A COMPUTATIONAL FRAMEWORK FOR INTEGRATION OF PERFORMANCE INFORMATION DURING THE BUILDING LIFECYCLE

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ABSTRACT: Optimal indoor environments in terms of thermal comfort and indoor air quality are essential to maintain healthy and productive spaces. To address the high occupant comfort and energy efficiency requirements, advanced HVAC systems that have narrow performance boundaries are used. It is crucial to achieve the satisfactory operational level for systems and buildings by the adoption of performance based verification strategies.

Performance-based approach requires the continuous verification of the actual performance against objectives during the building lifecycle. Building commissioning, building energy management systems (BEMS) and operations and maintenance are effective tools to verify optimum building performance and have the potential to embed performance assessment into the building lifecycle. However, transfer of performance information from one method or building phase to another is difficult. A considerable amount of valuable information is lost due to the lack of an integrated framework that bridges different islands of information. This becomes most problematic during the operational phase, where design data and performance trends are the main basis for decision making for facilities management staff. To achieve a persistent performance evaluation across phases and stakeholders, a flexible and seamless communication infrastructure across disciplines and processes is necessary.

The software architecture for a continuous performance verification and communication environment for indoor climate and ventilation systems is introduced. The purpose of the model is to provide a framework that integrates commissioning, BEMS monitoring and inspection/maintenance activities, to avoid erosion of domain information during handovers and over time. The model retains continual information of building and makes this information available during building operations and [re]commissioning. A formal relationship structure is proposed between performance indices to support traceability of design and operations decisions. The paper will be concluded with reflections into the future work, which includes implementation and proposed strategies for validation of the model by test cases.

KEYWORDS: building lifecycle performance assessment, building commissioning, BEMS.

1 INTRODUCTION

Indoor environment conditions rely primarily on the design decisions that the architects and engineers make. To maintain healthy and productive spaces, optimal indoor conditions should be provided. The high comfort and energy-efficiency necessities of modern buildings are steadily increasing due to the growing awareness of the building owners for creating better indoor spaces for their occupants, as much as high aesthetical quality. To meet these needs, advanced heating, ventilating and air conditioning (HVAC) systems are designed and used that have very limited tolerance for failure or underperformance. This is especially the case for facilities that belong to large-scale organizations with standards to be met such as federal, state and municipal buildings; accommodate critical services which have vital consequences if disrupted, such as police or fire call centers; and pose special indoor climate requirements such as museums, laboratories, hospitals and archive buildings, where negative indoor climate conditions can lead to deterioration of valuable exhibit materials, test samples or archival documents.

Two fundamentally distinctive but related performance domains are in focus in this respect (Table 1). The first domain, indoor climate (IC), is on the architectural side of the scale, primarily dealing with human requirements such as thermal and indoor air quality (IAQ) to respond to occupant comfort and health (Fanger 1972 and Butera 1998). The second domain, HVAC systems, tries to find reliable and realistic solutions to indoor climate necessities by the knowledge of typical engineering sciences. There is a reciprocal dependency between these two domains, such that, HVAC design and specifications stem from the IC concepts, and in return HVAC systems try to satisfy IC requirements. Most problems related to indoor air can be traced to underperforming or unmaintained HVAC equipment.

Achieving optimal operation of buildings systems require the adoption of performance assessment methods. The performance based approach starts during the programming phase with the elicitation of building performance requirements related to the desired IC conditions, which are qualitative statements about the user needs and expectations. These statements need to be translated into numeric performance values that respond to the specific IC decisions in order to be verified and validated objectively during design and operation. These values represent the expected behavior of a building, and ground the relationships and communication between stakeholders on an objective basis. Then equipment performance requirements are settled with regard to capacities to meet the thermal loads and the IAQ needs to be satisfied. This might be accomplished by expert knowledge, calculations, and/or performance simulation tools. Accordingly, the appropriate building systems are selected by system engineers. This is an iterative design process between requirements, systems design and existing market solutions, until a reasonable match is made. After the equipment submittals, maintenance manuals also are submitted to building operators to provide O&M services during the operations phase.

