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Buildings with environmental quality management: Part 1: Designing multifunctional construction materials

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Abstract

The quest for a sustainable built environment has resulted in dramatic changes in the process of residential construction. The new concepts of an integrated design team, building information modeling, commissioning of the building enclosure, and passive house standards have reached maturity. Global work on development of new construction materials has not changed, but their evaluation is not the same as in the past when each material was considered on its own merits. Today, we look at the performance of a building as a system and on the material as a contributor to this system. The series of white papers—a research overview in building physics undertaken in European and North American researchers—is to provide understanding of the process of design and construction for sustainable built environment that involves harmony between different aspects of the environment, society, and economy. Yet, the building physics is changing. It merges with building science in the quest of predicting building performance, it merges concepts of passive houses with solar engineering and integrates building shell with mechanical services, but is still missing an overall vision. Physics does not tell us how to integrate people with their environment. The authors propose a new term buildings with environmental quality management because the vision of the building design must be re-directed toward people. In doing so, the building physics will automatically include durability of the shell, energy efficiency, and carbon emission and aspects such as individual ventilation and indoor climate

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control. This article, which is part 1 of a series, deals with materials, and other issues will be discussed in following papers.

Keywords
Sustainable built environment, construction materials, building science, building physics, material evaluation, integrated testing and modeling

Introduction

A traditional title given upon completing an advanced academic work is doctor of philosophy. This article comes as an address from two philosophers, called teachers of building science (physics) and an architect who came to this field by different route, but who share the need to define the final goal before starting the work.

Speaking about application of building science, we need to start with defining some basic concepts. Leonard Bachman, in the course of Architecture at Houston University 2013, used the following definitions: (1) Data = characteristics or properties measured on materials or systems; (2) information = an effect of the process of transforming data into clusters on which decision process can be based; (3) knowledge = information that is in conformance with other fields of organized data; and (4) understanding = ability to reproduce knowledge from first principles and apply it to the unique situations.

Using these definitions, we agree that the ultimate objective of building science is to provide understanding of the process of design and construction for a sustainable built environment involves harmony between different aspects of the *environment, society*, and *economy*. A definition of sustainability involves different scales: country, region, city, or individual building. The term *balanced buildings* means a building where each of the above aspects is equally important, clarifies an understanding of the concept of sustainability. As we judge our research work from this perceptive, we may as well call the following review—a philosophical discussion.

This article is the first in series of research overview papers that extrapolate from 40 years of experience in passive housing. Yet, the use of solar energy in traditional passive house design is limited to the level to which the ventilation (natural or mechanical) can eliminate the summer overheating. To increase the solar energy contribution, we will use water-based heat pumps for surface heating or cooling and by hydronic means that controls the contribution of thermal mass to the energy balance. Furthermore, we will use moisture buffering materials to modulate indoor relative humidity. Effectively, the first lesson from the last 40 years that is presented in this article is that all materials used in modern house must be multifunctional and their selection is based on how well they satisfy requirements of the walls, floor, and roofs.

North American chaos in residential construction 1946–1990

North American buildings are conceived with a bias toward the heating season because heating is perceived to be more expensive than cooling. Energy conservation became a keyword after the crisis in the mid-1970s but has recently achieved national recognition. Statistical data, however, reveal that typical yearly energy use in multiple residential buildings (MURB) in 1990 in Vancouver, Canada, was 315 kWh/m^2. Since 1990, energy use in those buildings steadily declined, reaching 250 kWh/m^2 per year in 2002 (Finch et al., 2010). This would be fine, until we find that the energy use rates of 2002 are identical to those of MURB built in 1929. In other words, the uninsulated masonry buildings in the 1920s and the shiny, glass-clad buildings of today uses the same amount of energy, despite all of the energy-saving measures currently available. Is this because of the new facade standards and aesthetic values are expected.

