PART 1: WHAT IS BUILDING PERFORMANCE?

By James E. Woods, Ph.D., P.E.[1]

Many issues have changed, but others have not, in the ten years since my last series in *TABB Talk* entitled: *Current and Future Engineering Needs for TABB.*[2] This new series focuses on opportunities for an educated and skilled workforce (ESW) to learn and practice the principles that provide for the health, safety, security, and well-being of occupants while meeting the functional requirements of the facility through energy efficient control of heating, ventilating and air conditioning (HVAC) and other mechanical, electrical and plumbing (MEP) systems. The first article in this series described future challenges and opportunities that an ESW is likely to face. This and the subsequent articles in this series expand on these challenges and opportunities by addressing fundamentals for assuring quality building performance as determined at the technician, supervisor, and contractor levels: *Knowledge of What to Measure; Availability of Appropriate Instrumentation; and Interpreting Measurements* and *Evaluating Building Performance.*

Buildings primarily exist to: 1) provide safe, healthy, and secure conditions, and 2) facilitate the well being and productivity of occupants, owners, and managers. Throughout history, evaluating and controlling the performance of buildings to achieve this purpose has been pursued through available means and methods of design, construction, and operations. Vitruvius set a benchmark in about 15 BC: *"Well building hath three conditions: firmness, commodity, and delight"* (1).[3]

We have also learned from history that a clear understanding of the purpose of a building, together with knowledge of what and what not to measure, are needed before the performance of a building can be assured. Growing demands within the last 10 years for improved performance of buildings and their systems have intensified not only the need for reliable and valid testing, adjusting and balancing (TAB) of HVAC, MEP, and other systems, but also for overall assurance that the whole building is performing in accordance with the criteria needed to meet the design intent and the owner's functional requirements. This understanding begins by addressing three questions:

1. What is the basis of these growing demands?
2. Do the current criteria used in TAB and other evaluation procedures adequately address these demands?
3. Who determines what and how to measure the parameters and values for these criteria?

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2 Published in individual issues of TABB Talk, and as a set in 2003. Article 1: Current and Future Engineering Needs for TABB; Article 2: Diagnosing vs. Commissioning; Article 3: Procedures to Assure Human Responses, Occupant Performance, and Productivity; and Article 4: Procedures to Ascertain HVAC and Whole Building Performance for Normal and Extraordinary Conditions.

3 See References at the end of Part 3.of this article.

The objective of this article is to answer these questions by focusing on the fundamental importance of defining a decisive set of measurable criteria for evaluating, controlling, and assuring the intended performance of sub-systems, and the whole building as a system, throughout the phases of design and construction, and during normal and extraordinary (e.g., natural, accidental, and intentional disruptive events) operational conditions.[4] To meet this objective, this article describes means and methods by which these criteria can be credibly defined and measured by the technicians, supervisors, and contractors who comprise the ESW.

The knowledge base of the ESW must increase to meet these growing demands. This article, which is presented in three parts, is intended to encourage those with the talent and desire to accept these challenges by taking advantage of career opportunities through programs developed and offered by the International Certification Board and the Testing, Adjusting and Balancing Bureau (ICB/TABB).[5]

Part 1: What is Building Performance?

The first question[6] leads to a focus on the meaning of "Building Performance," which has evolved to have several connotations. The root of modern building performance evaluations may be the real estate industry, in which "property condition assessment" and "due diligence" reports have been prepared for decades as part of sales transactions. For these evaluations, expected building performance outcomes are calculated in financial terms (e.g., present net value of the asset, estimated cost of repairs, market price, return on investment). These outcomes can then be compared to validated references or "benchmarks" that are maintained by the industry. Similarly, the health care industry has conducted evaluations and certifications for more than 50 years to assure that the facilities perform within industry and governmental standards of health and safety (e.g., infection rates) and economics (e.g., benefits and costs per patient-day).

Due to changes in policies, regulations, marketing drivers, and advances in technologies within the last 10 years (2), expectations for "high-performance buildings" have resulted in the promulgation of additional criteria that pertain to attributes such as energy use, green buildings, greenhouse gas emissions, and sustainability. However, neither standardized methods of measurement nor benchmarks for these additional criteria have been nationally accepted for occupied buildings.

As indicated in Figures 1 and 2 in the previous article (2), performance is not static but changes throughout the lifespan of a building: each building performs acceptably, or not, during "normal" and "extraordinary" periods of operation. Assurance of quality building performance requires contiguous evaluations of residual risks through measurements of "performance," "preparedness," and "resiliency."[7]

Rational Definition

To credibly evaluate how well a building is achieving its two-fold purpose at any time during its useful life, valid and reliable measures of its performance are required. Based on principles of control theory and the assumption that a building functions as a system, such a rational definition was proposed in 2008 (3):

> **Building performance is defined as a set of measured responses of the building, as a system, to anticipated and actual forcing functions.**

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4 These phases and conditions were described in the first article of this series (refer to Figures 1 and 2).

