world

Citation: **Mark Bomberg, Anna Romanska-Zapala, and David Yarbrough Towards a new paradigm for building science (building physics),** *World* 2021, 2, 1-24. https://doi.org/10.3390/xxxxx,Received: Jan 23, 2021

Preprint

Towards a new paradigm for building science (building physics)

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

[1] Research Professor, D. Eng., Mechanical Eng., Clarkson U., Potsdam, NY, USA
[2] Assistant Professor, D. Eng., Dept. of Automatic Control & Info. Tech., Cracow Uni. of Technology, Poland
[3] Professor Emeritus, PhD, Tennessee Technological U., VP of R&D Services, Watertown, TN, USA
* Correspondence: mark.bomberg@gmail.com

Abstract: This paper presents a building construction approach that is based on forty years of experience and a focus on multi-disciplinary synergies. After 1980, the migration to science-based design was accelerated by the "Integrated Design Process (IDP)". As a result, building science became a significant force in reducing the effects of climate change.

The component associated with heating, cooling, and ventilation that is labeled"Environmental Quality Management" (EQM) or EQM-retro for interior applications will be discussed. The critical aspects of EQM-retro are:

- A two-stage process for new and retro construction that modifies financing patterns. In stage one, the object is to develop the best possible performance within an investment limit. In stage two, the cost is minimized
- Building Automatic Control Systems (BACS) are important for control thermal mass contributions of while achieving adaptable indoor climate as well as an integration of the HVAC system with the building structure.
- This is achieved with use of a monitoring application and performance evaluation (MAPE).
- Introduction of BACS and MAPE during design process improves the integration of building subsystems and energy optimization.

Examples showing increaseased occupant-controlled comfort, energy efficiency and flexibility of energy demand are presented in the paper.

Keywords: energy efficiency; building automatic control; energy use under field conditions; two-stage construction; cost-benefit evaluation; retrofit of residential buildings

0. FOREWORD

In North America, more than five billion dollars (US) has been invested in home energy management (HEM) since the beginning of the 21st century with over three billion dollars (US) in venture investments in the past five years [1]. The system is currently divided into two parts: a smart home with security, convenience, and comfort, and an extended home system which covers on-site energy generation, energy storage, and electric vehicle charging. The only area of overlap is home energy management, which unites the home system. So, there is a need to understand how this situation has developed.

In the 1970s, we discussed either passive houses or solar engineering as the choice for low-energy buildings. Building physics evolved and now we integrate all design activities. In the past, we debated placing solar shading either on the exterior or interior of the windows. Today, we have learned to shape facades to achieve the required shading. Currently, construction technology is in transition between the traditional approach and one based on sustainable built environment. [2,3]

What is missing in this transition is a concise presentation of the science behind the most effective and sustainable technologies, including examples where the benefits of integration can be identified. This

presentation will assist in the **identification** of research needs. When the existing technology [4-7] is reviewed, questions about the synergy between sub-systems emerge. [5,6]
During the years 2005-2008 in Central New York State, a DOE/NESERDA sponsored project called High Environmental House (HEP) was completed in Central New York State. [8-10] The goal was to find the limit of passive house measures[8], using the best quality assurance [9] and computer modeling [10] but without using renewable energy sources. We found that in comparison to 2004 code requirements a 50% energy-use reduction in comparison with typical builders could be realized. In addition, it did not matter what energy model was used because each of them had to be calibrated by field measurements on an actual house. This project led us to the development of the Environmental Quality Management" (EQM) concept. By the application of artificial neural networks (ANN) [11,12,13] to the data monitored on the actual building we avoided calibration of the model. Furthermore, use of ANN permits correlation of measured and calculated characteristic parameters and as well as the addition of sensors to detect faults in the operation of the system. Monitoring energy use and indoor climate and subjecting the data to a statistical analysis prior to ANN modeling reduces the prediction uncertainty and facilitates innovation. More specifically, synergies involving energy use, transient indoor climate and thermal-mass contributions can be enhanced by a computerized control system that utilizes weather-data forecasts in the steering of the HVAC operation.
In this context, the merger of energy with indoor climate brings together the two fields of home energy management. This paper highlights the power of integrating existing technologies. In the first part we identify the need for integration and in the second part we present an integrated energy and indoor environment control models. Today, sufficient confidence and experimental results exist to encourage others to participate in the research described in this paper.

PART 1: WHERE DO WE START

Progress in the retrofitting of buildings is presently unsatisfactory. With existing techniques, for example, energy use can be cut by 30-40% at a modest cost [1, 14]. Why are these techniques not commonly used for retrofitting? One of the possible reasons is that the design of new buildings involves all aspects of construction, while retrofits focuses on elements that yield a rapid return on investment. The concept of building as the system has existed for at least 30 years. Fixing a single aspect of building performance, therefore, cannot be considered an acceptable practice.

1. A ROAD TO BUILDING INTEGRATION

For centuries, bricks have been improved before being given to builders. Recently, social pressure to build sustainable buildings resulted in an integrated design process (IDP), where all critical decisions are made when the building concept emerges.[15] The new design paradigm requires prediction of performance before a building is erected. This intensifies the need for improved understanding of the actual performance of a building before it is constructed.

1.1. Mold growing on books in the desk of a Nanjing school

Books left for the winter in a school desk, were found covered with mold in the Spring. To improve indoor environment in warm and humid climates, walls could be retrofitted with a ventilated air cavity to remove excess moisture from walls. If air in the room is de-humidified, and the wall is covered with a capillary-active material (Haeupl [16]), and there is a moisture balance between day and night, then the system will slowly dry. Such a solution could not have been proposed for two reasons: (a) fear of loading water in the walls by over-pressurized ventilation air, and (b) lack of the real-time hygrothermal models (we have only parametric models). This example underlines the linkage of the indoor environment with energy use or health aspects.
Today, we are one more step beyond recognition of the inter-connectivity of spaces in a building, and one more step further from the interdisciplinary solution that is needed because the tragic experience with Covid 19 showed the need for improving our ventilation patterns.

1.2. Energy mirage

Since the 1973 energy crisis, energy efficiency has become a design objective. Multi-unit residential buildings (MURBS) can be used for comparisons.[17] The average annual energy used in MURBs during 2002 in Vancouver, Canada was 250 kWh/(m²·yr) with the same value observed in 1929 [18]. How is it possible that a building constructed today consumes the same energy as one built without insulation nearly a century ago? Today, we have closed combustion heating, thermal insulation [19], glazing systems with reflective coatings [20], earth-air heat exchangers [21,22], reviews of energy, energy compared with cost [23], indoor environment [24], and methods of optimization [25].

The above comparison is called an "energy mirage" because it does not have a simple explanation. The load-bearing function on the old masonry structure required thick walls and heavy floors, that created a huge thermal mass. They responded slowly to exterior conditions, leveling diurnal shifts in temperature and tempering interior conditions. The thermal mass of the building served as a "heat battery," releasing energy in proportion to the decreasing indoor temperature. These old walls were airtight because on each side there was a field-applied, lime-based plaster placed on a partial air gap (porous substrate). Lime develops strength slowly and this allows settlement of walls while the plaster maintains adhesion and continuity. Furthermore, thanks to its elasticity, lime creates micro-cracks while it resists formation of macro-cracks.[26] Both the plaster and masonry walls were serviceable and could easily be repaired. Double-hung windows in North America (casements in Europe) were well-integrated into the masonry walls. Although not perfect, the small window area limited their impact on air leakage.

Because of the slow thermal response of these buildings to exterior climate variation and to the periodic nature of the heating systems, the indoor temperatures varied between periods of comfort and discomfort as the service conditions changed.[27] Effectively, what these masonry buildings were missing by way of insulation was compensated for by a combination of overheating during the heating period, thermal storage and a low rate of cooling until the next heating period. Furthermore, to improve on shortcomings of the natural ventilation, the old rooms were typically much taller than the modern rooms.

This information does not surprise a building scientist who says: "OK, *so during these years all progress went into improving the comfort of the occupants.* Now, during a winter, the average temperature in a room is about 5 °C higher, so a large progress in comfort has benne achieved in two generations." All right, the authors continue: if you call the comparison between 1929 and 2002 an energy mirage because it shows the failure of relying on a perception, why do you use parametric models of energy to design buildings today? Well, the answer is - the models assist architects in design decisions.

This brings us to the role of an architect. In the past architects had a holistic view of a building. This is not the case today. In 1900, there were about 500 different construction products in the Swedish market, by 1950 the number increased to about 5000 and today there are more than 55,000 different products. [28] This suggests that the growth of specialized expertise, and this fragmentation of the design process has erased the capability of an architect to control all stages of design and construction.

In summary, whether we like it or not, the above two examples show that the interconnected world of multiple effects changed the way we design buildings.