Table 1. Performance Assessment Domains.

domains:	**content:**
INDOOR CLIMATE	Thermal comfort: air temperature, mean radiant temperature, humidity, air speed Indoor Air Quality: fresh air distribution, restriction of mass pollution (gasses, vapors, micro-organisms, smoke, dust, etc.)
HVAC SYSTEMS	Provide climate control by proper ventilation, heating and cooling with regard to the analysis of indoor climate requirements. Some HVAC components include heaters, chillers, air handlers, ducts, pumps, etc.

2 PERFORMANCE ASSESSMENT METHODS

Continuous performance assessment against target values after the construction and systems installation constitutes the second portion of the performance based approach. This work will refer to three assessment *methods.*

2.1 *Building commissioning (BCx)*

is a systematic and effective tool to ensure that buildings and systems perform as intended and meet the client's requirements. It is a multi-phase effort that ensures that the interrelated building systems are correctly installed and operating. (ASHRAE 1996). If started early in the programming or design process and pursued further towards occupancy, commissioning integrates and improves traditionally separate functions of design, equipment start-up, calibration, functional performance testing, inspections and related documentation. During occupancy, periodic verification of required performance is necessary by re-commissioning of the systems in every 5-6 years, after the replacement of an HVAC component or a major change in building use or occupancy. However in real life, commissioning currently is limited only to the acceptance phase. Although a follow-up commissioning at the end of the warranty period (typically at the end of the first year after equipment start-up) is common practice, it is not very common to monitor the systems to verify the performance objectives later on during the occupancy period. (Turkaslan-Bulbul et al. 2006)

2.2 *Building energy management systems (BEMS)*

are computerized systems through which the building operators can continuously control and monitor energy-consuming equipment performances by remote *sensors* and *actuators*, and a centralized *controller*. The main purpose of BEMS is to make the building systems operate more efficiently while maintaining comfortable indoor environments. BEMS have the potential to embed BCx performance testing through the occupancy phase by automated performance monitoring, fault detection and energy consumption metering features. Yet, BEMS are not reliable sources for performance assessment at building start-up, as the newly installed sensors need to be calibrated before consistent readings are acquired. Also, BEMS cannot handle manual work that requires human intervention and involvement such as visual inspections.

2.3 *Operations and maintenance (O&M)*

is the work required to maintain or restore building equipment and components to condition such that they can be effectively operated to meet specified requirements. O&M programs typically consist of manual preventive *inspections* and run-to-failure *corrections* of building systems. These actions can be carried out on a scheduled basis before failure occurs, or can be initiated by a performance measurement or equipment breakdown. A proper maintenance program avoids costly failures, ensures reliable operation, extends equipment life and helps the performance goals be realized.

Each *method* has advantages and limitations. These limitations can be in functionality, data management, automation, scope, persistence, ease of application, costs, or availability of services. The weaknesses of one method can be compensated with the help of another. However, currently, impartial measurements comprise the performance assessment of buildings. The multiplicity of these *methods*, as well as the information created and captured during the process, adds further complexity to the performance assessment.

2.4 *Problems and shortcomings with the existing tools, methods and approaches*

Performance assessment is a knowledge intensive effort. A comprehensive and lifelong performance assessment approach requires multiple assessment strategies interwoven throughout the building phases. However, these efforts generally are performed by different disciplines at different times in different time intervals. Different *domains* and *phases* related to performance assessment *methods* create islands of information isolated from each other. Domain knowledge is distributed and fragmented. Moreover, during the lifetime of a building, the experts that hold the knowledge about buildings and systems change frequently and a considerable amount of valuable information is lost with them. For typical systems, missing information can be compensated by the building operators' experience, but this is hardly possible for advanced and innovative systems. This becomes most problematic during the operational phase, where the design and long-term performance data are the main basis for decision making of the facilities management (FM) staff.

Fragmented performance information should be integrated for a seamless approach which requires a strong communication and information-sharing basis. However these *methods* have different languages and vocabularies of components. Although they try to accomplish common goals and deal with the same type of data, there is no continuity of information. One challenge in this respect is that performance assessment *methods* are not static and have no formal standardization. They evolve and expand over time, as related technologies and ICT solutions advance and the understanding of the HVAC systems and indoor climate change. So when the language of one method changes, the interfaces to and from other methods have to change as well.

