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A Method to Compare Measured and Simulated Data to Assess Building Energy Performance

By

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CIFE Working Paper #WP127
August 2010

STANFORD UNIVERSITY

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1 Abstract

Building energy performance is often inadequate given design goals. While different types of assessment methods exist, they either do not consider design goals and/or are not flexible enough to integrate new and innovative energy concepts. However, innovative energy concepts are needed to comply with new regulations that aim to decrease energy use in buildings. One reason for the missing flexibility of assessment methods is their development and testing based on one single case study, which makes them very specific and less flexible. Furthermore, existing assessment methods focus mostly on the building and system level while ignoring more detailed data. With the availability and affordability of more detailed measured data, a more detailed performance assessment is possible. However, the increased number of measured data points requires a structure to organize these data. Existing representations of building objects that would structure measured data typically focus on a single perspective and lack relationships between building objects that are present in buildings and that are needed to understand the interplay within heating, ventilation and air conditioning (HVAC) systems and assess their performance. This paper presents the Energy Performance Comparison Methodology (EPCM), which enables the identification of performance problems based on a comparison of measured performance data and simulated performance data representing design goals. The EPCM is based on an interlinked building object hierarchy that includes necessary relationships among building objects by integrating the spatial and thermal perspectives. We focus on the process of comparing performance data from the bottom up, starting with control set points and leading to total building performance data. This research is based on multiple case studies that provide real-life context for performance problems and measured and simulated performance data. We also prospectively validated the EPCM and the building object hierarchy with an additional case study.

Keywords: Comparing measured and simulated data, building energy performance data, validation, comparison methodology, building energy performance simulation

2 Introduction

Building energy performance problems are a well-known issue (Mills et al. 2005). Several studies show that heating, ventilation and air conditioning (HVAC) systems in buildings do not operate as predicted during design because of performance problems (Scofield 2002; Piette et al. 2001; Persson 2005; Kunz et al. 2009). These studies indicate an untapped potential to reduce energy consumption of buildings and highlight the gap between design and actual energy performance. In addition to these studies, new regulations aim to decrease energy consumption in buildings (e.g., Sissine 2007) and thus further increase the need to close the gap between design goals and actual energy performance of buildings.

Existing methods that compare measured and simulated data focus on the building and/or system level. When this focus is used, modeling inaccuracies can be hidden through compensation errors (Clarke 2001). Existing comparison approaches (e.g., Salsbury and Diamond 2000) describe the comparison in a generic fashion and do not include details about processes or tasks. Automated performance assessment methods focus on the component level or on specific types of systems (e.g., Xu et al. 2005). To assess the energy performance of all levels of detail in a building a comparison that ranges from the component to the building level and a systematic methodology are needed. Due to an increased number of data available, a hierarchy is needed that allows to relate different data streams to each other and sets them into context of the building and its HVAC systems. Examples of related data streams are space level and system level water temperatures that greatly depend on each other. Since measured performance data are linked to HVAC systems and components but also to spatial objects, a representation that combines both perspectives is necessary. The first building object hierarchy that considers the spatial and thermal perspective focuses on zone components (O'Donnell 2009) and does not include topological relationships as well as relationships between HVAC components of different HVAC systems. Since performance data are tied to spatial and HVAC components, a hierarchy is needed that combine both perspectives and that describe the relationships to neighboring as well as parent objects.

We developed the Energy Performance Comparison Methodology (EPCM), which supports identification of performance problems based on comparison of measured and simulated data. This method incorporates design goals by using building performance energy simulation (BEPS) models generated during design and provides an assessment of the actual building's performance compared to the performance simulated with design BEPS models. The BEPS models provide a benchmark for comparison of the actual performance. The benchmark includes design goals, which are otherwise often neglected during operation, and is a useful reference to understand the anticipated performance of the building. The EPCM was developed based on the experience of comparing measured and simulated data in two case studies. It was prospectively validated on an additional case study. This methodology builds on and extends three areas: measuring building energy performance, simulating building energy performance, and comparing the resulting measured and simulated data. Data acquisition systems archive the measured data for use by the EPCM. Detailed whole-building energy performance simulation tools such as EnergyPlus produce the simulated data for this comparison. This paper describes the EPCM in detail, including the formal representation of building objects in the form of a building object hierarchy that captures additional relationships of objects compared to existing hierarchies. Other critical aspects of the EPCM are the identification and appropriate consideration of measurement assumptions and simulation approximations, assumptions, and simplifications (AAS). Measurement assumptions document limitations of measurement systems while simulation AAS document limitations of BEPS models. The documentation of both types of limitations is needed to evaluate difference between measured and simulated data. In particular, these limitations can hinder a matching of measured and simulated data and thus need to be considered when comparing performance data. Maile et al. (2010b) discuss measurement assumptions and their use to understand limitations of measurement systems. Maile et al. (2010a) describe simulation AAS and their use to understand limitations of building energy performance simulation data. Within the EPCM, both the measurement assumptions and simulation AAS are analyzed to identify performance problems based on differences between measured and simulated data. During the assessment process the BEPS model is adjusted so that simulation results match more closely with the actual performance of the building.

Due to the increased level of detail and the goal of the EPCM to identify actual performance problems, we base our research on case studies to provide real-life context (Yin 2003) for performance problems in buildings. We elaborate on the development of the EPCM (section 3) and provide a discussion of existing performance assessment methods and highlight the shortcomings of existing methods (section 3.4). We describe the EPCM in detail (section 4). Results from applying the EPCM on a case study (section 5) and details about our validation of the formal representation and the methodology itself are shown (section 6). Through the validation, we show the generality of EPCM through different case study building usage and HVAC systems and the power of EPCM compared to standard practice. Lastly, we describe limitations and possible future research areas (section 7).

3 Development of the EPCM

We developed the EPCM based on two initial case studies and one validation case studies. We discuss the need for the case study research method and detail our selection of case studies. We illustrate early comparisons and their effect on the development of the EPCM as well as describe existing assessment methods in detail.

3.1 Research method: case studies

Since our main focus and goal of the EPCM is to identify performance problems in buildings, we needed a research method that allows the observation of performance problems in practice. In addition, the level of detail plays an important role in this research. Both criteria led to the selection of a case study based research method. Case studies are the typical research method in this field, with most researchers using a single case study. The problem with single case studies is the lack of generality of the resulting methods. Survey or interview methods are not applicable due to the lack of knowledge and standard practice that would be necessary for them. From a research validation perspective, it was also necessary to select different building types, so we could test the developed methodology with different HVAC systems and building usage types and illustrate the generality of the methodology. The differences and similarities of the three case studies are illustrated in Table 1. This table includes the existing design BEPS model tools, the ventilation type, and building usage, as well as a listing of the main HVAC systems.

Table 1: Description of the three case studies

Case study	Existing BEPS model	Ventilation	Building use	Main HVAC systems
SFFB	EnergyPlus	Natural	• Office	None
GEB	DOE2	Natural and mechanical	• Office • Academic • Labs	• VAV AHU's • Hot water loop with boiler • Chilled water loop with chiller and roof spray
Y2E2	eQUEST	Natural and mechanical	• Office • Academic • Labs	• 100% outside air VAV AHU's with active beams • Two district chilled water loops • Two district hot water loops

Based on the first two case studies, we developed concepts for a formal definition of measurement assumptions and simulation approximations, assumptions, and simplifications (AAS), a formal representation, and a comparison methodology.

3.2 Selection of case studies

An ideal case study for the EPCM meets three major criteria: it has an existing BEPS model; it provides extended measurements above the typical measurement level in existing buildings; and there is acceptable and consistent documentation about building geometry, HVAC systems, and controls. The quality of existing documentation determines the effort to create or update BEPS models, to create a building object hierarchy, and to define assumptions and AAS. Inconsistent documentation requires significantly more effort to verify drawings and equipment through on-site visits, and it may also require advanced measurements or tests to determine certain characteristics of the building that would usually be contained in quality documentation.

While it has been difficult to find such buildings to date, we identified and used three case studies that nearly met these requirements. All three buildings provided access to measurement data and as-built documentation about building geometry and HVAC systems. They were accessible to the research team by being in the San Francisco Bay Area (two in Stanford and one in San Francisco). All case studies included an existing BEPS model for the building, created at some point in the design process.

