JOURNAL OF
BUILDING
PHYSICS

Article

Buildings with environmental quality management: Part 4: A path to the future NZEB

Journal of Building Physics
1–19
© The Author(s) 2018
Reprints and permissions:
sagepub.co.uk/journalsPermissions.nav
DOI: 10.1177/1744259118790756
journals.sagepub.com/home/jen
SAGE

Anna Romanska-Zapala[1], **Mark Bomberg**[2] **and**
David W Yarbrough[3,4]

Abstract

The previous part of this article starts 100 years ago, at the time of the humble beginnings of building science, and brings us to the current stage of the net zero energy buildings (NZEB). We see how, over the years, knowledge from the observed failures of buildings has accumulated to become the basis for current building science. The strong interactions between energy efficiency, moisture management, and indoor environment and the need for their simultaneous analysis led to the concept of environmental assessment. More than 40 years of experience with passive houses (the first 10 were built in Canada in 1977) in process that would collect those developments into the mainstream of NZEB technology permits extrapolation to the future. As the first priority, we see a need for a fundamental change in the approach to NZEB—instead of improving the separate pieces of the puzzle before assembling them, we need first to establish the conceptual design of the whole system. Only after determination of the basic requirements for each subsystem and each assembly may materials that would fulfill the specific requirements of this assembly be selected. In this design process, the actual climate and socioeconomic conditions (including construction cost) vary, so we must deal with a set of design principles rather than a description of a specific construction technology. A guiding set of considerations is presented below to establish a system of environmental quality management (EQM).

---

[1] Department of Electrical and Computer Engineering, Cracow University of Technology, Kraków, Poland
[2] McMaster University, Hamilton, ON, Canada
[3] R&D Services, Inc., Cookeville, TN, USA
[4] Department of Chemical Engineering, Tennessee Technological University, Cookeville, TN, USA

Corresponding author:
Mark Bomberg, McMaster University, Hamilton, 1280 Main St W, Hamilton, ON L8S 4L8, Canada.
Email: mark.bomberg@gmail.com

Keywords
Building physics, building science, system integration, thermal upgrade, thermal rehabilitation, ventilated cavities, multi-layered walls, hygrothermal insulations

A transition to sustainable buildings

The integrated design process (IDP) differs from traditional design where a building is "engineered in pieces" by experts working individually (Bomberg et al., 2015a). An IDP is the modern way to realize "performance architecture," that is, design with a view to field performance. In this process, however, all members of the design team must have some knowledge of building science to enable translation of the user requirements into objectives that define the performance of the end-product. While architects continue to have an integrating role within these teams, they must understand building physics to be able to communicate with other experts in the design team. We have observed, however, that many universities teaching building physics focus on standards and differential equations instead of the functional analysis and logic needed to arrive at an integrated system. We believe that universities should teach the principles of design and interaction between different subsystems and analyze case studies to demonstrate both failures and successes (Bomberg et al., 2015b). For this reason, we will continue using North American term (as defined by late Prof. N. B. Hutcheon) "building science" to characterize the goal to predict the performance of the building under service conditions.

The imperative of near-zero energy buildings (NZEB) is a comprehensive environmental control issue in the process of design. Such a design includes the following:

- Economic considerations including energy efficiency of the envelope, with understanding of interactions between thermal, moisture, and air flows;
- Durability of materials and assemblies that have been evaluated for long-term thermal and moisture performance aspects that include the cost of operation and maintenance;
- Ecological considerations that include a comprehensive approach to environmental control in building, addressing all parameters of indoor environment (IE) such as health and fire protection, acoustics, thermal comfort, and air quality.

All members of the integrated design team must understand how combined the action of heating, ventilation, and air conditioning (HVAC) and building enclosure shapes the IE. By the identification of competence, we have defined the core of a design team to be (1) a structural engineer, (2) a mechanical engineer, (3) a building scientist capable of hygrothermal and energy modeling, (4) a construction cost estimator, and (5) an architect as the formal leader.

What are we missing in this transition?

Introducing building scientist capable of modeling was an important step that recognized input from building science to the architectural design process as a necessity. Since the 1980s, building science has accepted that both testing and modeling are necessary (Addelson and Collins, 1991).

Improved hygrothermal models should be linked with energy modeling. Multi-directional heat flow patterns created by thermal bridges, corners, wall–window or wall–floor connections and response to transient weather conditions require computer modeling. To achieve reliable results from hygrothermal modeling calibration of the hygric material characteristics must be completed. Currently, the hygrothermal modeling is suitable for predicting yearly changes of moisture in the building enclosure but makes only crude estimates for shorter periods and leads to questionable results when the interaction between moisture and ventilation inside the walls is concerned.

For EQM technology where the calculation of moisture exchange between material surface moving air is required, the current hygrothermal models are simply not reliable. Even though Luikow in 1960s used six differential equations describing continuity of energy, mass, and momentum for simultaneous heat, air, and moisture transport and Bomberg (1974) highlighted the difference in mass transfer coefficient between saturated and unsaturated capillary water flows, these phenomena are not important for construction practice and therefore not analyzed.