1.3. The holistic approach to construction

The holistic approach makes a significant difference in five aspects of design:

- Consideration of sustainability should be included in each design project, large and small, new construction or retrofitting.
- Buildings should be rated on their seasonal and total performances that includes energy efficiency, indoor environment, durability, initial and total cost of 15 (or 25) years of performance.
- Energy/ hygrothermal models should represent the real-time performance in the specified climate.
- HVAC performance needs to be optimized initially in the conceptual stage and finally during the occupancy stage.
- The building cost must include both the initial, maintenance, and operating costs

Design Objectives

One starts with resolving conflicts between an investor (future building owner) and society. Society wants a zero-energy use for a dwelling or small house. The investor wants a minimum purchase price. To alleviate this conflict, one may divide the construction process into two stages. In the first stage the builder is limited by the cost agreed upon with the investor and in the second stage the performance achieved should satisfy society demands.

Tradition was based on the rating scales not on evaluation of the performance. Comparative tests are designed for achieving high precision. For instance, measuring airtightness at DP 50 or 75 Pa improves test precision, while a typical air pressure difference in dwellings is 3 to 4 Pa with 10 Pa being a practical maximum. Flow rate versus DP varies with the size and structure of the building but there is always a fraction of uncontrollable air leakage. Nevertheless, there is a minimum value for fresh air supply for health reasons of 0.30 to 35 ACH. This limit would correspond to about 1.5 ACH when measured at 50 Pa. In effect, to compare airtightness and ventilation needs one should measure both air characteristics directly. [29]

Energy and hygrothermal models

Parametric models [30], assume independence of all parameters. Keeping some constant and varying others, one may calculate an effect. For example, energy efficiency is calculated with constant interzonal air flow rates and for calculating ventilation rates, we assume that the air temperature field in adjacent rooms is constant and known. A simultaneous interaction of two different simulations (co-simulation) e.g., using Energy+ and CONTAM show results different from the use of these programs separately.[31] WUFI+ is being considered for similar co-simulations.
Each energy model must include two components: (a) heat transfer caused by temperature difference and (b) thermal energy carried by air flows, but our knowledge about air flows is insufficient. Energy models require calibration with measured data. The uncertainty in air flows from field testing is demonstrated by using an acceptance criterion that is ten times larger than achieved with measurements in a climatic chamber. The only way to avoid the model calibration on a real ventilation measurement is to use monitoring application for performance evaluation (MAPE). It is shown later in the test that ANN-performance models that are based on actual data have the potential for achieving higher precision than uncalibrated numerical models.

Improving HVAC performance

Today, in large commercial buildings one performs a post-construction performance evaluation of HVAC. Should this also be done in residential buildings? Consider a smart house, with water-based heat pumps and two buffer tanks connected to rain and gray water, solar thermal and photovoltaic panels, solar loaded batteries to load the electric vehicle, heat exchangers for ventilation system and you see that the only difference between commercial and residential buildings is scale. Furthermore, advanced control system is needed for use of a shallow, horizontal ground heat exchanger for storing an excess of summer energy or for use as energy transfer from solar overheated rooms to the northern side of the building. Independent of the technical solutions used, all these control functions justify a building automatic control (BAC) expert in the IDP team who understands data acquisition and real-time control of equipment.

Handling of the cost-benefit relation

The most successful public/private programs (R2000 in Canada, Building America in the USA) dealt with the whole building system and included two critical aspects of cost-benefit analysis:

- Defining cost and performance level for the reference building, and
- Encouraging trade-offs within the total limit of expenditure

1.4 Interim conclusions

This review highlighted the need for a holistic approach to the cost of investment and to the building operation, in short, the need for holistic evaluation of building performance. In view of different shortcomings of the parametric energy and hygrothermal models used today and test methods based on comparative material ratings, the need to start the analysis from the first principles of building science.

PART 2. BUILDING AS A SYSTEM

2.1. Opportunities for a design change

In switching from components to the system performance, one should recognize the following needs:

1. To reduce or eliminate peak loads one should use a dynamic operation of thermal storage and design a thermal lag time between 12 and 16 hours,
2. To control the contribution of thermal mass one should place the heat source in contact with the mass of the building,
3. Design of ventilation and heating systems should be separated since they have different response times,
4. To improve moisture management, consider a possible use of over-pressurized ventilation
5. To ensure air redistribution without cross-polluting indoor space, when an adequate moisture management exists you should use an over-pressured air delivery and local exhausts
6. Design the thermal-mass contribution in relation to the climate and service conditions of the specific building

The above list represents a holistic thinking paradigm, where we treat heat, air and moisture as inseparable components in a complex called environmental quality management. But traditional modeling deals with each flow separately. Heibati et al. [30] analyzed the difference between the separate or integrated modeling using Energy Plus and CONTAM for the same building located in the extreme climates of North America. By using temperature fields calculated in one model as input to the air flows calculated in the other model the energy estimates under interactive conditions were obtained.

Table 1. Comparison of annual total energy calculated by Energy Plus alone and co-simulated with CONTAM for Montreal and Miami. [30].

Total yearly energy	Montreal	Miami
Consumption (GJ)		
Energy+	26	19
Co-simulation	21	17

The co-simulation results contained in Table 1 are smaller than those calculated separately. As the co-simulation is based on dynamic exchange of temperatures and airflow rates for one-hour time steps, it may be considered as the first step of integrated modeling of airtight and well-insulated two-story houses in Montreal or Miami. These cities represent heating dominated and cooling dominated locations.

2. WHOLE BUILDING PERFORMANCE

It is one thing to specify that buildings achieve stated energy efficiencies; it is quite another matter for that outcome to become a reality. To achieve it, professionals combine two different conceptual processes. On the analytical side is a complex array of tools, models and data describing materials; on the qualitative side is an assessment based on the experience and skills to make a particular building function. This duality exists when the actual design starts. The team brings to the forum experience from past work and varying opinions on the means to achieve these results. Using computer language, this is "off-line" information, while the tools and models used during the design are "on-line" information. In the proposed approach, the on-line process is modified, namely, using the guidelines for monitoring and the results of monitoring to create a model for the building being analyzed. [31,32,33]

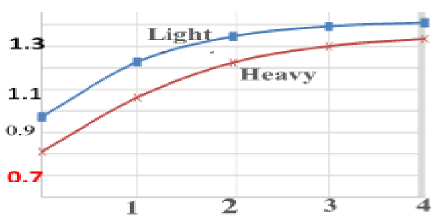

Figure 1. Structure type impacts the design cooling load versus cooling time, in days (Fadiejev et al. [34])

Figure 1 shows the results of energy calculations performed using actual weather data for a city in Central Europe. [34] Results are shown for two buildings, one with light wood-frame walls and the other with a heavy concrete walls and somewhat reduced thickness of insulation. Figure 1 shows that the cooling process stretches for three days for the light and four days for the heavy wall. Another observation from Figure 1 is that the difference between heavy and light walls is larger at the initial conditions, because more heat is stored in the heavy wall, and becomes negligible when quasi steady-state conditions are approached. Another comparison of older houses made in mid-1960s [35] showed a light-weight plastic house with an air-borne heating and mechanical ventilation had thermal mass effect a two-hour longer than a similar light house without air mixing. As a criterion for drying processes (under stable boundary conditions) one uses so called response time, a period needed to reach release of 50% of the thermal energy. Using the dimensional notations and semi-logarithmic plot one finds the response time at 0.65 for exponential and 0.67 for parabolic interpretation of the process. The latter, i.e., 0.67 of the difference between initial and final temperatures is used here. Figure 1 shows for the light wall, the 0.67 criterion is reached in 1 day while houses tested in mid-1960s showed response time 6 and 8 hours.

Another comparison of older houses made in mid-1960s [35] showed a light-weight plastic house with an air-borne heating and mechanical ventilation had thermal mass effect a two-hour longer than a similar light house without air mixing. As a criterion for drying processes (under stable boundary conditions) one uses so called response time, a period needed to reach release of 50% of the thermal energy. Using the dimensional notations and semi-logarithmic plot one finds the response time at 0.65 for exponential and 0.67 for parabolic interpretation of the process. The latter, i.e., 0.67 of the difference between initial and final temperatures is used here. Figure 1 shows for the light wall, the 0.67 criterion is reached in 1 day while houses tested in mid-1960s showed response time 6 and 8 hours.

The difference between 8 and 24 hours in maintaining indoor comfort highlights the significance of simultaneous requirements for airtightness and high level of thermal insulation. On the other hand, a dynamic operation of the building and controlled contribution of a large thermal mass is required for a reduction of peak loads.

