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Towards integrated energy and indoor environment control in retrofitted buildings

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Abstract

Only now, four decades after passive houses were designed in the US and built in Canada, the authors are able to discuss the next generation of new and retrofitted buildings in the same way. This paper presents a universal system for different types of buildings and climates that includes construction experience and is reinforcing multi-disciplinary synergies.

A next generation of technology uses adaptable indoor climate, integrates HVAC and building structure; applies field monitoring of energy and indoor environment and develops a performance model that is based on artificial neutral network. This approach, includes:

1. The self-learning ANN as a part of the building management system,
2. This management system guides energy optimization in a post-construction stage
3. A two-stage construction process for new and retrofits. The first stage prescribes investment level and optimizes performance; opposite in the second stage.

This paper highlights that some elements of the proposed methodology have already been applied in the practice. It also underlines that this integrated multi-disciplinary system can be applied with ~~a~~ different combination of technological elements.

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

FOREWORD

In the 1970's, passive houses and solar engineering were discussed as a choice for low-energy buildings. Building physics evolved and all design considerations must now be integrated. A choice between exterior or interior shading on the windows was debated in past; today, however, large windows can be built without any mechanical shading. The construction world is in transition between traditional construction and sustainable built environment. [1,2].

What is missing in this transition is a concise presentation of the science behind the examples of effective integrated technologies, where the benefits of integration are clearly identified. This leads to an **identification** of research needs. When the existing technology [3, 4, 5] is reviewed, questions about the synergy between sub-systems emerge. [6]

A certain vision was exemplified as "Environmental Quality Management" (EQM) with artificial neural networks (ANN) [7,8,9]. ANNs have been used since the 1960's in different applications, now the authors will use them for optimization of energy and HVAC efficiency based on field monitoring. It will be shown that monitoring energy and indoor climate and subjecting data to a statistical analysis prior to ANN modeling, reduces the prediction uncertainty. Furthermore, synergies including energy optimization, adaptable indoor climate and thermal mass contribution can be enhanced by a computerized control system that utilizes a forecast of weather data in the steering of the HVAC operation.

The novelty of this paper is to expose the power of integrating existing technologies. Sufficient confidence and experimental results exist today, allowing this progress report to be seen as encouragement of participation in the research described at the end of this paper. A few critical issues of the unified approach to construction are identified in the first part of this paper. The second part develops the message of this paper, namely that an integrated energy and indoor

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environment control based on monitoring-based ANN model developed for energy optimization leads to significant cost reductions, increases the number of building retrofits and thereby slows the rate of the climate change.

PART 1: WHERE DO WE START

Unsatisfactory progress in retrofitting of buildings is evident. Energy use can be cut by 30 percent at modest cost with existing techniques. 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 the retrofit focuses on elements with rapid return on investment. The concept of building as the system was firmly established three decades ago, replacing the traditional assembly of independent pieces showing that fixing one or two aspects of building performance is not enough.

1. A ROAD TO BUILDING INTEGRATION

For centuries, bricks have been improved before being given to builders. Recently, social pressure to build sustainable buildings has resulted in an integrated design process (IDP), where all critical decisions are made when the building concept emerges and before the detailed design starts [10]. The new design paradigm requires prediction of performance before a building is erected that defines assemblies that can be used to achieve the required performance. In this chapter two events highlight the need for a focus on a unified approach.

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 ~~a~~ mold in the Spring. To improve indoor environment in warm and humid climates, walls could be retrofitted with panels having a ventilated air cavity. If air intake is equipped with a de-humidifier, over-pressurized ventilation can create a heat and water exchanger. Furthermore, a thermally insulated, ventilated panel, could be covered with a capillary-active layer (Haeupl [11]) and the rate of air exchange calculated to balance the daily rate of wetting (night) and drying (day) of the cavity materials.

Such a solution could not be considered in the past for two reasons: (a) a fear of loading water in the walls under over-pressurized ventilation and (b) lack of real time hygrothermal models. This example is discussed to highlight the linkage of indoor environment and energy use or health aspects. Within 10 years of introducing airtight buildings, the National Building Code in Canada required use of mechanical ventilation for all spaces used by people. Science explained that one cannot build an energy-efficient house without controlling inter-zonal air flows and introducing air barriers into building enclosures as well as reliable ventilation and mechanical ventilation was considered more reliable than the "natural".