Inter-zonal air flow models became a central point for estimating the impact of air flows on heat, humidity, and pollutant transport, but they do not communicate with hygrothermal models because what is the entry point in one is the output of the other. Inverse solution of inter-zonal air flow models leads to a multitude of solutions and requires additional information. For example, the effect of air flows on the thermal performance of a ventilated wall is difficult to establish for four reasons:

(a) We do not know the boundary conditions as they are influenced by the connectivity with other spaces in the building;
(b) Some paths of air flow are unknown because they are not part of the design;
(c) There is both natural and forced convection in the wall ventilation channels;
(d) The film resistance for moisture flow depends on moisture content in the material layer adjacent to the air layer and if one neglects capillary hysteresis, it produces errors in the distribution of moisture content in the material.

The fact that one does not know the boundary conditions for air transport in real buildings leads to large differences between laboratory and field testing for airtightness. The criterion for acceptance of the wall in the use condition is 10 times higher than that for the same test on the same wall when performed in laboratory with known boundary conditions and one-dimensional (1D) air flow.

In summary, building physics should be re-focused on the development of computerized tools for predicting the field performance of integrated environmental control systems. The current class of hygrothermal models is parametric, that is, they deal with comparative simulations only. They must be improved to deal with the real-time solutions and linked with the energy models. The improved hygrothermal models must include information on air leakage through the walls and estimate the impact of air and moisture transport on energy. This would also improve the reliability of energy models.

Incorporating hygrothermal models into the energy calculations is important because moisture buffering not only modulates the indoor relative humidity but also reduces peak energy loads (Fadiejev et al., 2017; Simonson et al., 2004). Uncontrolled relative humidity affects both indoor air quality (IAQ) and durability of building materials. Expansion of hygrothermal modeling capability is necessary because water is a phase-changing substance (i.e. phase change material (PCM)). This affects both IE and heat transfer.

A need for change of the design paradigm. A new program in the European Union (EU) calls for a transformation toward sustainable cities for new and retrofitting of existing buildings. We claim that to do so we need to change the paradigm of thinking. Why?

Throughout history, specifically until 1950s, buildings were based on tradition. Since 1950, air conditioning became so cheap that all comfort requirements were satisfied by air conditioning. The point that brought it to our attention and that we call “energy conundrum” was a discovery that in 2002 and 1929 large residential buildings in the city of Vancouver used the same amount of total energy (Finch et al., 2010). It highlighted the role of thermal mass and adaptable comfort approach prompted us to re-examine the approach to the design of low-energy buildings. We obviously want to reduce the use of air conditioning, use the electrical energy mainly in the night, and combine the passive house measures with geothermal and solar engineering. Examination of different nature-based solutions brought us to the focus on the IE (Bomberg at al., 2018). We know that previous attempts to use large amounts of thermal mass and make night setback of thermostats do not solve the problem of energy, because we did not follow changes in the outdoor climate. Being passive does not produce energy reduction, we must include systems based on active controls and, therefore, we talk about *environmental quality management* (EQM) in two areas of considerations:

(a) Spatial management of the built environment;
(b) Buildings with EQM.

The first one is well known to the architectural community, while the second is not known at all. Therefore, the first step to sustainable cities should be started introducing EQM as it relates to buildings and specifically to retrofitting old buildings. To ensure the adaptability of new technology to local climate and socio-economic conditions, we introduced a cost–benefit analysis that is based on comparison with a reference building. Some countries, notably Poland with 1,471,800 dwellings built with large panels or blocks (Wójtowicz, 2014) and China with millions of concrete buildings, need an affordable technology not only for thermal upgrade but also for improving the IE in old buildings.

Technology proposed as EQM not only changes the paradigm of thinking, but it also integrates HVAC with the building structure, uses transient but controlled changes of indoor climate to control the input of thermal mass and moisture buffers, introduces recent development in algorithms for system optimization, and effectively reduces CO_2 emissions and energy consumption while maintaining high-quality IE. In a nutshell, over the last 5000 years we have been improving each piece of the puzzle before putting them together, and this time we want to design an ultra-efficient building system and at that stage produce the pieces so that they would fit together in the already designed system. This is the essence of EQM technology.

A need for building management optimized system. EQM technology includes the development of an integrated control system that performs optimization of different subsystems such as the water-based heat pump, solar thermal and photovoltaic (PV) panels, air intake ventilator, pre-heat or pre-cooling of the ventilation air, modification of its humidity level, heat exchangers for the exhaust air, hot water instantaneous delivery (or hot water tank), cold water tank and rain and/or gray water tank, illumination, and control of temperature in several spaces depending on their functions. Furthermore, it controls the use of surface heating/cooling that are integrated with building partitions, which will modify the contribution of thermal mass to the energy consumption. With adequate steering algorithm based on the history of use and predicted values of the outdoor climate, one can optimize indoor climate for any type of use and geographic location.

