Sensitive Homes: Remote Sensing and Monitoring Integral to Homes

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ABSTRACT

Aboriginal families are significantly more likely to live in poor housing conditions than the general population. Furthermore, in Canada, most of these houses are often located in colder regions, which challenge the construction, the indoor air, and the energy consumption. Poor housing is also related to poor child health outcomes. The overarching goal of this research is to develop a health monitoring system integral to homes that acts as preventive early warning system before problems become serious and sometimes irreversible. The underlying premise is that higher value can be gained from a system that combines different types of monitored data, such as indoor, construction, and energy, in building awareness and enabling better informed decision-making by homeowners. This paper presents the results from a pilot study to generate preliminary knowledge on the key challenges faced in attempting to develop and deploy such a system in remote regions. In the study, the indoor environment and the construction moisture of three new homes from the urban Squamish First Nations reserve in Vancouver are being monitored. The construction is typical of local urban reserve homes. The indoor parameters monitored are relative humidity, temperature, and carbon dioxide. The construction parameters monitored are the envelope moisture content and temperature. Expectedly, preliminary indoor environmental data indicate the houses are performing well. However, warning signals from the construction need close attention. Furthermore, occupants, unaware of the energy penalties, seem to be driving higher ventilation rates. Consequently, validated energy simulation models were used to inform occupants on the price of excessive ventilation habits. Squamish home builders were given a performance report, with alternatives to address current issues and improve performance in future houses. The results from the pilot study demonstrate the value of a holistic monitoring system integral to homes. Further work is required to address the practical aspects of the technologies involved and to elaborate on the knowledge to implement a monitoring platform to make the systems operational on a wider scale.

INTRODUCTION

Aboriginal families are significantly more likely to live in poor housing conditions than the general population, owing to usually lower construction quality, a lack of maintenance, and overcrowded living conditions (National Council on Welfare, 2007). Furthermore, in Canada, most of these houses are often located in colder remote regions. Shortage of skilled workers, unavailability of local building materials and dependence on fossil fuels for heating and electricity in the remote regions, coupled with rising population and shorter building season, challenges the construction, the indoor air quality and the energy consumption. Poor housing is also related to poor child health

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outcomes including higher infant mortality rates, Sudden Infant Death Syndrome, respiratory deceases (UNICEF 2009), and increase in life threatening infections, injuries, mental illness and chronic illness (National Collaborating Centre for Aboriginal Health, 2010).

This research follows a holistic approach for house health monitoring that attempts to characterize a healthy house from indoor air quality and envelope moisture data, and couple these with house energy consumption data. The overarching goal of this research is to develop a health monitoring system integral to homes. Such a system, as opposed to an ad-hoc temporary one, would be designed, planned, and fine-tuned for the house, just like the electrical system, to keep track of the quality of the house over time. A key part of such a system is the strategic placement of moisture content sensors in the walls to monitor envelope moisture as a function of the dynamically changing indoor and outdoor conditions. Such an integral home monitoring can act as preventive early warning system before problems become serious and sometimes irreversible. The underlying premise in this research is that higher value can be gained from a system that combines different types of monitored data, such as indoor, construction, and energy, in building awareness and enabling better informed decision-making by homeowners and builders. For example, moisture dependent microbiological contamination, in particular, and its health impacts are prevalent in Canadian homes (Lawton et al. 1998); monitored high CO2 levels signaling inadequate ventilation (dilution) cannot detect air borne microbial contaminants from construction moisture (source). Thus, the source of the air quality problem may remain undetected for a long time, and worsen, with serious consequences to the construction and the occupants.

The objective of the paper is to use a pilot study to generate preliminary knowledge on the key challenges faced in attempting to develop and implement such a system. In the study, the indoor environment and the construction moisture of three new homes from the urban Squamish reserve in Vancouver are being monitored. The construction is typical of local urban reserve homes, which do not require stringent home inspections by city officials. The building codes and best practice guidelines (HPO 2011) for coastal climate of British Columbia are not followed strictly; therefore, they are believed to be more vulnerable to durability issues than a conventional home. For example, some use of face-sealed wall assemblies along with the lack of emphasis on interface details e.g. window to wall interface, wall penetrations and balcony-wall interface make these homes vulnerable to water ingress due to wind-driven rain.

