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Formalizing Approximations, Assumptions, and Simplifications to Document Limitations in Building Energy Performance Simulation

By

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1 Abstract

Differences between measured and simulated building energy performance are often caused by limitations of building energy performance simulation (BEPS) models. These limitations can be documented with simulation approximations, assumptions, and simplifications (AAS). Existing literature mentions only a project-specific subset of these AAS and does not provide a formal process for detecting limitations of BEPS tools, differences between measured and simulated data and thus building energy performance problems This paper describes a list of critical simulation AAS that describe limitations of simulation input data, shortcomings of BEPS tools, and the use of simulation concepts by users. We describe semi-automated mechanisms for generating input data to reduce the influence of AAS on simulation results, and for identifying performance problems from differences between measured and simulated data. Based on four case studies, we provide specific evidence of AAS in EnergyPlus, include recommendations for improving BEPS tools generally for more realistic use during operation, and discuss future research directions to increase the quality of simulated performance data.

Keywords: Building energy performance simulation, approximation, assumptions, simplifications, simulated performance data

2 Introduction

Building energy performance simulation (BEPS) tools are gaining importance as analysis tools during the design of buildings. BEPS is typically used to compare design alternatives (Trcka and Hensen 2009) but not to predict actual energy performance of buildings. While it is true that aspects of building energy usage and of the building itself may not be known at various design stages, it is important to better understand what specific differences exist between a BEPS model and the actual performance of a building to improve predictions in the future. Previous studies also identify this need to assess actual operation based on design BEPS (Turner and Frankel 2008; Morrison et al. 2008). This assessment is particularly important for new and innovative heating, ventilation, and air conditioning (HVAC) systems and components to evaluate their performance in practice. To provide this assessment, we compared measured with simulated data of building energy performance to identify performance problems (Maile et al. 2010). These performance problems include as-built changes, operational performance problems, and problems with simulated performance generated with a BEPS tool.

The first task of simulating building energy performance is the selection of an appropriate simulation tool. BEPS models that are used for the comparison with measured data are typically developed either on a component level (e.g., Xu et al. 2005) or on a building level (e.g., Holst 2003). Detailed BEPS tools enable the simulation across different levels of detail from the component to the building level (component, space/zone, system/floor, building). A comprehensive list of available simulation tools references 382 existing building energy software tools (U.S. DOE 2010a). These tools cover different simulation areas, have different foci, and cover one or more levels of detail. Choosing a simulation tool that is suitable for a comparison with measured data is a difficult task because of this large number of available tools. Crawley et al. (2008) compare the 20 major BEPS tools in detail and provide a starting point for the BEPS tool selection.

Independent of the tool selection, each simulation tool typically has limitations and shortcomings that are only partially known and documented. These limitations are often formulated via approximations, assumptions, or simplifications (AAS) on a project-specific basis. Existing literature mentions specific simulation AAS (e.g., Gowri et al. 2009), but does not provide a list of critical simulation AAS.

Since our goal is to make BEPS more useful in practice we selected case studies as the research method. For four case studies we compared measured and simulated building performance at an increased level of detail to assess actual building performance compared to simulated performance. The case study research method provides sufficient detail and real-life context (Yin 2003) for building energy performance problems. With four case studies, we observed current practice of identifying performance problems, of using existing design BEPS models, and of simulating energy performance. Based on the first two case studies the San Francisco Federal Building (SFFB) and the Global Ecology Building (GEB), we defined AAS for BEPS formally and developed a process to use the formal AAS to help identify performance problems. The SFFB uses mostly natural ventilation while the GEB has both a mechanical and natural ventilation system. We prospectively validated this AAS approach and process with two later case studies the Yang and Yamazaki Environment and Energy Building (Y2E2) and Santa Clara County (SCC) building. Y2E2 has a hybrid ventilation system while SCC is completely mechanically ventilated. Multiple case studies of different building types and different HVAC systems provide more generality for our results compared to the typical research method in the field of using a single case study. For this work we focus on commercial buildings. Three of the buildings analyzed in the case studies have been completed recently, while one building is about 30 years old. One case study building relies on natural ventilation only, two have mixed natural and mechanical ventilation systems, and one has a mechanical ventilation system. The 30-year-old building has a conventional HVAC system, whereas the other three have more innovative systems. Three case studies had BEPS models developed during design, and one did not have an existing BEPS model due to its age.

