Post-Occupancy Evaluation Framework for Multi-Unit Residential Buildings

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ABSTRACT

There is a growing awareness in the residential building industry about the significance of energy use in buildings and the desire to minimize energy consumption and costs. In the construction industry, the importance of building commissioning to verify the installation and performance of various building systems is rising.

Post-occupancy evaluation (POE) of buildings goes beyond commissioning. POE is the systematic assessment of building performance during service and typically includes analysis of the users' perceptions.

A literature survey revealed the lack of a comprehensive POE methodology for multi-unit residential buildings (MURBs) that addresses the major building systems, including the building envelope. To fill this gap, a POE framework has been developed for MURBs. As very limited information is available in the public domain on the performance of MURBs, the information obtained from POEs could be of use to identify avenues of improvements to the benefit of building owners and occupants and to develop benchmark data on performance indicators to support the development of building codes, regulations, and guidelines. Evaluating the performance of new, innovative building systems and practices applied to newly constructed or retrofitted MURBs can serve to show whether promised benefits are actually delivered. The POE protocol focuses on seven performance areas: energy efficiency, water use efficiency, indoor air quality, lighting and the visual environment, acoustics, thermal comfort, and building envelope performance. This paper presents the literature survey findings, the protocol's objectives, the qualitative and quantitative indicators used to gauge performance, and an overview of the methodology's various tasks, with emphasis on the building envelope performance assessment, and its interaction with other systems.

INTRODUCTION

There is a general tendency in the building industry to design and construct buildings to meet higher performance targets, due in part to more and more stringent building code requirements, and in part to better meet the needs and expectation of occupants. This is true for the energy and water consumption of buildings, as well as other performance areas such as lighting, thermal comfort, and the building envelope.

Very little information is available in the public domain about the actual, in-service performance of buildings in general, and multi-unit residential buildings (henceforth called *MURBs*) in particular. Such information could be useful to identify avenues of improvements to the benefit of building owners and occupants and to develop baseline data on performance indicators to support the development of building codes, regulations, and guidelines. Evaluating the performance of new, innovative building systems and practices applied to newly constructed or retrofitted MURBs can serve to show whether promised benefits are actually delivered, potentially speeding their adoption by the industry and driving regulatory changes.

Building commissioning is becoming a more and more common practice and has as its main objective to ensure that systems—primarily mechanical and electrical systems—are constructed and operated as designed. The bulk of commissioning activities are typically conducted prior to building

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occupancy, with some commissioning projects also including follow-up reviews to address potential building performance issues prior to the expiration of warranty periods. As with post-occupancy evaluation (POE), commissioning has focused on non-residential buildings.

This paper starts with a definition of POE and presents key results of our literature survey on POE of MURBs. The development of a POE framework for MURBs—a work in progress—is outlined, including its objectives, performance areas, and specific performance indicators and metrics, where these exist. The paper discusses the building envelope performance assessment in greater details, including test methods. Finally, an overview of the framework's tasks is given, focusing on the performance assessment of the building envelope, and its interaction with different systems.

What is Post-Occupancy Evaluation?

Post-occupancy evaluation, or POE, is one of the best methods of obtaining performance data on existing buildings. Post-occupancy evaluation goes beyond building commissioning and is the systematic assessment of building performance during service, typically including but not limited to analysis of the users' perceptions, for various purposes. POE also commonly includes building monitoring to support the findings of the user surveys and assess the level of success of design strategies in meeting design performance targets or reference baselines. Post-occupancy evaluations have been undertaken for some 40 years (Leaman et al. 2010), although significant documentation on methodologies begins in the 1980s. POE fits in with building performance evaluation or verification, which includes a number of activities taking place during a building's life cycle to determine "whether facilities will work for the people that will use, occupy, or otherwise be impacted by them" (Mallory-Hill et al. 2012).

LITERATURE REVIEW

The POE tools available in the public domain which were reviewed during our literature survey are listed in Table 1, with their target building type. ASHRAE's "Performance Measurement Protocols for Commercial Buildings" (ASHRAE 2010c) was published just prior to the start of this work and was not included in the survey. The literature review was not intended to be exhaustive, but rather a sampling of available methodologies, focusing on their performance indicators, performance baseline or benchmark data, assessment techniques, monitoring instrumentation and methodologies, satisfaction surveys, and reporting techniques. Key findings relevant to the development of the protocol are highlighted here.

Two of the methodologies rely exclusively on the feedback obtained through surveys of occupants or various stakeholders (Baird 2010; Watson 1996, 2003; Watson and Fitzgerald 1998). The remainder of tools employs a combination of survey of stakeholders and qualitative and/or quantitative performance indicators to assess building performance.

Many of the surveys deal with assessment of non-technical areas, such as ease and effectiveness of building monitoring; occupant satisfaction with items such as washrooms and communal spaces (EcoSmart Foundation 2007); education on building features; office layout (Keen Engineering 2005); client satisfaction; and construction defects, construction cost, productivity, and profitability (HEFCE 2006).