The above list explains why we changed the name of the building management system (BMS) to highlight the process of optimization, namely, building management optimized system (BMOS) (Romanska-Zapala,et al., 2018). To be able to perform the system optimization during the post-occupancy stage, the BMOS includes two subsystems: (1) a specialized metering system to study changes in the selected parameters at the specific locations inside walls or spaces and (2) the traditional BMS that controls processes in walls, windows, and spaces to ensure the required quality of IE. These two subsystems are interrelated in both the equipment and software applications.

The need for BMOS is twofold: (1) to improve the capability of discovering malfunctions in the separate units or subsystems and (2) to introduce self-learning functions of the steering algorithms to permit optimization of these subsystems in the post-occupancy period. Subsystem (1) includes dedicated software that aims at improving quality of the IE and energy efficiency in the EQM technology. Yet to optimize its performance we need to have information collected over four different seasons, that is, a minimum of 1 year of post-occupancy. The information collected from this specialized metering system will lead to the development of a guide for the process of evaluation and optimization of the BMS system alone.

While the charging of motor vehicles and PV systems are now common practice for residential properties, any combination of alternative current (AC) and low-voltage direct current (DC) in the same grid may also affect the frequency distribution of the electrical current and associate with it loss of quality in the energy systems. Thus, another, yet not discussed, function of the BMOS is to ensure the quality of electrical current.

Summary of the transition to sustainable buildings

The EQM approach provides a vision of the integration of buildings with their environment. An aquatic habitat, in addition to recreation, provides rainwater management and tertiary water treatment and, with a small design modification, it can also provide thermal storage for a ground heat exchanger in the district heating system.

We know that cold climate buildings must be designed as clusters using the ground between them for geothermal engineering. It could be a block enclosed by four adjacent streets (Atelier Rosemont in Montreal, QC, Canada) or a free settlement, yet both thermal storage and rainwater management must be considered in the design of city clusters.

Progress in district heating resulted in lowering the temperature of the delivered water to a minimum to function as a lower terminal for a heat pump dedicated for each building. Some cities, for example, Montpelier (Vermont, USA), are already switching to resource combinations producing yearly zero energy.

While the prevailing housing research funding (Building America in the United States, Horizon 2020 in Europe) was focused on new buildings, old buildings, because of their select locations, can be of much higher value if we change the thinking paradigm. Since 1946, we have been fascinated by glass and air conditioning. Energy conundrum (discovery that 2002 and 1929 large residential buildings in the city of Vancouver used the same total amount of energy (Finch et al., 2010)) highlighted the role of thermal mass and adaptable comfort approach. This prompted us to re-examine the approach to low-energy building design. We want to reduce the use of air conditioning, use the electrical energy mainly in the night, and combine the passive house measures with geothermal and solar engineering. We believe that nature-based solutions will not only support more resilient responses to climate change, but also provide a stronger economic base for adaptation of the new construction technology.

Description of the EQM technology

It was about 100 years ago that Portland cement became popular for use in walls and we started using multi-layered walls. Now, we are trying to reduce the number of layers in the wall. To do this, we obviously need to use multifunctional materials (Bomberg et al., 2017). While we talk about multifunctional materials, we must also realize that criteria for these functions are not defined on the material level but on the assembly level. Building assembly is the lowest level in the building hierarchy in functional analysis, to which one can carry analysis down from the building level. The fact that many building codes ascribe technical requirements to materials instead of assemblies does not help.

For instance, the permissible level of material airtightness is one magnitude lower than that of an assembly and two magnitudes (100 times) lower than that of the exterior wall of the building (Bomberg et al., 2016). There is no conflict between building science and codes because the latter specify the minimum requirements and we design for requirements much higher than the minimum. Furthermore, codes deal only with the basic categories of safety and health, while the remaining categories are left for a qualified designer.

Layers in the exterior wall

For the sake of discussion, we consider four layers in any exterior wall, namely, (1) exterior cladding (façade), (2) exterior continuous insulation, (3) wind load transmission (middle) layer, and (4) interior trim and finish. The facade layer (1) controls fire, rain, air and water vapor entry, light, sound, solar radiation, and vermin; the thermal insulation (2) controls heat, but may also control air, water vapor, and sound; the structural layer (3) provides strength and rigidity but may also control air, water, and vapor transports. Finally, the interior finish layer (4) controls fire, air, water and vapor movements, and sound.

1. The facade layer may be either directly attached or be a rain screen with air gap (e.g. brick veneer) to provide rain control. In this case, the next layer, on the interior side of the air gap, should be a thermal insulating composite with a surface that fulfills all of the facade requirements.
2. Thermal insulating composites must also control acoustics. This means that if concrete is not used for the structural layer, then the finishing surface on the thermal insulation must contribute to the attenuation of structural vibration. Today, however, most popularly used materials such as mineral fiber with wind protection or polystyrene boards with taped joints do not fulfill all requirements for air, water vapor, and vermin entry.
3. The selection of the load-bearing layer depends on the height of the building but a suitable solution for a low rise is light-weight concrete that may or may not have a reinforcement.
4. The requirements for airtightness and fire resistance of interior finishes are fulfilled by gypsum board that is water vapor permeable but does not have any moisture buffer capability.