In this study, the indoor parameters relative humidity, temperature, and carbon dioxide; and the construction parameters moisture content in walls, attics and crawlspaces are monitored. Note that the paper does not attempt to demonstrate that such a small sample of houses is representative of all Canadian or First Nations' homes, or of homes in remote regions. Instead, it attempts to use a sample of typical new first Nation's homes to test the hypothesis on the need and value, particularly in remote regions, of having a holistic health monitoring system integral to homes.

PREVIOUS WORK

Many of the factors affecting house health performance are interrelated and vary with time. On one hand, various researchers have studied the trade-offs between ventilation and energy performance (Walker and Sherman 2008; Laverge et al. 2011). On the other hand, with regards to the relation between ventilation and the presence of microbiological contaminants, the results are conflicting. While controlled ventilation helps control indoor humidity levels and dilute these contaminants, uncontrolled air leakage, possibly driven by exhaust ventilation, can potentially bring moisture laden contaminants from damp envelope locations, and from out-of-the-envelope crawl spaces and attics. Lawton et al. (1998) monitored a group of houses in southern Ontario, and found that houses with higher levels of microbiological indoor contaminants had, on average, higher leakage-based air change rates. This demonstrates that, occupancy-related, CO2 is not a good surrogate for construction-related microbial indoor air quality. This paper proposes combining CO2 data with materials moisture contents and temperature (MC/T) data to produce a more complete assessment of the cleanness of the indoor air and the likelihood of microbial sources.

Associations between persistent dampness and adverse health effects have been acknowledged. However, relationships between persistent dampness, microbial exposure, and health effects cannot be quantified precisely at the moment (WHO 2009). As a consequence, no quantitative health-based exposure guideline or thresholds are recommended for acceptable levels of microbial contamination (IOM 2004). In light of this, ASHRAE (2012) and AIHA (2013) recommend keeping buildings and their systems as dry as possible, given their normal functions, to limit the potential for microbial growth and reduce dampness-related health risks. The moisture content (MC) of materials is the key parameter for assessing the risk of microbial growth on their surfaces; however, its extreme spatial variation over short distances (a few centimeters), and its dependence on the materials and the quality of the construction, limit its applicability as a universal indicator of dampness risk (ASHRAE 2012). Nevertheless, a premise of this project is that from the type of construction and building location, experts can identify the hidden envelope areas, surfaces, and materials that are more likely exposed and vulnerable to dampness. Such knowledge can then be used to lay out a dampness-warning MC sensor system. Building on this premise, this paper proposes a more holistic assessment of residential performance that combines monitored data from: the indoor environment, the construction, the occupants' behaviors, and the energy system to provide a more informed view of the residential performance for occupants, builders, and possibly to policy makers. To the authors' knowledge no such holistic approach has been proposed in the past.

METHODOLOGY

Three new houses were made available for our pilot study by the Squamish First Nations band in agreement with the homeowners. The houses are typical 2-storey, wood-frame construction single houses identified as house#1 [2,500 ft^2 (232 m^2)], house#2 [2,000 ft^2(186 m^2)], and house#3 [1,800 ft2 (167 m^2)] with ventilated attic, conditioned crawl space and a combined forced air heating/ventilation system with outdoor air intake at the return side. Research methodology includes:

1. Sensing system layout planning and instrumentation – The houses were instrumented with a wireless remote sensing system. A weather station was also placed on the roof of the nearby community center.
2. Testing, measuring, and questionnaires - Air tightness tests were conducted in the houses, as well as air flow measurements at the supply and return grilles of the forced air system. Information on house operation was obtained by an administered occupant-questionnaire and by direct inspection on our regular site visits.
3. Monitoring – The houses will be monitored for one year starting in September of 2012 when occupancy started. So far, nine months of data have been collected (up to May 2013).
4. Energy modeling & Analysis – An energy model was created and fine-tuned with air tightness tests, air flow measurements at the forced air system's supply and return grilles, and questionnaires to occupants. The model was validated by comparing simulated energy use with utility bills data, and using readings on the air handling unit on/off operation. The validated energy model was then used to assess the impact of the occupants'

behaviours on energy performance, and to compare the energy and indoor air quality performance of the current heating/ventilation system with other potentially better systems.

5. Integrated assessment of the results – The value of a health monitoring system was evaluated in terms of its capability to provide data that can be used to assess holistically the health of the house during its service life.