This is not a surprise to a scientist. Centuries of small improvements resulted in massive structures responding slowly to the exterior climate. In temperate climates, these buildings were relatively comfortable by employing simple provisions such as high ceilings, fans, and cross ventilation. In cold climates, heavy masonry stoves in the middle of a dwelling or radiators that worked a few hours a day provided heating, but the thermal mass of the building served as a "heat battery" releasing energy without using fuel, and, of course in proportion with decreasing indoor temperature.

These buildings were airtight because both sides of exterior walls were covered with lime-based plasters. Lime develops strength slowly, allowing settlement of walls while maintaining adhesion and continuity and thanks to its elasticity it resists macro-cracking and has a self-healing capability. Double-hung windows (casements in Europe) were well integrated into the masonry and repainted every few years with oil paint. Thermal controls were simple, with devices such as radiators controlled by a manual valve and a supply of steam or hot water from boilers resulted in indoor temperatures that varied between periods of comfort and discomfort as the exterior conditions changed. The number of openings was reduced mostly to those following the building's function.

The unbalanced progress in North American construction

Discussion of progress requires defining the frame of reference. What clearly would be a progress in house building industry we call retreat from the balanced buildings perspective because economic progress was achieved without resource optimization and without environmental considerations. No one has studied the impact of changing aesthetic tendencies on these values.

In 1900, there were about 500 different construction products to choose from in the Swedish market. By 1950, the number increased to about 5000 and today we can find 55,000 to 60,000 different products.[1] The growth of specialized expertise and the fragmentation of the design process erased the capability of an architect to control the design process. The economic effect and the need for innovative and attractive forms that were selling the buildings took over the design process.

In Europe, moisture was not a serious consideration because masonry is resilient to moisture and bricks exposed to freeze–thaw conditions were carefully selected.

The accumulation of water has been a major problem for wood frame buildings of North America. Bomberg et al. (2015) identified 12 papers and books printed between 1938 and 1958 that dealt with water vapor transfer and condensation. Yet, a lucid explanation of condensation, given in 1958 finally got the attention of code and standards bodies. Why?—at this time water damage became evident in many buildings.

Condensation analysis was able to establish the occurrence of condensation, but it did *not predict the amount of condensate because it dealt only with one aspect of water vapor transport* and liquid (condensed) water moves by osmotic, capillary, or gravitational forces. Bomberg et al. (2015) discussed this issue in detail to highlight that typical construction practices did not use the building physics knowledge.

In the meantime, the architect's fascination with large windows forced engineers to increase the level of thermal insulation until one found that light-weight buildings with large amounts of glass in the walls were leaky and had a multitude of microclimates within one building. Thermostats covering large zones could not provide adequate control. Heating slowly evolved to forced-air heating combined with, ventilation, or to fully air-conditioning (HVAC) systems. HVAC systems could provide summertime cooling and dehumidification, as well as wintertime heating and humidification. Thermostatic controls for these systems operated with tight set points. In short, mechanical systems took over 100% of the task of climate control.

Air quality and moisture concerns in North America

The simplified version of building physics that was used by many national codes led to stringent requirements for water vapor barriers (retarders). In Canada, for example, vapor barriers were required to have permeance of less than 0.75 perm [45 ng/(Pa m^2 s)] when measured on aged products. The emphasis on water vapor control received a disproportionate amount of *attention just because it is easy to calculate*. Some "authorities having jurisdiction" went as far as stating that no condensation was allowed.

The change of directions was brought about by construction practice. To replace traditional heating systems with electric baseboard heating, builders increased again the levels of thermal insulation in the cold regions of Canada. These electrically heated buildings, unfortunately, showed condensate on second-floor windows (Bomberg et al., 2015). These observations led to new recommendations for airtightness of the ceiling construction and new partition-to-ceiling details. The linkage between electrically heated houses and patterns of natural ventilation was now evident.