5 ICB/TABB is the first program to gain ANSI accreditation under ISO 17024 for certification in the HVAC testing, adjusting and balancing and fire life safety industry. This certification is a statement that the technician, supervisor and contractor demonstrate the highest level of professional expertise.

6 "What is the basis of these growing demands?"

7 Resiliency is defined as responsiveness and time to recover after an extraordinary event (5)

In this definition

Measured responses are expressed in terms of valid parameters and reliable values (i.e., criteria) that are systemically linked as shown in Figs. 1 and 2 in the previous article (2; 3; 4)[8]:

Human responses are the primary outcomes of building performance. They should be:

- Defined in terms of objective, perceptive, and judgmental measures (e.g., health, safety, security, accessibility, comfort, satisfaction, acceptability);
- Measured periodically and concomitantly with occupant exposures during normal conditions; and
- Measured as needed in preparation for, and recovery from, extraordinary conditions.

Occupant exposures are defined as the sub-set of physical and social factors that directly affect human responses and system performance (e.g., physical factors: temperature, humidity, and air movement; luminance, contrast, and glare; noise and vibration; indoor airborne contaminants; social factors: demographics; proxemics; secular trends; aesthetics).

- Initial measures of the physical factors should be obtained as part of the TAB process, at or before occupancy; initial measures of the social factors should be obtained as part of the functional commissioning process (Cx).[9]
- Subsequent measures should be obtained periodically and concomitantly with human responses and system performance during normal conditions; and as needed in anticipation of, and recovery from, extraordinary conditions.

System performance is defined as the sub-set of capacity and control factors[10] that directly affect occupant exposures, resource utilization, and economic performance (e.g., air and water distribution; luminous and acoustic radiant flux; power consumption; durability and reliability; maintainability).

- Initial measures of the capacity (e.g., heat and mass transfer rates) and control (e.g., sensitivities, response times, stability, resilience) factors should be obtained as part of the TAB and Cx processes.
- Subsequent measures of these factors should be obtained periodically and concomitantly with occupant exposures during normal conditions; and as needed in anticipation of, and recovery from, extraordinary conditions.

Resource utilization and economic performance are the secondary outcomes of building performance. They are the consequences of system performance and occupant behavior (e.g., whole building energy and water use, including renewable or recyclable resources; occupant performance; facility productivity; return on investment).

- Initial measures of resource utilization (e.g., whole building energy and water use) should be obtained as part of the TAB and Cx processes during specified loads (i.e., known forcing functions – see below).
- Subsequent measures of both resource utilization and economic performance factors should be obtained periodically during normal conditions with documented physical and social forcing functions; and as needed in preparation for, and recovery from, extraordinary conditions.

Forcing functions are physical and social forces that perturb the building system and the measured responses during both normal and extraordinary conditions, as shown in Figs. 1 and 2 (2). To understand and interpret the results of the measured responses, it is necessary to document, preferably by measurement, the magnitude or influence of the concomitant forcing functions.[11]

Sources of physical forces include climate (outdoor temperature and humidity conditions); wind, rain and snow loads (hurricanes, tornadoes, blizzards); earthquakes; fires; floods; indoor and outdoor thermal, chemical and biological releases; and blasts.

8 Characteristics of the measurement instrumentation will be the subject of the next article: Availability of Appropriate Instrumentation.

9 See subsequent section on Commissioning and Diagnosing Building System Performance. Training on commissioning processes is now available through programs developed and offered by ICB/TABB.

10 Capacity factors affect system performance at full-load conditions; control factors affect system performance at all part-load conditions (5).

11 The subject of the fourth article in this series will be: Interpreting Measurements and Evaluating Building Performance.

Sources of social forces include aesthetics; economic and other factors that motivate occupants, tenants and owners; secular trends (e.g., policies on smoking, green practices, fashions); and threats (e.g., job security, reliability of utilities, criminal intent, and terrorist activities).

By this definition, the set of response parameters and their values should remain consistent throughout design and construction and operations:

The parameters of the attributes should be defined and selected to characterize a building for its intended performance during normal and extraordinary conditions.

The values of the parameters should be defined and evaluated within predetermined limits of uncertainties or expected errors during the normal or extraordinary conditions.[12]

Evidence indicates that a building is expected to perform under "normal conditions" during 90 – 95% of its lifespan (5). Throughout this time, overall building performance is likely to change as shown in Figs. 1 and 2 (2): Changes in values of forcing functions cause changes in values of response functions, some of which then produce "feedback" effects on the forcing functions.

TAB and Cx programs in which basic sub-sets of rational site-specific criteria are defined, and methods for measuring and evaluating them, are now available through the International Training Institute (ITI). Advanced programs are being developed for technicians, supervisors and contractors, in conjunction with ICB/TABB.