In a nutshell, one may observe that some multifunctional materials are better at controlling acoustics, protecting thermal insulation from air ingress, or providing fire protection. There is, however, a new category of materials functioning similar to the traditional lime plasters or wood planks, namely, materials with moisture buffering ability, and they are needed for the next generation of low-energy buildings.

In part one of this article, we have highlighted the significance of thermal mass in the reduction of energy use (Fadiejev et al., 2017). We need to highlight two aspects of the modern architecture that contributed mostly to the elimination of mass effect on IE:

- Increased area of glazing and wall–window connections that created almost instantaneous transfer from the outdoor to the indoor space;
- High precision of air conditioning controls that stabilized indoor air temperature.

Furthermore, many architects do not realize that only 50% of the mass in exterior enclosure may contribute to the thermal impedance of the building and that the gains obtained through solar radiation (summer overheating) can only be re-distributed in the building (or removed) by strong air re-circulation systems or night ventilation. Both of these actions require the use of mechanical ventilation.

Heating/cooling system in the integrated EQM buildings

Bomberg et al. (2015a) recommended coupling between thermal mass and the large surface of a water-based heating or cooling system using water-based heat pump technology. This type of heating/cooling is more efficient than air-borne systems (Brennan et al., 2008) or other air-based heat pumps, because of the large thermal mass of water in the system. The most important aspect of water-to-water heat pump use is, however, the summer cooling. We know that highly insulated, airtight buildings even with window-to-wall percentage as low as 20% will result in summer overheating in a typical mixed climate.

EQM technology requires simultaneous presence of heating and cooling and for this reason the water source heat pumps are recommended. Having both cold and hot tanks, one can easily organize hydronic heating supported by solar thermal panels. Incidentally, those panels use shading devices on the wall exposed to solar radiation that fold down in the winter. Either a reinforced polyethylene (PEX) tubing that is used for heating can be switched to cooling for summer use or one can design a separate cooling area.

To achieve better control of the thermal mass contribution, one uses hydronic heating on the surface of the interior walls. Evaluating heating/cooling panels for a retrofitting of an old building in Nanjing, China (Hu, 2015) found that the impact of radiant panel location is significant (Table 1).

Table 1. Effect of location of the radiant panel on energy demand in dynamic operation mode.

Panel location	Heating demand (GJ)	Cooling demand (GJ)
Wall surface	58	24
Floor surface	98	31

These values were calculated using EnergyPlus with film coefficients typical for horizontal and vertical orientations. Hu also found that to achieve more than 90% efficiency in the desired heating one must use extruded polystyrene (XPS) insulation with a minimum thickness of 30 mm or when using expanded polystyrene (EPS) one must increase the minimum thickness to 40 mm (thermal resistance of the insulation layer about 1 $(m^2 K)/W$)

The above-discussed student project showed that hydronic heating panel for a new or for retrofitting the existing wall may improve the efficiency of heating while providing a control of thermal mass temperature. Yet, one must recognize that as the solar operation in various rooms will be different, we need to increase the number of sensors and precision of their controls but we will also need to re-circulate air to equalize temperatures in the whole building. We realize that mechanical ventilation of bathrooms and kitchen must now be separated from the main stream of air. The latter needs to be re-circulated to equalize the temperature and humidity in different rooms. This will be achieved by "clean air handler" mixing fresh air with the re-circulated air.

Typically, one allows temperature changes of 1°C per hour in a dynamic operation that should last a minimum 6 h a day (during either summer or winter) and this rate permits maintaining thermal comfort of the occupant. Yet, experience from other advanced zero energy buildings indicated that traditional air mixing methods are not effective enough in equalizing the temperature between different rooms. We have, therefore, proposed two additional measures to achieve the dynamic temperature equalization:

- Individual ventilation on demand in rooms with solar input;
- Using a hybrid ventilation system with overpressure of the supply air.

Yet, to be able to use air overpressure in the indoor space we must also improve the moisture management in the walls.

Hybrid ventilation systems in the EQM buildings

Using cold and hot tanks for water-to-water heat pumps permits pre-conditioning of outdoor air to a few degrees lower than the required room temperature and subsequent air filtration and dehumidification. Clean air is then mixed with a predetermined fraction of clean, return air and sent to each dwelling or a designated thermal zone with 10 Pa overpressure. Kitchens and bathrooms in each dwelling have a separate, manual or automatically (for night cleaning) operating exhaust. Furthermore, an individual ventilation on demand is installed at one window in all solar-exposed rooms.

Sending supply air with overpressure permits inducing air flow to points of the exhaust and operation of natural ventilation driven by the pressure difference in the space. Furthermore, it permits a break in operating exhaust ventilation. The time of operating fresh air delivery, exhaust ventilation delivering the return air to clean air handling unit, and natural ventilation will be included in each system, but experience from the High Environmental Performance house (Brennan et al., 2008; Wallburger et al., 2010) indicated that fresh air was delivered only for 20 min during each hour.