In a parallel development, air exchange rate in houses with flue-less combustion furnaces was found to fall below that required by codes, implying that well-insulated houses with substantial airtightness may not provide sufficient air exchange when built without chimneys. The 1980 Canadian National Building Code required that all dwellings have a ventilation system capable of providing 0.5

air changes per hour (ach). In 1990, based on the observations that these ventilation rates resulted in too-dry air in winter, this requirement was reduced to 0.3 ach. Now the focus on indoor air quality (IAQ) and moisture management moved from natural ventilation and vapor barriers to mechanical ventilation and air barriers. Incidentally, air, water (weather), and vapor barriers products gave rise to new industries.

From the building physics viewpoint, fully air-conditioned building eliminated all the advantages that had existed with the old masonry buildings. To use thermal mass, one should use variable interior temperatures. Without the contribution of thermal mass, the HVAC system must deal with peak heating and cooling loads and the size of the system must be increased. Furthermore, zones in large buildings were based on the assumption that interior air is static, whereas thermal stratification, multi-zonal air flows, and even the occupant activity, all of these factors worked against the satisfactory operation of systems where ventilation was combined with air-conditioning.

Finally, as the traditional HVAC systems operate on dry air temperature and achieving comfort during cooling involves both latent and sensible loads, the whole field of air dehumidification had to be created for the southern part of America.

Transition to low-energy housing (1990–2020)

It is difficult to find a precise time when codes and standards across the world started a race toward near zero or net zero energy structures. Canada, in the late 1980s, created integrated design process (IDP) teams mostly because we had no one with experience on how to deal with design of so-called sustainable buildings. Yet, design cost increases more when changes to the design are introduced later in the process so moving most decisions at the front of the process proved beneficial to all parties.

The integrated, performance-based design differs from the conventional way of design, where a building was "engineered in pieces" to objectives defined by experts working individually in the process of design. An integrated design process 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.

This knowledge of building science allows them to translate the user requirements into the measurable performance objectives that will eventually define the design process. While architects continue to have an integrating role within these teams, it is especially important for architects to understand building physics and communicate with other experts in the design team. We have observed, however, that many universities do not teach the principles of design and interaction between different subsystems but treat building physics as another academic topic where equations replace the process of functional analysis and logic of integration of different subsystems. For this reason, we keep in North America the term building science that was defined by late professor N.B. Hutcheon.

The imperatives of near zero energy buildings seek to address comprehensive environmental control (thermal, moisture, and air infiltration) as formative and integrated issue in the process of design. Such a design includes the following:

- 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 and includes the cost of operation and maintenance;
- Indoor environment (IE) that includes a comprehensive approach to environmental control addressing all parameters of thermal comfort and air quality.

In the past, environmental control involved only mechanical engineers. Today, large, advanced buildings use ventilation interacting with heating, cooling, humidity control, and even air purification. These strategies, however, should be scaled and applied for any size of buildings. All of the people in a design team must understand how combined action of HVAC and building enclosure shapes the IE. By identification of competence, we have defined a core of the design team: (1) civil engineer, (2) mechanical engineer, (3) building scientist capable of hygrothermal and energy modeling, (4) construction cost estimator, and (5) an architect as a formal leader together represent a core of the integrated design team.

What are we missing in this transition?

Energy modeling has been preoccupied with mechanical systems for heating, cooling, and ventilation while neglecting their interaction with building enclosures. To produce correct results, hygrothermal models must be added to the modeling effort. These models, however, must deal with real-time solutions and not only with comparative simulations. We need to improve current hygrothermal models that were originally developed for parametric study so that they may be used for real-time modeling of the interacting transport phenomena. The improved hygrothermal models must include information on air leakage through the walls and estimate the impact of air and moisture transport on energy.

Moisture buffering can not only modulate indoor relative humidity but also reduce peak energy loads. Uncontrolled relative humidity affects both IAQ and durability of building materials. Expansion of hygrothermal modeling capability is necessary because *hygrothermal insulation* instead of thermal insulation offers significant economic advantages and could allow the development of walls to act as heat and moisture exchangers.