The first two case studies are the San Francisco Federal Building (SFFB) and the Global Ecology Building (GEB). The later validation case study is the Jerry Yang and Akiko Yamazaki Environment and Energy Building (Y2E2) at Stanford. These case studies include one office building (SFFB), two mixed-use research and office buildings (GEB and Y2E2). The observed portion of SFFB has a natural ventilation system. GEB and Y2E2 have a mixture between natural and mechanical ventilation systems.

3.3 Early comparisons

The SFFB case study was our first case study, and thus it initiated early concepts around the EPCM. In particular, it was apparent from early comparison graphs that more knowledge was necessary to understand the meaning of specific comparisons of measured and simulated data. For example, Figure 1 illustrates two early comparison graphs. The left graph shows that the simulated space temperature did not match with the measured counterparts at 100% airflow. However, the right graph shows a reasonable match between measured and simulated space temperatures at 25% of airflow. The difference between the measured and simulated airflow can be explained with two assumptions. The first simulation assumption is that the bulk airflow in the BEPS model cannot capture all dynamic effects of the actual airflow. The second measurement assumption is that the velocity measurements are spot measurements and thus do not directly correlate with the average airflow over the opening area in the simulation model. These insights lead to the development of the EPCM and the concepts of measurement assumption (Maile et al. 2010b) and simulation AAS (Maile et al. 2010a).

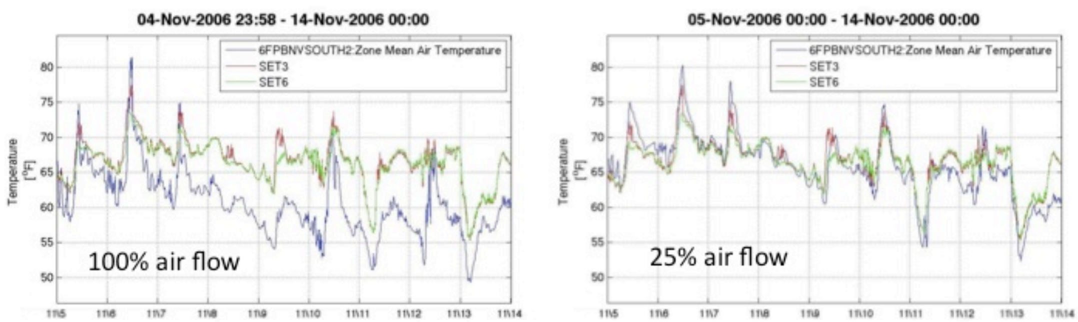

Figure 1: Example comparison graphs from SFFB

(left – Space air temperature comparison based on 100% airflow; right – Space air temperature comparison based on 25% airflow)

3.4 Existing methods to detect performance problems

Figure 2 shows existing methods for detecting performance problems in buildings on two dimensions: life-cycle phases and level of detail. Traditional commissioning tests the functioning of a HVAC component (Grob and Madjidi 1997). However, correctly operating HVAC components do not ensure efficient operation on the system and building levels. Furthermore, the increasing complexity of HVAC systems increases the difficulty of testing the proper functionality of HVAC systems. Another technique used during the commissioning is trend analysis (e.g., Austin 1997; Seidl 2006), which focuses on detecting performance problems by analyzing measured data. To address the problem of manual and time-consuming commissioning, several automated commissioning methods have been developed. For example, Wang et al. (2005) describe an automated commissioning method for a specific air conditioning system based on a simulation model that was specifically developed for that purpose. Xu et al. (2005) use a similar simulation model approach, but base their analysis on functional tests that require interference with the actual operation of the building. These methods use simulation models that are used only during commissioning and thus are not linked to design. These automated methods are limited to known and typical HVAC system configurations and require additional development for new or innovative configurations or HVAC components.

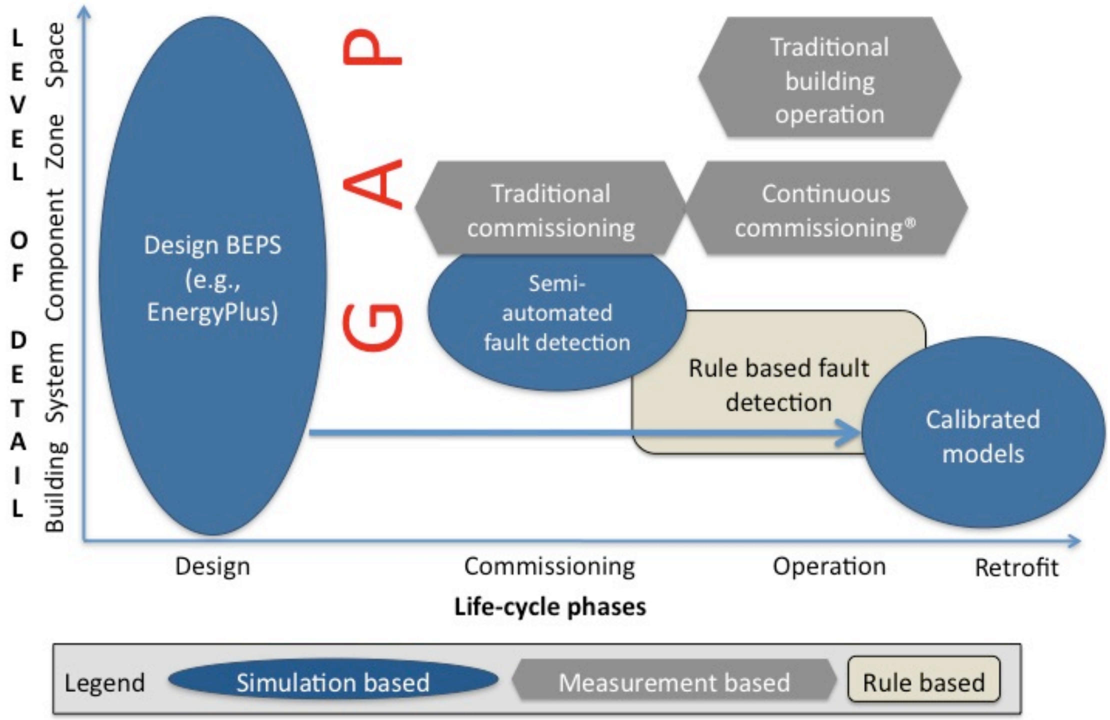

Figure 2: Overview of existing performance comparison methods

Traditionally, building operation is based on feedback from occupants. Building operators address issues on the basis of complaints and usually adjust local set points instead of troubleshooting the problem and resolving it (Katipamula et al. 2003). Thus, this approach focuses mostly on the space level, based on occupant complaints.

There are also a number of commercially available tools (e.g., Santos and Rutt 2001) that provide rule-based automated fault detection. Their focus is mainly on the system level. The disadvantage of those tools is the large installation effort and the predefined set of rules. Due to the need for predefined rules, new innovative HVAC systems and HVAC components cannot be evaluated with rule-based fault detection.

Last but not least, calibrated simulation models are often used to establish a baseline simulation model for comparison to possible retrofit measures. Calibrated simulation models are also used to verify the performance of HVAC systems, mostly on building and system levels. The problem with simulation model calibration is that compensating errors can mask modeling inaccuracies at the whole building level (Clarke 2001). As a result, problems in the building may not be identified due to the dynamic relationships among different parts of a building. Thus "calibration" is necessary on a component level to circumvent the compensation errors. A simulation model is often labeled as "calibrated" if it falls within a specific error margin (e.g., 5%). This results in a trial-and-error approach of changing input parameters until the result is within the specified error margin. That is why multiple "solutions" (input data configurations) are possible; thus, the selection of one possible solution is arbitrary (Reddy 2006).

Commissioning methods and calibrated simulation models typically describe a one-time event rather than an ongoing process for continuously controlling the performance of buildings. Several studies (Cho 2002; Frank et al. 2007) show that building performance decreases after one-time improvements. Therefore, we recommend data archiving and analysis over the complete life of a building.

All of these methods (except calibrated simulation models) fail to provide a link to design building energy performance simulation (BEPS). Thus, there is a gap between design BEPS and existing performance assessment methods. There are two main reasons why the link to design BEPS models is important. Design BEPS models contain the design goals, and thus these models should be the basis for an assessment to determine whether the completed product complies with the design goals. The second reason is to provide feedback to building design and the design BEPS model. Results of design BEPS models typically do not match with actual performance (e.g., Scofield 2002; Piette et al. 2001), thus a detailed method to detect differences between measured and simulated data is needed.