Today, we are one step further, because we recognize the inter-connectivity of spaces in the building that may provide the need to control use of the recycled air (a mixture between outdoor and indoor air). The experience of using the cruise boats for Covid19 isolation of people brought a tragic lesson for those who did not understand the health aspect of ventilation. (See later discussion in the future research projects)

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 [12]. An average annual energy used in MURBs during 2002 in Vancouver, Canada was 250 kWh/(m^2·yr) and the same value was indicated in 1929 [13]. We term this comparison as an "energy mirage". 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 [14], glazing systems with reflective coatings [15], earth-air heat exchangers [16, 17]. reviews of energy [18, 19, 20],

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energy compared with cost [21, 22, 23], indoor environment [24], reviews of standards and retrofits [25, 26], methods of optimization [27].

Let us analyze it carefully. The load-bearing function required thick walls and heavy floors producing a huge thermal mass. These buildings responded slowly to the exterior conditions, leveling diurnal shifts in temperature and thus tempering interior conditions. Tradition brought high ceilings, and natural ventilation. The thermal mass of the building served as a "heat battery," releasing energy in proportion to the decreasing indoor temperature.

In the 1920's, walls were airtight because on both sides they had a field-applied, lime-based plasters on porous separation (partial air gap). 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-cracking but resists formation of macro-cracking [28]. 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 [29]. 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 slow cooling until the next heating period.

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, the average, winter temperature in a room is about 5 °C higher so I see large progress achieved in two generations." Thus, if the basis for comparison between 1929 and 2002 was only in perception, why are we today relaying on perception form the parametric energy models when we design buildings.

There is one more aspect of the energy mirage, namely the role of an architect. In the past architects had a holistic view of occupants and the 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 55,000–60,000 different products [30]. 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, the above two examples showed that in the interconnected world of multiple effects, whether we like it or not, the way we design buildings is changing from piecemeal to wholistic.

1.3 The wholistic approach to construction

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

1. Sustainability should be included in each design project
2. Buildings should be rated on overall, seasonal performance
3. Results from energy and hygrothermal models should represent the real-time performance
4. HVAC needs the real optimization during the occupancy stage
5. The cost optimization must include both the initial and operating costs

<u>Design Objectives</u>

We start with resolving conflicts between society and the investor. Society wants zero or even a positive energy use in a small house. The investor wants a minimum purchase price. To alleviate this conflict, the design should include two construction stages. In the first stage the builder is limited by the cost agreed with the investor and in the second stage performance level should satisfy the society demands.

<u>Tradition was based on rating not performance evaluation</u>

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Comparative tests are typically designed for a 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 and fraction of uncontrollable air leakage; yet a minimum of the fresh air supply for the health reason is about 0.35 ACH. This limit would correspond to 1.5 ACH at 50 Pa. Thus, to compare airtightness and ventilation needs one should measure both properties and uncontrolled air leakage [31].

Energy and hygrothermal models

Parametric models [32], assume some parameters constant and calculate effect of changes in other parameters. 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 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 [33]. One is also examining WUFI+ for similar co-simulation [34] as a better match for initial design, but for optimization of energy use a different approach will be proposed later.

Our knowledge about air flows is insufficient; the uncertainty in the field testing is ten times greater than that of chamber testing. This suggests that any traditional energy model must be calibrated with real ventilation measurements. Moreover, the proposed ANN-based models must include two components: (a) heat transfer caused by temperature difference and (b) thermal energy balance with air flows. As the ANN performance model is based on measured data, it has the potential for a precision higher than achievable with traditional models.

Optimization of HVAC

In large commercial buildings one performs a post-construction optimization of HVAC. One wonders if this is also needed for 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 one realize that the only difference between commercial and residential is the scale. Furthermore, one may use a shallow, horizontal ground heat exchanger for storing an excess of summer energy or use energy transfer from overheated rooms on the northern side of the building. Independently of the technical solution used, all these control functions require an integrated system and justify a building automatic control (BAC) expert joining the IDP team.