Promisorial Definitions Related to Building Performance

The rational definition of building performance does not presume a predetermined quality of performance. Other definitions have been promulgated that promise a certain quality of performance (e.g., green, high, net-zero energy, sustainable), but they do not define the concomitant forcing or response functions in measurable terms so that the actual building performance can be evaluated and assured under normal or extraordinary conditions.

Examples of these promisorial definitions are:

Section 401(12) of EISA-2007 (6) defines a "high-performance building" (HPB) as one that "integrates and optimizes on a life cycle basis all major high performance attributes, including energy conservation, environment, safety, security, durability, accessibility, cost-benefit, productivity, sustainability, functionality, and operational considerations."

Section 401(13) of EISA 2007 (6) defines a "high-performance green building" (HPGB) as one "that, during its life-cycle, as compared with similar buildings (as measured by Commercial Buildings Energy Consumption Survey [CBECS] or Residential Energy Consumption Survey [RECS] data from the Energy Information Agency):

- reduces energy, water, and material resource use;
- improves indoor environmental quality, including reducing indoor pollution, improving thermal comfort, and improving lighting and acoustic environments that affect occupant health and productivity;
- reduces negative impacts on the environment throughout the life-cycle of the building, including air and water pollution and waste generation;

12 See Section below on Uncertainties and Errors of Measurement.

- increases the use of environmentally preferable products, including biobased, recycled content, and nontoxic products with lower life-cycle impacts;
- increases reuse and recycling opportunities;
- integrates systems in the building;
- reduces the environmental and energy impacts of transportation through building location and site design that support a full range of transportation choices for users of the building; and
- considers indoor and outdoor effects of the building on human health and the environment, including:
    1. improvements in worker productivity;
    2. the life-cycle impacts of building materials and operations; and
    3. other factors that the Federal Director or the Commercial Director consider to be appropriate."[13]

ASHRAE Standard 189.1-2011 (7) defines an HPGB as "a building designed, constructed and capable of being operated in a manner that:

- increases environmental performance and economic value over time,
- seeks to establish an indoor environment that supports the health of occupants, and
- enhances satisfaction and productivity of occupants through integration of environmentally-preferable building materials and water efficient and energy-efficient systems."[14]

In these promisorial definitions, the physical or social forcing functions for normal and extraordinary conditions are not identified, the hierarchy of the response and forcing functions is not addressed, and the italicized terms promise improvements of response functions and processes that may not be measurable.

These definitions also reveal that risks are inherent in promising building performance that cannot be objectively measured and evaluated for compliance with predetermined and agreed upon criteria during the contiguous phases of design, construction, and operations. Some of the risks associated with the unfulfilled promises of achieving HPGBs during the design process have been discussed by Butters (8). Similar risks are also expected as a result of unfulfilled promises made to justify modifications, renovations, or changes in operations within existing buildings.

Benchmarks and Rating Scales

Within the last 10 years, the use of benchmarks and rating scales has become more common for evaluating certain attributes pertaining to promised building performance, such as "green," "sustainable," and "energy-efficient."

A benchmark is a "metric" identified to characterize a sub-system, system, or whole building at a classified or specified level of performance.[15] Benchmarks are typically established by modeling or obtaining measured data from a large number of buildings and by normalizing the results with characteristics such as climatic zones, demographic zones, seismic and flood zones, threat potentials, building sizes, functional categories, system types, and types of ownership.

Benchmarks may be expressed as quantitative averages (e.g., Energy Utilization Intensities or Gross Energy Intensities) or as qualitative descriptors (e.g., the overall facility resilience associated with safety (seismic, wind, fire or flood) or security (blast, CBR or ballistic) events (9).

Benchmarks are typically established by authorities having jurisdiction (e.g., local, state, federal AHJs) or by owner's program requirements.

13 Neither the CBECS nor RECS database provides quantitative reference data for any response function in the EISA 2007 definitions of a HPB or a HPGB, except annual Gross Energy Intensity (Btu/GSF).

14 No database reference is cited in the ASHRAE 189.1-2011 definition of a HPGB with which either modeled or measured values can be compared.