Individual ventilation, on demand, in solar-exposed rooms. Bomberg (2010) highlighted that a ventilated air gap within the wall may be used to introduce a difference between the heat flux in each part of this wall. This concept is not new and was the basis of double-façade approach used to refurbish old concrete buildings in East Germany. Studies on dynamic walls in Center Recherché Industrielle de Rantigny (CRIR), France, in the 1980s, showed that the difference between static and dynamic performance of the wall is negligible. So if one uses indoor air for cavity ventilation, the wall may act as the heat exchanger and the energy loss is minimal. Yet, the ventilation concept may be useful for moisture management of the wall.

The air gap faces on one side a capillary active layer of eco-wrap (new material developed for fire and moisture control that also has required mechanical performance) and on the other side thermal insulation covered on the interior with a water vapor retarder. As in the winter, the relative humidity in the room is generally below 50%, and collecting air from the floor area and exhausting it after passing through most of the wall height will permit slow but long-term moisture removal from the masonry part of the wall, should such be applied as a structural layer or from old wall if retrofit is performed. At the same time, the layer of eco-wrap is designed so that it enables transport of moisture from the existing wall to the ventilated space.

The need for advanced control systems

Yet, the best building enclosure and HVAC system will not deliver high energy efficiency and optimized IE conditions under variable climatic conditions without smart operating systems. The integrated control system collects information from all subsystems and permit using advanced control strategy. Such a control strategy may even use an algorithm with forecasting capabilities based on input of the local weather data. The control algorithm will set parameters for heating, cooling, and ventilation with consideration of indoor and outdoor climatic conditions. As in EQM system one uses surface heating/cooling system integrated with walls, the control system also impacts the contribution of thermal mass to the energy balance.

General requirements for building automation. A building management and optimization system (BMOS) should include monitoring of all parameters needed for rapid diagnostics and doing so should follow one of the popular protocols for transmission of data. The BMOS and the computer network should use uninterrupted power supply (UPS) ensuring its function even if the public electrical grid stops working. Moreover, a check on the quality of the supplied energy may be needed if a low voltage is supplied to the BMOS.

The main area of building automation relates to the HVAC, and in the EQM system it is as follows:

- *Heating/cooling (H/C).* A low-temperature, water-based, surface heating (floor or walls) is used. Because of the risk of moisture condensation in cooling, one must consider response of materials and the construction of the assembly.
- *Ventilation and opening windows.* A building management and optimization system (BMOS) controlling ventilation may use three parameters: temperature, relative humidity, and CO_2 content. Thus, for the given air temperature one sets the required changes in ventilation rate and relative humidity. Typically, this is achieved with the help of a multi-variant analysis or neural networks. In the EQM technology, ventilation on demand eliminates the need for opening windows; yet when the occupant decides to open a window, an impulse sent from the switch will cause closing the action of the mechanical ventilation.
- *IE quality.* In all rooms and spaces, where calculating a predicted mean vote (PMV) is expected, one needs to monitor temperature, relative humidity, and CO_2 content.
- *Illumination.* The BMOS should control groups of lamps through the motion sensors. In spaces of little use, one should select lights with low cost of starting. The BMOS should also have the directional sensor for the intensity of the daylighting as well as the ability to control the devices operating the solar shading of windows (if installed).
- *Thermal output for the window shading devices.* In EQM technology, the shading is not adjustable but their thermal output varies. The signals from the shading devices are used for two purposes: (a) calculating when the solar energy from the shading devices should be harvested and (b) calculating the expected solar loads on windows for operating the cooling devices.

Specific requirements for optimizing control algorithms

- Optimizing control of air systems to reduce cost while maintaining adequate thermal comfort;
- Optimizing control of hybrid ventilation to maintain the required air quality and also to complement changes in conditioning;
- Controlling the electrical illumination to complement daylighting;

- Controlling the operation of solar thermal panels used as window shading protections;
- Reliable and continuous transfer of information and avoiding problems related to the control of these devices from a distance;
- Creating guidance for working algorithms of different technical and safety systems and their interaction;
- Control should be based on the predictability of weather changes, or even changes in the price of energy.

Optimization of BMOS during the building operation. The BMOS should include building automation, security, and fire protection. This permits further optimization, for example, the level of illumination (or partial illumination) may depend on the occupancy factors. If a movable, solar shading protection is used, this may be modified based on weather forecasts.

The operation of BMOS is different during different seasons and to optimize its performance over the full year, one must collect information over at least three and preferably four different seasons and use the changes in each season for subsequent optimization. Previous work (Wallburger et al., 2010) showed that optimization during the building operation is a very important component for a number of reasons:

(a) In different rooms, one needs to heat and cool at the same time;
(b) Additional sensors must be placed in critical places as the backup for the control system, for example, a need for early warning when cooling generated a certain level of water condensation.