We developed the Energy Performance Comparison Methodology (EPCM) that compares simulated design with measured building performance data to determine differences and identify performance problems. The methodology focuses on building energy performance that depends on both the activities of occupants and the performance of HVAC systems as a response to occupant activities and outside conditions. Data acquisition systems archived the measured data. Detailed BEPS tools produced the simulated data for the comparisons. In this paper, 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 commissioning and/or BEPS. This paper focuses on simulating building energy performance and documenting corresponding limitations with AAS. Two related papers provide details on measurements and on the comparison process for measured and simulated data. Maile et al. (2010a) discuss measurement data sets, measurement assumptions, and data acquisition systems in this context. A second paper (Maile et al. 2010) elaborates on the actual comparison tasks of the methodology by describing the iterative process.

Since AAS describe limitations of BEPS models, we discuss the semi-automated creation of BEPS models (section 3.1). Preferably, the assessor uses an existing BEPS model to provide the link to design goals; otherwise, he establishes a new model based on design documentation. We discuss previous work regarding accuracy of simulation results and highlight the difficulty of quantifying accuracy within complex BEPS models (section 3.2). Furthermore, we define the terms *approximation*, *assumption*, and *simplification*. We provide a list of critical AAS (section 3.3) we developed based on the literature review and the case studies. We categorize these AAS and describe a process to use these AAS in the context of the EPCM (section 3.4).

Based on the mentioned difficulty of selecting an appropriate whole-building simulation tool, we define requirements for simulation tools used in the context of the EPCM and discuss how the eight most comprehensive BEPS (in terms of available HVAC components and HVAC system types) tools fulfill these requirements (section 4). We describe HVAC systems, available BEPS models, and limitations of the used BEPS models for each case study (section 5) and discuss the effects of those limitations on the comparison. We summarize the limitations of BEPS tools in general and specifically for EnergyPlus and provide recommendations based on these findings (section 6). We validate the AAS concept in context of the EPCM (section 7) and discuss limitations of this research, and mention possible future research areas (section 8).

3 BEPS and its AAS

Three fundamental limitations of BEPS are the quality of input data, the shortcomings of the particular use of simulation concepts, and the shortcomings of system and component models embedded in BEPS tools. All three limitations influence simulation results. Input data consist of building geometry, internal loads, HVAC systems and components, and control strategies. To reduce potential errors and ambiguity of input data we describe a process for creating simulation input data semi-automatically (section 3.1), which builds on research at Lawrence Berkeley National Laboratory (Bazjanac 2008). We discuss existing error calculation techniques to better understand the influence of simulation errors on results (section 3.2). Based on this discussion, we describe a more detailed concept of AAS that describe limitations of BEPS tools including a list of critical AAS (section 3.3) and the related process to identify performance problems from differences (section 3.4), which is a key process in the overall comparison methodology that is described by Maile et al. (2010a).

3.1 Semi-automated creation of simulation input data

In the context of the case studies, we relied on EnergyPlus as a simulation tool. Section 4 provides details about this tool selection and the reasoning behind it. Depending on the availability of a BEPS model the assessor either creates a new BEPS model or updates an existing one. The process involves integrating all necessary input data for BEPS, building geometry, internal loads, HVAC systems and components, and control strategies. While the building geometry generation is semi-automated, interpreting mechanical drawings and other data sources to compile input for the remaining data is mostly a manual process due to a lack of software tools that define those data and/or provide a link to BEPS. We describe both the process of creating a new EnergyPlus model and the process of updating an existing model in detail in the following section, starting with the former (Figure 1), since the assessor can use a simplified version of this creation process to update an existing model.

If two-dimensional architectural drawings are the starting point for a BEPS model, the assessor first needs to create a building information model (BIM) in a model-based CAD tool. This BIM must contain detailed geometry, construction assemblies (in particular, information about material type and thickness), space definitions, and thermal zone assignments. Thermal zones are an agglomeration of one or more spaces that share thermal characteristics such as orientation, size, HVAC system type, and internal loads. Detailed models at the later stages of design typically contain more zones and reduce the number of spaces that belong to a zone. Spaces that belong to one zone early in design may end up in two different air systems and may start to differ in their thermal characteristics due to increased detail and/or changes to the design. All of the mentioned data are required for BEPS as described by Maile et al. (2007a). The assessor exports this BIM from the CAD tool in the Industry Foundation Classes (IFC) format (buildingSMART 2010). It is essential that the exported data include space boundaries and that the definitions include relationships to spaces. These space boundaries describe boundary surfaces between spaces as needed for thermal simulation. Bazjanac (2005) explains space boundaries, their definition, and importance. IDFGenerator converts data in the exported IFC file into the input definition format (IDF is the data input format for EnergyPlus). IDFGenerator includes a geometry simplification tool (GST) and uses predefined and embedded data transformation rules. Bazjanac (2008) discusses these data transformation rules in detail. The resulting IDF file contains all relevant information and data about the building geometry (including definitions of all materials and their thermal properties). This IDF file also contains simulation run control parameters, such as convergence tolerances and the simulation time period. GST/IDFGenerator also supports creation of partial IDF models (by spaces and floors), which is helpful in encapsulating parts of the building during the comparison process.