4 Energy Performance Comparison Methodology (EPCM)

The goal of the EPCM is to provide feedback to building design and operation. This feedback is based on performance problems and the subsequent estimation of their impact on thermal comfort and energy consumption. In this paper we focus on the tasks of the EPCM up until the identification of performance problems.

We call the person performing the tasks of the EPCM the *performance assessor*. Because such an assessment of actual building energy performance compared to design goals is rather rare in practice, we chose a new description for that person, who can be a HVAC design engineer with background in measuring, simulating, and/or commissioning.

The EPCM steps (the preparation, matching, and evaluation steps) and tasks are based on the flow of data (Figure 3). Step 1, the preparation step, includes tasks that create or update the BEPS model, set up data collection, and establish a building object hierarchy. All tasks in the preparation step are performed once for a project. Maile et al. (2010a) detail the creation, or preferably the update, of a BEPS model. Maile et al. (2010b) describe the task of setting up data collection. In addition to performing these two tasks, the assessor also establishes a formal representation of building objects in a building object hierarchy. This hierarchy consists of different levels of detail (building, system, component, zone, space, and floor level) and is later used to relate corresponding data streams.

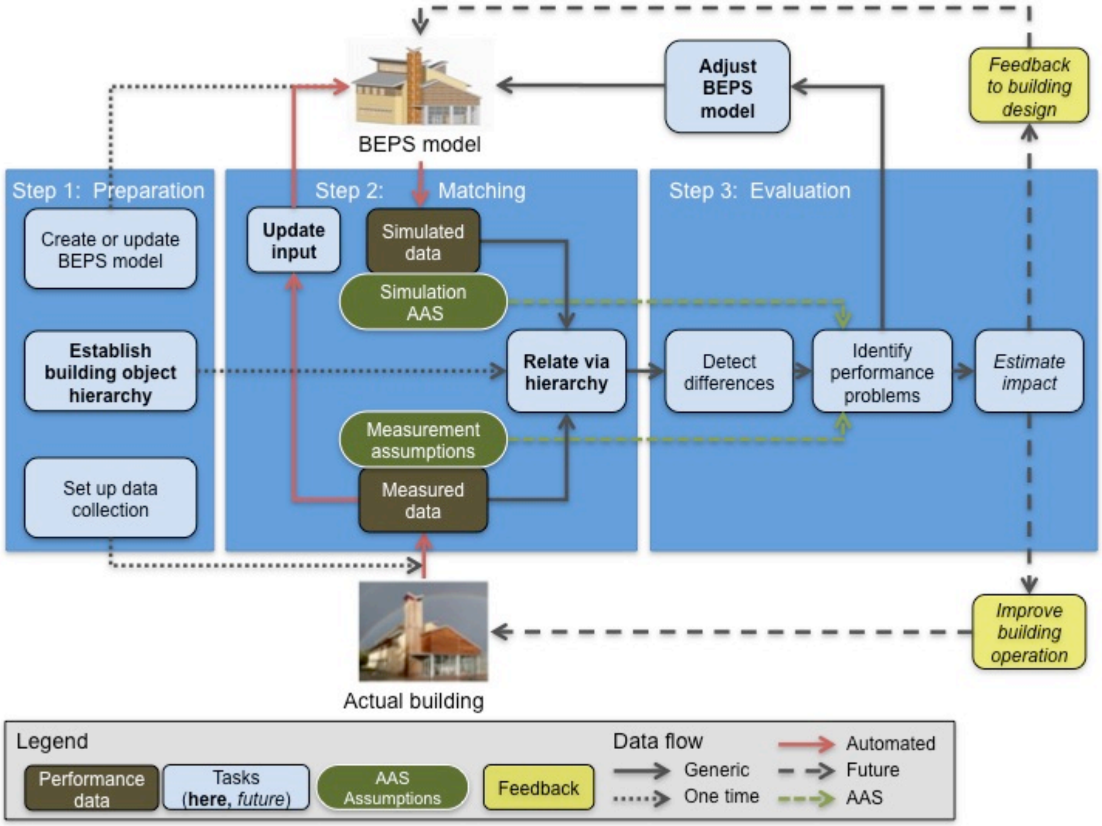

Figure 3: Overview of Energy Performance Comparison Methodology

The matching step (Step 2) builds on the prepared automation of measured data collection and the creation of simulated data based on BEPS models. To reflect actual boundary conditions around the building, the assessor needs to perform an update of input data for the BEPS model (see section 4.1). This allows simulating the response of the building given the actual boundary conditions. With the preparation step, measured data are automatically archived, and simulated data are automatically generated, given a complete description of the simulation input and the automated update of input. To describe limitations of measurement systems, measurement assumptions are attached to the object instances of the building object hierarchy from a list of critical measurement assumptions (Maile et al. 2010b). To describe limitations of BEPS, simulation approximations, assumptions, and simplifications are also attached to the object instances based on a list of critical simulation approximations, assumptions, and simplifications (Maile et al. 2010a). The building object hierarchy is also used to relate measured and simulated data streams into data pairs (section 4.2). An example of a data pair is a measured space temperature and its corresponding simulated space temperature for a specific space in the building.

In the assessment step, the assessor identifies differences between the members of the above mentioned data pairs, on both a visual and a statistical basis (section 4.3). Based on these differences, the assessor identifies performance problems with the help of measurement assumptions and simulation approximations, assumptions, and simplifications (section 4.3). Based on the identified performance problems, the assessor performs an iterative process (section 4.4) of adjusting input data of the BEPS model to eliminate incorrect design AAS to improve the matching of measured and simulated data. Since the actual building operation and measured data cannot be changed retrospectively, this iterative process focuses on simulated data. For each specific time frame under observation, the BEPS model is adjusted to eliminate AAS and incorporate changes of the actual building compared to the design BEPS model, to match measured and simulated data more closely. Since the actual building is a dynamic environment, changes to the building typically occur. In particular, changes to the control strategy or changes to the usage of the building or changes to the geometry are important for the use of EPCM. This is why we introduce events that describe these changes to the building and define time frames for investigation within the EPCM.

4.1 Updating simulation input

This section describes how to update simulation input data with measured data. For a meaningful comparison of measured and simulated data, it is important to define accurate boundary conditions, typically residing in a weather file, around a given building. While outside weather data are obvious boundary conditions, simulation input can also consist of other additional measurements. These other measurements include occupancy, plug loads, electric lighting, and others. In addition, input for the simulation may include space temperature set points, particularly if those are user-adjustable.

The initial update includes external boundary conditions, which are outside air temperature, solar radiation (separate direct and diffuse radiation measurements are preferred), wind speed and direction, as well as wet bulb temperature or relative humidity (whichever is available). Throughout the iterations of the EPCM, more measurement data are used as input for the simulation. If available, the set of input updates includes space temperature set points and measurements related to internal loads. While space temperature set points are most likely available on a zone respective space level, internal load measurements are typically not available at this granularity. If the measurement data are less detailed than the simulation data (e.g., floor-based measurements, but a space-based BEPS model), the assessor needs to convert the measurement from floors to spaces (floor area to space area) and assign different weights depending on space types.

We developed a simple data conversion tool (WeatherToEPW Converter) that automatically extracts the relevant data from the HVAC database and updates the related weather file and project-specific schedule file that define the set points for the BEPS model (Figure 4). BEPS tools use weather data files to account for different weather conditions at different locations. EnergyPlus uses the EPW file format (Crawley et al. 1999). Typically, these weather files contain data from multiple years, compiling typical months based on statistical criteria (Marion and Urban 1995). The tool has a flexible time interval, which can range from one minute up to one hour (these interval boundaries are inherited from the weather file format). The tool automatically averages data or fills smaller gaps through interpolation. It includes unit conversions and uses a solar model from Duffie and Beckman (1980) to calculate direct normal radiation from total and diffuse horizontal radiation. This conversion of radiation is necessary to comply with the data format of the weather file. The tool also contains an optional routine to convert pressure differences across two building facades into wind speed and wind direction (simplified in windward versus leeward direction). This routine was developed based on documentation of EnergyPlus (U.S. DOE 2010). Both routines, the solar conversion as well as the pressure conversion, are necessary to comply with the input data definitions of the weather file. Only the SFFB case study required the use of this pressure conversion functionality.