To gain a better understanding of the different options involved in the design of BMOS, we report a paper of Nosek (2018) who analyzed relative humidification (RH) of indoor air in winter measuring the following:

(a) RH in the supply channel before entry to the humidifier;
(b) RH in the supply channel after leaving the humidifier;
(c) RH in the air exhaust channel;
(d) Range of air flows in relation to the capacity of carrying moisture;
(e) Information when the maximum RH is reached (typically 90%–95%);
(f) Information about steam production by the humidifier;
(g) Information about failures in the steam production that must be corrected.

The information listed in points (a) through (c) is optional because one can use the RH level as the criterion. Yet if a rapid diagnosis of a humidity problem is needed, one needs the data from (a) through (c).

Let us now examine how the physical location of the control function affects the work of the integrated control system.

1. The traditional solution: an independent cabinet with a locally programmed controller that deals with all issues of the humidification and the control problem is reduced to the signal transmission between the local control system and BMOS that is located in the ventilation center.
2. In the control unit of the ventilation center, with analog–digital signals transmitted directly to the sensors in the humidifier, we talk about remote control.
3. As above but using the communication line for remote object programming.

The most effective is option 3, that is, the remote steering with the "object" programming. This system is universal and can be designed for precise response. The type and quantity of information can easily be modified by the programmer and does not modify the physical installation of the system. Furthermore, one can send information about each unit, even when a cascade system is used, and in case of faulty behavior one can switch off only one unit. In option 2, when a number of sensors and detectors are connected directly to the controller of the humidifier and their data are sent through the transmission line, one does not expect much modification in the controlled process. In such a case, the cost of directly sending a digital/analog signal is lower than that in option 3.

Finally, the worst is option 1, most popular today, because in addition to the limitations of modification the process gives us a multitude of different lines (cost) and need to deal with the cabinet at the location when malfunction was observed (or inferred from the BMOS analysis).

This example shows that even in the case of a single operation the progress in BMOS technology gives us three different options, each better for the specific type of application.

Rehabilitation of old buildings: a continuum in time of retrofitting

Another dimension of the EQM technology is that it allows use of the same approach for new low-energy buildings and for rehabilitation of the old. A project in Montreal, QC, Canada demonstrates the power of planning the construction process for a longer period of time. Atelier Rosemont (2016) in Montreal, QC, Canada is a cluster of buildings designed to be upgraded over a period of 10 years to demonstrate the power of integrated planning and execution from the standard neighborhood to NZEB that also include the community areas. The Atelier Rosemont project highlights how vague the boundary between new constructions and retrofitting of old buildings can be and that the system integration proposed in dynamic EQM projects is not a dream. EQM technology is to make a integration, in time and space, much easier to achieve (Figure 1).

Figure 2 shows the stages of energy reductions that were applied from 2008 (0% of total energy reduction) to 2018 (92% of total energy reduction), namely:

Figure 1. An affordable, low-rise, energy-efficient multi-unit residential building “Atelier Rosemont” in Montreal; rain retention basin is shown on the bottom right (credit: Nikkol Rot).

- High-performance enclosure, common water loop, solar wall—36% reduction in the total energy use per square meter and year;
- Gray water power pipe—42% reduction in energy use;
- Heat pump heating system (planned with horizontal heat exchanger)—60% reduction;
- Renewable 1: evacuated solar panels for hot water heating—74% reduction;
- Renewable 2: PV panels bring the total energy reduction to 92% (year 2018).

Thus, as it was planned, in the span of 10 years these buildings reduced energy use by whole 92% of the original use.

The EQM technology in broader view

Even the best construction technology cannot ensure high efficiency in energy use and high level of IE over winter and summer without the use of BMOS. It has been established that changes in outdoor environment and the impedance of thermal mass will work against our objective unless a control system can override the passive measures. To modulate response of the building to the ambient environment, we need to integrate control of ventilation, heating, and summer cooling with thermal mass and operate the building in a dynamic fashion that responds to the changes in outdoor conditions. It is therefore necessary to expand traditional BMSs with the optimization function. We call the integrated control system, provided with optimization, and if possible equipped also with predicting capability “building management and optimization system” (BMOS). The EQM technology

Figure 2. Stages of improvements from 2008 to 2018 in Atelier Rosemont, Montreal (credit: L'OeuF s.e.n.c (65)).

implements BMOS to ensure that this system can work independent of the building type and its geographic location.

Finally, we propose a set of evaluation criteria that will define expected performance of the EQM building indicating to designers and quality assurance (commissioning) experts how to ensure the EQM system performance.

Commissioning of the EQM building

This article discussed requirements for the design process but the quality assurance (or commissioning) must also be considered during the design and construction of the building. From the construction practice, one can formulate two air flow criteria that must be met during the building construction:

- *Air flow between two adjacent floors.* Criterion is 0.3 ACH for the floor at 50 Pa pressure difference. To measure the floor connectivity, one may use two blower door systems or perturbations method combined with interzonal air flow models. If doors separating staircase from the corridor have a small opening that can be opened or closed tight, the measurements are much simpler.
- *Air flow from the floor to/from outdoors.* The criterion for air leakage and ventilation through exterior walls (if measured on each floor) is 1.5 ACH.