Handling of the cost-benefit relation

In public/private collaborative programs (R2000 in Canada, Building America in the USA) one identified two critical aspects of cost-benefit analysis:

(1) Defining cost and performance level of the reference building, and
(2) Allowing trade-offs within the total limit of expenditure

1.4. Opportunities for a design change

Given the shortcoming of dealing with only one of many factors affecting the outcome, one may list the following requirements for energy efficient buildings:

1. Design a thermal lag time between 12 and 16 hours
2. Use dynamic operation of buildings and thermal storage to eliminate peak loads
3. For controlling thermal mass contribution, place energy sources in contact with the mass
4. Separate the ventilation and heating systems because their response times are different,
5. Use over-pressured delivery and local exhaust controls to ensure air circulation and effective removal of pollutants

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6. Develop new moisture management to facilitate use of over-pressurized ventilation
7. Use the same technology for all climates and all types of buildings old and new

The above points represent a holistic thinking paradigm, where we treat heat, air and moisture as inseparable components in the complex called environmental quality management. [7, 8, 9].

How does integration of different functions affect the results of modeling? Heibati et al. [33] analyzed the difference between the separate or integrated modeling between Energy Plus and CONTAM for a building located in the Northern and Southern climates of America. By using temperature fields calculated in one model as input to the air flow calculations 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. [33].

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. The co-simulation is based on dynamic exchange of temperatures and airflow rates for one-hour time steps and may be considered as a first step of integrated modeling of airtight and well-insulated two-story houses in Montreal or Miami.

1.5 Conclusions from the Part 1 review

This review highlighted the need for a wholistic approach to the cost of investment and operation as well as performance evaluation of buildings. In doing so, the parametric energy models currently used, may not be suitable for controlling and optimization of HVAC. Real time models to HVAC optimization proposed in this paper, will be based on monitoring and building characterization.

PART 2. BUILDING AS A SYSTEM

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 the 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 "online" information. In the proposed approach, the online process is modified, namely, using the guidelines on monitoring and the results of monitoring one will create a model for the analyzed building [35, 36].

2. WHOLE BUILDING PERFORMANCE

Figure 1 shows the results of energy calculations performed using actual weather data for a city in Central Europe [37]. Results are shown for two buildings, a light wood-framed structure and a heavy concrete wall, the latter with 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

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not constant; it is larger in initial conditions as more heat is stored in the heavy wall and becomes negligible when quasi steady-state conditions are approached.

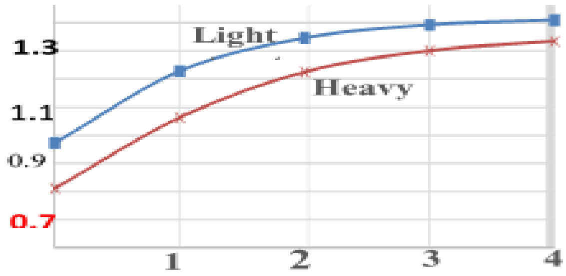

Figure 1. *Structure type impacts the design cooling load versus cooling time in days (From Fadiejev et al. [37]).*

Another comparison of older houses made in mid-1960's [38] 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, 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 will be used here. Figure 1 shows for the light wall that the 0.67 criterion is reached in 1 day while houses tested in mid-1960 showed response time 6 and 8 hours.

The difference between 8 and 24 hours in maintaining indoor comfort highlights the enormous significance of simultaneous requirements for airtightness, high level of thermal insulation and high contribution of thermal mass that in turn requires the dynamic operation of the building.

3. A TWO-STAGE CONSTRUCTION PROCESS

Figure 2 shows that a good design may reduce utility bills without increasing the cost and that some passive measures create rather small increase in the cost [39, 40]. With a larger use of passive measures, the ownership cost (mortgage plus utilities) goes through a minimum and grow. There is another characteristic point on the curve shown in Figure 2, namely a point of equilibrium in which the cost using the photovoltaic (PV) panels is the same as that of traditional passive measures. One may switch to renewable sources of energy and continue until reaching zero energy. This happens at a substantial mortgage investment, typically about 50 – 70% increase of the minimum cost. Yet, the unpublished experience from the Building America program indicates that a typical investor accepts only 10 percent increase over the reference.

Thus, the rational design of low energy buildings hinges now on the capability of selecting the reference buildings. In line with this need, the American Photovoltaic Institute selected reference buildings based on the ASHRAE / DOE climate zones [40] 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 can be generated for any location from parameters such as degree-days and design temperatures. In this manner, the passive houses moved American housing one step closer to the goal of sustainable development.