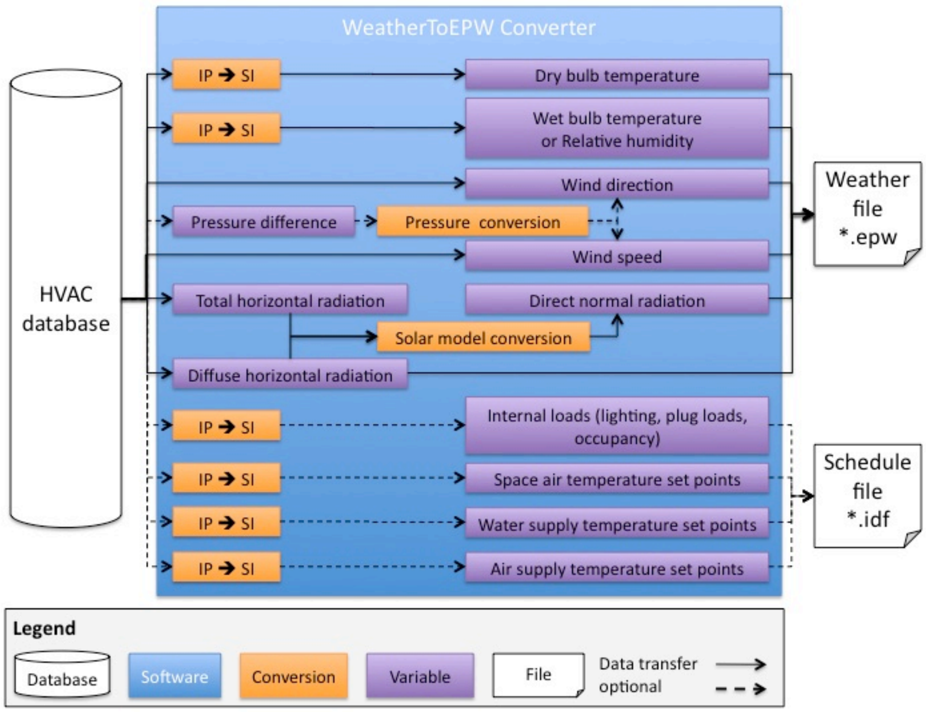

Figure 4: Weather converter data flow

4.2 Building object hierarchy

Due to the large number of data points (e.g., 2,231 data points at Y2E2), a formal representation is needed that allows organizing these data points. Such a representation needs to link building objects so that reasoning about differences between measured and simulated data of related building objects becomes possible. While various approaches exist for defining a building object hierarchy, almost all focus on only one perspective. Most common is a thermal perspective hierarchy, consisting of HVAC system, sub-system, and HVAC component levels (Husaunndee et al. 1997; Bazjanac and Maile 2004; Visier et al. 2004). Another common representation is a spatial perspective that includes building, floor, and zone/space levels. O'Donnell (2009) combines both perspectives into one tree structure that is focused on the zone object. The relevant HVAC hierarchy is connected to each zone, which leads to duplicate instances of HVAC systems and components and does not account for relationships among components of different HVAC systems. Furthermore, O'Donnell's representation lacks a space object. Interval Data Systems (IDS 2004) discuss the usefulness of various perspectives to building objects such as facility, organizational, or HVAC system hierarchies. However, they do not mention the relationships among different viewpoints.

A BEPS model typically contains some of these relationships between building objects. In EnergyPlus, each zone is part of the building and indirectly linked to neighboring zones through connected surfaces objects. The concept of a floor, i.e., an agglomeration of spaces, is missing in EnergyPlus. However, the HVAC components are part of a specific HVAC system and are organized in branches that connect the HVAC components including the flow direction. In addition, the HVAC components on the zone level are linked to the related zone objects.

Measured and simulated data points represent different objects on different levels of detail in a building. Due to increasing numbers of available sensors in buildings, the current focus on HVAC systems and HVAC hierarchies does not capture the interconnections between HVAC and spatial objects. Thus, we define a hierarchy that contains both spatial and thermal perspectives (Figure 5).

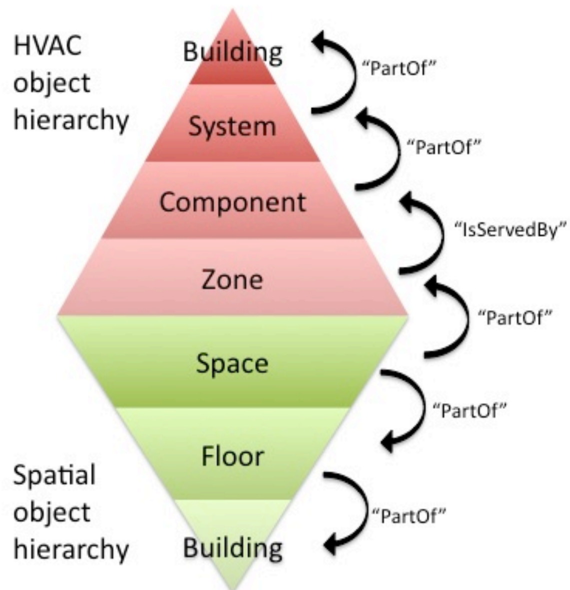

Figure 5: Pyramid view of building object hierarchy

These two perspectives are primarily linked between zones (here thermal zones) and spaces. This zone-space relationship is a "PartOf" relationship, as are most of the other relationships illustrated in Figure 5 (building-system, system-component, building-floor, floor-space, zone-space), except the component-zone relationship, which is classified as an "IsServedBy" relationship. In addition, a number of other relationships are contained within the building object hierarchy, as illustrated in EXPRESS-g (Figure 6). All building objects in this representation inherit the parameters of the main root object, which are as follows:

- Name (string)
- Measurement assumption (string)
- Simulation approximation (string)
- Simulation assumption (string)
- Simulation simplification (string)
- Data pairs (object)
    - Measured data point identifier (string)
    - Simulated data point identifier (string)

Figure 6 also illustrates additional relationships between components ("IsConnectedTo") and spaces ("IsNextTo"). Hereby, the directionality of the "IsConnectedTo" relationship is important, to clearly define the topology and flow direction between components.

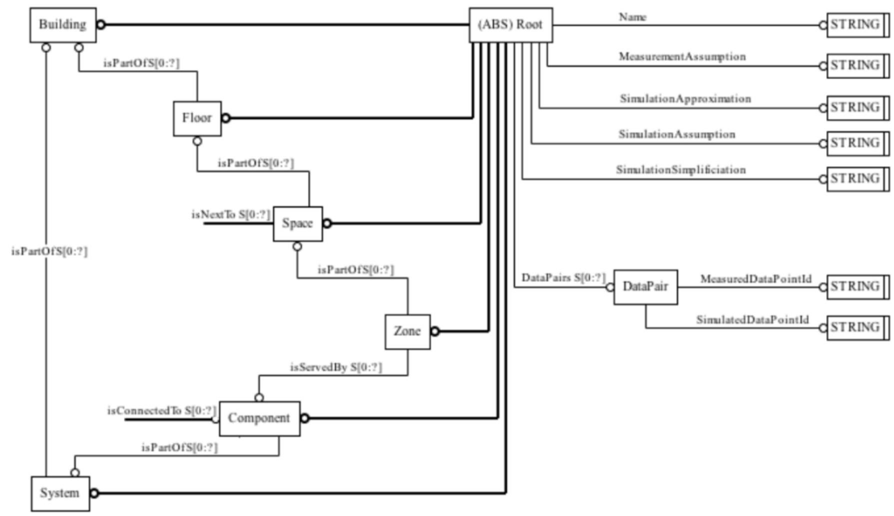

Figure 6: Graphical EXPRESS representation of building object hierarchy

Two additional uses of the building object hierarchy are the attachment of measurement assumptions and simulation AAS to the corresponding object instances and the attachment of data pairs to the corresponding object instances. Figure 7 illustrates a partial building object hierarchy from the Y2E2 building object hierarchy. The tree on the left shows the HVAC hierarchy and the one on the right shows the spatial hierarchy.