2.2. A TWO-STAGE CONSTRUCTION PROCESS

Figure 2 shows that a good design may initially reduce utility bills without increasing the cost and that some passive measures may create a small increase in the cost. [36,37] With a larger use of passive measures, the ownership cost (mortgage plus utilities) goes through a minimum and continue to grow. There is another characteristic point on the curve shown in Figure 2, namely a point of equilibrium in which the cost using the passive measures is the same as photovoltaic (PV) energy. One may switch to PV sources of energy and continue until reaching zero energy. This happens at a substantial investment, typically about 50 – 70% increase of the minimum mortgage cost. Yet, the unpublished experience from the Building America program indicates that a typical investor accepts up to 10 percent increase over the reference cost.

Thus, the rational design of low energy buildings requires a proper selection of the reference buildings. In line with this need, the American Photovoltaic Institute selected reference buildings based on the ASHRAE / DOE climate zones [37] and considered 115 locations for cost optimization that included air tightness, window upgrades with a 15°C minimum interior surface temperature, heating and cooling demands, and peak heating and cooling loads. Statistical models were fit so that cost of the target properties were generated for any location from parameters such as degree-days and design temperatures. In this way, the passive houses moved American housing one step closer to the goal of sustainable development.

Figure 2 shows that a typical investment based on the money return at a prescribed time, stops far below the zero-energy building. To alleviate this difference, one proposes a two-stage construction process. In the first stage one achieves performance level possible for the selected cost, while the second stage continues to optimize the cost for the Near Zero or Zero Energy building. In the first stage the building is completed at a low performance level (acceptable to the building code and the investor), while the designer proposed also continuation to zero energy level. The second stage starts a few years later.

The second stage of the new construction project will be subject to the same financial restrictions as a retrofitting project. Nevertheless, the stage two of any construction or retrofitting project has the advantage of known property value and an estimated cost of the new construction or repairs. This information is invaluable for a capital-secured investment.

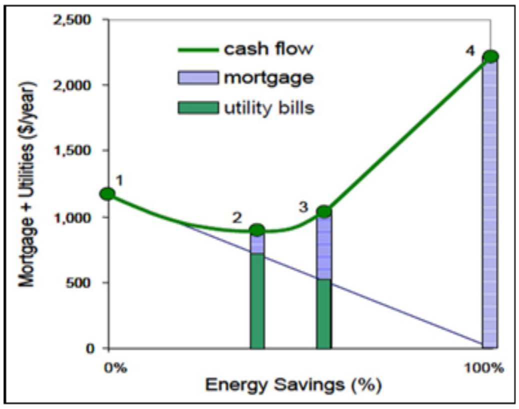

Figure 2. Costs of utilities (green) and mortgage (blue) versus energy savings from zero savings to 100% savings. Point 1 is the starting point, point 2 the energy conservation measures alone, and point 3 the beginning of PV contribution (from Wright & Klingenberg [36] with permission).

2.3. *REHABILITATION OF BUILDINGS IN STAGES*

As the two-stage solution is also suitable for retrofitting of existing buildings, one can see below, in the Montreal project. [38]

Figure 3. Stages of improvements from 2008 to 2018 in Atelier Rosemount, Montreal, (credit L'OeuF s.e.n.c., with permission).

Atelier Rosemont in Montreal, Canada is a cluster of buildings designed for retrofitting that spanned a period of 10 years [38]. Figure 3 shows a building with stages of energy reductions that were started after 2008 (the base year: 0 % energy reduction) to 2018 (92 % cumulative reduction), with steps that introduced:

- High Performance enclosures; a common water loop; solar walls provided 36% reduction
- Gray water power - the cumulative energy reduction grows to 42 %
- Heat pump heating - all passive measures resulted in 60% reduction
- Domestic Hot Water with evacuated solar panels to achieve 74%
- Photovoltaic panels reduce external energy to arrive at 92% cumulative reduction.

The Atelier Rosemount cluster included a mix of different types of dwellings including-social dwellings. This project highlights that modern thinking in construction eliminates the boundary between new construction and retrofitting of old buildings. It also shows that the two-stage approach with dynamic operation of buildings as proposed in the EQM technology can become a reality including the proposed integration in time and space [31,32,33]. Over the ten-year period, the building energy use in Atelier Rosemount fell to 8 % of the initial level as shown in Figure 3. [38]

2.4. MAKING IT AFFORDABLE

The above shown data agree with the experience gained from the Building America program. A high level of thermal insulation and air tightness can reduce energy consumption by 45 – 50 % in cold climates. An example from the New York State discusses the construction process [8], quality assurance [9] and the used energy modeling [10]. The passive measures can reduce energy use by 55–60 % [11,34,36,38]. Adding heat pump technology and geothermal and solar contributions to energy the total energy use can be reduced to 70 % in cold climates [39,40] and up to 80% in warm climates characteristic of the United States or Asia [41,42].

Nevertheless, there is a need to manage solar gains, even in a cold climate they can result in overheating. To balance heating and cooling may require major changes in design, e.g., using different types of heat pumps (HP), a water-sourced HP coupled with ground storage in cold climate, or a split-level HP coupled with large thermal mass in warm climate. Other measures that should be considered are:

- Automatic systems designed already in the conceptual stage of design [43]
- Adaptable indoor climate approach and control systems to maintain the indoor environment in the comfort conditions [44],
- Capability of post-construction HVAC optimization for all types of buildings and in turn an introduction of new skills to the IDP team, namely an expert in automatic control [33].

3. WHAT IS NEEDED TO ACCELERATE ENERGY CONSERVATION

A summary of a conference published as "Energy efficiency and durability of buildings at the crossroads" [41] was to increase the impact of future designs by Architects active in Building Enclosure Councils in 34 large American cities. This paper stated:

"Yet, it is not clear how to achieve the major change that is required. However, it is clear, based on past successful programs, that only a systems approach will achieve those goals in the future. We are past selling magic new materials and miraculous one-issue solutions. Every building, old or new, needs to be treated as a system in which every component is a piece of the puzzle. Quick fix efforts for one or more components in the building envelope, at best, may not achieve enough, and at worst, may cause damage. This requires advice from experienced practitioners of all types. ***The green value*** *of actions* ***is determined by the resulting building performance****, not by the perception that an action is green.*

In this respect there is no difference between the evaluation process for houses and large office buildings. Though, in the latter case we are highlighting the role of mock-up and commissioning tests and the need for involving the full design team in review of those elements since they have a fundamental effect on building performance."

This position paper also quoted a United Nations report, namely:

"The good news is we have got a huge source of alternative energy all around us. It is called energy conservation, and it is the lowest cost new source of energy that we have at hand. Since 1973 alone, improvements in energy efficiency resulted in a 50% reduction of our daily energy use, which is the same as discovering 25 extra million barrels of oil equivalent every single day. Clearly saving energy is like finding it".

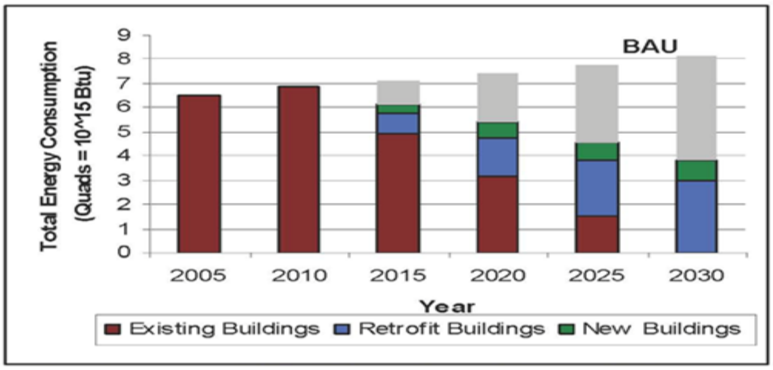

Figure 4. Two components in 2030 targets, Lawrence Berkeley Nat. Lab [41] (reprinted with permission).

Figure 4 presented at this 2008 conference [41], by Dr. Selkowitz, highlighted that market forces must be supported by public/ private initiatives. The 2030 objectives require actions in both new and upgrading the existing buildings, the latter **should be thermally upgraded before 2030**. Examining this Figure now, its appear that new construction is on schedule; while the retrofitting is a failure. Why?

This failure may be explained by the fact that the integrated design process was not used for the retrofit projects. Thus, while a progressive approach was used for new construction it was ignored in retrofitting of existing buildings..