It is time that building physics become re-focused on development of computerized tools for predicting field performance of integrated environmental control systems. Better computer modeling is necessary to fine-tune the desired outcomes of these systems and without these tools the performance of new systems cannot be understood and evaluated. Thus, building physics must create new tools to reach an active and leading role in the movement toward net zero and near-net zero energy buildings (NZEB).

For NZEB, multifunctional materials are a must

From a building science viewpoint, we have spent 5000 years in monolithic structures, and the last 100 years in multilayered structures. Now, we are trying to reduce the number of layers in the wall. To do it, we obviously need to use multifunctional materials. While we talk 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.

Observe that there is difference between science and many building codes where requirements are ascribed to a specific material instead of an assembly. In some cases, it works reasonably well while in others it is a miserable failure. For instance, U values or thermal transmission in masonry buildings being ascribed to the continuous insulation layer is close to an acceptable solution, but the same for a steel frame building is not possible as it depends on where this insulation is located and how environmental effects affect field performance. Even worse is the situation about airtightness where permissible level of material airtightness is one magnitude lower than that of an assembly and two magnitudes (100 times) lower than the exterior wall of the building (Table 1).

In reality, there is no conflict between building science and codes because codes specify the minimum requirements and we should always design for requirements 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 as indicated in the above table.

For the sake of discussion, we must consider four layers in any exterior wall, namely (1) exterior façade, (2) exterior continuous insulation, (3) loadbearing

Table 1. Performance requirements as defined by Hutcheon (1953).

Control heat flow
Control air flow
Control water vapor flow
Control rain flow
Control ground water flow
Control light and solar radiation
Control noise and vibration
Control pollutants, odor, and vermin
Control fire
Provide strength and rigidity
Be durable, resilient,[a] aesthetically pleasing and economical

[a]Word “resilient” is added because consideration of flooding, hurricanes, and similar events is recent.

(middle) layer, and (4) interior trim and finish. It is clear that the façade layer (1) must control fire, rain, air and water vapor entry, light, sound, radiation, and vermin; the thermal insulation (2) controls heat, but may also control air, water, vapor, and sound; the loadbearing layer (3) provides strength and rigidity but may also control air, water, and vapor transports. Finally, the interior finish layer (4) should control fire, air, water and vapor movements, and sound. Yet, the whole wall must be durable, economical, and have control of ground water.

How are those layers actually working?

- Façade layer may be either directly attached and perform required functions or be a rain screen enclosing an air gap behind[2] (e.g. brick veneer) to provide rain control. In this case, the next layer, on the other side of the air gap, should be a thermal insulating composite with a surface that fulfills all of the façade requirements.
- Thermal insulating composite must also control acoustics. This means that if heavy concrete is not used for loadbearing, then the finishing surface on the thermal insulation must contribute to the attenuation of structural vibration. Today, however, popular solutions 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.
- The selection of the loadbearing layer depends on the height of the building but for a low rise a light-weight concrete with metal mesh reinforcement that is additionally protected from corrosion[3] is a suitable solution.
- The requirements for airtightness and fire resistance of interior finishes are fulfilled by gypsum board that is water vapor permeable and have little buffer capability (Figures 1 and 2).

Effectively, one must remember that multifunctional materials are developed and evaluated for a specific application and their use in different applications requires a new evaluation.

An example of a multifunctional wall composite

Large windows exposed to the sun are recommended by many architects who follow the wishes of the occupants. Glass connects occupants with the outer world and is here to stay. So an engineer has to solve the technical problems instead of trying to limit the size of windows. We have observed that windows expose occupants to asymmetric heating and cooling surfaces and dynamic changes in air temperature. To alleviate the discomfort issues, we need to re-examine two sets of issues, namely:

(1) Dual function control for water-to-water heat pumps to address both heating and cooling required to compensate for the overheating.
(2) Re-circulation of ventilation air to equalize temperatures in sunny and shaded areas.