The existing tools to support the whole lifecycle needs of building performance assessment are manifold. The first type is computer aided facility management (CAFM) tools that store, present and analyze information about facilities. Building performance information falls into the category of technical functions in a CAFM tool, which includes building installations operations and maintenance, safety, energy management, etc. They provide central FM services such as preventive maintenance scheduling, automated work orders, physical asset histories and inventory control. Most CAFM tools also can interface with BEMS and pull sensor data to associate it to the existing space and installations in the central database. However these tools only focus on the FM ---s and the functionalities they have fail to capture the whole scope and content of a integrated performance assessment approach.

Building diagnostics and information monitoring tools exist such as PACRAT and Whole Building Diagnostician (WBD), with automated diagnostics, energy performance tracking, data visualization and documentation capabilities (Arney et al. 2003) (Katipamula et al. 2002). Diagnostics modules utilize rule based expert systems that hold and maintain considerable levels of information about equipment, performances and sources of faults. However they inherit the shortcomings of expert systems such that they lack human understanding and common sense required during O&M decision making and ad-hoc reasoning. Furthermore they don't have the adaptability and flexibility to deal with changing facility environments and circumstances, as mentioned above.

Relevant building information modeling (BIM) problems are addressed in ICT by the interoperability efforts to supply sustainable data and information coverage during the whole building lifecycle. IFC (Industry Foundation Classes) is an example of such standardized model-based approaches developed to represent the conceptual and physical objects and activities in the AEC industry (Liebich et al. 2004). However, achieving and maintaining semantic integrity in such a massive model has its challenges. New data sources and properties continuously need to be added to an already heterogeneous combination and thus achieving completeness of the model is cumbersome. Existing data sources also alter their specifications, and applications may alter the requirements for the data they receive. Moreover, FM classes in IFC are not sufficient to provide data structures and technologies required to fully support building performance information. (Yu et al. 2000). Although recent releases of IFC allow user-defined property definition to customize project specific information, it still falls short of establishing the formal semantics of the building performance domain objects and processes.

3 OPPORTUNITIES FOR IMPROVEMENT

In order to achieve persistent performance assessment of buildings, a flexible and seamless communication infrastructure across different *domains* and *phases* is required. Therefore, a data model to integrate performance assessment for *indoor climate* and *HVAC systems* will be developed. A data model represents the logical structure of a system and captures the data requirements, attributes and behaviors of objects within the model. The purpose of this model is to avoid erosion of performance information during handovers and over time by providing a framework that bridges different information islands of design specifications, building commissioning, BEMS monitoring and O&M. The physical *components* included in the model are (1) rooms and (2) air handling units (AHU). An AHU is a part of an HVAC system that is responsible for circulating conditioned air throughout a building. A typical AHU consists of fans, heating and cooling coils, air filters, terminal boxes, and other necessary equipment to perform the functions of ventilation, cleaning, heating, cooling and mixing of air. The components of an AHU are usually assembled in order to meet the specific comfort needs of a building, air flow requirements and the heating/cooling capacities. So, two separate AHUs are rarely identical with respect to the combination of their parts and their behaviors. There can be many different system configurations, depending on the number of zones, duct system type, and air volume systems. The criteria upon which these decisions are made are usually based on budget and needs. Thus, operational and performance assessment strategies for each building and equipment configuration differ widely.

3.1 *Representation of data*

The approach for data representation is the elaboration and decomposition of domains to the point that building performance can be expressed in manageable metrics: *performance indices* (See Figure 1). In the model, the AHU is decomposed into its subcomponents with respect to ASHRAE (American Society of Heating, Refrigeration and Air Conditioning) Systems and Equipment classification. Similarly, the indoor climate domain is embodied by two aspects for this model: *thermal comfort* and *indoor air quality.*

Performance information in the model emerges as these *performance indices* that belong to each component. These *indices* are explicitly represented as classes in the data model. There are four types of *indices*: *requirements, functional performance tests, inspections* and *corrections* (see Table 2). *Requirements* are brief and qualitative descriptions of specific needs and objectives about the indoor climate and HVAC components. They are usually specified by indoor climate specialists and HVAC engineers during the design phase, and remain unchanged during the lifetime of the building unless a major change in functionality or occupancy occur. *Functional performance tests* address the requirements, and verify the numeric performance parameters that fulfill the performance requirements. They are carried out by BCx and/or BEMS. *Inspections* are manual examinations made on building systems to prevent equipment degradation, either periodically or upon an inconsistency with the performance tests. They can be a part of the O&M program or BCx. *Corrections* are actions necessary to be taken periodically, or after the identification of a problem with building systems during BCx or O&M inspections. During the operations phase, the resulting values of these four *indices* are logged in the tool by the commissioners, BEMS and building operators continuously.