> This is thought to correspond to the airtightness of 0.8 $l/(m^2 s)$ at 50 Pa pressure difference. We postulate a criterion that is much higher than that for passive houses in Germany for a number of reasons (Bomberg et al., 2016).

We do not know about any verified technical guidelines for assessment of IE quality during commissioning of the completed building. For the final quality assurance, we recommend *on the basis of experience* that the following parameters be tested, indicating a set of benchmarking values for the expected performance:

- *Cooling time in heating failure.* Benchmarking criterion—with outdoor temperature (t_o) between 0 and −3°C, the period of cooling from $t_i = 20°C$ to $t_f = 14°C$ should not be shorter than a prescribed time, for example, 8 h. If the same temperature difference is used but different room temperature is applied, one can perform this test using dimensionless temperature $(t_f - t_o)/(t_i - t_o)$.
- *Heating time in cooling failure.* With the outdoor temperature of 29°C or higher, the increase of air temperature from 20°C to 24°C should not be shorter than a prescribed time, for example, 4 h.
- *Heating effectiveness.* Benchmarking criterion—temperature increase from 15°C to 20°C when the ventilation system is operating should not take more than a prescribed time, for example, 120 min.
- *Estimating the age of indoor air.* Benchmarking criterion—the age of air in the middle of a room calculated as the average of three measured values should not be higher than 70 min implying that the whole air volume is exchanged in 1 h.
- *Effectiveness of air re-circulation, test number 1.* Benchmarking criterion—increase in one step the concentration of CO2 in one room supply channel to 50% ± 5% for 1 min and check if after 20 min the difference in this and two adjacent rooms is lower than 10%. This is an important test and should be included in the list of the required commissioning tests.
- *Effectiveness of air re-circulation, test number 2.* Benchmarking criterion—measure in a hot summer and in a cold winter in three rooms in three selected points on the height of 1.2 m and none of the differences should not exceed a prescribed limit, for example, 1.5°C.
- *Risk for interior surface condensation.* Benchmarking criterion—using IR camera when the exterior temperature is below zero, measure the temperature at the floor, corners of the exterior walls, on the structural beam over the window, and all possible locations of the thermal bridges. With the air temperature of 20°C, the surface temperature should not be lower than 14°C. If the exterior temperature is much lower than −3°C, one may use the concept of dimensionless temperature as discussed in the cooling test.
- *Effectiveness of humidity control.* Benchmarking criterion—measure the relative humidity (RH) in the room and increase it stepwise for 10% in the

period shorter than 5 min. Measure RH in the same point after 30 min; it should be less than 5% higher than the original measurement.

Discussion on buildings with EQM

Elimination of the summer overheating, good ventilation of indoor space, and large windows exposed to sun are encouraged by many architects in response to the desire of the occupants. Glass connects occupants with the outer world and is here to stay. Thus, an engineer has to solve the technical problem instead of trying to go backwards and prescribe small windows to avoid summer overheating.

We know that large windows expose occupants to asymmetric heating and cooling surfaces and dynamic changes in air temperature. To alleviate discomfort, we need to re-examine two sets of control issues:

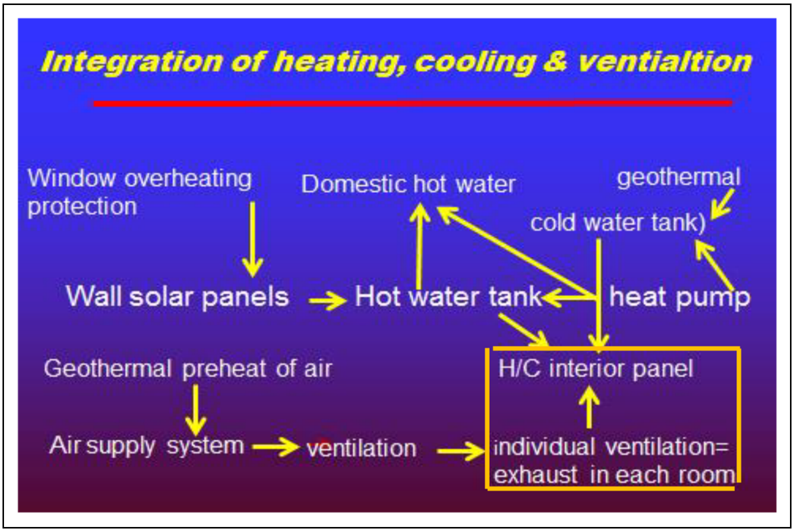
1. Dual control for water-to-water heat pump to address both heating and cooling required to compensate for the summer overheating;
2. Re-circulation of the ventilation air to equalize temperature in sunny and shaded areas.

The complex of factors interacting on IE is presented in Figure 3.