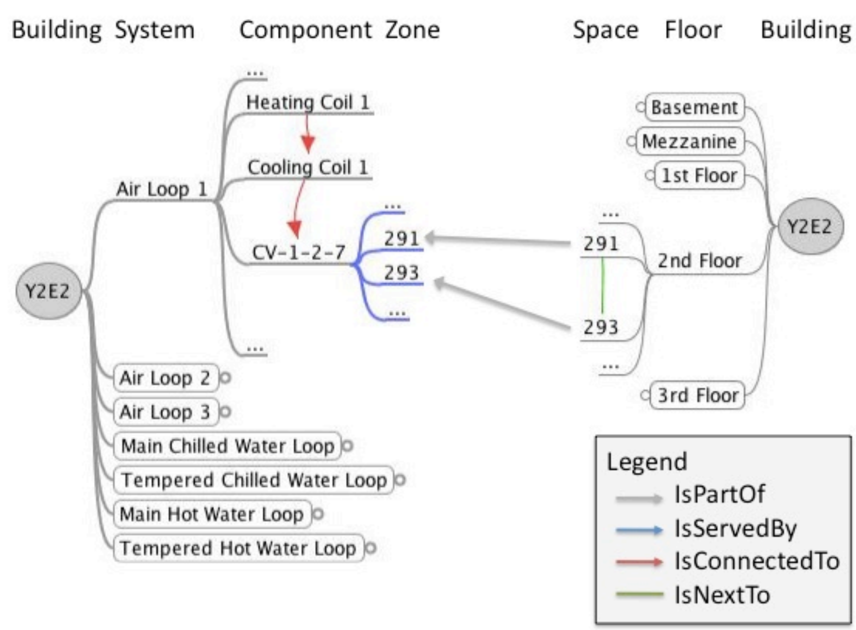

Figure 7: Example of a partial building object hierarchy of Y2E2

Due to simulation AAS, the building object hierarchy of the BEPS model may be slightly different (missing components, simplifications, workarounds, etc.) than that of the actual building. In the context of the EPCM, the building object hierarchy is always based on the actual building, since measurements are based on the actual building. Simulation AAS assigned to the building object hierarchy describe the simulation simplifications and allow circumventing this issue of different hierarchical representations of the actual building and the BEPS model.

Figure 8 shows an example that illustrates the use of the building object hierarchy. Airflow on the system and component level correlates during occupied hours but is different during unoccupied hours. While it is not clear where the difference originates by only considering the system level, by considering the component level it becomes clear that there is a relationship between the two differences due to similar characteristics. However, the origin is still unclear without the knowledge of the simulation simplification on the space level that the active chilled beam model is single speed (compared to two speed). Thus the airflow at the lower speed is zero in the model and causes the difference in both graphs. The relationships of the building object hierarchy enable such a reasoning, which would be rather difficult if not impossible without it.

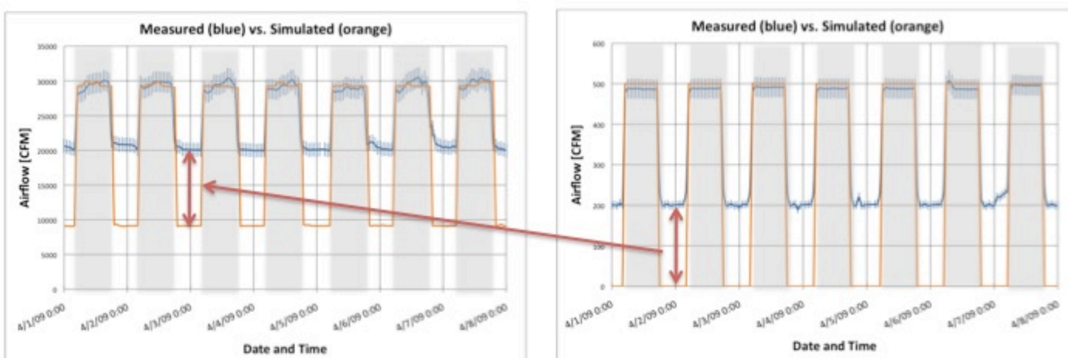

Figure 8: Example comparison of airflow on the system (left) and component (right) level (during occupied hours (grey) measured and simulated data match reasonably close while during unoccupied hours there is a difference between measured and simulated data on the system and component level)

4.3 Process of identifying performance problems with the knowledge of measurement assumptions and simulation AAS

Limitations of measurement systems in buildings as well as limitations of BEPS models are the reasons that specific data points in a building may not match simulation results. Measurement assumptions describe limitations of measurement systems (Maile et al. 2010b) and simulation AAS describe limitations of BEPS models (Maile et al. 2010a). We use measurement assumptions and simulation AAS to identify performance problems from differences between measured and simulated data as illustrated in Figure 9. It is critical to consider all known measurement assumptions and simulation AAS to make the measured and simulated data as trustworthy as possible and to avoid mistaking an explainable difference for a performance problem.

The starting point for this process is a data graph containing the measured and simulated data values of the same variable. The first step is to detect differences between the simulated and measured data. We use simple statistical variables, the root mean squared error (RMSE) and the mean bias error (MBE), to detect differences. The RMSE gives an overall assessment of the difference, while the MBE characterizes the bias of the difference (Bensouda 2004). If an assessor finds a difference, he uses the assigned measurement assumptions and simulation AAS to determine whether the difference is in fact due to a performance problem. If he cannot explain the difference with assumptions or AAS, he classifies the difference as a performance problem. Otherwise, if the assumptions or AAS explain the difference or if there is no difference, the assessor moves on to the next data pair of measured and simulated data.

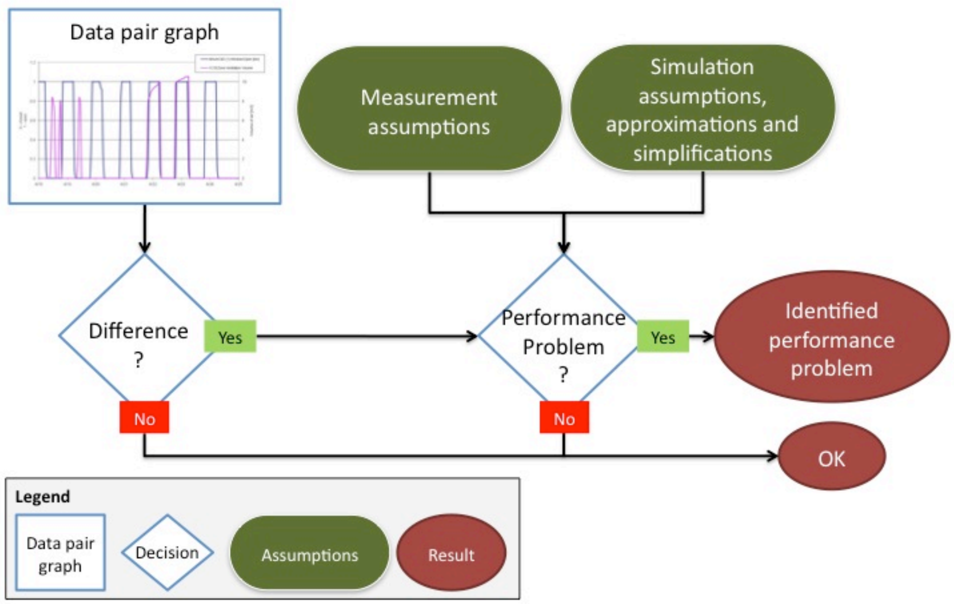

Figure 9: Process for using measurement assumptions and simulation AAS to detect performance problems from differences between pairs of measured and simulated data

4.4 Iterative adjustment of the BEPS model

A key concept of the EPCM is its iterative adjustment of the BEPS model (Figure 10). We chose a bottom-up approach for this iterative adjustment, due to the possibility of compensation errors at the building or system level. Thus, at the system level, measured and simulated data may match but hide differences, because they have opposite effects (Clarke 2001). Hyvarinen and Karki (1996) state that no standard practice exists for a bottom-up approach due to the lack of availability of measurements at the component level at that time. Due to the presence of an increasing number of sensors in buildings, component-level measurements have become increasingly available in the meantime and allow the use of a bottom-up approach.