THE MONITORING SYSTEM

A distributed data acquisition system was used with battery-powered data loggers deployed in strategic locations to acquire data from cabled nearby groups of sensors. Sensors were deployed in groups of 8 or less in order to minimize sensor cabling and number of data loggers used (each data logger support 8 channels of either resistance or voltage inputs). The data loggers transmit the data wirelessly to a central gateway computer placed in house#3, which, in turn, uses Internet to transmit data to a central platform combining a repository and analytical tools.

In each home, a relative humidity and temperature (RH/T) sensor was located in the family area, attic and the crawl space. A CO2 sensor was also placed in the family area and master bedroom. Moisture content (MC) sensors were placed in selected areas of the following locations: the underside of the roof sheathing; the walls underneath the windows, particularly close to the corners and the bottom plate; the envelope bathroom walls; and the floor joists at the crawl space. The majority of the MC wall sensors were placed on north facing walls, because these walls have the lowest drying potential. One ON/OFF switch type sensor was placed in the air handling unit in one house.

RESULTS: ANALYSIS AND DISCUSSION

This section presents selected monitoring data from the pilot study. The data has not been statistically processed because it has no statistical meaning given the size of the sample. Furthermore, this study does not claim that these houses are representative of houses in remote cold regions. The premise that these houses have typical problems, given the climate; quality and the type of construction; and that the occupants play a role in exacerbating these and sometimes even causing more problems, these houses provide a good experimental setting for challenging the proposed sensing system, with challenges that can be generalized to houses in remote regions.

Monitoring results

The houses have been monitored for nine months so far, from September of 2012 to May of 2013. However, in order to better appreciate the patterns on the data, this section presents monitoring data from the last five months (January to May, 2013), with emphasis on winter months (Jan-March) which are most critical from indoor air quality, energy, and durability points of view. It should be noted that in house#3 the owner is a heavy smoker that spends most of the time in the house carving wood. Unfortunately, in that house the CO2 sensor went out of calibration. After several unsuccessful attempts to fix the sensor the homeowner got frustrated; this forced us to decommission the sensor.

Figures 1 and 2 present weather station data with typical values for a moderate marine climate; in Figure 1 the relative humidity remains high and tends to follow an inverse relation with the temperature. In Figure 2, the solar radiation is low and the rain is not as intense as expected for this period of the year.

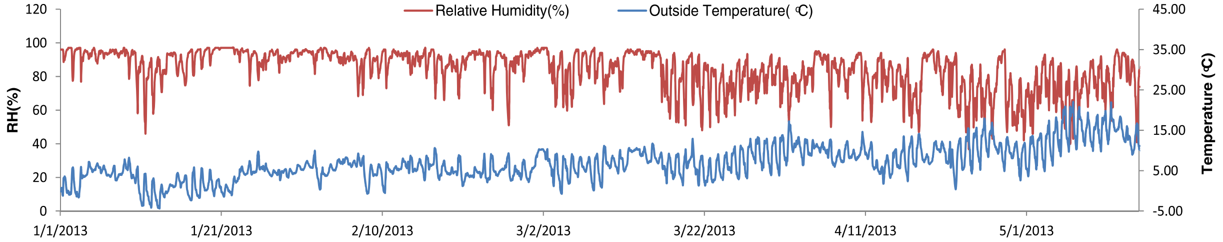

Figure 1 Hourly averaged outdoor temperature and relative humidity.

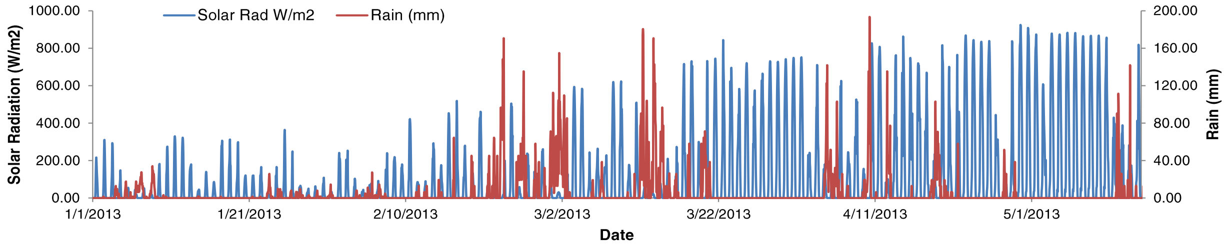

Figure 2 Hourly rainfall and solar radiation.