Figure 2 illustrates that typical investment based on the money return at a prescribed time, stops far below the of zero or positive energy building. To alleviate this difference, one may propose 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 cost for the selected

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performance level. In the first stage the building is completed at a minimum performance level that is acceptable to the building code and the investor, while typically the designer predicts continuation to zero energy level. The second stage starts a few years later. For small houses, the zero level will also include the night charging vehicles.

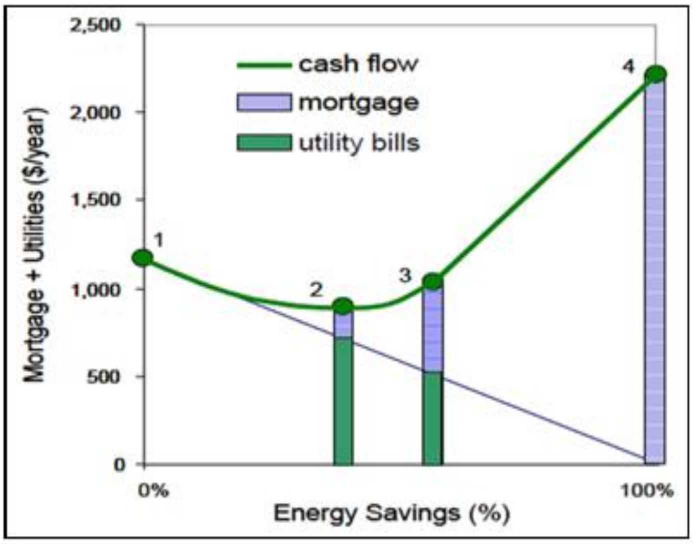

Figure 2. *Costs of utilities (green) and mortgage (blue) versus energy savings from zero savings to 100% savings. Point 1 is the starting point, point 2 the energy conservation measures alone, and point 3 the beginning of PV contribution (from Wright & Klingenberg [40] with permission).*

Nevertheless, the two-stage construction requires the design for both stages at the same time. The second stage of the project will be subject to the same financial restrictions as a retrofitting project, with two critical issues: (a) a value of the existing property versus surrounding properties and (b) estimated cost of repairs. Having a professional estimate of the cost is invaluable.

4. REHABILITATION OF BUILDINGS IN STAGES

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

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 [41]. Figure 3 shows a building with stages of energy reductions that

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were started after 2008 (the base year: 0 % energy reduction) to 2018 (92 % cumulative reduction), with steps that introduced:

1. High Performance enclosures; a common water loop; solar walls provided 36% reduction
2. Gray water power - the cumulative energy reduction grows to 42 %
3. Heat pump heating - all passive measures resulted in 60% reduction
4. Domestic Hot Water with evacuated solar panels to achieve 74%
5. 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 [7, 8, 9]. Over the ten-year period, the building energy use in Atelier Rosemount fell to 8 % of the initial level (Figure 3) [41].

5. 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 [42], quality assurance [43] and the used energy modeling [44]. The passive measures can reduce energy use by 55–60 % [36, 37, 39, 41]. Adding heat pump technology and geothermal and solar contributions to energy the total energy use can be reduced to 70 % in cold climates [45, 46] and up to 80% in warm climates characteristic of the United States or Asia [47, 48].

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 [9], e.g., using:

- Heat pumps, in cold climate, a water-sourced HP coupled with ground storage, in warm climate, a split-level HP coupled with large thermal mass
- Adaptable indoor climate approach and control systems to maintain the indoor environment in the comfort conditions [49, 50],
- Automatic systems designed already in the conceptual stage of design
- 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 [9].

6. WHAT IS NEEDED TO ACCELERATE ENERGY CONSERVATION

In 2008, an outcome of Conference was published as "Energy efficiency and durability of buildings at the crossroads" [47] to increase awareness and impact future designs in 34 local Building Enclosure Councils. This position 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."

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

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"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 was presented at the 2008 conference [47], by Dr. Selkowitz, who highlighted that market forces must be supported by public/ private initiatives. To achieve 2030 objectives both new buildings and retrofitting of existing buildings must save the same total amounts of energy. Figure 4 indicated that **all existing buildings should be thermally upgraded before 2030**. Examining Figure 4 in 2020, we are doing well with new construction; yet retrofitting is a total failure. Why?