15 Definition derived from (9).

Examples of benchmarks are:

- "On January 18, 2013, the District Department of the Environment published the final rulemaking for energy benchmarking of private buildings in the D.C. Register (60 DCR 367). The rulemaking is supported by multiple guidance documents, with technical details on what needs to be reported and how, including forms for requesting utility data, and instructions for the adjustments being made to the program for its initial year" (10).
- Section 422(c) of EISA-2007 sets a "goal" to achieve zero-net energy[16] in: any commercial building newly constructed in the U.S. by 2030; 50% of the commercial building stock of the U.S. by 2040; and all commercial buildings in the U.S. by 2050 (6).
- Section 1.8.2 of the GSA P100-2014 states that "To meet the goal of reducing total site energy usage by 30 percent by 2015 as compared to a 2003 baseline, energy targets are established for all new construction. The A/E must design all new buildings to have an energy performance below the EISA 2007 energy target or 30 percent below ASHRAE 90.1 [-2007], whichever is lower" (11)

A rating scale is a set of categories or a range of numerical values designed to elicit information about a quantitative or a qualitative attribute.[17] Rating scales may be used as a basis to set benchmarks. Examples of rating scales for building performance that are currently popular in the US include:

US Green Building Council LEED™ Rating Scale (12): Certified, Silver, Gold, and Platinum building performance categories are awarded, depending on the number of "credits" applied for and allowed by a third-party evaluator.

Green Building Institute (GBI) Green Globe Rating Scale (13): One to four Green Globes for building performance categories are awarded, depending on the number of "points" applied for and allowed by a third party evaluator.

US Environmental Protection Agency (EPA) Energy Star Rating Scale (14): A numerical rating is determined as the ratio of inverse frequency distribution for normalized values of EUI to average CBECS values for the same categories of buildings (zero to 100%). Scores of 75% or higher may lead to a certification from the EPA. This scale only includes ratings for energy consumption for certain types of buildings; it does not pertain to overall building performance.

ASHRAE Building Energy Quotient (bEQ) (15): This building energy labeling program awards an energy performance rating of A+ (i.e., net zero energy) to F (i.e., unsatisfactory). For existing buildings, an In Operation label is offered based on measured energy use. For new and renovation projects, an As Designed label is offered based on a comparison of modeled energy use under as-built conditions to the modeled energy use under "standardized conditions." This label does not pertain to overall building performance.

Note that the EPA Energy Star and ASHRAE bEQ rating scales address only one attribute, energy consumption; whereas, the LEED and GG rating scales also address some other attributes. However, none of these rating scales pertain to measures of human response, safety, security, or system performance during normal or extraordinary conditions.

The basis of the growing demands for improved performance of buildings and their systems is the meaning of "Building Performance." In Part 1, rational and promisorial definitions have been discussed together with the reliability of popular benchmarks and rating scales that are being used for performance evaluations. As indicated in this Part, currently available promisorial definitions, benchmarks and rating scales, are likely to result in significant uncertainties with regard to differences between measured and promised whole building performance. Parts 2 and 3 in this article are intended to introduce methods that are capable of reducing these uncertainties through techniques that can be used by an ESW.

16 Section 422 (c) defines a "net-zero-energy commercial building" as "a high-performance commercial building that is designed, constructed, and operated (A) to require a greatly reduced quantity of energy to operate; (B) to meet the balance of energy needs from sources of energy that do not produce greenhouse gases; (C) in a manner that will result in no net emissions of greenhouse gases; and (D) to be economically viable."

17 Definition derived from Wikipedia, accessed 30 May 2013.

PART 2:

WHAT IS BUILDING PERFORMANCE?

By James E. Woods, Ph.D., P.E.[18]

The second question being addressed in this article is: "Do the current criteria used in TAB and other evaluation procedures adequately address these demands?" This question focuses on how the current TAB and other evaluation procedures can be used or modified to provide reliable assurance that the primary purpose of a building is sustained when perturbed by forcing functions. This performance can only be assured if the response functions remain balanced and resilient when perturbed by forcing functions during normal and extraordinary conditions (i.e., in "dynamic equilibrium").

Current TAB and functional Cx procedures typically result in data that pertain to discrete steady-state responses of components and sub-systems during testing periods of minimum or unknown loads (i.e., forcing functions). These procedures can result in significant time separations in data acquisition, ranging from days to months, and contain significant uncertainties with regard to dynamic equilibrium in supply and return air distribution, inter-zonal air pressurization, air-side and hydronic-side balances of heat exchangers, and controls calibration. Moreover, these procedures seldom provide concomitant data pertaining to occupant exposures, human responses or rates of energy and water utilization.

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Relational Performance Criteria

As shown schematically in Fig. 1, a set of relational performance criteria is needed to evaluate the dynamic equilibrium of the response functions among interactive subsystems, each interfacing through a building automation system:

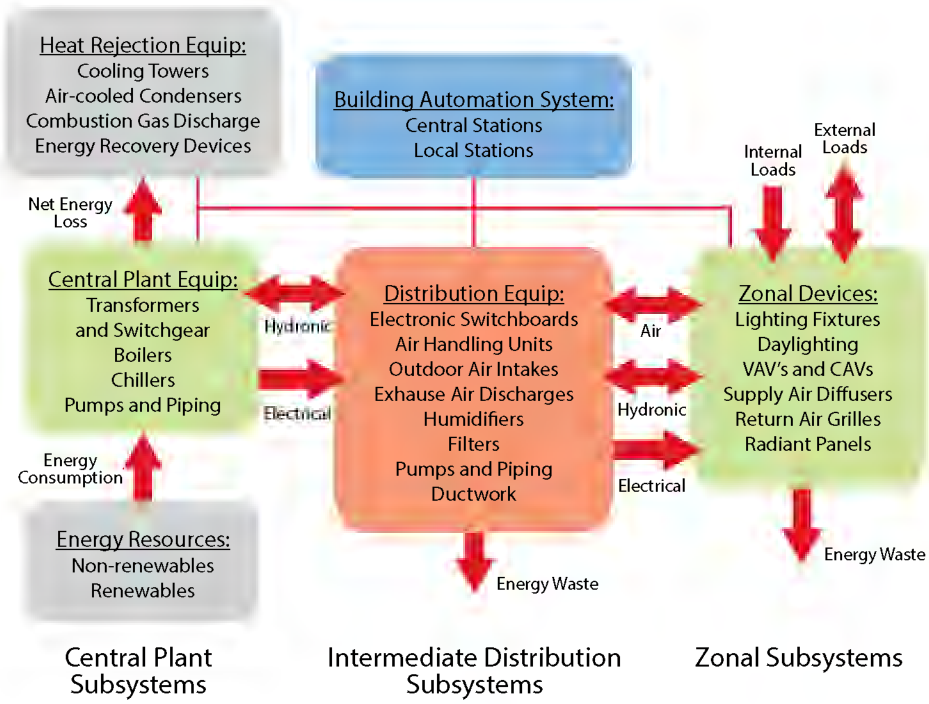

Figure 1. Schematic of an HVAC system in dynamic equilibrium.

The zonal subsystems control occupant exposure parameters within acceptable values of thermal, visual, acoustic, and air quality in response to changes in external and internal loads by balancing:

- Electrical power to lighting fixtures and controls to maintain acceptable illuminance, luminance, contrast, glare, and accessibility;
- Airflow rates to VAV and CAV terminal units, supply air diffusers, return and exhaust air grilles, and associated ductwork to maintain acceptable temperature, relative humidity, interzonal pressurization, contaminant concentrations, and noise levels in the zones;
- Hydronic or electrical power to radiant surfaces or other in-space heat exchange devices, and associated piping or electrical circuits to maintain acceptable temperature in the zones;

The intermediate distribution subsystems control the performance parameters of the distribution equipment within acceptable values in response to concomitant changes in zonal demands and central plant forcing functions by balancing:

- Electrical and hydronic throughput power (e.g., kW, Btu/hr) to the zonal subsystems;
- Conversion efficiencies of electrical and hydronic power to air transport power (e.g., Btu/hr, lb/hr, cfm) through components within the intermediate subsystems including: variable speed motors, outdoor air intakes, heat exchangers, humidifiers, air cleaners, and associated ductwork and piping;
- Effectiveness of load diversification, and switchover to emergency or standby equipment within the intermediate subsystems;
- Maintenance and operational requirements of components;
- Safety and security requirements.

The central plant subsystems control the performance parameters of the central plant and heat rejection equipment within acceptable values in response to: 1) concomitant changes in demands from the intermediate zones; 2) the availability of depleteable and renewable resources; and 3) the effectiveness of the heat rejection equipment by balancing:

- Conversion efficiencies of depleteable and renewable resources to electrical power through transformers, switchgear, and raceways; and to hydronic power through boilers, chillers, and pumping and piping systems;
- Dissipation and reclamation efficiencies of rejected heat through combustion gas discharge equipment, cooling towers, air cooled condensers, energy recovery equipment, and associated fans, ductwork, and pumping and piping systems;
- Effectiveness of load diversification, and switchover to auxiliary equipment within the central plant, including: electrical power transfer stations; generators of electrical and thermal power from renewable resources; emergency and standby electrical power generators; storage systems for electrical and thermal power (e.g., batteries, fuel tanks, and hydronic storage tanks); and domestic water storage tanks;
- Maintenance and operational requirements of components and equipment;
- Safety and security requirements;
- Energy and water utilization rates at the building boundary;
- Calculated source energy utilization and GHG emission rates;
- Economic performance (e.g., productivity, sustainability) of the whole building system.

The Building Automation System (BAS) interfaces with each subsystem and integrates the response functions to achieve the dynamic equilibrium expected for the performance of the building at all peak and part-load conditions. Because a human interface is required to assure the building performance, the sophistication of the BAS must be compatible with the availability and training of personnel who operate and maintain the systems, including the effectiveness of: (2)[19,20]

- Sensing, monitoring and controlling the indoor exposure conditions and alarms;
- Monitoring and interfacing with fire, life-safety, and security systems;
- Monitoring and controlling the energy utilization and operational costs at zonal, intermediate, central, and whole building thermodynamic boundaries;
- Monitoring and controlling renewable energy production and delivery to the building and to the grid.