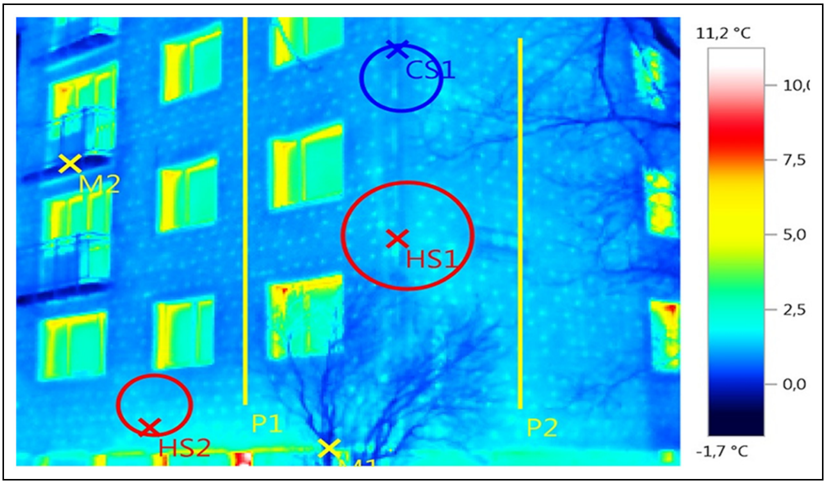

Figure 1. Infra-red camera shows all thermal anomalies on exterior thermal insulation composite system with 14-cm-thick expanded polystyrene. Connectors and hot water lines are shown as hot spots (HS) in contrast to corners and trees that are seen as cold spots (CS).
Source: From Adam Grylewicz (workshop at TU Cracow, 2015).

Figure 2. Façade of a building at Cracow TU after thermal upgrade with ETICS having a thick layer of thermal insulation. Drying on mechanical fasteners is faster that adjacent insulation that is still wet from morning condensation.
Source: Photo courtesy of Tomasz Kisilewicz.

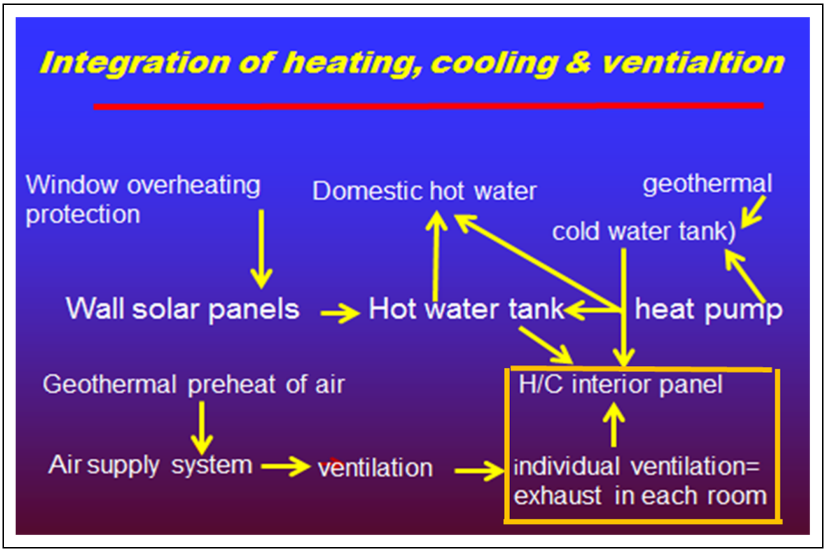

Figure 3. Two fundamental requirements that are shown in a frame in the right, bottom corner impact the process of integrated design of environmental control.

Figures 1 and 2 show that increasing thickness of thermal insulation to about double of this that was introduced in 1970's brought back the forgotten effects of thermal bridges as their effect on temperature differences has also been doubled. The complex of factors interacting on IE is presented in Figure 3.