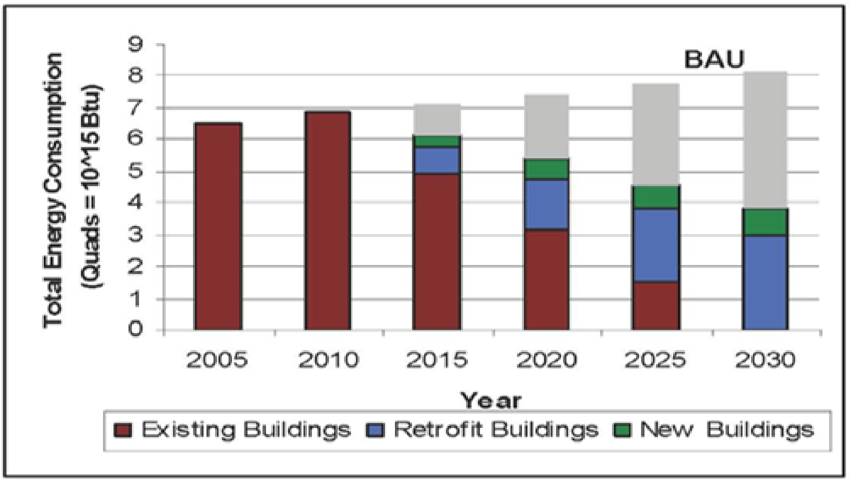

Figure 4. *What will it take to achieve 2030 targets, slide prepared in 2008 by the Lawrence Berkeley National Laboratory [47] (reprinted with permission).*

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."***

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

1) 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 carbon emissions. Stage one is unchanged. Stage two, designed jointly with the first stage is started after a few years later.
2) All residential buildings should be operated under adaptable indoor climate and use control systems to optimize heating, cooling, illumination and ventilation.
3) All building automatics is a subject to optimization of the heating, cooling and ventilation systems during the subsequent occupancy stage.
4) Even though this paper uses example of Energy Quality Management (EQM, or thermo-active building energy management system) the discussed methodology is applicable to other systems.

To allow energy optimization, we need to monitor and model the energy performance based on an individual building-energy model. The role of automatic controls was highlighted already in year 2008 for dynamic facades:

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"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 to dynamic operation of buildings. The improvement in film photovoltaics has the potential to increase the functions of 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 viability of solar reinforced shallow geothermal storage in conjunction with heat pump technology even for NY state.

This critical step 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.

7. 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·a), today it is about 50% of the previous number [3, 35] and advanced buildings use about 25% of the previous number as the (70 kWh/(m^2·a) is commonly used as the upper limit for low energy buildings. Thus, impossible forty years ago, today **a merger of solar, geothermal and passive measures is not only possible but also necessary**. 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 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, 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-steps:

1) 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.

2) 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.

3) 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?

4) 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 [9],

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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.

1.6 A concept of energy model for the control of automatics

A concept of the neural network for monitoring and characterization of buildings with Environmental Quality Management is described in [49, 50]. One start with monitoring energy performance that are collected by the MSS (Modular Statistical Software) [49]. Data collection includes recording performance 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 other 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 [49, 50] is used in the next stage of modelling.