The 2008 white paper states:

"At the far end there is an AIA commitment to achieve a 2030 carbon neutral future. There is a chasm that must be bridged if the goals are to be achieved and there is confusion on how we can accelerate the process of renewal. Despite the large amount of knowledge and industrial know-how available, we realize that the old vision has ceased to be valid. ***We need to create a new vision because the stakes are high."***

Twelve years later, the authors continue the discussion started in the 2008 and after evaluating many different ideas, the authors propose the following amendments:

- Both new construction and retrofitting projects should be divided into two stages to solve the conflict between the limited investment funds and the society demands for reduction of the carbon emissions. Stage one is unchanged. Stage two must be designed jointly with the first stage one but the construction will be started sometime later.
- All residential buildings should be operated under an adaptable indoor climate as the transient indoor environment facilitate the contribution of thermal mass.
- In all buildings with possible exception of single houses one must use control systems to operation of heating, cooling, illumination and ventilation.
- All building automatics is a subject to analysis of performance and improvement of the heating, cooling and ventilation systems during the post-construction (at least one year of occupancy stage because summer and winter conditions require different set-ups).
- Even though the authors use an example of Energy Quality Management (EQM, or thermo-active building energy management system) in this paper, the same methodology is applicable to other operating systems.
- One may consider using an individual monitoring and performance characterization model of energy and indoor environment instead of existing parametric models. Yet such models are only now being developed must first be evaluated under field conditions.

The role of automatic controls for dynamic facades was highlighted in 2008 [Dr. Selkowitz, 41]

This implies that windows with a high R-value and a moderate solar heat gain coefficient (SHGC) should be used in cold climates. In hot climates, the energy flows are dominated by solar gain which is highly variable depending upon *climate, latitude, season, and orientation, and needs vary – i.e., cooling load controls vs daylight admittance and view vs glare control. Thus, in hot climates as well as in mixed climates, static control needs to be replaced by dynamic control of solar gain. This approach should drive design strategies and technology for the near term. In the more distant future, windows should become even greater net energy suppliers by becoming more fully integrated with photovoltaic capabilities."*

Now is the time to switch both opaque and transparent parts of the building enclosure to dynamic operation. The improvement in film photovoltaics has a great potential to increase the functions of both components of the facades. In this context, a small step that may create a scientific revolution, is to treat the existing buildings not as the energy problem but as the energy solution. This is an obvious conclusion for the Southern US states, yet calculations show that even in NY state, shallow geothermal storage integrated with water-sourced heat pump is viable.

A critical step introduced in this paper is a two-stage construction concept. It implies that there is no difference between constructing a new building or retrofitting an old one. The economic implications of two-stage construction are significant because the work is carefully planned and the investment is financially secured. This is equal is valid for the new construction as for retrofitting.

4. UNIVERSAL APPROACH TO ENERGY-EFFICIENT DESIGN

Forty years ago, average energy consumption in new residential buildings in North America was 200 – 300 kWh/(m^2·yr), today it is about 50% of the previous number [3, 10] and advanced buildings use about 25% of the previous number. The value of 70 kWh/(m^2·yr) is commonly used as the upper limit for low energy buildings. Thus, while an impossible forty years ago, **a merger of solar, geothermal and passive measures is not only possible but also necessary today**. Of course, the significance of solar and geothermal contributions will be different between cold and warm climates, but the principles are the same.

As the total energy use depends on factors such as micro climate surrounding a building, building type and size, number of occupants and on the degree of technological development of the society, we should refrain from use of percentages or partial indicators like U-value. The only criterion justified to define energy performance is the average annual energy consumption per unit of the floor area. This can be established either with or without consideration of the electrical devices used by occupants and used to characterize a trend or for compare cases. Moreover, in practice one prefers using electrical energy instead of the primary energy. This simplification is justified by the goal to decarbonize construction as well as use of heat pump technology, where the favorable coefficient of performance compensates the difference in efficiency of electricity production and transfer.

Effectively, the integrated, environmental design process may include four-stages:

- First, all passive energy measures and factors affecting indoor environment such as temperature, indoor air quality, acoustics, daylight, illumination, hot and sewer water management, aesthetics and building resilience in disaster situations are addressed. Energy design after including all passive measures in the step 1, follows to the step 2 and includes all low exergy measures, e.g., thermal energy storage, solar thermal panels, convective cooling, and finally in the step 3 includes other renewable energy sources, e.g., photovoltaic, thermal energy redistribution, electrical storage).
- Secondly, the building automatic control systems to integrate heating, cooling, ventilation, and other indoor climate controls including use of geothermal and solar means for energy generation and storage is addressed.
- Next, an economic analysis to determine the level of investment for the initial building design or the initial stage of retrofitting. For example, one must decide to what extent should photovoltaics be included in stage one of the construction or retrofitting process?
- Finally, one develops a comprehensive operational manual for the building and provides the design for stage 2 of new construction or retrofitting. This step also estimates costs for stage 2 of a project.

Except for identical treatment of retrofitting and new construction, the only difference from the standard practice is the step 2. As building automatics is now included in the IDP team, for an HVAC optimization one needs to perform monitoring of the field performance and develop a model of energy performance characterization.

Furthermore, for building manual to appear, it must be requested in the contract documents. Observe that no standard calls for a manual of operation for a passenger car and yet all people expect to receive one. So, buyers could start expecting it for a smart house.

4.1. A concept of energy model for control of building automatics

A concept of the neural network for monitoring and characterization of buildings used with Environmental Quality Management has been described. [10, 12]. One starts with monitoring energy performance, collecting data to the MSS (Modular Statistical Software) as shown in Figure 5 [43]. Data collection includes information about energy use in installations such as heating, cooling, ventilation, maintenance of relative humidity, re-circulation of indoor air, and information about the exterior climate. The modular structure of the software and the option of parameterizing the system allows user to tailor the solution to a specific object as a connection to building automatics. While transforming it to the form required for analysis, the MSS completes them with information from standards and the actual building characterization. After some statistical analysis and removal of the statistical outliers, the data set is prepared for use in the building automatic system.

The system architecture is such that all client information such as external database, weather data or BMS system information go through the interpreting module and the layer of business logic to the application server being on the way transformed to the structure needed by the MSS. The application server is responsible for performing all operations: registering new measured data, reading all the raw data, performing aggregations and statistical analysis as well as for communication with all modules including internal database.

Results are presented in form of Tables and graphs and the output from the MSS is used in the next stage of modeling.

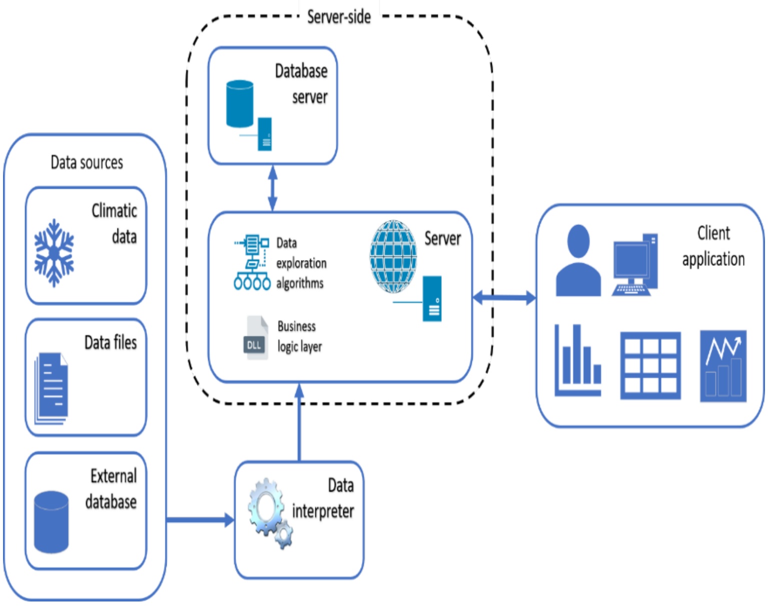

Figure 5. Conceptual representation of modular, statistical system (MSS}.

After a feasibility study [11], a neural network for monitoring and characterization of buildings with was developed for a real case of verification under steady room temperature [43]. Using surface temperatures measured on adjacent rooms and operational characteristics of heating and ventilation equipment one calculated the response of the building exposed to the variable outdoor climatic conditions. The paper [45} showed ANN model can estimate a mathematical relationship with high precision when following two stage selection procedure: (a) for a number of neurons in hidden layer with view to network stability and fitness under randomly changing initial conditions, (b) for relative errors of the network. The absolute value of the relative errors ($MaxARE$ [12, 45]) was determined for this estimator to less than 1.4% for each of the ANN development stages, which proves that our objective of monitoring and field performance characterization in a complex interacting environment can be reached.

While the papers [43, 45] presented a road map for design and evaluation of ANN-based model of the given performance aspect under the steady state, in the next step we will expand the neural network for adaptable indoor climate conditions with thermal gradient and air pressure gradient as two separate driving forces.

4.2. Application of Environmental Qualtiy Management (EQM) technology

The concept of EQM technology was initiated ten years ago [44,45] and is far from being completed. Nevertheless, this progress report can accelerate retrofits as the EQM concept has already been verified in practice.