It shows an integrated heating, cooling, and ventilation system where a water-to-water heat pump is supported by a solar thermal collector that heats and stores water. The storage provides hot water through reinforced polyethylene (PEX) tubing to panels located on the interior of the exterior wall. At the same time, a central air-supply system, drawing geothermally pre-conditioned air, delivers it to each room. The room (if it is exposed to solar radiation) is also provided with individual ventilation. The framed area in Figure 3 (right, bottom corner) shows both the individual ventilation and heating/cooling panel.

This solution addresses several different dimensions of IE, namely (1) IAQ, (2) personal control of IAQ, (3) noise control, (4) individual ventilation, (5) thermal comfort, (6) thermal, and (7) humidity buffers to reduce rapid changes in the IE. These elements result in occupant satisfaction in the case of residences and increased productivity in the case of work environments.

Figures 4 and 5 show the construction of a composite panel under discussion. The structural support was made from 40-mm-thick extruded polystyrene board; insulation board 1 was made from expanded polystyrene, while eco-wrap material was lime–cement–ash mixed with rice fibers and hulls powder as well as other industrial recycling materials. The heating/cooling pipe was 12 mm in diameter.

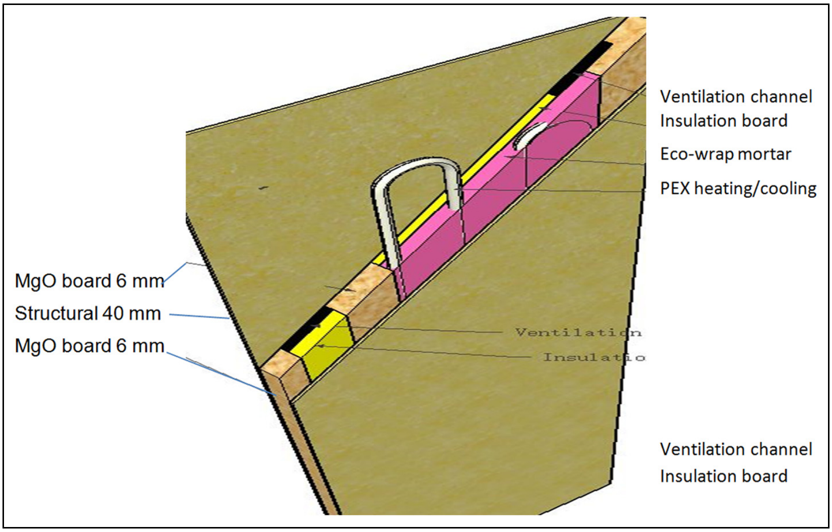

Figure 4. Multifunctional composite panel for interior of buildings (Hu, Workshop TU Cracow, 2015).

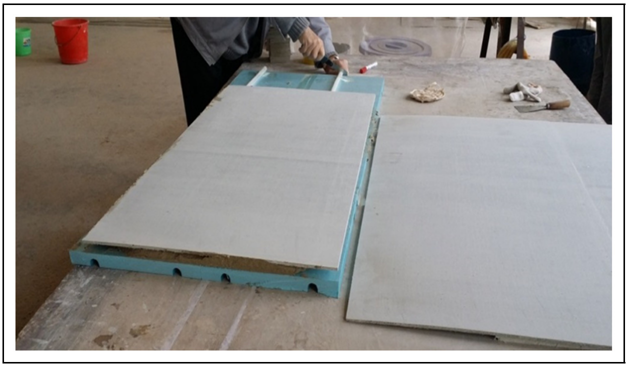

Figure 5. Multifunctional composite panel for interior rehabilitation of buildings (Hu, 2015).