In general, the houses have good ventilation with uniform CO2 levels (excluding the house with the decommissioned CO2 sensor). Peaks of CO2 between 1400-1800 ppm were observed during night-time in bedrooms and higher occupancy periods in common areas. These high levels of CO2 can cause discomfort (body odor) and impaired performance in occupants (Persily A K 1996). Figure 3 takes a closer look at indoor CO2, temperature and relative humidity (RH) for months of March and April in house#1. In this case, as confirmed with a questionnaire, as the weather got milder, the occupants opened the windows whenever they felt they wanted "fresh air". This is reflected in the low readings, sometimes below 600 ppm. The patterns are similarly observed in the relative humidity and temperature readings.

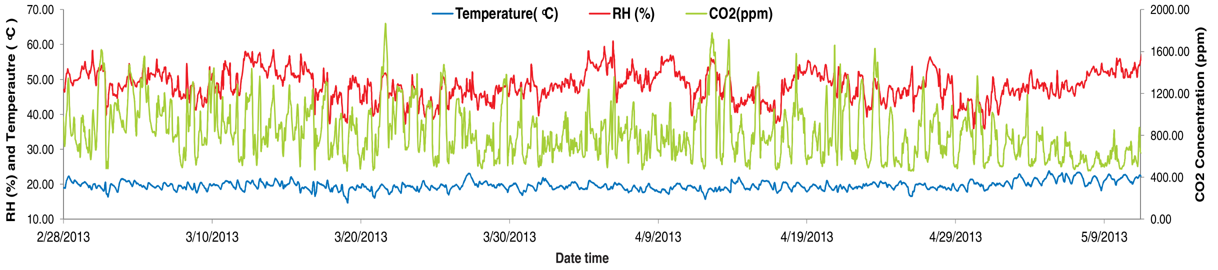

Figure 3 Hourly CO2, temperature and RH in master bedroom of house#1.

Figure 4 shows the temperature and relative humidity in the heated and ventilated crawl space in house #2. In this case a longer period was selected (October/2012 to May/2013) to appreciate the drying out foundation moisture in winter. The temperature fluctuates more in crawlspace than in the rest of the house because it is unoccupied and has no thermostat control. At first sight the crawl space appears to be performing well. Infrared temperature readings at the foundation walls show wall temperatures ranging between 51.8°F (11°C) (close to the corners) and 59°F (15°C), which are close to the dew point of the indoor air. Therefore, potential for moisture condensation in these walls exists.

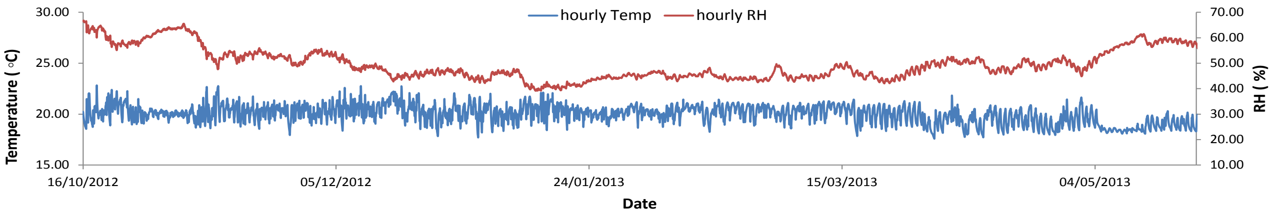

Figure 4 Hourly temperature and relative humidity in crawlspace of house #2.

In Figure 5, the attic air is saturated with moisture during the months of December, January, and February and close to saturation in October, November, and March. This is confirmed with the moisture content (MC) data at the underside of the roof sheathing. Note that the attic is not part of the envelope. However, it is connected unintentionally through cracks, with noticeable air flows during the blower door test. Even though the MC readings show a seasonal wetting and subsequent drying during the warmer seasons, the wetting period is long and maintains MC above acceptable levels between November and March. Comparing Figure 5 with Figures 1 and 2, it can be appreciated that more sun and higher temperatures are driving moisture evaporation from the roof sheathing.