Historically, the thermal mass effects on energy consumption were eliminated because:

- Large glazing fraction and leaky wall window interfaces increased short circuits by air and solar energy transfer across the walls,
- High precision in maintaining constant indoor air temperature eliminated effect of heat storage
- A large window delivers solar heat to a floor. With limited efficiency of air circulation, one must reduce solar loads by shading or increase the capability for heat removal by employing hydronic systems [31,32,33]. In the EQM technology one recommends locating heating pipes in the interior walls and cooling in a perimeter of the kitchen floor. (Kitchens and bathrooms have only floor heating system). Sometimes, the heating, cooling and ventilation functions are combined, e.g.in retrofitting panels.

The location of radiant heating is important. Hu, using Energy+ with air-film coefficients typical for horizontal and vertical orientations showed significant differences (Table 2) [45]. These panels had small thermal resistance, about 1.0 (m^2·K)/W) while the heating efficiency was about 90%.

Table 2. The effect of radiant panel location on energy demand in dynamic operations.

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

Experience with low energy buildings in the NA indicated that traditional air mixing methods are not sufficient to equalize summer room temperatures [39]. Thus, the EQM technology proposes two additional measures for temperature equalization:

- Individual ventilation on demand in rooms with solar input.
- Use of a hybrid ventilation system with overpressure of the supply air. For this case the current moisture management in walls is insufficient and must be improved.

Heating panels may include air gaps for individual ventilation [46,47]. This concept is not new and studies on dynamic walls in Centre Recherche´ Industrielle de Rantigny, France, in the 1980s, showed that the difference between static and dynamic thermal performance of walls is negligible. When the wall is provided with an air gap to act as a heat exchanger, one can also improve its moisture management by covering the wall surface with capillary active layer. In this case, the air gap is contained between a capillary active layer on the one side and the interior thermal insulation. The latter, generally is provided with an interior water-vapor retarder.

In cold climates, in winter, air relative humidity is below 50%, and air passing through a ventilated cavity may slowly remove moisture from the old wall as the capillary-active layer is designed to enable transport of water from the wall to the ventilated space [11,48,49].

4.3. EQM in the context of other research projects

The breakthrough in practical application of EQM technology came in 2020 with an ASHRAE Technology Award that recognized outstanding achievements in innovative designs of buildings for occupant comfort, indoor air quality and energy efficiency in a Shogakukan building in Tokyo, Japan with Thermo Active Building System [42], that is another name for EQM technology. Using night temperature of 19 °C and increasing to 20 ˚C in the morning and later during a period from 9:00 to 15:00 increasing to 26 ˚C thermo-active system followed the adaptive climate prescription. Hydronic radiant cooling was installed in ceiling by using a box-like construction of the floor to replace the suspended ceiling construction. The exhaust air from the room was used to cool the floor making a double cooling system. Post-occupancy optimization of the HVAC (he second requirement of EQM technology) was made in 2017-2018 and the cooling energy used by the building was reduced to 12 kWh/ (m^2·a).

The layer of exterior thermal insulation in Shogakukan was very thick, namely 450 mm. because the split between water and air in Tokyo was 50/50 while in the EQM technology we require at least 90% on the hydronic side allowing reducing thickness of standard insulation by about 50%. Use of concrete walls and floors is ideal from the thermal mass point of view but having no choice we may resort to another means to provide interior thermal mass to the building. Nevertheless, replacing concrete walls with multi-layered structure will introduce a big and still unresolved problem of modern construction, namely the interstitial air transport.

5. DISCUSSION ON MOVING FORWARD

A booklet entitled "A building revolution", published in 1995 [48] says: "design decision today contributes not only to the local environmental problems but to the regional and global ones, and to health problem as well". The booklet tells almost all we know today about excessive use of materials, wood in particular, water, unhealthy indoor air, the need for climate sensitive design, preferential mortgages for green houses, give examples that starting from 1985 to 1995 the fraction of triple pane windows grew from zero to 40%. Yet, this booklet, like many other books and articles did not affect the construction tends. Why?

Builders respond directly to people's needs. Within a few years of energy crises in mid-1970's the airtight houses became a norm. Yet, a ventilation rate in a single dwelling located in a multi-unit building (despite airtight enclosure), varies all over the map, because builders do not understand interzonal and interstitial air flows. One may talk about energy efficiency and quality (performance) but these are not measurable quantities and as long as we do not couple them with those features that the occupant understands e.g., thermal comfort, heating or cooling bill we will not affect the market place.

5.1. Looking for the "market pull" in retrofitting

Individual comfort and control of the indoor environment are the established components of the market pull, now the Covid19 experience is adding the need for variable ventilation rates and possible elimination of recycled air. Less important but still on the positive side is elimination of visible heaters or ventilators in favor of devices hidden in the construction. Finally, on the cost side we are looking for trade-offs. Concept of the Passive House in Germany won because the funds were reverted from very expensive boilers to an improved building enclosure.

One proposes a two-stage construction pattern to both new construction and retrofitting to ensure that the second stage of construction becomes a subject to low-risk, long-term capital-based financing. As such it may generate funding for local contractors and suppliers to boost to the job market but the occupants will be able to improve their comfort and reduce the cost of home ownership and thereby the society will reduce the carbon emissions. Therefore, one will use the holistic approach and a streamlined design process.

Inclusion of building automatics significantly increases the cost of buildings so it must be seen as a necessity for integrating indoor environment with energy, as means to introduce monitoring application for performance evaluation (MAPE) that in itself leads to HVAC optimization and smart house development. The main reason for exposing the role of building automatics is the fact that it is an enabler to many small improvements and modifications that compounded willr educe the cost of the building system.

5.2. Using adaptable indoor climate.

The main reason for the reduction of the climate impact of buildings is the fact the proposed design is based on adaptable comfort (De Deer, [49]). Hancock and Warm, proposed the extended-U model, called a *Maximal Adaptability Model* that discuss relatively stable broad range and rapidly deteriorates at the boundaries of thermal acceptability as illustrated in Figure 6.

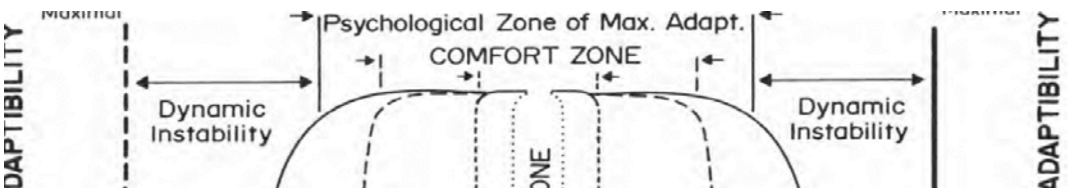

Figure 6. Relation between stress and adaptable comfort zone [49].

Over the whole optimal range of the indoor temperature the relative performance does not fall less than 4 percent. Effectively, if the temperature changes slowly e.g., 1 °C during 1-hour period, occupant do not feel any discomfort. As standards in Europe and North America permit using adaptable climate, the only reason for keeping a constant indoor temperature can be a tradition. Seventy years ago, a thermostat relied on a contact between platinum wire and mercury. Later people tried to vary thermostat setting to find that what they saved on switching once, they lost on switching back because they modified only one factor in an inert passive system. Today with advanced, active systems, coupled with thermal mass contribution this is a non-issue.

Adaptable comfort was used in the Tokyo's application of EQM technology (termed as thermo-active) [42] and is critical to all climates having large difference between temperature during day and night. It is also critical if an increased effect of thermal mass (or other means of energy storage) is used for interaction of the building with smart electrical grid.

5.3. Understanding air flows in the building

The second critical of the proposed design relates to understanding of air flows in buildings. This part of building science is probably one most neglected area in the construction practice and not much progress was made since 1990's when the interstitial airfield was defined [50 - 52]. The model shown in Figure 7 represents an electrical analog of the hotel room [50]. The airflow rates are represented by current, differential air pressures (V) and the flow resistance relates to the air leakage path (R). Ambient air pressure under no wind is considered as electrical "ground." Electrical generators represent the "drivers" such as wind, stack and effects of mechanical systems. Alternating current generators (AC) represent wind whereas direct current generators (DC) represent stack effects (temperature differences = constant voltage), exhaust or supply for HVAC system (generator with constant current). The DC generators are used in two different forms, in one form they provide a constant voltage, and in the other form they provide a constant current. This is analogous to representing the stack effect (constant voltage) and an HVAC system flow (constant current). This approach was used in Sweden and USA since 1960's to highlight connectivity of building spaces and the leakage effects of HVAC systems where the nodes represent either rooms or interstitial spaces. One can see the mass balance at each node while allowing the introduction or removal of flows at intermediate "nodes."