The reason for showing this example is twofold: (a) a demonstration of how multifunctional materials and assembly form a seamless matrix of integrated design and (b) to stress that during the integrated design one reviews all relevant experiences in environmental control. Typical issues involve the following:

- Fresh air delivery. Note that the medical profession determined the amount of fresh air needed for people about 100 years ago (Baker, 1912),[3] yet there is no consensus on how to overlay these requirements with different HVAC systems whose air-mixing efficiencies vary.

- For a good ventilation system, all significant sources of pollutants should be removed at the source of pollution.
- Large central ducts and short high-velocity small-diameter ducts show good acoustical and air-delivery performance (Wallburger et al., 2010).
- Balanced ventilation systems that include supply and return ducts or central supply with individual exhaust completing the supply have also a good record of performance.
- Partitions (interior walls) in buildings to satisfy airtightness and of fire codes create a multitude of zones with individual climate controls. Water-based radiant systems with smart controls have a good record of performance in maintaining thermal comfort.
- Water-to-water heat pumps used with hydronic heating systems can operate at low temperature and be easily integrated with solar thermal panels.
- Variable refrigerant flow (VRF) technology allows using different heating or cooling rates as required in different rooms.
- A dedicated central ventilation system is beneficial when dehumidification is needed. With independent dehumidification and ventilation systems that provide coupling to thermal mass, buildings can maintain comfort during large periods of the summer simply by reducing humidity. This potentially saves substantial amounts of energy.

Integration of testing and modeling on assembly level

In 1970s, when the theory of functional analysis was under international consideration, a new category of performance tests was introduced. One example of such test was an impact test that used a 50 kg mass sand bag on a 150 cm string. Before the test is started, the string is stretched horizontally. When released, the gravity forced the bag to go along a circle and hit the wall. This test obviously is better than an impact test with a small and hard object but does it really represent a real hazard of damage by impact?

We can call this a "performance-oriented" test because such a test is easier to correlate with the damage mechanisms observed in the field performance. This may be better understood when examining the stages in test development contained in Table 2.

Table 2. The process of test method development.

Stage 1: development of a test measure
2. Identify factors leading to the objective
3. Determine how to quantify these factors
4. Choice of measuring method and unit (test method)
Stage 2: setting limits on the test
5. Write a test procedure
6. Determine precision and bias
7. Evaluating how the measurement meets an objective

Looking at Table 2, one realizes that the vague objectives of performance-oriented tests with unknown accuracy do not provide better linking the outcome of the test to field conditions than it was a case with the standard rating test. Thus, neither a rating test nor a performance-oriented test alone is sufficient for evaluating field performance of a construction assembly. An assembly is a building element such as a wall, door, window, or roof that consists of a combination of materials and typically provides a separation between spaces. In many cases, one of the spaces is the outdoors and if weather is a boundary condition describing it for the purpose of modeling this requires a substantial set of skills.

Bomberg et al., (2016a), has observed that almost all hygrothermal models used today are simplified by neglecting capillary hysteresis despite the fact that such is included in modeling used in soil science or in evaluation of in stress/stain caused by hygrothermal changes. Nevertheless, these models permit on evaluation of effects such as material variability and changes in climate on the heat, air, and moisture transmission through a building assembly.

Thus, like in other engineering disciplines, we must use a *process of integrated modeling and testing*. This statement is self-evident because testing cannot address the effects of variable weather conditions and modeling cannot address interaction between structural and environmental stresses, strains, and probable deficiencies of materials. Adamson et al. (1968)[4] and Bomberg and Allen (1996) have applied the limit states[5] approach to energy efficiency and durability assessment. To support modeling approach, Bomberg and Pazera (2010) extended the issues of material characterization for input to hygrothermal modeling and model calibration.

We will continue this review in two blocks of issues:

- Energy efficiency of the building;
- Priorities in environmental control during design.

Energy efficiency of the building

Design of low-energy buildings by an integrated team brings a new demand for all participants of multidisciplinary team. Understanding of how building functions is necessary for solving conflicts arising between different requirements, for example, continuity of function and separation of space.