The framed area postulates the need of individual ventilation in each room with large widow and large area of heating/cooling devices such as wall surface behind which we have hydronic heating/cooling devices. This is a simple conclusion from the basic premises of indoor climate design, but it should be noted that this simple solution addresses eight, uncorrelated with each other dimensions of IE: visual comfort, indoor air quality, personal control of IAQ, noise control, connection to the outdoor environment, individual ventilation, thermal comfort, and thermal and humidity buffers to reduce rapid changes in the IE. Those are the critical elements for comfort in work or home, building durability and satisfaction, productivity, and health.

Closing remarks

Several practical trends and scientific observations merged in the concept of passive house but the narrow focus on technology alone can only be considered as an interim step. When an occupant opens windows during inclement weather, he or she may destroy all the "energy efficiency of the technology." The history of building science from its beginnings almost 100 years ago up to the development of NZEB gave us understanding that the next generation of buildings will be designed with the IE as the starting point. If we satisfy the occupant need for large windows, individual ventilation on demand, and hydronic heating/cooling systems built in walls or floors, we are making progress toward sustainable buildings. Furthermore, when our heating/cooling system operates at low temperature without noise and



Integration of heating, cooling & ventialtion

Window overheating protection

Domestic hot water

geothermal

cold water tank)

Wall solar panels

Hot water tank

heat pump

Geothermal preheat of air

H/C interior panel

Air supply system

ventilation

individual ventilation= exhaust in each room

Figure 3. Two fundamental requirements that are shown in a frame in the right bottom corner are the key to the process of integrated design of environmental control.

visible heaters or ventilators, we are on a solid basis for the next generation of buildings.

We highlighted that a central air delivery system must deliver cleaned and dehumidified air. Exhaust points in bathroom, kitchen, and in the exterior walls are operated with double controls, manual and automatic to maintain the required ventilation rate in the dwelling. Of course, a high level of thermal insulation and air tightness and several technical features of the EQM technology can smoothly interact only with the assistance of advanced control systems.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) received no financial support for the research, authorship, and/or publication of this article.

References

Addleson L and Colin R (1991) *Performance of Materials in Buildings: A Study of the Principles and Agencies of Change*. Oxford: Butterworth-Heinemann.

Atelier Rosemont (2016) Information notes Canadian Mortgage and Housing Corporation.

Bomberg M (1974) Moisture flow through porous building materials. PhD Thesis, Lund Institute of Technology, Lund (Report 52, LTH, 1–188).

Bomberg M (2010) A concept of capillary active, dynamic insulation integrated with heating, cooling and ventilation, air conditioning system. *Frontiers of Architecture and Civil Engineering in China* 4(4): 431–437.

Bomberg M, Gibson M and Zhang J (2015a) A concept of integrated environmental approach for building upgrades and new construction: Part 1—Setting the stage. *Journal of Building Physics* 38(4): 360–385.

Bomberg M, Kisielewicz T and Mattock C (2015b) *Methods of Building Physics in Design of Zero Energy Ready Buildings*. Kraków: Cracow University Press, 1–300.

Bomberg M, Kisilewicz T and Nowak K (2016) Is there an optimum range of airtightness for a building? *Journal of Building Physics* 39(6): 395–420.

Bomberg M, Romanska-Zapala A, Yarbrough D, et al. (2018) Discussion on the network for environmental quality management. *MOJ CE* 41(5): 397–417.

Bomberg M, Yarbrough D and Furtak M (2017) Buildings with environmental quality management (EQM), part 1: Designing multi-functional construction materials. *Journal of Building Physics* 41(3): 193–208.

Brennan T, Henderson H, Stack K, et al. (2008) Quality assurance and commissioning process in High Environmental Performance (HEP) demonstration house in NY State. Available at: http://www.nibs.org/page/Best

Fadiejev J, Simonson R, Kurnitski J, et al. (2017) Thermal mass and energy recovery utilization for peak load reduction. *Energy Proceedia* 132: 38–44.

Finch G, Burnett E and Knowles W (2010) Energy consumption in mid and high rise residential buildings in British Columbia, EE3−3. Available at: http://www.nibs.org/page/Best

Hu X (2015) Radiant heating/cooling panels in China. *Paper Presentation at the "Inbuild" Workshop at TU Cracow*, Kraków, 5 November. Nanjing: Southeast University Nanjing.

Romanska-Zapala A, Bomberg M, Fedorczak-Cisak M, et al. (2018) Buildings with environmental quality management (EQM), part 2: Integration of hydronic heating/cooling with thermal mass. *Journal of Building Physics* 41(5): 397–417.

Simonson C, Mikael Salonvaara J and Ojanen T (2004) Heat and mass transfer between indoor air and a permeable and hygroscopic building envelope: Part I—Field measurements. *Journal of Building Physics* 28: 63–101.

Wallburger A, Brennan T, Bomberg M, et al. (2010) Energy prediction and monitoring in a high performance Syracuse house. Available at: http://www.nibs.org/page/Best

Wójtowicz M (2014) wielka płyta—Problem techniczny czy społeczny? ITB, Conferences of PAN and PZITB (Krynica) (in Polish).