Table 2. Performance Indicators in the Data Model.

Performance Indicator Types	Class Attributes	Example Indicator Instances for a Fan class
Requirement	*name, description*	*Provide efficient heating, a desc.*
Functional Preformance Test	*name, description, design_value, unit, test_measurements[]*	*entering_air_temp, a desc., 15, C, measurt[]*
Inspection	*name, description, frequency, inspections[]*	*motor_overheating, a desc., 6, inspect[]*
Correction	*name, description, corrections[]*	*Lubricate_bearings, a desc, corr[]*

The model contains a performance *indices library*. The users of the system can freely select their specific performance *indices* from this repository to meet the building's needs. However, these indices will remain insufficient when new technologies emerge with new sets of system attributes. So it is important to give the users the flexibility to extend the library by adding their own *indices* when the existing library fails short of satisfying the building's performance assessment needs. The selected set of *indices* will be representative of the given context and its limits of performance assessment. By this means, the instance of a model that meets the information needs of a building can be generated (See Figure 2)

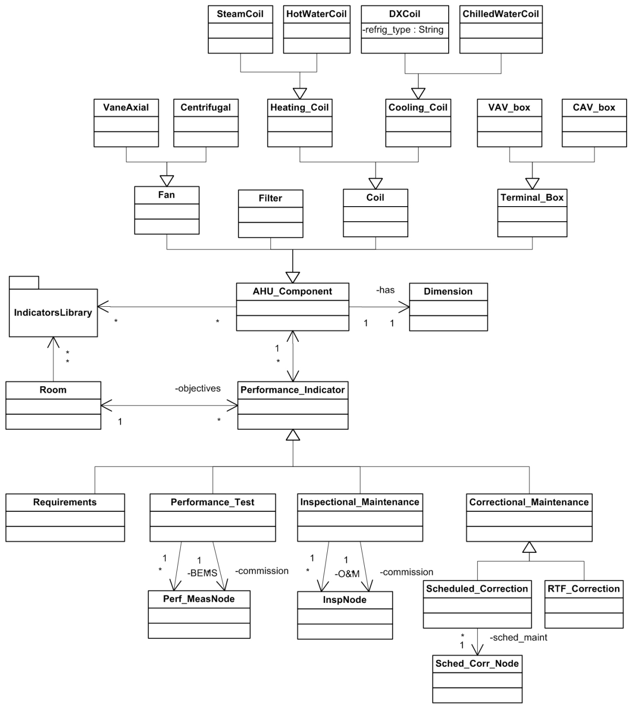

Figure 2.

3.2 *Data traceability*

The model, as explained in the data representation section, doesn't hold any domain knowledge or has any intelligence on reasoning between various *performance indices* itself, but provides a basis for simple data management. Each performance *indicator* is stand-alone and independent. Expert knowledge is introduced to the model by the users of the model, by establishing relationships between *indices* of IC concepts and corresponding HVAC systems by a data traceability approach.