To our knowledge, building physics is taught as individual subject and in most cases with focus on specific technical solutions. This may be suitable for those who major in the topic but for other engineers and architects the stress should be on design principals and interaction of different subsystems.

To achieve this objective, we need to reform education process in civil, mechanical, and architectural faculties by introduction of one subject that, for the sake of identification, we call, "Principals of building science," a course that should be taught in parallel to low-energy building course.

Developing a vision for design of low-energy buildings

For many decades, we used reliance on air-conditioning to shape IE, neglecting experience from time when buildings responded slowly to the change in exterior climate and used interior thermal mass as a "heat battery." To use controlled thermal mass of the building interior and restore the balance between requirements for building enclosure and mechanical devices become a key to sustainable design.

To this end, we propose a term *Building with Environmental Quality Management (EQM)*. The process of design and optimization includes three stages:

- Using all possible passive measures in design of the house even though the only two of the many existing passive house criteria are required. In this process, new multifunctional materials and integrated HVAC with building enclosures are introduced;
- Using low exergy geothermal and solar thermal measures to interact and to extend passive measures;
- Using photovoltaics or other renewable measures to the extend economics allows.

Developing a real-time hygrothermal models

We use the building component (assembly) level as the basis of evaluation. The multitude of possible paths prevents us from going down to the material level. To link materials with subsystems while simultaneously addressing the effect of material variability and climate, we need to upgrade our modeling capability. One often talks about modeling system to highlight the need for linking of these models.

Whether these models are linked with Energy plus or IDA-ICE, the hygrothermal part of the system must be:

(1) 2D or 3D real-time calculation code, that is, include capillary hysteresis and continuity of momentum on the material boundaries;
(2) Have one set of output data allowing it to be considered as input to the next calculation;
(3) Dynamically linked with whole building energy calculation;
(4) Include verification of material and assembly characteristics.

Developing wall assembly characterization

Despite the fact that laboratory and field testing use the same scale and identical construction, there is no equivalency between laboratory and field performance test on assemblies. This is caused by the difference in the boundary conditions and connectivity of the building assembly with adjacent assemblies. Air is entering to the walls and floors in places much different than it is leaving the building. For instance, air may enter through electrical or plumbing penetrations but exit at wall–window interface. Results of the airtightness testing provide examples of missing equivalency between laboratory testing and the difference is often as large as one magnitude large. Furthermore, field airtightness is often weather dependent.

To address the effect of weather, we must use hygrothermal models but these models must be calibrated for the actual materials and wall assemblies. Methodology of hygrothermal models verification and calibration on the material level was discussed elsewhere (Bomberg and Pazera, 2010). Yet, there are no publicly available methods of characterization of air flow through a wall assembly. Such development is necessary if we want to use hygrothermal models for the real-time calculations.

Experience indicates that such a method should be based on a combination of a tracer gas and blower door technology *to characterize degree of connectivity of a wall assembly with interior and exterior air* (Thorsell and Bomberg, 2011).

Closing remarks

A "White Paper's" (research overview) role is to highlight week points in the emerging knowledge and the process often starts with the vision. It may be stated that over last 40 years we have produced enormous volume of new technology but without the leading focus, this progress may not be efficiently used. We propose a new label for our activity so that the vision of EQM would allow seamless connection between HVAC and building enclosure as both of them shape IE. EQM includes passive house design and low exergy measures; it does not change anything but requires quantification of all effects of these measures that we undertake to manage the indoor environment.

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Notes

1. Since the 1946 paper of Johansson, rain screens are often a requirement for walls exposed to water impingement and poor drying conditions.
2. Protection is required because these materials are more permeable than concrete.
3. Baker (1912).

4. Adamson et al. (1968).
5. Limit states methodology was introduced to structural dimensioning about 100 years ago and in 1960s to building physics by a book in Swedish (Adamson, Bergstrom, and Nevander) describing needs for Scandinavian research program.

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