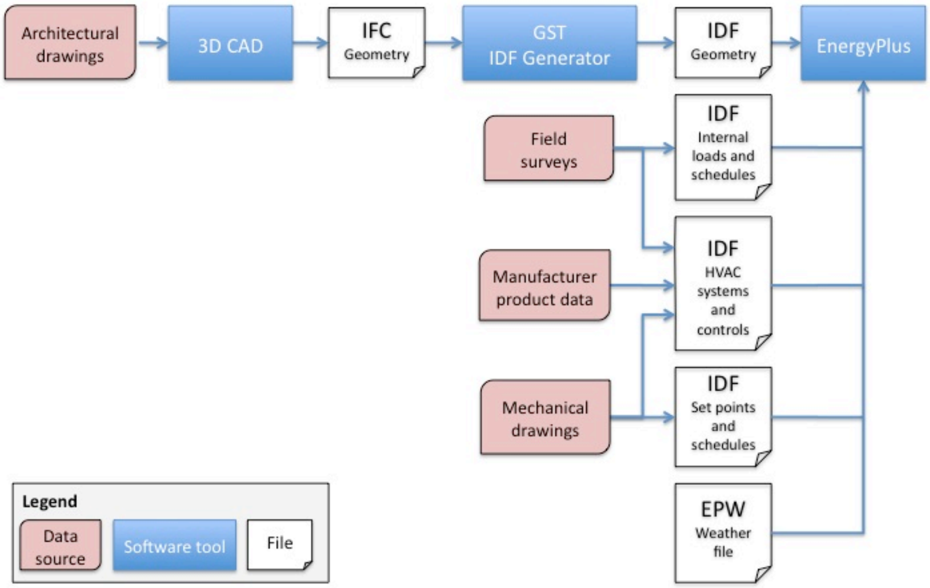

Figure 1: Creation of an EnergyPlus model

The assessor needs to define HVAC systems and components manually in IDF format and add them to a separate IDF file. Mechanical drawings form the basis for necessary data regarding HVAC system topologies and HVAC component parameters. The assessor also gathers missing component data (necessary for EnergyPlus objects) from manufacturer product specifications or field surveys. This task is currently tedious, due to the lack of a comprehensive graphical user interface for EnergyPlus. Future developments of EnergyPlus interfaces and data exchange capabilities with HVAC design applications will help to simplify these tasks (e.g., LBNL 2010). Another important type of import data are the control strategies of HVAC systems in the EnergyPlus model. The assessor can refer to mechanical drawings and/or documents that describe the sequence of operations for these control strategies. It is important to distinguish between original information (as established during design) and updated information (as determined during field surveys). This differentiation is important, because we want to establish a comparison between the original design BEPS model and actual operation as well as learn about specific changes between final design and actual operation. The reasons and more importantly the implications of these changes may not be known and may need further investigation within the methodology to determine the implications. Finally, the assessor needs to update a weather file to complete the data set needed for the EnergyPlus simulation. Table 1 shows approximated durations of the tasks to create input data for each of the four case studies (excluding the development of software tools). We describe the specific HVAC systems and the BEPS models for each case study in section 5.

Table 1: Approximated time effort for BEPS model creation for each case study

Tasks (time effort in hours)	SFFB	GEB	Y2E2	SCC
3D CAD	10	20	80	480
GST/IDFGenerator	N/A	N/A	< 0.1	0.2
Internal loads and schedule	2	10	40	80
HVAC systems and controls	N/A	10	100	500
Set points and schedules	2	5	25	40
Weather data	< 0.1	< 0.1	< 0.1	< 0.1

We used the EnergyPlus macro language (input macro format; IMF) to integrate these different IDF files (U.S. DOE 2010b) to allow easier manipulation of these possibly large text files (several MB, or about 200,000 lines). Table 2 summarizes the number of different building objects for each case study to provide an indication of the size and complexity of each of the BEPS models.

Table 2: Summary of number of building objects per case study

Number of	SFFB	GEB	Y2E2	SCC
Thermal zones	13	22	513	1,007
Building surfaces	382	158	6,455	21,741
HVAC systems	0	5	22	89
HVAC components	0	17	89	163

The authors developed a macro-based spreadsheet that allows the definition of zone and system level parameters and runs a Visual Basic macro in the background, which automatically generates the corresponding EnergyPlus IMF macro files. An EnergyPlus preprocessor (EPMacro) converts this set of macro files into a complete IDF file that can be used for the simulation (Figure 2). A particular benefit of this spreadsheet approach is that it is easy to change simulation input data. As new comprehensive graphical user interfaces become available, this process of creating EnergyPlus models will become easier and less time consuming (from days and weeks to hours).