The use of relational performance criteria, introduced in this Part, is intended to reduce the uncertainties inherent in the current benchmarks and rating scales described In Part 1. The use of relational performance criteria to evaluate "dynamic equilibrium" will enhance the current TAB and functional commissioning procedures and provide increased reliability in the evaluations of building performance during design, construction and operations. Part 3 further describes responsibilities and accountability for determining which parameters and values to select when an ESW is evaluating or assuring the performance of buildings.

19 See References at the end of Part 3.of this article.

20 Basic training in the operations of BAS is currently available through ITI.

The subject of the fourth article will be: Interpreting Measurements and Evaluating Building Performance.

PART 3:

DEFINING AND USING MEASURABLE PARAMETERS AND VALUES

By James E. Woods, Ph.D., P.E.[21]

The third question being addressed in this article is: "Who determines what and how to measure the parameters and values for these criteria?" This question focuses on the knowledge and responsibility of those defining the measurable parameters and values (i.e., criteria) of attributes that can be used to evaluate, control and assure, within acceptable limits of uncertainty or error, the performance of a building during design, construction, and during normal and extraordinary operations. This issue also leads to a broader question: who is accountable for the performance of the building?

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Codes, Standards, and Guidelines

CURRENTLY IN THE U.S.:

Minimum criteria and requirements for occupant health and safety, and more recently energy, have been promulgated in model codes, which are typically modified and enforced by local governmental "authorities having jurisdiction" (AHJ).

- Compliance with prescriptive criteria and requirements, which can be demonstrated by observation and not necessarily by quantitative measurement, is typically a "go or no-go" decision that does not address limits of error or uncertainties of the forcing and response functions.
- Compliance with performance criteria and requirements may be quantitatively demonstrated by simulation and modeling, based on assumed values of forcing functions that may or may not be verifiable. Simulated values of the forcing and response functions are likely to include significant errors and uncertainties when compared to actual building performance.
- Contractors are accountable for obtaining "permits" and for demonstrating compliance with the criteria and requirements during new construction and major renovation projects through "substantial completion" (i.e., initial occupancy); but not during operations beyond the warranty periods, or for minor repair or renovation projects.
- For fire and life-safety, the owners or managers are accountable for maintaining occupancy permits and for demonstrating compliance with the criteria and requirements during the lifespan of the building.

Prescriptive and performance criteria for additional attributes (e.g., security, energy and water consumption rates, indoor and outdoor environmental quality, materials use and recycling, sustainability) are typically defined in standards and guidelines that are developed and promulgated by voluntary (i.e., non-governmental) organizations. Some of these criteria may be adopted into model codes (16).

- Unless these criteria are codified or adopted into the contract documents, the contractors, building owners, and managers are not liable for compliance. Professional and general liability insurance companies may preclude some of these criteria from coverage.
- Voluntary compliance with these criteria may be demonstrated by a label or certificate[22], often without obtaining measurements. The actual building performance is not assured by these certificates and labels.
- Limits of error or uncertainties are typically not addressed in these standards and guidelines.

Certain performance criteria may also be defined in contracts between owners and contractors, such as "energy service" or "energy savings" companies (ESCOs). The objective of an ESCO contract is to realize energy cost savings that exceed the cost of the contracted service to the owner.

- A potential conflict of interest inherent in an ESCO contract is that compliance with other criteria, such as health, safety, security, and productivity may be compromised to realize the promised energy cost savings.
- The ESCO is typically accountable only for the energy cost savings; the owner remains accountable for the overall performance of the building.
- Limits of error or uncertainties in the data needed to determine the energy cost savings are typically not defined or quantified in ESCO contracts.

Relational Criteria and Procedures

A knowledge gap exists as the current codes, standards and guidelines do not provide relational criteria with which an ESW can evaluate or assure the dynamic equilibrium of a building's performance to within acceptable limits of error or uncertainties. Comprehensive building performance can only be assured when a set of relational criteria is defined, agreed upon by the accountable persons (e.g., owner, designer, contractor), and used to evaluate the balance and resiliency of the response functions when perturbed by forcing functions during normal and extraordinary conditions. For continuity, these criteria and corresponding procedures should be consistent for independent testing (TAB and functional Cx) and for continuous balancing through the use of the BAS and BIM:[23]

Criteria for response functions must be demonstrably sensitive to perturbations of the forcing functions, as described in the following sections and in more detail in the next article in this series;[24]

For consistency in evaluating the dynamic equilibrium of the response functions among the interactive subsystems, the set of parameters and values must be rational, measurable, and relational during all phases of design, construction and operations:

- During design, the performance of the "virtual" building should be analyzed, within acceptable limits or error or uncertainties, by simulation of the intended response functions to expected magnitudes of the normal and extraordinary forcing functions.
- During construction, including substantial completion, the response functions to actual or simulated forcing functions should be evaluated by initial testing (e., TAB), functional Cx, and calibration of the BAS.
- During operations, the response functions to actual forcing functions should be measured and controlled by the BAS, and periodically verified by independent testing and commissioning.

