion that passive building environmental performance is highly dependent on the responsible behavior of informed inhabitants.

FUTURE DESIGN CONSIDERATIONS

These surveys took place under perfect ambient conditions for natural ventilation where average daily temperature was 14^{o}C and relative humidity was under 80%. Further surveys under late Spring and Summer conditions would validate the efficiency of this naturally ventilated building to control indoor temperature and air quality. From the results presented in this paper and past complaints from the users, it is reasonable to suggest that under hot and humid conditions, the building's current configuration would need major improvement to keep temperature and air quality within accepted standards.

Therefore, future developments of the project will seek to optimize the protection against solar and conductive heat gains by the requalification of the SW façade and the dissipation of excessive heat gains by convective forces. The façade renovation can be relatively straight forward by the correct specification of materials physical properties (high reflectance and thermal resistance) and combined sun shading/light shelves devices in order to control solar heat gains and glare. Such passive robust strategy has been successfully used in Québec's cold climate [13]. However, the dissipation of excessive heat gains by natural ventilation depends on much more challenging thermodynamic exchanges between the building's own thermal inertia differentials and between the building and its surrounding environmental sink. Pilot surveys were therefore conducted within the building and its surroundings to assess the potential of such thermodynamic exchanges.

The infrared thermograph camera was again used to assess the surface temperatures of the school's surroundings. Measured temperatures were plotted over a satellite image (Google Earth) using ADOBE Photoshop software. This simplified method allows to evaluate heat/freshness islands around the school based on Hartz & al. proposed methodology for urban climatic studies [14]. Figure 13 shows the extrapolated microclimates around the school. The color-scale indicates the surface temperature of different urban surfaces. White-yellow patterns represent heat islands and purple pattern represents freshness islands. Linking surface temperatures to actual ambient temperatures remains a research challenge [14]. This figure nevertheless suggests an important asymmetry of surface temperatures between the playground on the SW side of the school (30^{o}C) and the front yard on its NE side (19^{o}C). Studies show that heat islands reduce the potential of pre-cooling by natural night ventilation [15]. The actual playground heat island clearly reduces the potential for diurnal ventilation because the asphalt surface combined with the highly absorbent dark brick façade warms air by convection and irradiates heat into the building, particularly on sunny warm days. On the other hand, teachers in NE classrooms commented that they refrain from open the windows even if the thermal environment was uncomfortable in order to mitigate the traffic noise.

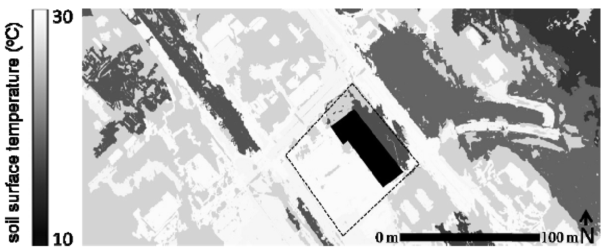


Figure 13: Surface temperatures around the school.

Both surrounding surface temperatures (microclimate) and acoustical conditions deter the applicability of cross ventilation in this building; the SW dominant wind blowing over an overheated surface before entering the building and the NE openings being kept shut for acoustical reasons albeit the presence of a cool microclimate. Future strategies should look at means of improving the cooling potential of the SW playground by the integration of high reflectance porous surfaces and plants. On the NE façade, ongoing design research is including “noise-free natural ventilation strategies” as proposed by [16] and [17] for urban school building design solutions. These strategies include absorption material on intake cavities and the optimisation of opening dimensions in order to maintain an acceptable window sound insulation. Simulations using CFD modelling should validate the applicability of outside-in ventilation strategies such as: 1) simple single sided natural ventilation (top-bottom openings), 2) cross ventilation, and 3) chimney effect ventilation through the existing staircases. Inside-out ventilation drawing fresh air from the central corridor to double-façades on both sides of the building will also be validated. A double-façade system would have the triple advantage of acoustic, thermal and visual control. On the NE façade, such a system could help mitigate the urban sound transmission whereas on the SW façade, it would optimize winter passive solar gains and minimize summer solar gains and glare by adjustable sun shading devices.

ACKNOWLEDGMENTS. The authors would like to thank Mr Michel Tardif from Natural Ressources Canada (NRCan) for this research grant the teachers and pupils of École Feuiltault for their invaluable help and participation in the survey.

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