The performance areas addressed in the tools also vary depending on the tools' objectives. For instance, the HEFCE (2006) tool is intended for higher education institutions to better understand both technical aspects (such as energy and water use during construction and during service) and non-technical aspects (like predictability of procurement costs and time and productivity) of the building life cycle from construction through building service. As another example, the EcoSmart tool seeks information on the implementation

Table 1. POE Protocol and Target Building Type

POE Protocol	Target Building Type
EcoSmart (EcoSmart Foundation 2007)	MURBs
Keen Engineering POE protocol (Keen Engineering 2005)	Office buildings
Watson (Watson 1996, 2003); Watson and Fitzgerald (1998)	Various
Higher Education Funding Council for England (HEFCE 2006)	Higher education buildings
Baird (Baird 2010)	Sustainable commercial and institutional buildings
Post-Occupancy Review of Buildings and their Engineering, or PROBE (Cohen et al. 1999; Leaman, Stevenson, and Boyce)	Offices, institutional industrial and government buildings
Soft Landings Framework (BSRIA 2009)	Non-specific
Building Research Establishment (BRE)'s Design Quality Method (Cook 2007)	Various, including schools, hospitals, and housing
Sanders (2010)	Housing
Birt and Newsham (2009)	Commercial and office buildings

of major technical design strategies to assess their success. As such, the tool focuses primarily on technical performance areas such as energy and water consumption. The tool also serves as a post-mortem on the design and construction process, with the goal of eliciting feedback to improve not only future buildings, but the design and construction process.

It is also of interest that a POE developed for a specific target building type cannot necessary be applied "as is" to another building type. For instance, the performance areas and associated indicators (such as interior design: office layout, visual privacy, ease of interaction, etc.) employed to assess the performance of office buildings are not necessarily applicable to MURBs. Moreover, many baselines and benchmarks applicable to specific building types cannot be used as a performance comparison for others, as shown in the variations in energy and water use benchmark data given for different commercial buildings (ASHRAE 2012).

Leaman et al. (2010) state that far more POE studies have been conducted on non-domestic buildings. Our findings with respect to POE tools were similar: of the ten tools reviewed, only two were developed specifically for residential buildings—EcoSmart (EcoSmart Foundation 2007), and Sanders' methodology (Sanders 2010). The EcoSmart protocol is an extensive tool comprised of 11 mandatory components addressing various aspects of residential building performance, including but not limited to energy consumption, water use, indoor air quality, thermal comfort, and lighting. Building envelope performance is not included. Also, while an occupant survey is included as one of the components, no survey has actually been developed for the protocol. The Sanders methodology is limited in that it has been developed strictly to evaluate the energy performance of dwellings. The literature also revealed that existing tools provide little information with respect to benchmark data for MURBs performance comparison.

OBJECTIVES OF THIS PROTOCOL

To fill the gaps in the existing POE methodologies for the performance assessment of MURBs, a new POE methodology was developed. There was a desire that the methodology be modular, and could be implemented for newly constructed buildings, newly retrofitted or rehabilitated buildings, or simply buildings where the performance is to be assessed. Also, the methodology would provide baseline or benchmark data, where such data are applicable and available.

The specific objectives of this methodology are the following:

1. To compare the overall performance of a building relative to baselines or benchmarks.
2. To determine the extent to which a building meets its occupants' and the building management team's needs and satisfaction.
3. To provide feedback on the building design, construction and commissioning process.
4. To evaluate the success of specific innovative measures and systems, and unique building features, compared to conventional technologies.

PERFORMANCE AREAS AND INDICATORS

The POE methodology for MURBs includes the performance assessment of seven areas referred to as performance areas:

1. Energy efficiency
2. Water use efficiency
3. Indoor air quality
4. Lighting and the visual environment
5. Acoustics
6. Thermal comfort, and
7. Building envelope performance

This section provides a general description of the performance areas, their relevance to building performance, and the qualitative and quantitative performance indicators or metrics used to assess performance.

Energy Efficiency

Energy efficiency is a key performance area in this methodology as it addresses the rising importance of energy efficiency, the reduction in energy consumption, associated costs, and environmental impact. Several performance indicators were established to evaluate the energy performance of MURBs:

- Annual energy consumption per square meter of conditioned space (gas, electricity, propane, diesel, fuel oil, etc.). Energy use is reported on an energy type basis and as aggregated total of different energy types.
- Energy consumption per square meter of conditioned space, normalized for weather conditions. Normalized energy use reported on an energy type basis and as aggregated total of different energy types.
- Disaggregated energy use by system or end use.

Normalization of energy data is conducted to account for varying weather conditions on energy consumption. Normalization can be conducted following the general procedures and guidance discussed in ASHRAE (2012, 2011). A good explanation of the process is given by Avina (2012). Note that this type of energy analysis should be conducted by an experienced professional or contractor.

While some large property owners and developers may have their own proprietary benchmark data, statistically valid data for MURBs is not readily available in the public domain at this time. The Canada Mortgage and Housing Corporation (CMHC) provides some information (HiSTAR database [CMHC 2001]), but information is limited and based on small sampling of buildings. Thus, finding comparable buildings may be difficult.