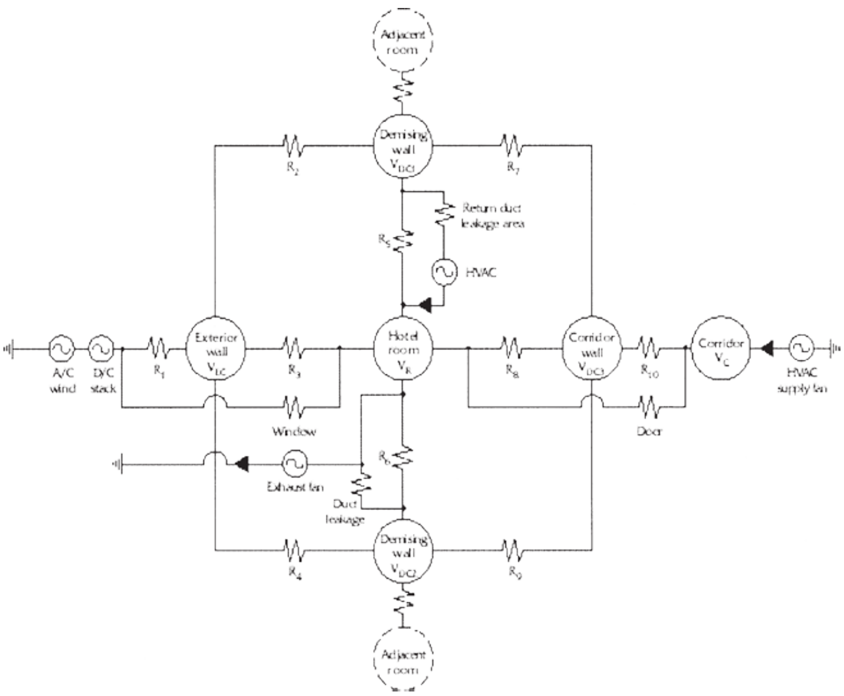

Figure 7. Lstiburek [50] defined various components of air flow on example of a hotel room using an electrical analogy. Reprinted with permission.

As we know, calculation of energy is not possible without consideration of air flows through the enclosure and interior walls of the building [50] we have introduced as the gradient of air pressure as a second driving force in the ANN energy model. Nevertheless, research should be undertaken to develop test methods for the control of air movements in buildings because they are critical for control systems and this knowledge will decide if progress in energy efficiency and indoor environment is achieved. As long as ventilation was roughly constant one could measure flows and adjust some valves connecting air ducts, but with recent progress in variable ventilation rate in is a need to quantify air flows more precisely and this becomes an important area for research needed for dynamic operation of buildings.

It is easier to control dynamic air flows if an over-pressure of air is used. But to do so, there is a need to control the moisture balance in materials. Furthermore, to perform interior retrofit it is often necessary to dry existing walls or even roofs and the whole new technology of ventilated air cavities with or without capillary active layers is this second necessary area of future research.

The lessons from Covid19 are clear. In traditional mechanical ventilation systems only part of the air is removed, and the incoming fresh air is mixed with the returned air in an air handling unit. We talk about air dilution because the whole volume of indoor air is removed in a period of 2 or 3 hours. Even in the carefully controlled ventilation, e.g., in the cabin of the airplane, a natural convective heat of passengers powers an internal loop mixing the old and fresh air. Effectively, when we talk about reducing ventilation to the level need for breathing, i.e., air exchange rate 0.33 ach it means that the whole volume is air is removed in 3-hour period, we assume that there are no stagnate zones of air i.e., a perfect mixing in all spaces. This is a minimum of ventilation for a cold day of winter. Yet, in spring or fall when we have excess thermal energy stored in the walls or furniture, we should be able to have 300 % of the minimum and if here is someone with flue or other airborne virus, we need perhaps reduce the time of air exchange to ½ hour i.e., have 600 % of the minimum. Design of such a ventilation today is as easy as the standard ventilation and a number of papers were recently published in California (where the climate is the envy of many) explains it advantages. The same is possible in other climatic zones, under two conditions (a) we must use an integrated design and have a precise model energy to tell us for how long we may increase ventilation to a given level not to modify room temperature for more than one-degree K (two- degrees F). In this context, the lesson from Covid19 is that all residences could benefit from using the so called DOAS (direct outdoor air supply) technology. The central supply of air is going first through a heat exchanger, dehumidifier and HEPA filter and is pressurized to 10 Pa above the reference level. Each exhaust air outlet should be placed on the same floor level, air going either through a separate heat exchanger or through the wall that functions as a heat exchanger. Adding exhaust ventilation on demand is optional. It can be installed in solar exposed rooms with large area of windows and provided with a manual or automatic operated exhaust ventilator. An automatic function of the ventilation system is used during the nighttime to clean the whole dwelling (and to reset it to a reference temperature if an adaptable climate control system is used).

5.4. Increasing interior thermal mass in the building

Adaptable comfort was used in the Tokyo's application of EQM technology (termed as thermo-active) [42] and is critical to all climates having large difference between temperature during day and night. It is also critical if an increased effect of thermal mass (or other means of energy storage) is used for interaction of the building with smart electrical grid. The Tokyo application [42] uses concrete as it has the thermal mass and physical properties suitable for mechanical loads in Japan, yet concrete exterior walls are not likely to be found in our buildings. This forces us to consider what would be the best modeling capability for a distributed mass.

There are two possible approaches in modeling: (a) simultaneous simulation (co-simulation) of two differential equations models or (b) monitoring and ANN-based performance model. Speaking about approach (a), some work showed co-simulation of Energy+ and Contam [30] give results different from running these models separately but does not improve precision of these models. Conversely, using a modular statistical package [10], and ANN model [45] appears to give much lower uncertainty. The issue was partly discussed elsewhere [40,53-57]. Yet, considering that ANN model is capable of addressing the real occupancy and climate factors measured under field conditions, we decided to share it with other researchers. As Confucius said "the 3000 miles journey must be started with a first, small step"; this paper is a step on the path to building automatic controls to provide a dynamic operation of buildings that are based on the adaptable indoor climate and upon these conditions the type (b) model is a winner.

In September 2019 issue of ASHRAE journal, there is an article entitled: "Renovation extends Building Life 100 years "[58]. It presents a transformation of an old US Army warehouse into energy efficient community cultural center and home for 21st century art students. The article says: The project is a model for sustainable renovation as it promotes economic and environmental values by addressing thermal mass, daylight, tempered and filtered direct outdoor air supply (DOAS) ventilation and high efficiency radiant slab for heating. Energy bills are 76% better than modeled results.

6. FUTURE RESEARCH

In the first part of the paper, we presented the background that led to the integration, in the second part we exemplified the integrated concepts of the building science and the following, closing part of the paper we identify the critical research issues that needs to be addressed in the transition to the next generation of the building science. We group these issues in the following sections:

- Real time hygrothermal and energy modeling
- Wetting and drying of existing walls

HVAC optimization

1. Real time hygrothermal modelling

1.1. Improve hygrothermal models in the following aspects:

(a) the continuity of momentum for water transport on all boundaries i.e. linkage between rate of the flow inside of the porous medium and in the air as the current model use Lewis analogy that is not valid for a multiphase waterflow,

(b) introduce the independent domain approximation for dealing with the capillary hysteresis of water,

(c) introduce the limit of water saturation for modeling of air flow without effect of air entrapment

1.1. Verify experimentally the transfer of water vapor to a moving air in ventilated cavity for the whole range of laminar, transitory and turbulent flows

1.2. Develop a test method for determination of air connectivity of the exterior enclosure with adjacent materials or spaces

1.3. Introduce correction for (1.2) to energy model conforming to the requirements (1.1) and compare with a verification field measurement

2. *Monitoring application and performance evaluation (MAPE)*

2.1 Provide guidance on monitoring those properties that are needed for the ANN model

2.2 Verify ANN energy model on dynamic application to the real case of evaluated building

3. *Wetting and drying of the capillary active material*

3 .1 Develop capillary active board to replace current dry wall (MgO or gypsum based)

3.2 Study its performance on at least 2 m long cavity to establish the sequential drying and wetting

3.3 Establish optimum overall conditions and guidance for application of the ventilated cavity in moisture management

Completing the elements from the above list would permit one to use over-pressurized supply ventilation with the dynamically ventilated interior cavity that is a proposed solution for the interior retrofitting technology

7. CLOSING DISCUSSION

“It’s a strange thing about the human mind that, despite its capacity and its abundant freedom, its default is to function in a repeating pattern.” Nicole Krauss in a letter to Van Gogh

These are the words that come to mind when thinking about the history of residential buildings. Activity, started about 5,000 years ago, looking from user point of view, only about 100 years ago became organized in scientific manner, has always been based on a tradition. There is an ongoing transition to science, yet it is not complete. When the transition is complete, Building Science has the potential to be highly efficient with impact on the rate of climate change.