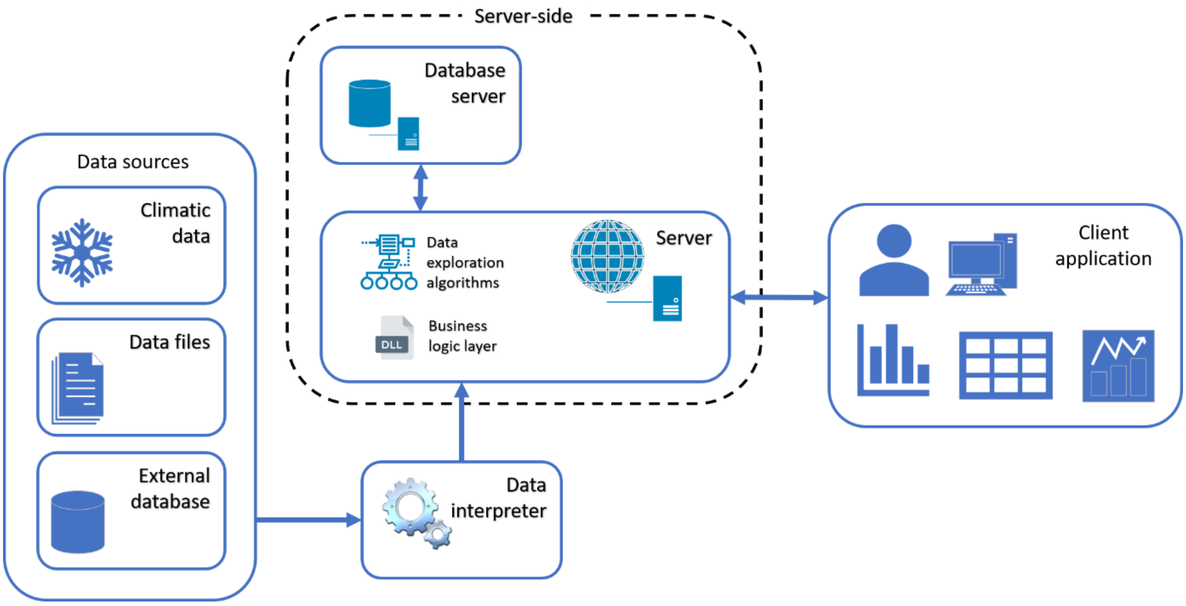

Figure 7. *Conceptual representation of modular, statistical system (MSS}.*

After a feasibility study [16], a neural network for monitoring and characterization of buildings with was developed for a real case of verification under steady room temperature [50]. 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

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variable outdoor climatic conditions. The paper [50] 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 ($MaxARE$ [49, 50]) 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 paper [47] 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.

7.2 Application of EQM technology

Work on the EQM technology was started ten years ago [51] 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. As the efficiency of air circulation is limited, one either reduces solar loads by shading or employing hydronic systems [7, 8, 9]. EQM technology recommends locating heating in the interior walls and cooling in a perimeter of the 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) [52] These panels had small thermal resistance, about 1 (m^2·K)/W) yet 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 [45]. Thus, 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. In this case moisture management in the walls must be improved.

Heating panels may include air gaps for individual ventilation [52]. 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 acts as a heat exchanger, by covering the wall surface with capillary active layer, one enhances moisture management. In this case, the air gap is contained between a capillary active layer on the one side and the interior thermal insulation that is provided with an interior water-vapor retarder.

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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, 53, 54]

7.3 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 [48], 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.

2 DISCUSSION

A booklet entitled "A building Revolution", published in 1995 [55] 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, similar to many other books and articles did not affect the construction tends. Why?

Builders respond to people's needs. Within a few years of energy crises in mid-1970's the air tight houses became a norm. Yet, a ventilation rate in a single dwelling located in a multi-unit building (despite air tight enclosure), varies all over the map, because builders do not understand interzonal and interstitial air flows. We 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.

Therefore, one must use the wholistic approach and to streamline the design process. Passive house in Germany won because money was reverted from expensive oilers to 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.

The main technical reason for the reduction of the climate impact of buildings is the fact the proposed design is based on adaptable comfort (De Deer, [56]). 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 (Figure 6). Over the

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whole optimal range of the indoor temperature the relative performance does not fall less than 4 percent. Effectively, as long as 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. 70 years ago, the 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.