Water Use Efficiency

Research published by CMHC cites that one of the common inadequacies of multi-unit residential buildings is high domestic water consumption (Kernan et al. 2002). The importance of water use efficiency is reflected in the emergence of incentive programs such as Toronto Water's multi-unit toilet replacement program and commercial and residential washer rebate programs (Detta Colli). The efficient use of water impacts not only the withdrawal of this natural resource from rivers, aquifers and reservoirs, but also the infrastructure required to supply it and to treat it pre- and post-consumption.

The efficient use of water can be characterized using one of many quantitative performance indicators:

- Water consumption per occupied floor area
- Water consumption per unit
- Water consumption per occupant

Available benchmark data is typically given on a basis of volume of water per square meter and/or per unit. While some large property owners and developers may have their own proprietary data, statistically valid data for MURBs are not readily available in the public domain. CMHC does provide some information, but the information is limited and based on small samples of buildings (CMHC 2001).

Indoor Air Quality

Poor indoor air quality (IAQ) is a concern as it can adversely affect the health of occupants. Sources of contaminants include emissions from materials (particularly in new buildings), products used by occupants such as cleaners, and air leakage from garages and garbage chutes. Occupant activities such as bathing can cause high indoor humidity conditions if the moisture is permitted to accumulate. Mold growth stemming from water penetration or condensation on interior surfaces is another source of contaminants.

Quantitative indicators of indoor air quality performance include the following:

- Carbon dioxide (CO_2) elevation over exterior ambient conditions
  Carbon monoxide (CO)
- Total volatile organic compounds (TVOCs)
- Humidity ratio (or relative humidity [RH])
- Temperature
- Exhaust (ventilation) air flow
- Volatile Organic Compounds (VOCs)
- Particulates

Other than the applicable building code, there are various sources of baseline data for the performance indicators:

- ASHRAE Standard 62.1-2010 establishes maximum acceptable levels for a wide range of indoor air pollutants, and defines required ventilation rates (ASHRAE 2010a).
- Health Canada's "Exposure Guidelines for Residential Indoor Air Quality" (Health Canada 1989)
- Health Canada updates to 1987 report for CO, formaldehyde, ozone, toluene, and molds (Health Canada)

This POE methodology for MURBs recommends using the lowest published values for the maximum permissible TVOC concentrations.

Qualitative performance indicators include perceived odours and observations of water stains, visible water on surfaces, visible mold, and pests such as insects. Qualitative "measurements" rely on the judgment of a trained or knowledgeable person and generally there would be no numerical baseline or benchmark against which the "measurement" can be compared; rather, a subjective basis of comparison applies, such as "obvious tobacco, cooking or perfume smells on entering suite" (Morrison Hershfield 2012).

Lighting and the Visual Environment

Adequate levels of lighting, both natural and artificial, are important for the visual comfort and health of occupants. Lighting can also impact energy efficiency in that taking advantage of daylighting can reduce energy consumption, as can the use of energy efficient fixtures. However, the efficient use of resources is affected by the durability of fixtures.

There are several performance indicators for assessing the performance of the lighting system. Measurable indicators include:

- Illuminance
- Daylight factor (DF)
- Light trespass

Qualitative performance indicators include:

- Visibility
- Aesthetic
- Control flexibility
- Daylight
- Light pollution and light trespass

Sources of baseline information for lighting illuminance are found in the *Lighting Handbook* (Illuminating Engineering Society 2011) and the applicable building code. The Canada Green Building Council (CaGBC)'s *LEED Canada Reference Guide for Green Building* provides some guidance with respect to lighting pollution and trespass (CaGBC 2009). An average DF between 2% and 5% is generally considered the suitable range to balance good visibility and daylight appearance (NIBS 2012), although lower DF values may be appropriate for some spaces such as living rooms.

Acoustics

Noise from neighbouring units, common spaces, building mechanical and plumbing systems, building services, and the outdoors, can impact the comfort of occupants. Noises can be in the form of airborne sound transmission or vibration noises transmitted through the building structure.

Quantitative performance indicators to assess the acoustical performance of a building assembly (floor, party wall, etc.) and associated sources of benchmark data include the following:

- Noise from neighbouring units (and amenities) or other uses
    - Applicable building code requirements for sound insulation (Sound Transmission Class (STC) ratings)
    - Reducing Noise in Your Apartment, About Your Apartment Series (CMHC 2005).
- Noise from services (heating, ventilation, and air conditioning [HVAC], plumbing systems, and garbage chutes), including equipment that generates noise that radiates outdoors):
    - *ASHRAE Handbook—HVAC Applications*, Chapter 48 Noise and Vibration Control (ASHRAE 2011).
    - Legislation (municipal by-laws, provincial regulations).
- Noise from outdoors (e.g., rooftop equipment, traffic):
    - LU131 – Noise Assessment Criteria in Land Use Planning (Ontario Ministry of the Environment 1997).
    - Directive 038: Noise Control (Alberta Energy Resources Conservation Board 2007).
    - Applicable legislation and regional guidelines.
- Noise from services: elevators and garbage chutes
    - *ASHRAE Handbook—HVAC Applications*, Chapter 48 Noise and Vibration Control (ASHRAE 2011).
    - European noise codes for building services.