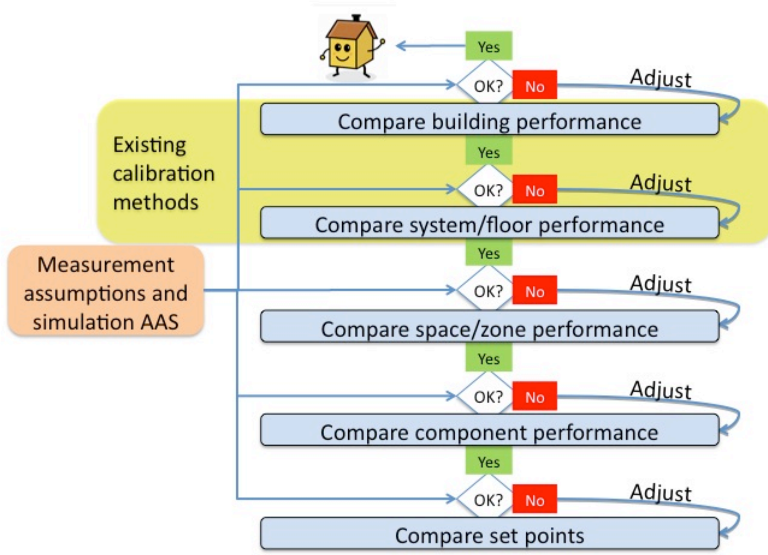

Figure 10: BEPS model adjustment process

The starting point is the comparison of the set points in the BEPS model with the set point in the control system. This is an important first step to ensure that the goals of the actual building and the BEPS model are aligned. This also allows the assessor to identify differences between control set points and actual set points due to changes or errors. If set points and control strategies cannot be represented in the BEPS model as they actually occur, measured data at the set points are used as input for the BEPS model set points. This allows the BEPS model to mimic the behavior of the actual set points and generates simulation results that are closer to actual measured values. This is particularly important if certain aspects of the control strategy cannot be represented in the BEPS model due to limitations of the tool. The assessor needs to document identified set point problems and communicate these to the building operator or responsible person to initiate necessary steps to resolve the problems. This process of iteratively adjusting the BEPS model creates the need to properly document the changes between different versions. For example, the adjustment of a control strategy in the BEPS model to reflect a currently incorrect control strategy may need to be reversed once the control strategy is fixed in the building.

After the assessor has evaluated the set points, the next iteration phase is concerned with the component and space level. This component comparison allows identifying specific differences between the actual component behavior and the component's model behavior. Here one may find components that are less efficient than those specified during design, or similar issues. Once the assessor has compared space and component performance the next step is to look at system performance. Here the focus is on system-specific variables and the energy consumption of systems. Lastly, the comparison is done on the building level. Existing simulation model calibration methods typically compare only at the building and system levels and are highlighted for comparison in Figure 10.

A technique to simplify and decrease the simulation time is to use partial BESP models during the adjustment process. Encapsulating a specific part of the BEPS model while providing measured data as boundary conditions for that specific part enables a more detailed analysis of a specific aspect of the BEPS model. For example, to investigate a specific space in further detail neighboring space conditions can be overwritten by the measured conditions; thus the assessor can focus on analyzing that particular space without the effects of neighboring spaces.

Another important factor for evaluating building energy performance data are events. While events related to atypical occupancy (such as events with increased occupancy or decreased occupancy) can easily be integrated into a BEPS model, changes in the geometry, the HVAC system or the controls of the building may require a different version of the BEPS model. The importance of these events is twofold, reflected by atypical schedule events and change events. Atypical schedule events, such as occupancy changes, can be reflected in occupancy schedules. Change events, including control, HVAC system, and geometry changes, typically require the use of a different version of a BEPS model. For example, it may not be possible to implement two substantially different control strategies within the same BEPS model. Geometry change events due to remodeling efforts require the use of different versions of the BEPS model. An example from Y2E2 is a lab area in the basement that was remodeled to be a multiuse space with offices integrated into the lab area. The documentation of these events is important to clarify the use of different versions of BEPS models.

Table 2: Examples of events at Y2E2

Event	Start (date and time)	End (date and time)	Object level	Consequences
Building shutdown	June 26 2008 6:00 PM	June 27 2008 6: 00 AM	Building	No data during shutdown; data around shutdown may show unconventional values
Natural ventilation control strategy change #3	October 11 2009 3:00 PM	Permanent change	Atria	Improvement of control strategy
Construction in lab area	January 13 2008 6:00 AM	July 26 2008 4:00 PM	Space B27	Geometry change, HVAC changes and construction activity
Student orientation week	September 26 2009	September 28 2009	Building	Unusually high occupancy at red atrium

These events are linked to the building object hierarchy on the corresponding building object level to allow a proper assignment to the related aspect of the BEPS model. Design BEPS tools do not provide an easy way to deal with significant changes in the BEPS model other than having two separate BEPS models for the two configurations. Table 2 shows examples of events that we encountered in the Y2E2 building.

Change events require the use of different versions of BEPS models. Thus, new versions of BEPS models may require new assessment of the building performance, and in particular of the building objects that were changed. These change events most likely have an effect on the energy performance of the building. As illustrated in Figure 11, change events may require new BEPS model adjustments and a reevaluation of related aspects of the buildings energy performance.

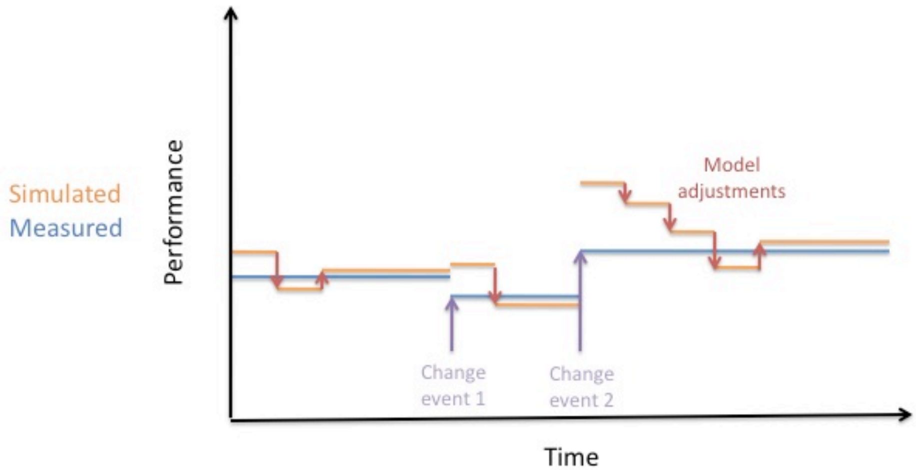

Figure 11: BEPS model adjustments and change events

5 Results of applying the EPCM

To assess the building energy performance of the Y2E2 case study, we applied the EPCM to a subset of data from Y2E2. After completing the preparation step and setting up the matching step, the evaluation step is the key aspect of the EPCM. Within the evaluation step we iteratively compared measured and simulated data pairs and adjusted the BEPS model of Y2E2 according to the process described in section 4.4. The data subset we focused on was from January to May of 2009 considering all building, floor, system, and component level data in addition to about 10% of the space level data (54 spaces). This is the same dataset that was used during the CEE243 class, whose results were later used to validate the EPCM (section 6). Maile et al. (2010b) provide a description of the available measurements at Y2E2. For more detail about the HVAC systems of Y2E2, we refer to Maile et al. (2010a). We went through a total of 10 iterations over all levels of detail as illustrated in Figure 12.

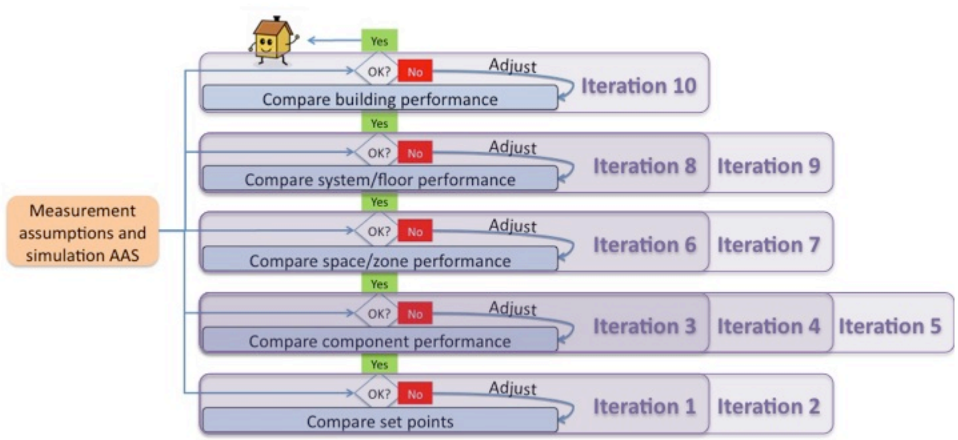

Figure 12: Iterations for the Y2E2 case study

For example, iterations 1 and 2 focused on the set point level. Thus, each iteration focused on one level of detail at the time while considering relationships to other levels of detail via the building object hierarchy. On average one iteration took about a week including the analysis of each data pair as well as the adjustment of the BEPS model and the verification of these adjustments (each task accounted for about one third of the time).