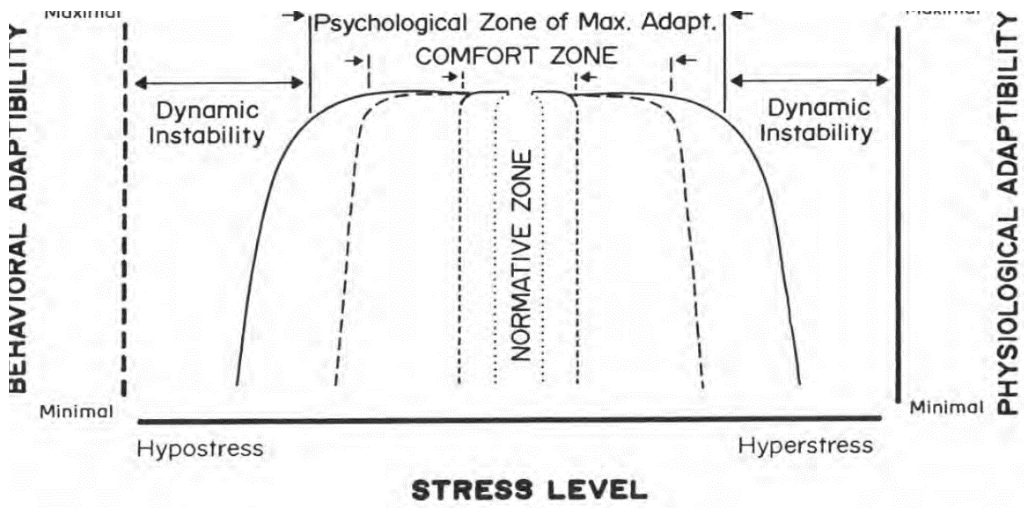

Figure 6. *Relation between stress and adaptable comfort zone [56].*

Adaptable comfort was used in the Tokyo's application of EQM technology (termed as thermo-active) [47] 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 second critical of the proposed design relates to understanding of air flows in buildings. This part of building science is probably the single most neglected area in the construction practice and not much progress was made since 1990's when the interstitial air field was defined [57 - 59]. The model shown in Figure 7 represents an electrical analog of the hotel room [58]. 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."

As we know, calculation of energy is not possible without consideration of air flows through the enclosure and interior walls of the building [58] 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

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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.

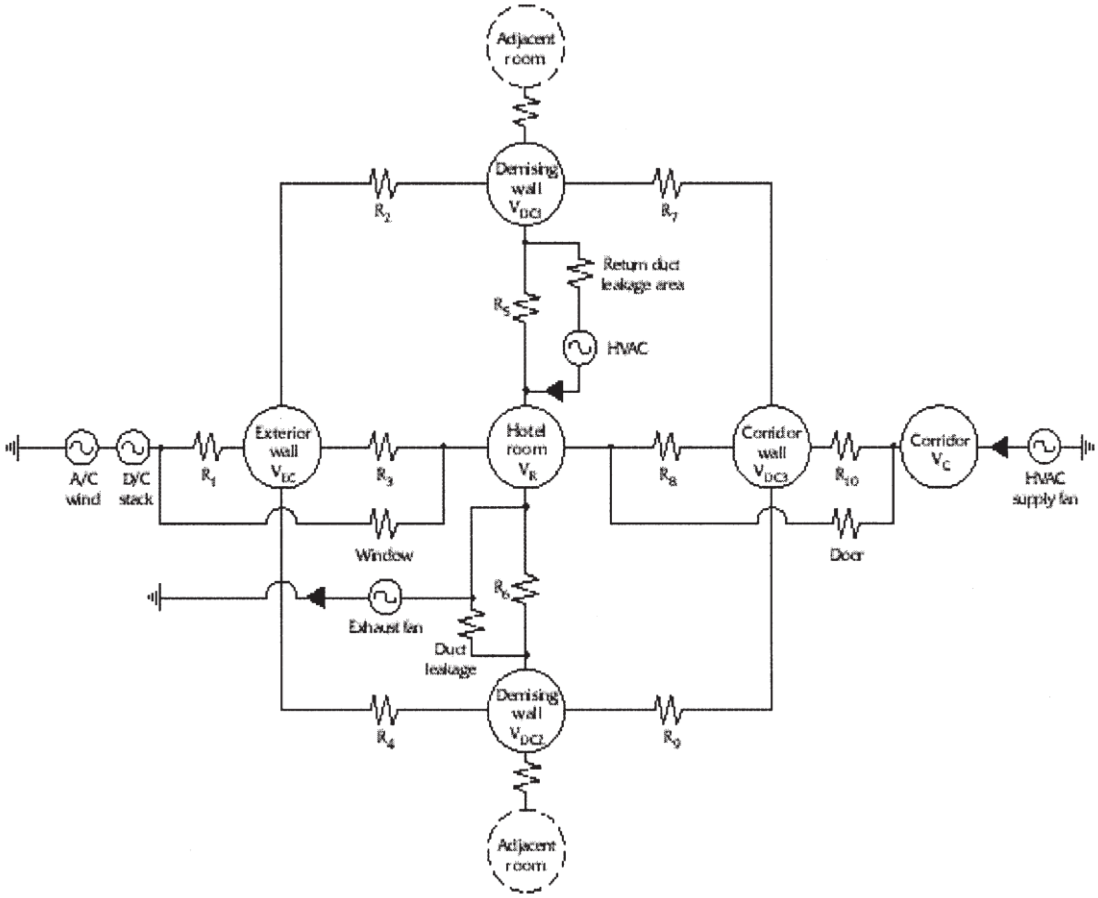

Figure 7. *Lstiburek [58] defined various components of air flow on example of a hotel room using an electrical analogy. Reprinted with permission.*

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. In 1947 a vented-exterior air cavity was introduced to control rain penetration in Sweden and in 2020 another ventilated cavity was added on the interior side to establish a new moisture management strategy for retrofitted walls.