There are no codes in Canada for noise levels from building services and *ASHRAE Handbook—HVAC Applications* (ASHRAE 2011) does not address noise from elevators or from garbage chutes. A combination of European noise codes for building services and ASHRAE guideline levels (even though they are for HVAC noise and not elevators or garbage chutes) can give an idea of how loud the noise is relative to typical benchmarks for background sound.

Thermal Comfort

Poor thermal comfort due to building envelope air leakage, inadequate thermal performance of the envelope and thermal bridging, and an ineffective mechanical system is listed as one of several complaints cited by building occupants (Kernan et al. 2002). Poor thermal comfort can affect the health of building occupants, and can also impact the energy efficiency of the building, as building occupants may increase the thermostat setting or open the windows in the heating season to improve their comfort level.

Quantitative performance indicators for thermal comfort include the following:

- Air temperature
- Humidity ratio or RH
- Operative temperature

Operative temperature assessments include examination of air velocity, humidity levels, radiant loads, and asymmetries as described in ASHRAE Standard 55 (ASHRAE 2010b), the industry-wide most accepted standard for thermal comfort. These performance indicators characterize thermal comfort by quantifying temperature and humidity conditions that are outside the normal range of comfort. Sources of benchmark data include ASHRAE Standard 55, building codes, and/or project design specifications.

Qualitative indicators that rely on the judgment of a trained or knowledgeable person on the POE team, include:

- Drafts
- Hot/cold surfaces
- Uneven temperature within space (including stratification)
- Temperature swings

Building Envelope Performance

None of the existing POE tools surveyed in the literature covered the building envelope in a comprehensive manner. The performance of the building envelope is included within this methodology because it impacts several factors:

- Occupant health (poor thermal comfort due to air leakage and an inadequate thermal envelope; poor indoor air quality resulting from mold growth on building envelope surfaces, for example)
- Energy efficiency (e.g., heat loss due to low thermal resistance of envelope systems and localized thermal bridges; heat loss due to air leakage)
- Resource efficiency and environmental impact (filling of landfills and extraction of new resources associated with replacement of failed building envelope systems)
- Affordability and economic viability (costs associated with replacement of building envelopes caused by short material life cycles/low durability or premature failures)

The building envelope as a whole consists of many systems or assemblies, with each of these including several components. Together, the assemblies provide environmental separation. Given the complexity of the building envelope, several indicators can be used to assess the envelope's performance, some of which are generic, and some which depend on the specific materials, cladding materials in particular. The building envelope is expected to meet these performance criteria:

- Air leakage control (airtightness)
- Water tightness

- Control of heat transfer
- Vapour diffusion control
- Condensation resistance (of glazing systems)

Many of the above performance indicators can be assessed qualitatively by a trained and knowledgeable person. Typically, a visual review is conducted to identify the presence of building envelope issues such as water leakage and condensation on interior surfaces. Simple tools such as a psychrometer (to measure ambient temperature and humidity) and an infrared gun or digital thermometer with integrated thermocouple (to measure surface temperature where thermal bridging or condensation is suspected) may be used to supplement the visual review.

Smoke testing can be conducted as a diagnostic tool to help locate air barrier breaches using a simple smoke pencil or following a more sophisticated test method such as that described in ASTM E1186 (ASTM 2009). This ASTM standard also provides an infrared thermography methodology for detecting air leakage. Quantitative air leakage testing of windows and doors can be conducted using a test method such as ASTM E783 (ASTM 2010a). Envelope system and whole building air leakage testing are possible, but have several limitations and would be considered outside the scope of a standard POE methodology.

For both the quantitative and qualitative performance indicators, sources of baseline data include the project specifications, performance targets, and the applicable building code. In Canada, air leakage characteristics for air barrier materials must meet a minimum airflow rate of 0.02 $L/s{\cdot}m^2$ at a 75 Pa pressure difference. Appendix A of the 2010 *National Building Code of Canada* (CCBFC 2010) provides recommendations for maximum air leakages rates of air barrier systems, varying with the interior ambient relative humidity, for opaque insulated building envelopes for most Canadian locations. However, air leakage testing of air barrier systems is not practical in completed buildings and as such is outside the scope of the POE. Air leakage of glazing systems such as windows and window walls are typically given in project specifications.

Water leakage testing of glazing systems can be conducted using ASTM E1105 (ASTM 2008) or a modification thereof, at the air pressure difference given in the project specifications, to confirm the performance or diagnose a water leakage problem for a higher level POE assessment. Performance criteria (i.e., test air pressure difference) would be given typically in project specifications.

Locating breaches in the waterproofing membrane for exposed membrane roofs can be conducted following the methodology outlined in ASTM C1153 (2010b); for exposed membrane and protected membrane roofs, flood testing is an option to confirm watertightness—refer to ASTM (2005).