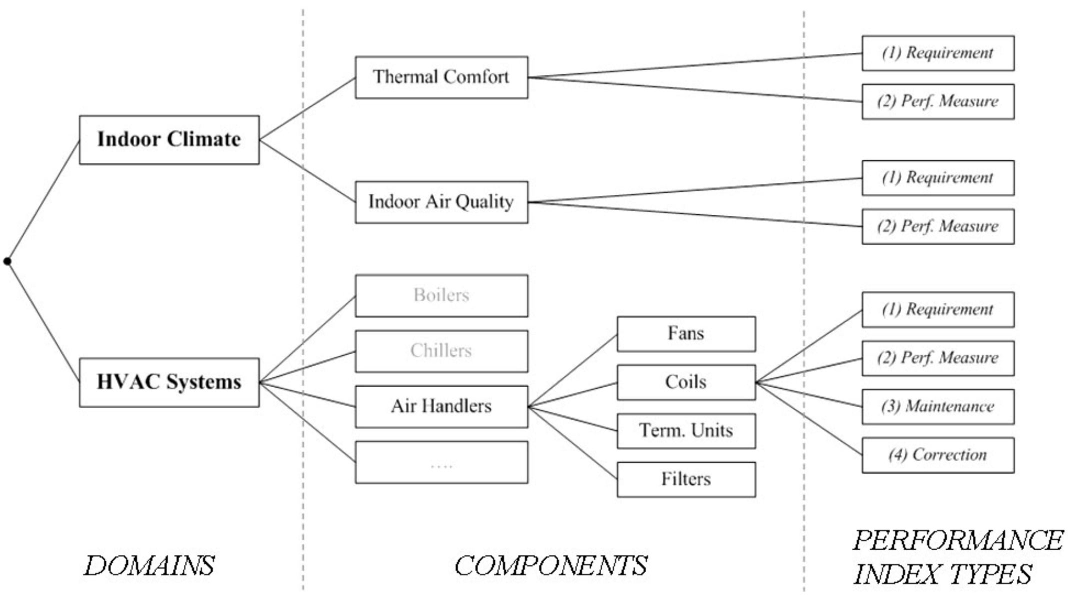

Figure 1.

In software architecture, traceability is defined as the ability to trace semantically related objects within the same model and corresponding items contained by parallel models during their lifecycle. It usually refers to software requirements and how they evolve during the stages of design and implementation as an assurance of the final product fulfilling the goals and objectives (Edwards and Howell 1991). Traceability facilitates communication between stakeholders by structurally bringing the concepts that are of importance to the model together and making them available among stakeholders. Various traceability tools exist, with capabilities such as creating parent/child relationships, functional hierarchies, definition of keywords and attributes to requirements and other system artifacts, ad-hoc and pre-defined querying, requirements extraction from documents, customized report generation, and maintenance of information about allocation of requirements to system components or functions (Ramesh et al. 1997).

Building design, construction and operations are incontinuous in nature. The collected information is fragmented although they are semantically related. These relations can be in the form of subsequent decisions taken in time, actions that are triggering or dependent on each other, dependencies, hierarchies, and so on. To address the integration of the information indices, a formal *relationships structure* will be created for data traceability. There are two basic types of traceability. Vertical traceability refers to the relationship established among the parts of a model, expressing the interdependencies between object of the same level. Horizontal traceability refers to the lifecycle of model objects and their integration in time. For the model, both types of traceability are necessary for capturing relationships across both product and process dimensions respectively. The vertical relationships ensure the integration of domains; in a way to relate indoor climate requirements to HVAC performance indices (See Figure 3). One example is the ventilation rate requirement of a room that is contained within indoor climate domain linked with the air flow capacity of a fan. The horizontal relationships trace the lifecycle decisions and triggers between indices. As an instance, a logical sequence of *requirement* (provide_adequate_ventilation) > *performance_test* (airflow) > *inspection* (is_obstructed) > *correction* (clean_blades) for the fan class can be given.

These relationships cannot be embedded in the model because of the volatility of the existing languages of *methods* and *domains* as previously discussed. So the relationship generation should be dynamic and on the highest level (end user level), and be performed considering the particular building instance at hand. These relationships will also make possible the lacking reasoning mechanism between building lifecycle decisions. In this way, it will be possible to track how the design objectives yield into design values and which HVAC operation problems trigger which comfort violation. The relationships network will be organized in a *hierarchical tree structure* that will allow backward and forward information mapping (See Figure 4). The relationship types are to be identified and richer traceability schemes will be introduced in the future. These relationship types, as in performance indices, can be selected from a *relationship library* or created by the users of the system.

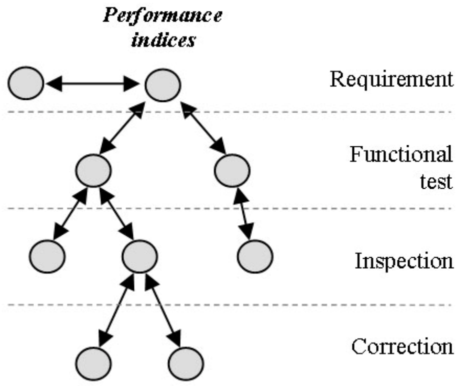

Figure 4.