To understand how complicated is the retrofitting situation today, we return to 2008, when a Federal and New York State Governments sponsored project “High Environmental Performance” (HEP) house in de Witt, NY was completed. This project was to verify the potential for passive retrofit measures and the yearly use of energy by the HEP house was 55% lower than one required by the 2004 NY standard. In 2008, at a national conference the Lawrence Berkeley National Laboratory (LBNL) presented a plan for the future energy reductions. It included two routes, one with a 90% reduction in new buildings and the second for retrofitting of all existing buildings. While the first route is on track, the second one is stalled. This is a serious problem that must be addressed because there is abundance of technology that is not used in retrofitting.

On the side of technology, we have presented an award-winning technology demonstration in Japan [42], recent progress in the increased ventilation approach in California, new developments in ANN technology where a full-scale test showed the *total uncertainty of 1.4%, for energy [45] and 4% for indoor climate [55} i.e,.* a precision beyond the capability of the traditional modeling. We highlighted the synergy between various measures used in Tokyo building [42] and US Army warehouse [58].

On the side of science, we explained that in 1947, building physics introduced an air cavity behind rain screens to control rain penetration. In 2020, building physics focused on the indoor environment, postulated presence of a second air cavity dividing the existing (*structural part of the wall*) from interior environmental control panels. The presence of cavity permits to use one of the two approaches: analytic or analog. If analytic approach can be used, the second air gap jointly with thermal insulation, phase change materials and/or capillary active layer will provide a heat and mass exchange function. If the risk for freeze-thaw damage is small, e.g., moderate climate, the air and moisture barrier can be applied on the surface of the existing wall allowing on environmental separation of both parts of the wall. Thus, if it is not the science or technology than it must be the lack of social responsibility that prevent the progress in retrofitting.

While new building construction has long time ago moved towards the scientific basis, the retrofitting still clings to rapid return on investment on separate actions instead of the whole system.

Kuhn [59] observed that evolution, with small changes accumulating for some time, creates a situation when a big and noticeable change (often called a revolution), takes place for almost no reason. Today, we observe that such a revolution is waiting on the society push and the smart building technology will come through.

8. CONCLUSIONS

The above paper may be summarized with the following are the conclusions:

1. We have technology to retrofit existing buildings but to use it we must change the paradigm of our thinking. We cannot continue designing pieces and put them together, we must first design the whole system and select material or components to fulfil specific functions that satisfy the system.
2. When using integrated design process and trade-offs between subsystems we may reach the required effect with lower cost and make retrofitting affordable.
3. To this end we propose:
   - (a) 2-stage construction process
   - (b) Use of heat pump and geothermal and /or solar energy with a storage of its excess
   - (c) Integration of hydronic heating, cooling and hybrid ventilation sources with the building enclosure or interior partitions
   - **(d)** Building automatics as a part of design that enables electronic control of thermal mass contribution in the adaptable indoor climate
   - (e) Building automatic system includes a monitoring application and performance evaluation (MAPE) system to increase the occupant comfort and reduce energy use containing a Modular Statistical System and an Artificial Neural Network
   - (f) The MAPE system increases the flexibility of energy demand and improve the building interaction with an electrical grid. The indoor environment is design to allow 5 °C daily changes over 5 or 6-hours period and resetting at the time selected by the grid load distribution
   - (f) Panelized system, for ensuring the quality assurance and labor training for the field installation
4. An example of environmental quality management (EQM) technology was used to demonstrate the approach to retrofitting design, the subsystem used in the EQM can be modified as long as the main elements of EQM such as system integration that includes heat pump, some type of energy storage, solar thermal and PV panels , 2-stage construction process and building automatics are included.

Supplementary Materials: none

Author Contributions: All authors participated equally in all aspects of the paper, MTB and ARZ – conceptualization and methodology, DWY conceptualization and writing

Funding: This research received no external funding

Institutional Review Board Statement: Not applicable

Informed Consent Statement: Not applicable

Data Availability Statement: Not applicable

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Continental Automated Building Association, Press release Dec 16,2020
2. **https://zeroenergyproject.org/case-studies/white-claw-farm-net-zero-deep-energy-retrofit** (visit May 10, 2020**)**
3. The results of a 1-year Net-Zero-Energy Home case study, https://cleantechnica.com/2016/08/31 (visit May 10, 2020

4. Thorsell T and Bomberg M, Integrated methodology for evaluation of energy performance of the building enclosures. Part 3: uncertainty in thermal measurements. Journal of Building Physics 2011, 35: 83–96.
5. Bomberg M, M. Gibson M and J. Zhang, A concept of integrated environmental approach for building upgrades and new construction: part 1—setting the stage. Journal of Building Physics, 2015, 38(4): 360–385.
6. Bomberg M, Wojcik R and Piotrowski Z (2016a) A concept of integrated environmental approach, part 2: integrated approach to rehabilitation. Journal of Building Physics 39(6): 482–502
7. IEA HPT Annex 40 Internet: http://www.annex40.net (IEA HPT Annex 40 is a corporate research project on heat pump application in Nearly Zero Energy Buildings (HTP = the Heat Pumping Technologies, IEA=International Energy Agency).
8. Bomberg M., Brennan T., Henderson H., Stack K., Wallburger, A., Zhang J., 2009, High Environmental Performance (HEP) — residential housing for NY state. *A Final Report to NY State Energy Research and Development Agency and National Center of Energy Mgmt and Building technology,* manuscript, 2009, USA
9. Brennan, T.; Bomberg, M.; Henderson, H.; Stack, K. Quality Assurance and Commissioning Process in High Environmental Performance (HEP) House in NY State. Available online: http://www.thebestconference.org/best1 (own copy)
10. Wallburger, A., Brennan, T., Bomberg, M., & Henderson, H. (2010). Energy prediction and monitoring in High Performance Syracuse house. Retrieved from http://thebestconference.org/BEST2
11. Romanska-Zapala A, P, Dudek, M, Górny and M. Dudzik, Decision-making algorithms for sustainable built environment: Part 1: Modular statistical system for an integrated environmental control, submitted to NSB 2020
12. Romanska-Zapala A and M. Bomberg, Can artificial neuron networks be used for control of HVAC in environmental quality management systems? Central European Symposium of Building Physics, Sept 23-26, 2019, Prague
13. Dudzik M., A. Romanska-Zapala and M, Bomberg A neural network for monitoring and characterization of buildings with Environmental Quality Management, Part 1: Verification under steady state conditions, Energies, 2020 (13)
14. Dudzik M, Toward characterization of indoor environment in smart buildings; Part 1: Using the Predicted Mean Vote criterion, submitted to J. of sustainability, 2020
15. https://zeroenergyproject.org/zero-energy-building-case-studies,
16. Häupl, P.; Grunewald, J.; Fechner, H. 1999 Moisture behavior of a "Gründerzeit"-house by means of a capillary active inside insulation, Proceedings of the "Building Physics in the Nordic Countries 1999, pp. 225-232, Gothenburg
17. Finch, G., Burnett, E., & Knowles, W., Energy Consumption in Mid- and High- Rise Residential Buildings in British Columbia, 2010, EE3-3. Retrieved from www.thebestconcerence.org/BEST2
18. Private communication with Mr. G. Finch, Sept 2010
19. Kisilewicz, T; Fedorczak-Cisak, M; Barkanyi, T, Active thermal insulation as an element limiting heat loss through external walls, *Energy and Buildings*, Volume: 205, UNSP 109541, DOI: 10.1016/j.enbuild.2019.109541, DEC 15 2019
20. Fedorczak-Cisak, M ; Radon, M, New generation window glazing and other solution in low energy buildings, *Sustainable building and refurbishment for next generations,* 2013 p. 333-336,
21. Romanska-Zapala, A ; Furtak, M ; Fedorczak-Cisak, M; Dechnik, M, Cooperation of a Horizontal Ground Heat Exchanger with a Ventilation Unit During Winter: A Case Study on Improving Building Energy Efficiency, 3rd World multidisciplinary civil engineering, architecture, urban planning symposium (WMCAUS 2018), IOP Conference Serie Materials Science and Engineering, 2019, 471, DOI: 10.1088/1757-899X/471/9/092075
22. Romanska-Zapala, A; Furtak, M ; Fedorczak-Cisak, M; Dechnik, M, Need for automatic bypass control to improve the energy efficiency of a building through the cooperation of a horizontal ground heat exchanger with a ventilation unit during transitional seasons: case study, 3rd World multidisciplinary civil engineering, architecture, urban planning symposium (WMCAU), IOP Conf. Mat. Sci. and Eng. IOP Publishing: Bristol, UK, 2019, 471, DOI: 10.1088/1757-899X/471/9/092076, 2019
23. Fedorczak-Cisak, M. Knap, K. Kowalska-Koczwara, A. Pachla, F. Pekarchuk, O, *Energy and Cost Analysis of Adapting an Existing Building to 2017 Technical Requirements and Requirements for NZEB*, 3rd world multidisciplinary civil engineering, architecture, urban planning symposium (WMCAUS 2018), IOP Conference Series-Materials Science and Engineering, V. 471, 2019, DOI: 10.1088/1757-899X/471/11/112094
24. Piasecki, M; Fedorczak-Cisak, M; Furtak, M; Biskupski, J, Expérimental Confirmation of the Reliability of Fanger's Thermal Comfort Model Case Study of a Near-Zero Energy Building (NZEB) Office Building, *Sustainability*, May 1 2019 11(9), DOI: 10.3390/su11092461
25. Fedorczak- Cisak M., Kotowicz A., Radziszewska-Zielina E, Sroka B., Tatara T., Barnaś K., Multi-criteria Optimisation of the Urban Lay-out of an Expérimental Complex of Single-family NZEB, *Energies*, 2020, 13, p.1541