While field determination of the U-factor for installed envelopes is not practical, infrared thermography is possible for qualitative assessment of thermal bridging and missing insulation using methods such as that given in ASTM C1060 (ASTM 2011).

Thermal performance and condensation resistance can be indirectly assessed using a glazing property detector (for glass thickness, cavity space width, presence and location of low-e and low-e product) for comparison with project requirements. Except for simple measurement of ambient temperature and humidity, the qualitative and quantitative tests are considered to be higher-level assessments, and as such they are to be conducted if warranted, to help determine a possible cause and resolution for a problem, or, alternatively, indicate the need for further, more specialized expertise and equipment. For premature and unexpected failure of a building envelope component (for example: brick cracking, metal corrosion, and sealant failure) a more in-depth investigation is suggested as this is would generally be beyond the scope of a POE.

OVERVIEW OF POE TASKS

The objectives of the POE can vary depending on the needs of the commissioning party, be it a MURB developer, apartment building owner, condominium board, or a researcher. Whether the MURB is a condominium or a rental apartment building, the owner(s) and/or their representative(s) need to be included at the start of the POE process, to make them aware of the purpose and process of a POE and the specific objectives. Their participation is also critical to maximize the participation of the individual suite occupants. Ideas should be sought from the owner(s) to encourage the participation of the occupants in the occupant satisfaction survey. The POE results' level of confidentiality, if any, should be discussed and agreed upon. The confidentiality of information obtained from individual suite occupants, such as occupant satisfaction survey results and energy bills, also needs to be addressed.

The POE assessment of a building requires technical expertise, depending somewhat on the level of assessment (see below). The POE should ideally include the design team so that the designers can provide important information on the goals that drove the design, specific performance targets, the strategies developed to meet these goals, and any challenges encountered.

A flowchart showing the overall outline of the methodology is provided in Figure 1. The methodology consists of four steps, each with one or more tasks. The four steps are the following:

1. Data collection from stakeholders
2. Surveys and interviews
3. Data collection from site
4. Information transfer

Each of the seven tasks included in the data collection from site applies to a different performance area (energy efficiency, indoor air quality, etc.). The POE methodology incorporates a modular format so that it can be customized to suit the objectives of the POE mandate, and to follow up on the findings of the occupant and/or building management surveys.

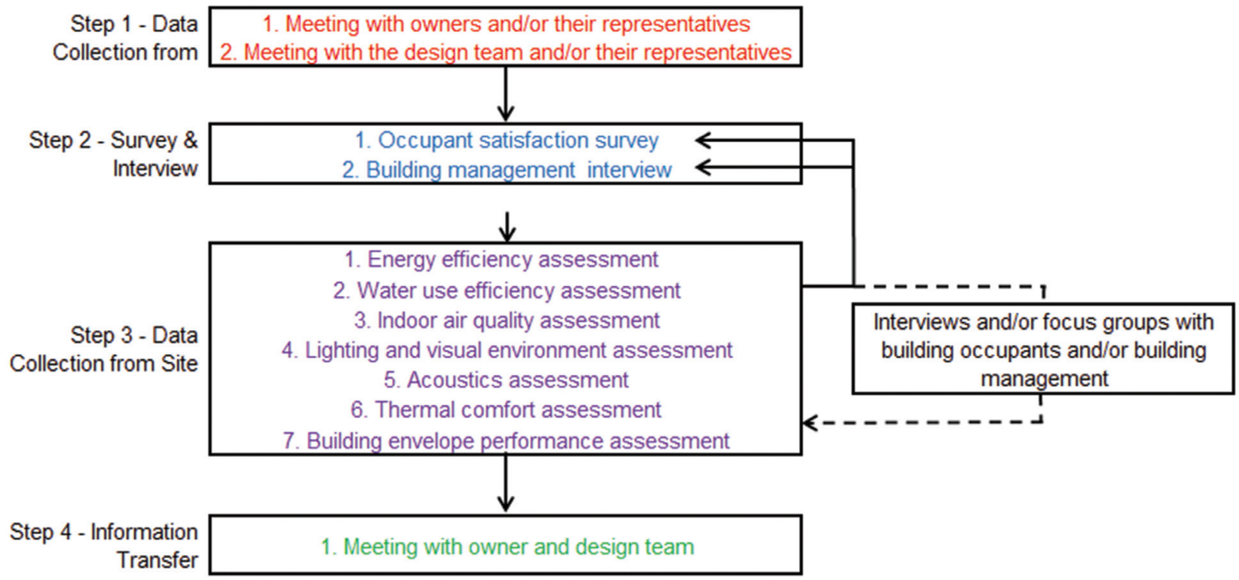

Figure 1 *Flowchart of POE methodology for MURBs.*

For each performance areas, there are two levels of assessments: Level 1 and Level 2. A performance area assessment begins with a Level 1 study. Generally, furthering the study with a Level 2 study is merited when the Level 1 assessment is inconclusive or cannot adequately explain a discrepancy with the design target, baseline, benchmark, or results of the occupant survey. A Level 2 study generally requires a higher level of expertise and more sophisticated and costly instrumentation.