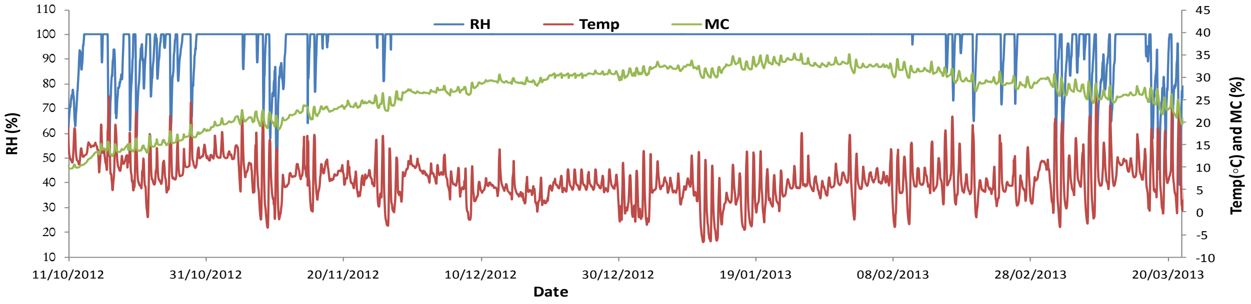

Figure 5 Hourly temperature, RH, and Moisture Content in the Attic of house#1.

Figure 6 shows the MC at selected representative wall locations. The Figure shows that the MC has been maintained relatively stable up until the beginning of March, when drying is observed. However, in all cases except for the south wall, the MC is higher than the 28% limit for fungal germination, and 19% limit for fungal growth; in the east wall the MC is above the 35% limit for fungal spores flourishing and growth (HPO 2011).

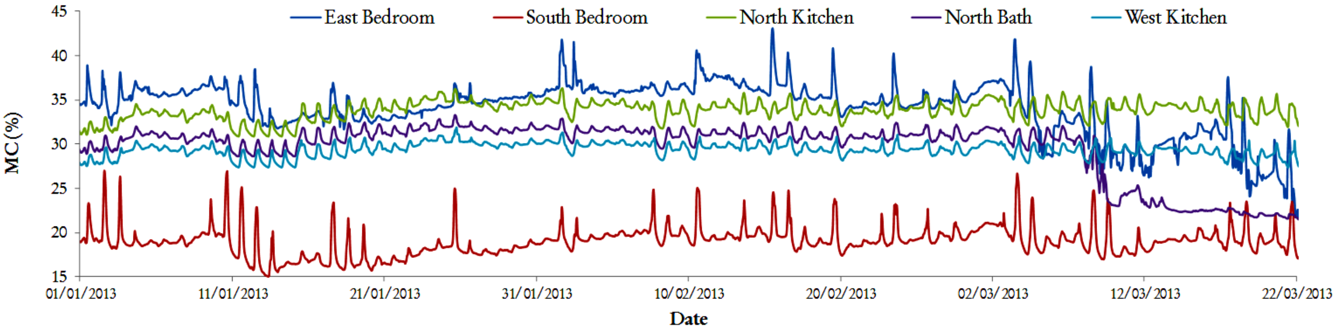

Figure 6 Hourly MC on various elevations.

Sensor data was cross-validated using additional sensors whenever possible. Figure 7 shows the comparison of CO2 concentrations in the kitchen of House#1 from two different kinds of sensors (Sensor #1: Telaire 7000 CO2 sensor; Sensor #2: Cozir-A CO2 sensor (2000ppm)). It should be noted that these sensors were placed at different heights on the wall. Both sensors showed similar variations in CO2 values, but sensor#1 installed at lower height showed higher values as expected (since the CO2 is heavier than air, it tends to have higher concentrations at lower levels).

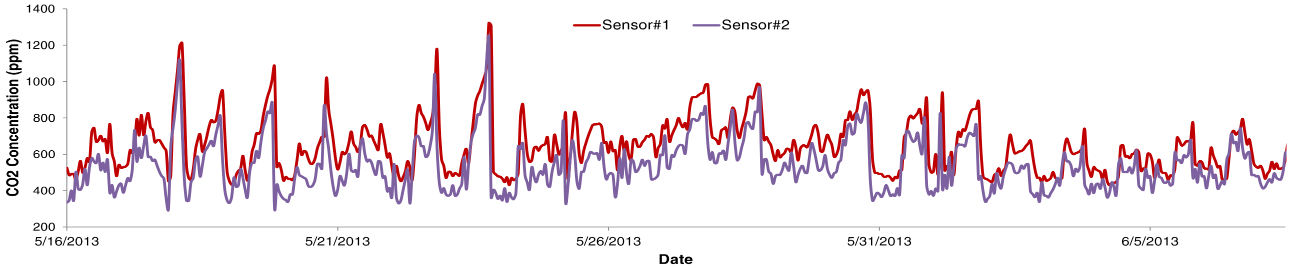

Figure 7 Comparison of two CO2 sensors for validation

IAQ-Energy Analysis

An energy model was created for house#1. The model was calibrated with blower door and air flow measurements at the outdoor air intake, the air supply grilles, and the returns of the forced air system, and with the use of a questionnaire to the occupants. Due to space constraints, details of the modeling are not given in this paper. Figure 8 shows the validation of the model that compares the simulated energy consumption with the actual consumption, obtained from utility bills.