22 See Benchmarks and Rating Scales, described above.

23 See discussion of BAS and BIM in the first article (2).

24 Article 3 will focus on Availability of Appropriate Instrumentation.

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Optimization and Uncertainties

Data points are currently installed in a BAS primarily as needed for monitoring and for direct digital control (DDC) of the controlled devices in the zonal, distribution, and central systems (see Fig. 1). However, not all of these data points may be necessary to evaluate and assure the performance of the building to within an acceptable level of error or uncertainty. By applying optimal control techniques, a decisive set of the data points can be selected with which to "optimize" the performance of the building as a system (17). For example, certain measureable outcomes (e.g., secondary response functions of resource utilization, economic performance) can be selected as "objective functions" to be minimized (e.g., energy utilization rates, life-cycle costs) or maximized (e.g., rate of return on investment, reliability, durability, productivity, sustainability) while operating within the limits defined for the "constraint functions" (e.g., primary response functions of human responses; intermediate factors of occupant exposures and system performance, central system performance, and forcing functions).

All measures contain uncertainties. Unless controlled, the propagation of errors from measuring, controlling, and evaluating building performance can be significant and lead to excessive false-positive or false-negative errors. To perform a credible building performance evaluation, it is necessary to define acceptable limits of error and to estimate the uncertainties associated with the measured values of the forcing functions, objective functions, and constraints:

- Allowable deviations from expected accuracy should be identified and defined for each parameter or variable to be used in optimizing building performance.
- An uncertainty (i.e., propagation of error) analysis should be conducted for each train of sensors, controllers, and controlled devices that provides data for the optimization process described above.
- A contingency matrix should be developed to evaluate the acceptability of the uncertainties. It is not possible to minimize both false positive and false negative errors.
- The consequences of committing a false positive or a false negative error with each train of system uncertainties should be evaluated.[25]

Programs on evaluating and assuring optimal building performance are being developed for technicians, supervisors and contractors, in conjunction with ICB/TABB.

25 Article 4 will focus on Interpreting Measurements and Evaluating Building Performance.

Commissioning and Diagnosing Building System Performance:

While measurable parameters and values are useful in commissioning procedures (Cx), they are essential in diagnostics procedures (Dx). These two procedures are related but not synonymous (18). Although these procedures will be discussed in more detail in Article 4 of this series, an overview of their differences is given here:

Cx is not necessarily quantitative; it may only be observational (i.e., check lists) or may include functional evaluation of the commissioned systems and assemblies, qualitatively or quantitatively (19). Qualitative evaluations typically do not include uncertainty analyses.

Dx is quantitative, based on uncertainty analyses, and focuses on compliance with relational criteria. Cx may incorporate Dx procedures.

Dx may be used to:

- Assure performance of subsystems or the whole building as a system;
- Identify faults or failures in building system performance during design, construction, and operations;
- Evaluate dynamic equilibrium and optimal performance of a building as a system for normal and extraordinary conditions.

Dx may incorporate the use of BIM and BAS.

The following is a brief outline of the Dx procedures for a new or existing building:

1. Determine purpose and scope of the Dx: assurance or fault/failure detection (this step will define the acceptable limits of error, or uncertainties) for the process.
2. Determine level of desired accuracy of the Dx.
3. Establish a set of performance criteria for acceptable accuracy and precision.
4. Formulate and quantitatively test hypotheses.
5. Interpret and prognosticate results (see Article 4 for additional information).

Current and Future Needs for "Test, Adjust, and Balance" (TAB)

The three processes that comprise TAB are, and will continue to be, the essential core in assuring the performance of a building. Knowledge of these active processes provides a solid base upon which the ESW can evaluate dynamic equilibrium and optimal building performance throughout the lifespan of a building:

- **TESTING** is the process in which measurements are obtained through approved manual and automated procedures (i.e., protocols) to determine if the components, subsystems, and whole-building system are adequately performing in compliance with the specified criteria for response and forcing functions.

  Examples of testing are: determining if the leakage and flow rates (i.e., response functions) in components, sections, and assemblies of air and water distribution systems are acceptable when challenged with specified static pressures (i.e., forcing functions).

- **ADJUSTING** is the process of modifying the components, subsystems and whole building system to attain compliance with the specified performance criteria, after initial testing.

  Examples of adjusting are: sealing leaks, calibrating and adjusting the control components, and retesting to assure compliance with the specified performance.

- **BALANCING** is the process of proportioning the adjusted response functions of the components, sub-systems, and whole-building system to within acceptable tolerances (i.e., limits of error) of the specified values when perturbed by specific loads or forcing functions.