26. Pazera M and M, Bomberg, Hygric properties of Portland cement and cement-lime plaster (stucco) for frame wall construction, 11th Canadian Conf. Bldg. Science and Technology Conference, Banff, Alta, 2007
27. Bomberg, M., Kisilewicz, T., & Mattock, C. Methods of building physics, Cracow University Press, 2017; pp. 1–301
28. Extracted from the Swedish Technical Journal in the field of building materials and technology.
29. Bomberg Mark, Tomasz Kisilewicz and Katarzyna Nowak, Is there an optimum range of airtightness for a building, *J. of Building Physics*, Vol. 39 (4), 2015
30. Trechsel H.R. Ed., Moisture analysis and condensation control in building envelopes, *ASTM manual series* MNL 40, 2001, ASTM 23
31. Heibati, RS, W Maref, HH Saber, Assessing the Energy and Indoor Air Quality Performance for a Three-Story Building Using an Integrated Model, Part 1: The Need for Integration, *Energies 12* (24), 4775, 20
32. Romanska-Zapala, A., M. Bomberg, M, Fedorczak-Cisak, M. Furtak, D. Yarbrough and M. Dechnik, Buildings with environmental quality management (EQM), part 2: integration of hydronic heating/cooling with thermal mass, Journal of Building Physics, 2018, 41(5) p. 397–417
33. Yarbrough DW, M Bomberg, A Romanska-Zapala Buildings with environmental quality management (EQM), part 3: From log houses to zero-energy buildings, *J. Build. Phys.* 2018,43
34. Romanska-Zapala, A., Bomberg M., Yarbrough D., Buildings with environmental quality management (EQM), part 4: A path to the future NZEB. *J. Build. Phys.* 2018, *43*, 3–21
35. Fadiejev J. R. Simonson, J. Kurnitski, M. Bomberg, Thermal mass and energy recovery utilization for peak load reduction, Energy Proceedia, 132, 2017, 38
36. Golembowicz M., Heat and moisture investigation of the plastic-only building. (In Polish), Bulletin Inf. Naukowo-Tech. ITB, Warszawa, No.23.,1967

36 Wright G., Klingenberg K., Climate-specific Passive Building Standards, U.S Department of Energy, Building America Program, Office of Energy Efficiency and Renewable Energy.2015

37 Klingenberg, K., Kernagis, M., & Knezovich, M. (2016). Zero energy and carbon buildings based on climate-specific passive building standards for North America. J, of Building Physics, 39, 2016, 503–521.

38 Atelier Rosemount, Canada Mortgage and Housing Corporation, Newsletter, 2016

39 Mattock Ch., Harmony House EquilibriumTM project, Canada Green Building Council, Annual Conference Vancouver, B.C. June 8 to 10, 2010, HD+C Ltd

40 Yarbrough D., Bomberg M., Romanska-Zapala, A., On the next generation of low energy buildings, Advances in building energy research, Adv. In Building Energy Research, Special Publication 2019, DOI /10.1080/17512549.2019.1692070

41 White paper, Energy efficiency and durability of buildings at the crossroads, Building Enclosure Technology and Environment Council, National Building Enclosure Council and Nat. Institute of Building Science. Sept. 2, 2008

42 Kosuke Sato, Eri Kataoka; Susumu Horikawa, Thermo Active Building System Creates Comfort, Energy Efficiency, J, ASHRAE, March 2020,62(3), p42-50, ASHRAE.org

43 Piotr Dudek, Mariusz Górny, Laura Czarniecka, Anna Romańska-Zapała, IT system for supporting the decision-making process in integrated control systems for energy efficient buildings, 5th Anniversary of World Multidisciplinary Civil Eng.-Archit.-Urban Planning Symposium - WMCAUS 2020, Prague, Czech Republic, 2020

44 Bomberg Mark, 2010, A concept of capillary active, dynamic insulation integrated with heating, cooling and ventilation, air conditioning system, Frontiers of Architect. & Civil Eng. China 2010, 4(4): 431–437

45 Hu, X., X. Shi and M. Bomberg, Radiant heating /cooling on interior walls for thermal upgrade of existing residential buildings in China, presentation to In-Build Conference, Cracow TU, 2013, (own copy)

46 Gnoth, S., P. Häupl and H. Fechner, New Aero-Thermo-hygric Behavior of Building Structures with Open and Closed Cavities, retrievable from sgnoth@abv.fh-lausitz.de

47 Simonson C.J. M. Salonvaara, T. Ojanen, Heat and mass transfer between indoor air and a permeable and hygroscopic building envelope: p. II – verification and numerical studies, J. of Bldg Physics, 2004, 28 (3): 161-185

48 Roodman D. M. and N. Lenssen, A building revolution: how ecology and health concerns are transforming construction, World watch paper 124, March 1995, pp. 1-67

49 De Deer, Richard, and Fan, Zhang, Dynamic Environnent, Adaptive Comfort, and Cognitive Performance, 7th International Building Physics Conférence, IBPC2018, Syracuse, 23-26 September, 2018, NY, USA p1-6

50 Lstiburek, J. W., Toward an understanding and prediction of air flow in buildings, Ph.D. Thesis, Toronto U,1999,

51 Lstiburek, J. W., Kim Pressnail and John Timusk, Transient Interaction of Buildings with HVAC System — Updating the State of the Art, J. Bldg. Physics,2000, 24(2) p111-131

52. Lstiburek, J. W., Kim Pressnail and John Timusk, 2002, Evaluating the Air Pressure Response of Multizonal Buildings, J. Building Physics, v. 25: p.299-320

53. Dudzik, Marek, Mielnik, Ryszard, Wrobel, Zofia, Preliminary analysis of the effectiveness of the use of artificial neural networks for modelling time-voltage and time-current signals of the combination wave generator, 2018 International Symposium on Power Electronics, El. drives, Automation and Motion, JUN 20-22, 2018, Amalfi, Italy, 2018, WOS:000445031300179
54. Gadek, K, Dudzik, M, Strek, A, A Novel Three-Head Ultrasonic System for Distance Meas. Based on the Correlation Method, Measur. Science Review, p.1335-8871, Dec, 2014, 1, 6, wos:000347956800005
    Bomberg M Romanska-Zapala A., and D. Yarbrough, History of American Building Science: steps leading to scientific revolution, J of Energies in review
55. Bomberg M, Romanska A, Yarbrough D, Nosek G (2018) Discussion on the Network for Envir. Quality Management. MOJ Civil Eng. 4(1): 00093. DOI:10.15406/mojce.2018.04.00093
56. Dudzik, M., Drapik, S., Jagiello, A., Prusak, J., The selected real tramway substation overload analysis using the optimal structure of an artificial neural network, 2018 Int. Symposium on Power Electronics, Electrical drives, Automation and Motion (SPEEDAM), JUN 20-22, 2018 Amalfi, ITALY, 2018, WOS:000445031300069
57. Tymchenko, O., Vasiuta, S. Khamula, O, Sosnovska, O., Dudzik, M. Hehenberger, P, Using the method of pairwise comparisons for the multifactor selection of infographics design alternatives, 20th Int. Conf. on Res. and Education in Mechatronics (REM), MAY 23-24, 2019, Univ Appl Sci Upper UT. Ukraina, WOS:000482479800022
58. Solrain, E, and Tyler Bradshaw, Renovation Extends Building Life 100 years, ASHRAE
59. Kuhn TS, The structure of scientific revolution, 1970, the Chicago University Press,

.