The interviews with building management and building operators are intended to be conducted prior to the site data collection, so that the information gathered during these interviews can assist in selecting the number and location of suites to be monitored. However, in some cases, it may be useful to go back and revisit the building management and/or operators after the monitoring, in order to better understand the site data results.

Step 1—Data Collection from Stakeholders

Meeting with the Owners and/or Their Representatives. The purpose of this meeting is to establish a relationship between the owner and the POE team, to explain the purpose and process of the POE, confirm the performance areas to be assessed for the specific building, and to elicit necessary information to proceed with POE. Possible levels of release of the POE results are also to be discussed and formally agreed upon (confidential/publicly released without building name/publicly released). Findings from a POE may be released publicly to disseminate information to the construction industry or as a marketing strategy following a major retrofit in an apartment building, for example. General questions about the building performance and how it meets the owner's needs, as well as questions specific to the performance areas can be asked, such as:

- Detailed building occupancy (relevant to energy efficiency and water consumption performance areas)
- Building commissioning or any subsequent commissioning (relevant to energy efficiency performance area)

This is also an opportune time to obtain documentation from the owner, including building drawings and specifications, building commissioning reports, metered data for energy and water consumption, and/or any other relevant document pertinent to the POE. A customizable data collection form was formulated as part of the POE development to suit the needs of the POE team and the objectives of the POE.

Meeting with the Design Team and/or Their Representatives. Holding a meeting with the design team and/or their representatives is intended for a POE of a newly completed building or a building having undergone a major retrofit. Design team representatives present at the meeting should at least include the lead project architect and mechanical engineer.

During the meeting, the POE team will discuss the components that will be involved in the POE, and the possible levels of release of the POE results. The main objective of the meeting is to obtain information about the building's design goals and strategies, including but not limited to the following:

- Proposed use and occupancy
- Main design goals and strategies used to attain such goals (relating to performance areas to be evaluated)

- Any provisions made during design for the building to be ready for a post-occupancy evaluation (contractual provision, setting up files for utility bill analysis, instrumentation, etc.)
- Any innovative or high performance features
- Features of the building to be specifically evaluated in the occupant satisfaction survey

A data collection form was developed that can be customized and expanded to suit the needs of the POE team depending on the performance areas that will be evaluated for the MURB.

Step 2—Survey and Interview

Occupant Satisfaction Survey. While the need for an occupant satisfaction survey can be argued, in this POE tool for MURBs the occupant satisfaction survey is compulsory as it meets one of the objectives of the protocol—to bring information to the POE team about the building performance as perceived by the occupants. The occupant satisfaction survey is modular in form, enabling the user to extract questions to suit the building-specific POE objectives. A cover letter accompanying the survey describes the purpose of the survey, the party requesting the information, the person who should respond to the survey within each suite, and reassures the respondents that results will be kept confidential within the POE team. The format of the questionnaire (paper-based, computer-assisted, or multi-modal) and its advantages and limitations should be discussed with the owner(s) and/or their representatives, or the property manager during the start-up meeting. The POE protocol also makes recommendations with respect to strategies for maximizing the survey response rate, survey data processing, analysis and reporting, and provides ideas for further work, such as conducting one-on-on interviews and focus groups.

Building Management Interview. The interview with building management staff serves primarily to inform the staff about the POE, explain its purpose and process, and to obtain information about the history and operation of the building, including possible issues with the following, as is pertinent to the building-specific POE:

- Moisture
- Thermal comfort
- Lighting
- Mechanical and electrical system operation
- Acoustics
- Premature failures

The POE team should seek reports on the following:

- Previous repairs and replacements
- Outstanding deficiencies that may affect the building performance (e.g., water leakage through cracks in exposed concrete exterior walls)

In addition, information about the building is requested regarding operational goals, the metering plan (if relevant to the POE), and the most successful and least successful aspects of the building (e.g., an innovative domestic hot water heater results in quick delivery of hot water to suites; air leakage has been reported at the building's windows). A data collection form was developed to facilitate data entry for this task.

Step 3—Data Collection from Site

The protocol presents guidance on the expertise required to carry out each level of the POE for each performance area and level of assessment, as well as instrumentation, measurements and conditions, complementary data collection, interactions with other systems, the anticipated time and effort required, estimated minimum cost of typical equipment, and the need for further investigation.

For every POE performance area investigated (energy efficiency, water use efficiency, building envelope performance, etc.), a visual walk-through is to be conducted by the POE assessor, with the objective of confirming the construction of building systems in various parts of the building and reviewing their condition.

In-suite reviews should be done in the presence of the suite occupant(s) to permit feedback from them whenever possible. For some performance areas, there may be benefit in obtaining feedback from the occupant prior to setting up the physical monitoring. For instance, the building envelope technician or engineer should discuss condensation complaints with the occupants to better understand the nature of the complaint (time of occurrence, etc.) in order to select the most appropriate type of test and timing for the test.