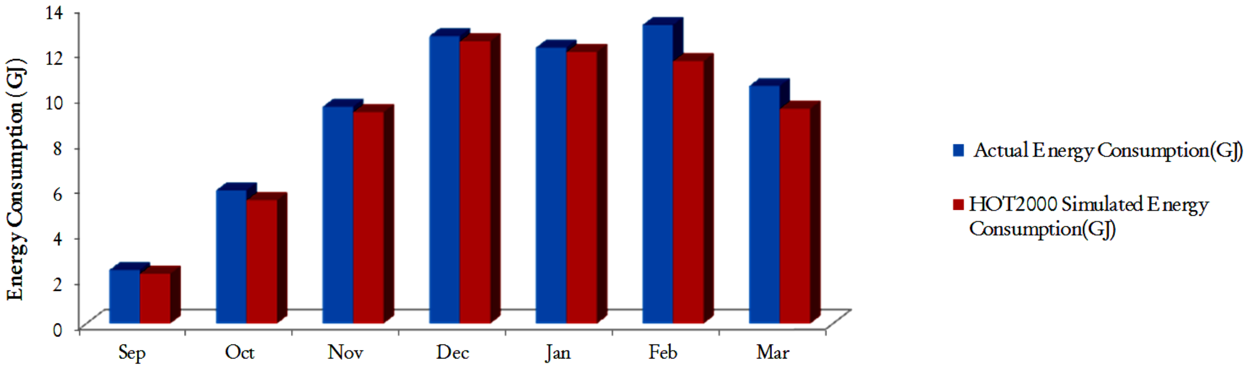

Figure 8 Comparison of simulated vs. actual energy consumption.

The energy model predicted that the house will consume 78.9GJ (22.1MWh) of energy annually. 70% of this energy will be consumed for space and domestic hot water heating (Figure 9) and one fourth of the total heat losses will be due to ventilation which included both air infiltration and mechanical ventilation.

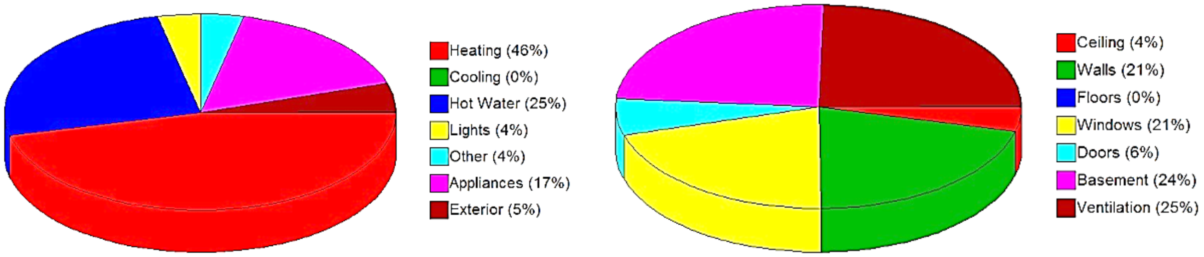

Figure 9 Components of annual energy consumption (left) and components of annual heat loss (right).

Three ventilation systems were evaluated to provide the required air change rate for the whole house (ASHRAE 2010): Continuous central exhaust fan, continuous supply fan, and dedicated HRV (Heat Recovery Ventilator). Figure 10 shows the comparison of annual energy consumption and ventilation heat losses (%) in above simulated systems.