Table 3 illustrates the result of iteration 1 by showing the investigated data points and whether a difference and performance problem was detected for each. The process of identifying differences and performance problems is described in section 4.3. The evaluation of each data pair started with comparison graphs over the complete data period analyzed (5 months) down to weekly time series graphs to consider more detail. We found that most differences can be identified with monthly graphs and investigated in further detail with weekly graphs.

Table 3: Y2E2 summary table of comparison result of set points after iteration 1

No.	Investigated points	Difference	Performance problem
1	AHU1 air temperature set point	NO	NO
2	AHU2 air temperature set point	NO	NO
3	AHU3 air temperature set point	NO	NO
4	AHU1 air pressure set point	N/A	N/A
5	AHU2 air pressure set point	N/A	N/A
6	AHU3 air pressure set point	N/A	N/A
7	Main hot water loop temperature set point	YES	YES
8	Main chilled water loop temperature set point	YES	NO
9	Temp hot water loop temperature set point	YES	YES
10	Temp chilled water loop temperature set point	YES	YES
11	Main hot water loop pressure set point	N/A	N/A
12	Main chilled water loop pressure set point	N/A	N/A
13	Temp hot water loop pressure set point	N/A	N/A
14	Temp chilled water loop pressure set point	N/A	N/A
15	Atrium C&D Floor 1 window status	NO	NO
16	Atrium C&D Floor 2 window status	NO	NO
17	Atrium C&D Floor 3 window status	YES	YES
18	Atrium A&B Floor 1 window status	NO	NO
19	Atrium A&B Floor 2 window status	NO	NO
20	Atrium A&B Floor 3 window status	YES	YES
21	Radiant slab day time temperature set point	YES	YES
22	Radiant slab night temperature set point	YES	NO
23	Server room rack temp set point	NO	NO
24	Space temperature set point - typical office heating set point	YES	NO
25	Space temperature set point - typical office cooling set point	YES	NO
26	Space temperature set point - typical lab heating set point	YES	YES
27	Space temperature set point - typical lab cooling set point	YES	YES
28	Space temperature set point - fan coil unit cooling set point	YES	YES

We categorized the identified performance problems into three categories:

- Measurement problems
- Simulation problems
- Operational problems

Measurement problems are problems originating in the measurement system. These range from simple scaling or mapping errors to problems with the type or setup of the measurement system. The former can be resolved in a short time frame (hours to days) whereas the latter can only be resolved in the long-term (months) if at all. Simple measurement problems are resolved immediately and more complex measurement problems are documented via measurement assumptions to ensure their consideration later in the comparison.

Simulation problems originate in the BEPS model. Since the simulation problems can often be corrected easily, the evaluation process of the EPCM includes the adjustments of BEPS models. Hereby, input data and tool usage issues can be corrected. Other issues resulting from limitations with the simulation tool itself are documented via simulations AAS. These BEPS model adjustments aim to move the BEPS model towards the actual performance and simplify the later comparison process. An example of a simulation problem was the set point of the hot water loop supply temperature (point no. 7 in Table 3 and performance problem no. 19 in Table 4). The difference and problem originated in the control strategy that was implemented in the building and is different from the control strategy of the design BEPS model.

Operational problems illustrate problems with the actual operation of the building. These are typically control problems, component problems or problems due to ineffective HVCA system types or components. An example of an operational problem was the window statuses on the 3rd floor of the building (point no. 17 in Table 3 and performance problem no. 14 in Table 4). The actual window status followed a random pattern and thus showed a difference compared to the simulated window status.

An example of a difference that is not a problem is an office set point (point no. 24 in Table 3). This difference was caused by the use of different techniques for defining occupied and unoccupied temperature set points. These different techniques were formulated by the assessor as a simulation AAS, which explain the difference and indicate that this is not a performance problem.

These discussed performance problems were found during the first iteration of examining the set point level. By applying the EPCM over all levels of detail, we identified 41 performance problems, which include the detailed performance problems just discussed (Table 4).

Table 4: Identified performance problems and problem instances at Y2E2 with EPCM

No.	Description	Category	Instances
1	Hot water flow rate stays constant even though valve position changes	Measurement problem	1
2	Radiant slab valve position is only 0 or 100% open (should change in increments)	Measurement problem	1
3	Current draw shows integer values only	Measurement problem	1
4	Sum of electrical sub meters << total electricity consumption	Measurement problem	2
5	Active beam hot water supply and return water temp are reversed	Measurement problem	1
6	Active beam hot water temps are inconsistent with hot water system temp	Measurement problem	1
7	Chilled water valve position does not fully correlate with chilled water flow	Measurement problem	1
8	Temperature values out of range (e.g., 725 deg F)	Measurement problem	3
9	Pressure values out of range (e.g., 600 psi)	Measurement problem	1
10	Minimum flow rate is 1 GPM	Measurement problem	1
11	Heating coil valve cycles open and close rapidly	Operational problem	3
12	Heat recovery bypass valve opens and closes rapidly during transitional periods	Operational problem	3
13	Night purge on the 1st and 2nd floor seems to be on a regular schedule rather than dependent on outside and inside temperatures	Operational problem	4
14	Night purge on 3rd floor seems random and does not follow control strategy	Operational problem	4
15	Radiant slab control valve position does not show step behavior as desired	Operational problem	1
16	Heat recovery cooling mode does not coincide with coil cooling mode at all times	Operational problem	3
17	Occupancy schedules differ (5 day work week -> 7 day work week)	Simulation problem	5
18	Fan coil unit capacity not sufficient	Simulation problem	3
19	Hot water loop set point differs (150 deg F instead of 180 deg F)	Simulation problem	1
20	Server room cooling base load significantly higher than anticipated	Simulation problem	1
		Total number of problem instances	41

Based on these identified performance problem instances a detailed validation against other performance assessment methods is provided in section 6. We shared these problems with the building operator, who has confirmed the problems and has resolved some of them in the meantime or plans to address the others in the near future.

6 Validation

This section includes the validation of the building object hierarchy (section 6.1) and of the EPCM (section 6.2). Based on the results from applying the EPCM on the Y2E2 case study, we prospectively validated the EPCM by comparing it to standard methods used to detect performance problems. On key characteristic of prospective validation is that results can be presented within a timeframe that allows practitioners to make business decisions

(Ho et al. 2009). This characteristic enabled the improvement of the building operation of the Y2E2 case study and the verification of actual performance problems with the building operator. The criteria used for this validation was the number of performance problems identified and the effort involved to identify this number of performance problems. The result of the validation indicates that by using the EPCM, the assessor found the largest number of performance problems, compared to other methods. In particular, the assessor was fastest, on a time effort per performance problem basis, by applying the EPCM. We also show additional qualitative evidence that the building object hierarchy supports the understanding of the specific relationships of building objects on the Y2E2 study. The validation was performed with the help of 11 students, in the context of a class (CEE243) at Stanford University.

6.1 Validation of the building object hierarchy

The building object hierarchy is part of the EPCM, and thus the following validation (section 6.2) of the EPCM also indirectly validates the building object hierarchy. In addition, the value of the building object hierarchy was apparent from the feedback of students, who created an instantiation of the building object hierarchy for the Y2E2 case study in the context of a class. These students used available documentation, in the form of HVAC system schematics and spreadsheets containing information about space and zone relationships to HVAC systems, to create an instantiation of the building object hierarchy. While the source information was accessible to the students before they created an instantiated hierarchy, they found the process of creating the hierarchy particularly useful for understanding the different types of relationships among different building objects. While this is only qualitative evidence, it shows the usefulness of the hierarchy for understanding and documenting relationships among building objects in a building. Additionally, the building object hierarchy and its relationships are necessary to identify about 50% of the performance problem instances at Y2E2.

6.2 Validation of the EPCM

The prospective validation of a methodology needs to establish that the methodology performs better for the defined criteria than other methods that address the same problem on the same data set. To illustrate the value of high level of detail, we also differentiate between problems identified by using the EPCM over all levels of detail and by using the EPCM at the building and system level only (EPCM system). We used two criteria to validate the EPCM:

- Number of performance problems
- Time effort per performance problem.