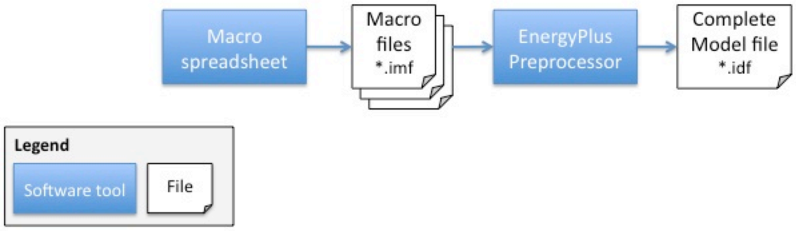

Figure 2: Macro process for generating a complete EnergyPlus model file

The second and preferred process to obtain an EnergyPlus model is through updating of an existing model. The easiest scenario involves using an existing EnergyPlus model that may need small adjustments to reflect the latest design changes or the increase of detail. It is important to keep as-built changes out of the original model, since we use the process to highlight changes via the comparison methodology. This will allow highlighting of the effects of last minute decisions or changes. Scenarios that are more difficult include situations where there are existing BEPS models in a format other than EnergyPlus. Due to its widespread usage, DOE-2 models are often available. In this case a DOE-2 Translator (U.S. DOE 2010b) provides partial semi-automated support to convert this model into EnergyPlus syntax (Figure 3). It supports the conversion of geometry (spaces and surfaces), schedules, materials and constructions, but does not convert any HVAC data. Two of our case studies included an existing DOE-2 model that we used as basis for an EnergyPlus model.

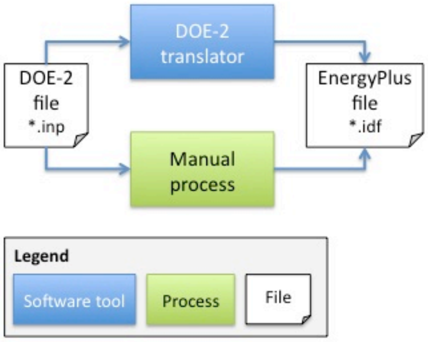

Figure 3: The process of using DOE-2 translator to generate an EnergyPlus input file

3.2 Accuracy of simulation results

The accuracy of simulation results depends on a number of issues: accuracy of input data, accuracy of BEPS tools, and accuracy of the representation of a specific BEPS model of the actual building. In general, simulation results can only be as accurate as their input (Corrado and Mechri 2009). For a comparison of measured and simulated data, some input data can be directly based on measurements (e.g., outside air temperature, outside air humidity, or space air temperature). Maile et al. (2010a) discuss accuracy of measurements, which can be described with error margins at specific confidence intervals in the context of sensor errors (see an example of visual representation of error margins in Figure 5). The accuracy of the remaining input data, i.e., data that are not based on measurements, is hard to quantify. Various studies (e.g., Corrado and Mechri 2009) have used sensitivity analysis to determine the most influential parameters for specific projects. However, these influential parameters vary for different climates and projects and are thus project-specific. If the accuracy of input data can be quantified with error margins and confidence intervals, these additional characteristics of input data may be propagated through the simulation by so-called error calculations (e.g., IPMVP Committee 2002; De Wit and Augenbroe 2002). However, error calculations do not consider the accuracy of the equations embedded in BEPS tools or the appropriate use of the tool. These error calculations are typically done for simulations that are based on a couple of equations. Since it is practically impossible to quantify all sources of error, we describe the limitations of BEPS tools with AAS to enable an assessment of simulation results compared to measurements. This approach is described in the following subsection.