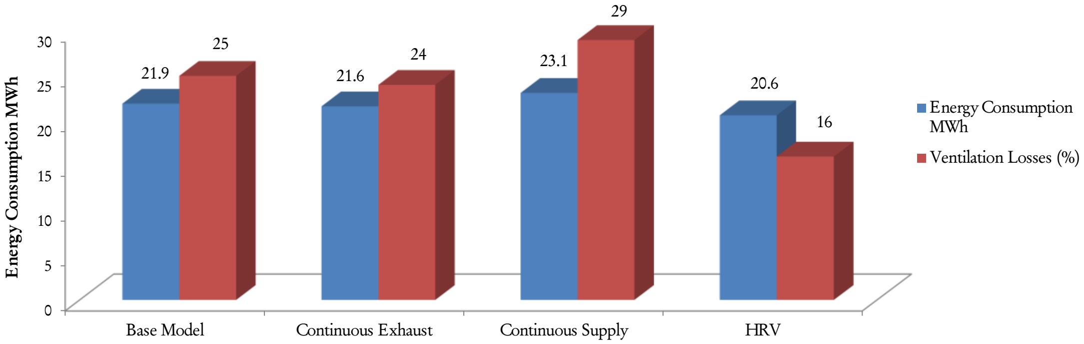

Figure 10 Comparison of different ventilation systems.

Simulations show that HRV ventilation system is the most economical one, while supplying balanced uniform air distribution to the house. Exhaust ventilation is considered more adequate for cold climates than supply ventilation. For the marine climate of Vancouver any of the options above would work from a durability point of view. However, window opening by the occupants would override any ventilation system operation assumption.

Integrated analysis of the results from the pilot study

Overall, the houses seem to be performing well and there is no sign for alarm to the owners or the builder. The indoor environmental data (CO2, RH/T) indicate that the houses have good ventilation (CO2) in general. Instances of higher values of CO2 could be related to increased occupancy which could result in occupant discomfort. RH/T data show no signs of risk for microbial air borne contamination due to excessive moisture. In house#1, CO2 and RH/T sensors give clear indication that the owners in one house are opening the windows at times when is not convenient from an energy point of view. The energy penalty can be calculated and is appreciated in Figure 8. The sensors in the crawl spaces suggest that foundation moisture is drying out and these seem to be performing well. Additional sensors at the corners of the foundation walls would help find out if there is a risk for moisture condensation at these locations. The attic needs close attention because the moisture levels are high and sustained for a long period. A preventive solution needs to be devised such as sealing the ceiling cracks and possibly improving the attic ventilation. Similarly, the moisture content of certain walls needs close attention. An engineering assessment would need to be conducted if higher values persist. A breakdown of the results from the energy simulation, cross-validated continuously with utility data (e.g. Figure 9) give feedback to the occupants on the items they can control to reduce energy consumption. For example, knowing the energy impacts from opening windows may lead the homeowners change that habit, particularly when reasonable CO2 levels are sensed.

CONCEPTUAL ARCHITECTURE OF THE HEALTH MONITORING SYSTEM INTEGRAL TO HOMES

Figure 11 illustrates the components of a ***Health Monitoring System*** integral to homes, created using the knowledge gained from the pilot study. The system consists of two components that provide feedback to the Occupants and learn from the behaviors. (1) ***The Sensory System*** that includes indoor environment, energy, and envelope sensors. And (2) ***The Reasoning System*** with three engines: the *Occupants Behaviors Inference Engine*, that infers occupants' behaviors from sensory data; The *Building Performance Inference Engine*, that infers performance as indicated in Figure 10; and the *Learning Engine*, that learns from occupants' changing behaviors, from the sensory data, and from actual energy performance data obtained from the Smart Meter (if one is installed). The dotted lines indicate feedback from the ***Health Monitoring System*** to the occupants; and from the occupants and the smart meter to the *Learning Engine*. The goal of the reasoning system is to infer occupants' behaviors and house performance from a limited number of sensors, and give feedback to occupants so that they can change behaviors, adapt, and take control of the house performance. Thus, through sensing, reasoning, and feedback to occupants the need for a complex and expensive electromechanical control system can be avoided, perhaps leaving automated source control only for kitchen and bathroom exhaust fans.