We compared the EPCM to the following methods:

- Building operator (traditional building operation)
- HVAC designer (calibrated BEPS models)
- CEE243 (11 students applying traditional commissioning methods – mainly trend analysis)
- EPCM system level (EPCM with only system level data)

A challenge of such a validation is that it is not known how many performance problems actually exist within a defined data set. Hereby, we differentiate between problem areas, performance problems and performance problem instances. Problem areas are broad issues of insufficient performance such as the building has a heating issue without knowing any details of where this issue originates. A performance problem is a generic description of a performance inefficiency typically at the component level such as the natural ventilation control strategy following a different pattern than anticipated. A performance problem instance is the actual occurrence of a specific performance problem at a specific time at a specific component (e.g., the control strategy at the 2nd floor atria does not follow the designed control strategy during the week of April 18th to 25th 2009). To establish a known set of performance problem instances, we analyzed measured data from Y2E2 with the help of 11 students in the context of a class (CEE243) based on traditional commissioning methods (mainly trend analysis) and validated the detected performance problem instances with the building operator. We used this known set of performance problem instances for comparison with the results obtained by an assessor using EPCM. Table 5 shows the number of performance problem instances identified per problem category. In comparison to the class results, the HVAC designer identified six possible broader problem areas using the calibration method, focusing on building and partial system level data. We could verify four out of the six identified broader problem areas as actual problem instances and found no evidence of actual problem instances for the other two. The building operator was only aware of two of the identified performance problem instances. By applying EPCM to the data set, we could identify all of the problem instances the class identified (except a pressure sensor issue that did not have a corresponding simulation data point) and even discovered additional problem instances, particularly related to incorrect design assumptions. These problem instances clearly show the power of the EPCM compared to a variety of other methods that are currently used in practice. In retrospect, we identified performance problem instances via EPCM that would not have been found without the use of HVAC component level data. A comparison between the reduced data set (EPCM system) and the full data set (EPCM) shows that about half of the problem instances could not be identified without the use of HVAC component level data. Based on our estimates of time effort, it can be concluded that EPCM is not the fastest method overall, but it has the best ratio of identified performance problem instance versus time invested. Future developments and automation of the EPCM will likely decrease the time effort involved to implement this method.

Table 5: Summary of identified problem instances at Y2E2
(number in parenthesis indicates all identified problems including problems that could not be verified)

Problem categories	**Number of actual identified problem instances**				
	Building operator	**Designer**	**CEE243**	**EPCM system**	**EPCM**
Measurement problems	1	1 (2)	13	5	13
Simulation problems	1	3 (4)	None	8	10
Operational problems	None	None	16 (17)	8	18
Total	2	4 (6)	29 (30)	21	41
	Time effort for identifying problem instances				
Time effort (estimated hours)		200	1100	250	450
Time effort per problem		50	38	12	11

To provide external validation, one student applied the methodology for a subset of the data (~25%) and had a 90% consistency with our use of the methodology. The difference between the two comes from missed AAS and the background knowledge that was needed to interpret some of the AAS, which the student did not have.

7 Limitations and future research

This section describes limitations of our research as well as possible future research directions based on this work. The EPCM allows an assessor to identify a larger number of performance problems faster (per problem) than other performance assessment methods. As indicated in section 4, the estimation of impact and feedback to the building operator or building design was not the focus of this research and is an area for future investigation. In view of the significant control problems identified, we feel that the process of implementing control strategies needs improvement, in particular through interoperability between control software tools. While some automation of the tasks to identify performance problems was accomplished during this research, further automation of tasks that are currently done manually is another area of future research. Once such tasks are automated, real-time performance assessment is a next step for future research.

7.1 Estimating impact on thermal comfort and energy consumption

Based on the identification of building performance problems, which was our main focus at this stage of the research, it is possible to estimate the impact on thermal comfort and energy consumption by relating the differences between measured and simulated data over various levels of detail. Describing a detailed process for estimating this impact was out of scope of this research. The combination of assessing performance problems and evaluating their impact would allow one to sort the performance problems by impact; thus the assessor and building operator would be able to focus on performance problems with the highest impact on thermal comfort and energy consumption. We see this as a fruitful area for future research.

7.2 Feedback based on identified performance problems

While we have not looked at a detailed process for how best to provide feedback on the building design and the building operation, the identified performance problems provide a basis for such a feedback. In our case studies, we have used an informal approach to communicate performance problems that we found with building operators and building designers. This communication indicates a first step towards closing the gap between building design and operation. One example of such an important lesson is our evaluation of the energy consumption of a server room that used about 50% of the base-cooling load of the building. Despite its importance for energy consumption, the server room was not included in the design BEPS model, which made it practically impossible to predict building energy consumption accurately during design, since a major source of energy consumption was not included in the BEPS model. Although feedback to building design was out of scope of this research, future researchers could look into ways to efficiently provide feedback to building designers and explore ways that they can learn from this feedback.

7.3 Better integration with controls

The disconnect between actual controls and the controls available in the BEPS tool was apparent from the case studies. Interoperability between design HVAC control tools, control of BEPS, and actual control algorithms with the control hardware of a building could eliminate errors in the current process of implementing control strategies. Finding new ways to share control strategies across tool boundaries would improve the reliability of control strategies in buildings and decrease errors that occur with the current manual implementation of controls.

7.4 Automation of EPCM

One major topic for future research is the automation of the EPCM. Figure 3 indicates the tasks we automated. We spent considerable time developing data transformation software tools that ease the generation of the input to BEPS tools, support data transformation such as unit conversions, update simulation input data, and graph data. The integration of all these tools into a comprehensive user interface that supports all aspects of the EPCM is another area for possible future research. Due to the time effort of performing manual tasks such as detecting differences of data pairs, we did not analyze all available data for the building (only about 30% of the available data points over a 5 months period). With more automation, the complete analysis of all data would become more manageable.

7.5 Real-time energy performance assessment

Once the EPCM is completely automated, a real-time performance assessment based on design BEPS models becomes possible and may provide crucial timely information to the building operator. With estimation of the impact of performance problems in addition to automation of the EPCM, it will be possible to determine the severity of performance problems. Based on this information, the automated EPCM could provide the building operator with timely information about the most important performance problems. A fully automated EPCM could also determine whether control changes in the building have the effects that were expected based on simulated performance.

8 Conclusion

To compare measured and simulated data the EPCM includes steps and tasks that systematically eliminate or highlight inappropriate simulation approximations, assumptions, and simplifications in a BEPS model and highlight inappropriate measurement assumptions, so that it is worthwhile to examine the remaining differences more closely to identify actual performance problems. By aligning the BEPS model as closely as possible to the actual situation in the building, it becomes a much more useful tool for finding performance problems. This paper describes the key novel concepts and processes that enable this systematic adjustment of the BEPS model so that it matches actual building conditions as closely as possible. The two contributions of this paper are the Energy Performance Comparison Methodology (EPCM) and the building object hierarchy that integrates two perspectives (HVAC and spatial). The EPCM allows an assessor to identify a larger number of performance problems with a lower time effort per performance problem compared to other standard methods, by comparing measured and simulated building energy performance data. It includes details about the process for assessing performance data, including a bottom-up approach for iteratively adjusting the BEPS model. The key aspect of this methodology is that through iterative adjustments, the BEPS model moves from a design BEPS model to a BEPS model that more closely simulates actual building performance.

Existing building object hierarchies mostly concern only one perspective. O'Donnell (2009) combines two perspectives (HVAC and spatial), focused on the zone object. We developed a building object hierarchy that provides two perspectives (spatial and thermal) that are linked on the zone and space levels and provide additional relationships among objects that are not contained in other hierarchies. For the validation case study, the building object hierarchy provided relationships that are needed to find about 50% of the performance problem instances.

Existing approaches to compare simulated with measured data fall short of including details over all levels of detail and often do not consider design BEPS models. We have developed a methodology that includes those details and a link to design BEPS models, and enables the systematic identification of performance problems. The EPCM, combined with the knowledge of measurement assumptions and simulation AAS, enables a better understanding of the differences between measured and simulated data and allows the assessment of building energy performance compared to design. The EPCM still contains manual tasks, but future developments could increase the automation of tasks and decrease the time effort involved. With additional automation, future investigations will lead to real-time performance assessment. More importantly, the EPCM is a step in closing the gap between design simulation and actual operation, which is becoming more important as new regulations and requirements are developed to save energy in buildings.

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