To address water management in the walls, a capillary active material should be incorporated in the wall system. To this end organic fibers were incorporated into MgO boards [51] and they can also be incorporated into the gypsum boards. Alternatively, gypsum panels may be covered with a thin hygroscopic coating to slow the humidity changes during the ventilation of the indoor spaces.

Adaptable comfort was used in the Tokyo's application of EQM technology (termed as thermo-active) [48] 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 [48] uses concrete as it has the thermal mass and physical properties suitable for

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mechanical loads in Japan, yet concrete exterior walls ae not likely to be found in our construction. This forces us to develop a modeling capability for distributed mass situations.

After initial concepts [59, 60] and having achieved the first step of verification of the EQM technology by documenting integration Energy+ and Contam [32] as well as WUFI+ [33] a modular statistical package [48], feasibility [16] and verified under steady state ANN model [50], the history of American Building Science [62], and low-energy buildings [46], application of the statistical package [49] and a virtual network [63], and recent progress in ANN technology [64 - 66] we have decided to share EQM methodology with other researchers and jointly introduce the scientific revolution in the traditional thinking.

The critical element in this decision is the development of another alternative to parametric modeling, namely one based on integration of monitoring. The authors believe that ANN models for indoor climate and energy use are an important step to optimization of building energy performance under field conditions. 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 is based on the adaptable indoor climate.

In September 2019 issue of ASHRAE journal, there is an article entitled: "Renovation extends Building Life 100 year "[67]. 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.

In summary, with award winning technology demonstration in Japan [48], recent progress in the increased ventilation approach in California and new developments in ANN technology as well as with the verification under steady state full scale test where the ANN model showed the *total uncertainty of 1.4%, i.e.* a precision beyond the capability of the traditional modeling, the authors believe that it is time to publish this progress report. We hope that this paper provides the reader with a better understanding of the synergy between various measures used in Tokyo building [48] and US Army warehouse [67].

3 FUTURE RESEARCH

The following research issues need to be addressed:

1. *Energy modeling based on differential equations*

1.1 Introduce dynamic linkage to hygrothermal models

(1) Improve hygrothermal models with: (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 moisture saturation for modeling of air flow without effect of air entrapment

(2) 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. *Energy modeling based on ANN*

2.1 Determine a relation between the weights and interactions between factors

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2.2 Determine a method for indoor environment characterization
2.3 Provide guidance on monitoring those properties that are needed for the ANN model
2.4 Verify ANN energy model on EQM 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 regions
3.3 Establish optimum overall conditions and guidance for application of the ventilated cavity in moisture management

After completing the key elements from the above list one can proceed to evaluation of the over-pressurized supply ventilation with the dynamically ventilated interior cavity that is a proposed solution for the interior retrofitting technology.

10. CONCLUDING REMARKS

Kuhn 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 [68]. Today, we observe such a revolution is happening to the smart building technology. The idea of avoiding imports of oil combined with the social pressure for sustainable built environment led accumulation of many small changes (integrated design procedure, energy rating of buildings, green economy, and merger with information technology) to create a basis for the 4th industrial revolution. The first revolution was based on steam obtained from burning coal, the second burned oil, the third used a massive generation of the electricity and the fourth one is based on distributed energy sources combined with information technology. During the fourth industrial revolution buildings are moving from being heavy users of energy to being providers of energy.

In 1947, building physics explained the need for exterior air cavities located behind rain screens to control rain penetration. In 2019, building physics postulated the need for humidity and pollution control and focus on the indoor environment. In such a system, we postulate presence of a second air cavity dividing the structural part of the wall from interior insulation can be used to allow removal of water from retrofitted walls. The second air gap functions as a heat and mass exchanger when phase change materials and capillary active layer are included. Undoubtedly, the most important change brought to current building technology is the capability of air control and optimization of HVAC to reduce the cost of its operation while ensuring good indoor environment.

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