  Examples of balancing are: achieving proportional mass and heat transfer rates through supply and return air and water distribution systems to within specified tolerances of the design intent.

Currently, TAB focuses on assuring acceptable steady-state performance of the "zonal" and "intermediate" air and water distribution subsystems during normal conditions (see Fig. 1 in section 2). In the future, the TAB processes will be enhanced for the ESW to evaluate and assure the dynamic equilibrium among all of the interactive sub-systems, during normal and extraordinary forcing functions. These enhanced processes will also include evaluations of the concomitant occupant responses to the zonal exposures (i.e., primary outcomes) and resource utilization and economic performance (i.e., secondary outcomes).[26]

The scope of TAB processes available to the ESW is envisioned to include evaluation and assurance of the dynamic equilibrium of all of the inter-related systems in the building. Examples of these systems are:

- HVAC systems, including air-side and water-side performance.
- Plumbing systems, including supply, sanitary, and specialty systems.
- Other mechanical systems, including health care and other processes.
- Acoustic and vibration systems, including architectural, mechanical, and electrical noise suppression.
- Lighting systems, including illuminance, luminance, contrast, glare, and electrical and thermal loads.
- Other electrical power systems for balance and reliability.
- Building enclosure systems for thermal, moisture, and air resistance.
- Fire, life-safety, and security systems for sensitivity and reliability.
- Building automation and control and energy management systems (i.e., BACS and EMS) for accuracy and reliability.

26 Refer to the rational definition of building performance, above

TAB is not synonymous with Cx or Dx, but is essential to both of these processes:

- Cx is a passive process that provides feedback to the owner on whether components and subsystems have been designed and installed as intended, either by submitted checklists, or by observations of functional tests.

  TAB is essential to Cx and should be completed before the functional component of Cx is initiated.

  TAB can maximize Cx effectiveness.

- Dx is an active process that tests the acceptance or rejection of a hypothesis[27] regarding the performance of a building as a system (18).

  TAB is essential to Dx and should be conducted after the hypothesis has been formulated. Imbalances in dynamic equilibrium may be causes of occupant complaints, or system faults or failures.

  TAB is also a critical process in remediation of the faults or failures.

To become accountable for assuring specified building performance through Cx and Dx procedures, TAB personnel (i.e., technician, supervisor, and contractor) need:

- **COMMON SENSE:** This is a basic talent that can be augmented by education and training. Common sense is the most important characteristic that an ESW can possess.
- **FORMAL EDUCATION AND TRAINING:** These acquired talents are important components in understanding the why in relationships between the physical and social forcing and response functions, and, thus, the knowledge of what and what not to measure.
- **EXPERIENTIAL EDUCATION AND TRAINING:** Learning by doing and practicing what common sense dictates from formal education and training defines the essential ESW.

27 The "null hypothesis" is typically expressed in terms of accepting the performance of the functional relationships among occupant responses, sources of occupant exposures, and system performance. The "alternative hypothesis (or hypotheses)" is typically expressed in terms of rejecting this performance. The hypothesis is tested by measurements.

CONCLUSIONS

The first article in this series described future challenges and opportunities that an ESW is likely to face. This article expands on the challenges and opportunities by focusing on three questions: 1) What is the basis of these growing demands? 2) Do the current criteria for TAB and other evaluation procedures adequately address these demands? 3) Who determines what and how to measure the parameters and values for these criteria?

1. **The basis of the growing demands during the last 10 years has centered on a concept described as "Building Performance." By comparing a rational definition with promisorial definitions, benchmarks and rating scales, it is evident that perceived building performance has not yet been rationalized with measured building performance. As the demand grows for documentable improvements in building performance, the need and accountability for reliable measures of response functions to actual forcing functions during normal and extraordinary conditions will increase.**
2. **Current TAB procedures typically result in initial data pertaining to discrete steady-state responses of components and subsystems during testing periods of minimum or unknown loads (i.e., forcing functions). Moreover, these procedures seldom provide data that include uncertainty or limit of error analyses for normal or extraordinary operational periods, or for concomitant data pertaining to occupant exposures, human responses or rates of energy and water consumption. As indicated in Fig. 1, a set of relational performance criteria is needed with which to reliably evaluate the dynamic equilibrium of the response functions among interactive subsystems, each interfacing through a building automation system.**
3. **No one entity is currently responsible or accountable for defining the measurable parameters and values (i.e., criteria) of attributes that are needed to evaluate and assure, within acceptable limits of uncertainty or error, the performance of a building during design, construction, and during normal and extraordinary operations. Codes, standards, guidelines, benchmarks, rating scales all have different methods for defining the criteria and for assuring their compliance: permits, contracts, rating scales, and labels. As new demands occur, such as optimization control and uncertainty analysis, the roles and opportunities of the ESW will increase, including the opportunities of assuming accountability for the performance of a building.**

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