General Guidance for Building Monitoring. As stated earlier, the occupant satisfaction survey is a compulsory component of the protocol. This is, in part, because the results of the occupant satisfaction survey can guide the POE team with respect to selecting the number and specific suites to be monitored in Step 3. For instance, one would expect that if a significant number of complaints are received with respect to a given performance area, the number of suites investigated on that issue would be larger than if the level of satisfaction was found to be good or neutral. The following considerations are given when selecting suites for monitoring:

- View all suites with low occupant satisfaction (a limit on the number may be placed if the suites are very numerous).
- View suites with similar layout/orientation with high or neutral satisfaction or no response.
- Also view a variety of suite layouts and locations (floor and orientation), as appropriate for that performance area.

Reviewing similar suites with varying levels of satisfaction allows the POE assessor to distinguish the presence of a genuine problem versus a highly sensitive occupant. Sampling the suites with good satisfaction or no response permits qualitative and/or quantitative verification of systems that appear to be functioning as designed and constructed.

Viewing a variety of suite layouts and locations provides a more representative "picture" of the building as a whole. The suite selection may depend on the performance area being investigated. Thermal comfort and building envelope performance are both strongly affected by the orientation of the suite's exterior walls and the percentage of glazing. Clustering the suites selected for thermal comfort and building envelope monitoring to those on the south side of the building, for example, will likely cause skewed results.

At first, the POE team is suggested to select a larger number of suites than what is strictly necessary, for each performance area. The suite selection should then be discussed with the building management staff to exclude suites that are unsuitable for the given assessment purpose. For instance, consider a suite with good occupant satisfaction with acoustics being initially selected for physical measurements. If it is then discovered that the neighbouring suites are vacant, the POE team should omit this suite from the monitoring protocol, as the occupants' perceptions are based on the vacancies rather than good acoustical performance.

The following section provides guidance specific to building envelope performance assessment. For this and other performance areas, two levels of assessment are provided: Level 1 is intended to be a simpler, less costly assessment method requiring a lower level of expertise and less sophisticated instrumentation and tools. Should the Level 1 assessment reveal performance issues that are not clearly understood based on the available information, the Level 2 assessment may be warranted.

Building Envelope Performance Assessment—Level 1

Expertise Required. The minimum level of expertise required is a building science technologist or professional with at least five years of experience.

Instrumentation Required. This assessment level relies mainly on visual observations of trained personnel. The instrumentation required to carry out the work includes a psychrometer for ambient air temperature and relative humidity spot measurements, an infrared surface temperature meter (or similar device), and a smoke pencil or smoke generator to qualitatively detect air leakage.

Measurements and Conditions. The assessment should be based on the issues identified in the occupant and building management satisfaction surveys. The assessor should review the issues raised in the surveys and select a representative number of suites, ensuring that a representative sample of suites from each type of unit and exposure are included. The sample size is at the discretion of the POE team, depending on the building configuration.

Complementary Data Collection. The following information could be of use to obtain an understanding of the building construction, its climatic exposure, and history:

- Architectural drawings and specifications
- Shop drawings and submittals of systems and components such as windows, doors, and roofing products
- Test reports of systems tested during construction, such as testing of glazing system for air and water leakage
- Building performance audit report, if available
- History with respect to outstanding construction deficiencies, failures since construction completion, repairs and replacements, etc.
- Building geographical location, features in the surrounding landscape and built environment (e.g., location on the top of a hill, protection from the weather by nearby buildings)
- Information on local climatic conditions (winter and summer design temperatures, annual rainfall, moisture index, etc.)

Interaction with Other Systems:

- There can be strong interactions between a building's envelope and a building's mechanical systems. For instance, the occurrence of condensation and/or mold formation on envelope interior surfaces can indicate inappropriate selection of glazing systems or thermal bridging with respect to the envelope, but it can also indicate a deficient heating system due to poor mechanical ventilation or air distribution. Alternatively, such issues can be caused by a low temperature setpoint.
- Building envelope design and construction will impact thermal comfort.
- Formation of mold growth on interior building envelope surfaces or within the building envelope, due to condensation or water penetration, can cause indoor air quality issues.

Time and Effort to Collect Data. Allow for two or more days on site, depending on the size of the building, plus reporting time.

Typical Minimum Equipment Cost. Purchase costs for the tools vary, but estimates are as follows: digital psychrometer for spot measurements, \$250; infrared surface temperature meter, \$100 to \$1,000; smoke pencil or smoke generator, negligible cost. As these are typical tools, building science firms are likely to own these tools.

Building Envelope Performance Assessment—Level 2

Expertise Required. The minimum level of expertise required is a mid- to senior-level building technologist, professional engineer, or architect.