	Requirements	Func. Perf. Test	Inspections	Corrections
Interior				
	IAQ	air_temp		
	thermal comfort	co3		
		static_air_pressure		
		humidity		
Air Filter				
	clean air from particulat	air_flow	is_filters_inst_in_airflow_	clean_airfilter
	min. pressure drop	max_velocity	is_proper_filter_installed	change_airfilter
	ASHRAE standards	max_initial_pres_drop	is_filter_doors_secure	secure_filter_door
		min_ASHRAE_efficiency	has_no_air_leakege	
			is_clean	
			is_dry	
			no_contaminants_visible	
			no_odor_noticable	
Fan				
	provide adequate ventil	static_pressure	no_belt_excessive_wear	adjust_belt_tension

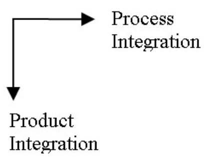

Figure 3.

3.3 *Future directions*

To validate the data model, a proof-of-concept software tool that will implement the model will be developed. The goal of model validation is to test the model by making it used in real life in order to assess if it addresses the right problems, provides accurate information about the system being modeled and meets its intended requirements in terms of the methods employed and the results obtained. The users of the tool are primarily the building operators to support long-term performance assessment during the occupancy phase. The tool can also be used by commissioners to analyze the performance and behavior of the building and HVAC systems for analysis and solution-finding during re-commissioning. Nevertheless, the tool requires design data input during programming and design, so building owners, architects, HVAC engineers, indoor climate specialists, and other connected stakeholders also are potential users during the earlier phases for performance specification. This tool is intended as a communication and information-sharing base, so it brings all these actors together on a common ground for a more integrated and consistent process.

The tool will then be evaluated with respect to software quality characteristics specified by ISO 9126 Quality Model. This evaluation will be based on a functional ground, in terms of the tool's *suitability* (the capability of the software to provide an appropriate set of functions for specified tasks and user objectives) and *accuracy* (the capability of the software to provide right or agreed results or effects) (ISO/IEC 2001). The tool will be tested in two levels. The first will be a *formative* and developmental evaluation by the researcher. This will be followed by the second level of testing that is *summative*, with operators of the buildings from the case studies and real data. The evaluation method of participant remarks will be questionnaires and structured interviews about the functionality of the tool. To filter the problems arising from the interaction between the user and tool, separate usability questionnaires will be used, and content based problems related to the proposed model will be distinguished from usability issues. The final results will be measured against predetermined criteria and resultantly provide an overall picture at the final stage.

The case studies for data model refinement and evaluation will be made in collaboration with the Dutch Ministry of Housing, Spatial Planning and Environment (VROM), Maintenance Department. The three pilot studies of building inspections were recently completed by VROM, and these data will be used both for finalizing the model and software testing. A second parallel research project will start shortly that extends this work to the whole building inspections required by VROM. Where this research specifically focuses on the building indoor climate, the new research project will cover the wider domain of maintenance inspections including climate, electrical, transport installations and building exterior.

4 CONCLUSION

In this paper, we described the preliminary data model that integrates information related to various building performance assessment methods that continuously verifies the design requirements throughout the building lifecycle. Large amounts of data is created and shared amongst various sources during performance assessment and remain fragmented and unused unless the semantic continuity between performance concepts are computationally structured. Supporting the assessment process with an integrating tool is necessary, but also poses serious challenges. These challenges can be resolved by extendible and flexible information structures that stay in parallel with the dynamic nature of the industry.

Building performance assessment is an extensive field that includes many domains from building installations, lighting, indoor climate, structure and so on. The scope of the proposed model is kept rather narrow in order to demonstrate how indoor climate domain information and traceability can be represented in detail. Because it explores the prospect of data integration within a very limited area, it is currently not possible to implement the model and method as part of a general building management system or a computer aided facility management tool. However, the new research project in collaboration with VROM offers possibilities to expand the work into a larger domain of building performance where further performance domains are investigated and tested. This offers possibilities in exploring new types of traceability relationships across domains in the direction of whole building performance integration, and the tool's usability in the real life.

The model and implementation currently relies upon the findings of the case studies. One drawback in this approach is related to the variance of building performance assessment practices. Operational strategies and performance evolution approaches vary greatly from building to building. While the model currently includes three performance assessment methods, this might not be the case for the pilot buildings and some parts of the model might remain untested for the missing assessment method. Moreover, the level of knowledge and cooperation of the building operators while testing of the tool will be a key issue in the quality of feedback acquired. Despite these concerns, the wide range of possible case studies as rich sources of data is expected to overcome the challenges posed by adopting a case study approach.

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