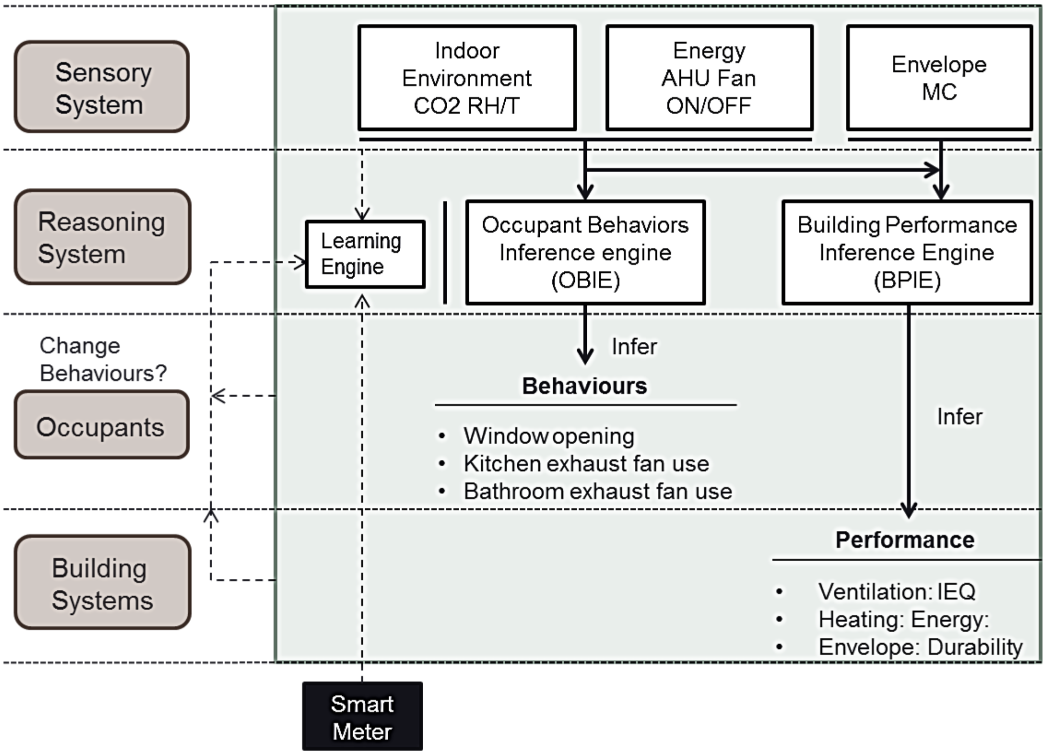

Figure 11 Conceptual Architecture of the ***Health Monitoring System*** Integral to Homes.

The ***Health Monitoring System*** is building science knowledge/principles based. This knowledge needs to be managed stochastically given the many uncertainties and dynamic nature of the boundary conditions. The system would be designed, fine-tuned and commissioned for each particular typology of houses, heating and ventilation system, and boundary conditions. The reasoning algorithms would be calibrated by memorizing characteristics of time-series generated sensor data during the learning phase, where the house is assumed to behave normally. This phase would subsequently help identify anomalous behaviors. It is envisioned that once operational, the system would learn from experience and fine-tune itself. An unexpected challenge from this project was having an occupant who is heavy smoker and carves wood in his house. Given that smoke produces CO2, the authors thought that CO2 could be a good surrogate for the presence of smoke. However, apparently, the combination of gases and fine particulate matter from tobacco smoke affected the CO2 sensor readings. This needs to be confirmed. Even with the advent of more sophisticated sensors, such as VOC sensors, the authors believe that a residential ***Health Monitoring System*** needs to be kept as simple as possible, and cannot be meant to prevent health risks that are more conveniently handled through source control. It is for the sake of simplicity, that the ***Reasoning System*** is proposed, i.e. to eliminate the need for an unnecessary number of sensors.

CONCLUSIONS, LIMITATIONS AND FURTHER WORK

The pilot project demonstrates the value of a well-planned and deployed remote sensing system integral to homes to provide holistic feedback to homeowners and builders on durability, indoor air quality and energy efficiency, so that they can manage their homes more proactively. This system can provide valuable information for improvements in construction and mechanical systems in future homes. This study emphasize that occupant's behavior can have a significant impact and is critical for the design of any resilient residential indoor environmental system. Higher need for such a system would be felt from communities in remote regions where the conditions are harsher and professional help is scarcer. This paper presents the initial steps in the development of an integral remote sensing system. The challenges are great, particularly in the sensor technology development, power and maintenance requirements, and cost. These challenges were not explored in this paper. However, the technologies are advancing fast and hopefully they will become widely available soon. In the meantime, the pilot study is still in progress and will be used to help elaborate on the knowledge and reasoning components of the remote sensing system. The pilot study will be expanded further on statistically representative sample of houses. Partnerships with the manufacturers and researchers will be established to test alternative heating and ventilation technologies; and develop intelligent sensing systems and control algorithms.

ACKNOWLEDGEMENTS

The authors are grateful to the British Columbia Institute of Technology (BCIT) as well as the BC House Protection Office (HPO) for funding this research project and making it possible. The authors also wish to express appreciation to the Squamish community for their logistic support and particularly to the homeowners for giving us access to their homes.

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