Instrumentation Required. Simple, relatively low-cost, non-destructive testing measures are provided below and depend on what type of assessment is being carried out:

- Condensation of windows, walls, ceilings; mold growth on windows, walls, ceiling; ghost marking of wall framing:
    - Psychrometer for measurement of indoor air temperature and relative humidity and outdoor air temperature.
    - Infrared thermographic camera for measuring surface temperatures and for qualitative assessment of thermal bridging, missing insulation, and air leakage.
    - Temperature instrumentation (thermocouples) for quantitative measurement of interior surface temperatures on window frames, glass, walls, etc.
- Condensation of glazing assemblies: glazing property detectors for glass thickness, cavity space width, presence and location of low-e coating and low-e product.
- Water leakage testing for glazing systems: water spray rack, fan, and pressure manometer.
- Air leakage testing for diagnosing the location of air barrier breaches in the building envelope: smoke generator, a blower door, and pressure manometer. A flexible pipe may be useful to focus the smoke to localized area.
- Quantitative air leakage testing for determining the air leakage rate of installed glazing systems: fan, pressure manometer, and flow meter.
- Windows and doors:
    - Icicle formation and difficulty of operation: non-destructive assessment of fit of sash to frame and condition of weatherstripping, etc.
- Roofs:
    - Water leakage: for exposed membrane roofs, thermography and/or spray/flood testing of roof to locate leak; for protected membrane roofs, spray/flood testing.

If specific issues described below are observed with respect to claddings, glazing system and roofing systems, a more in-depth study would be required, which would generally be beyond the scope of a POE.

- Brick: cracks of bricks and/or mortar, efflorescence, bowing, water runoff and staining pattern, and ice accumulation.
- Pre-cast panels: cracks, bowing, water runoff and staining pattern, sealant failure, and staining below drainage openings.
- Metal panel: premature sealant failure, coating delamination, and corrosion staining.
- Exterior insulation and finish system (EIFS): premature sealant failure, failure of the EIFS finish coat (debond/re-emulsification), cracks, and debonding panels.
- Siding (wood, vinyl, cementitious cladding): bowing cracking, coating delamination, and staining.
- Glazing systems: fogging of insulated glazing units and cracking of insulated glazing units.
- Roofing systems: blistering of roof membrane, tenting of the membrane, displacement of ballast and insulation in a protected membrane roof (also called an inverted roof), missing shingles and other components, and displacement of components.

Measurements and Conditions. Conducting the measurements following these conditions could be of benefit to the assessor:

- When investigating issues such as formation of condensation, mold and ghost marking on building envelope interior surfaces, weather conditions (i.e., time of year) should replicate those identified in the occupant or building management survey as much as possible.
- Field tests should be conducted following standard test methods and practices where these exist. Refer to the “Building Envelope Performance” heading in the above “Performance Areas and Indicators” section.

Complementary Data Collection. In addition to the information reviewed during the Level 1 study, review of field review reports by the architect and/or the building envelope consultant may bring forward construction issues shedding light on matters raised during the POE.

Interaction with Other Systems. See the Level 1 procedure.

Time and Effort to Collect Data. For each test: one or more on site, depending on type of test, size of building, and complexity and number of tests.

Typical Minimum Equipment Cost. Purchase costs for the tools vary and depend on quality and number of features (costs shown for order-of-magnitude only): digital psychrometer for spot measurements, $250; infrared camera, $7,000; thermocouples and data logger, cost per data logger ranges from $400 to $1,700 and up, depending on the number of thermocouple inputs, cost of thermocouples is insignificant.

Costs of the above equipment, as well as for water and air leakage testing apparatus (water spray racks, fan, manometer, smoke generator, etc.) are commonly used equipment typically included in fee charged by consultant.

Further Work. A higher level of study is possible, and, if warranted, could include conducting exploratory openings and destructive testing. However, conducting further extensive investigation and the use of highly specialized expertise and equipment would generally be considered outside the mandate of a POE.

Step 4—Information Transfer

Meeting with the Owner and Design Team. The purpose of the final meeting with the owner and the design team is information transfer. The building owner, the entire

POE team, and the design professionals should be present at this meeting (if the latter are involved in the POE process).

The POE team presents the main results of the study and discusses how the actual building performance compares with predicted or design targets or industry benchmarks, focusing on building-specific design goals. Any successes, challenges or disparities related to these goals should be identified and discussed. Lessons learned pertaining to building design and operation should be identified and possible strategies for communicating these lessons to a wider design community should be discussed. Recommendations for further investigation should also be presented.

CONCLUSION

This paper presents a methodology for the post-occupancy evaluation of multi-unit residential buildings to meet specific objectives. Seven performance areas are included in the methodology: energy efficiency, water use efficiency, indoor air quality, lighting and the visual environment, acoustics, thermal comfort, and building envelope performance. The methodology is a modular, customizable tool that can be adapted to suit the objectives of the commissioning party. The overall process of the methodology is described step-by-step, from the initial data collection from stakeholders, to the surveys and interviews, data collection from site, and the information transfer.

The findings from POEs of MURBs can be fed back to the stakeholders to improve the operation of existing buildings, and the design, construction, and operation of future buildings. POE outcomes can also serve to provide evidence of the actual performance of innovative systems, equipment, and practices to hasten their adoption by the building industry. The performance data can lead to the determination of benchmarks, which could be used by the building industry and regulatory bodies in the development of building codes.

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