3.3 Identification of simulation assumptions, approximations, and simplifications

AAS are present in every simulation, since a simulation is always a reduction of a real life physical process. For example, most simulation tools approximate the heat transfer calculation by using a spatial 1-dimensional approach instead of the real 3-dimensional. Approximations, assumptions, and simplifications are defined as follows:

- Approximation: A mathematical quantity that is close in value to but not the same as a desired quantity (Approximation 2010)
- Assumption: Something that one accepts as true without question or proof (Assumption 2010)
- Simplification: The process of making something less complicated and therefore easier to do or understand (Simplification 2010)

Based on these definitions, we can differentiate among the AAS of BEPS models, those of input data, and those related to the use of simulation concepts. AAS of BEPS models are embedded in the simulation model, whereas AAS of input data describe how specific input data are derived. AAS related to the use of simulation concepts reflect how users define and apply a specific aspect of the simulation. These AAS, if contained in the model or input data, are usually not well documented and depend on arbitrary decisions of users (Bazjanac 2008). Documenting these AAS is the basis for using them within the EPCM and provides important details about the basis of the simulation model. Based on the three definitions of AAS and their three different contexts (input data, model, and use), we have defined nine categories of AAS for EPCM. We developed a list of critical simulation AAS based on existing literature and applied it to each of the case studies. This list uses the nine categories of AAS as follows. For each item, the relevant case studies (if any) and reference information are given in parentheses. We provide details about the BEPS models and their limitations and AAS for each case study in section 5.

Input data approximations:

1. Diffuse solar radiation is approximated with a solar model and total radiation measurements (SFFB, GEB, Duffie and Beckman 1980)
2. Wind direction and speed are approximated based on façade pressure difference (SFFB)

Model approximations:

3. View factor approximation of surfaces is appropriate (SFFB, GEB, Y2E2, SCC; U.S. DOE 2010c)

Usage approximations:

4. Internal loads are approximated on the space level from floor level measurements (Y2E2)
5. The district chilled/hot water object can approximate the performance of other not supported supply (Y2E2, GEB)
6. Connected multi-temperature water loops are approximated with standalone water loops (Y2E2)
7. (Sinus-) curved surfaced are approximated with rectangular planar surfaces (SFFB)

Input data assumptions:

8. Zone infiltration is typical (GEB, Y2E2, SCC; Gowri et al. 2009)
9. Wall constructions are built based on design specifications (SFFB, GEB, Y2E2, SCC)
10. Manufacturer data of HVAC components reflect actual performance (GEB, Y2E2, SCC)
11. Heat gains from lights are assumed to appear as zone loads (SFFB, GEB, Y2E2, SCC; U.S. DOE 2010d)

Model assumptions:

12. Buildings do not have curved walls, columns, beams, and non-rectangular walls (GEB, SFFB, Y2E2, SCC)
13. Relationship between valve position and air flow is proportional (Y2E2)
14. Idealized models assume that the thermal box can reduce the flow rate to the design minimum value (Y2E2)
15. Windows and solar collectors are always clean (Y2E2; U.S. DOE 2010c)
16. Component performance is constant (no degradation; SFFB, GEB, Y2E2, SCC)
17. Façade Cp pressure values represent actual conditions (SFFB, Y2E2; Ferson et al. 2008)
18. Ducts are perfectly insulated (GEB, Y2E2, SCC; Klote 1988)
19. Ducts have no air leakage (GEB, Y2E2, SCC)
20. No air stream reheating is provided by the circulation fans or by the ducts (Y2E2)

Usage assumptions:

21. Heat transfer between floors is ignored (partial model; SFFB)
22. Internal loads represent actual building usage (SFFB, GEB, Y2E2, SCC; Morrissey 2006)
23. Thermal subzones are somewhat arbitrary (SFFB; Pati et al. 2006)
24. Zone temperature set point for a set of zones is identical (Y2E2)
25. Zone infiltration loads are negligible or considered part of the ventilation loads (SFFB; Suwon 2007)
26. Zone solar and transmission loads affect the perimeter zones only (Y2E2, SCC;)
27. A single air flow return path is representative of the actual splitter return path (Y2E2)
28. Two level branching represents three level branching (Y2E2)
29. Splitting of thermal zones because of zone equipment limitations is acceptable (Y2E2)
30. Boundary walls of partial models are adiabatic (SFFB, Y2E2)
31. Control strategy is based on temperature control only (Y2E2)
32. A specific component performance (e.g., cooling tower, hot steam supply and related heat exchanger) performance can be neglected (GEB, Y2E2)

Input data simplifications:

33. HVAC model configuration is simplified (GEB, Y2E2, SCC)
34. Surrounding shading objects (e.g., trees) are simplified (SFFB, Y2E2; U.S. DOE 2010c)

Model simplifications:

35. Control response time is instantaneous (SFFB, GEB, Y2E2, SCC)
36. Airflow model assumes bulk air flow at the zone/space level (SFFB)
37. Zone is well-mixed (SFFB, GEB, Y2E2, SCC; Li 2009, Energy Design Resources 2005)
38. Pressure drop is neglected (Y2E2, GEB, SCC; U.S. DOE 2010d)

Usage simplifications:

39. The BEPS simulation model uses perimeter/core zone modeling compared to zone type modeling (GSA 2009)
40. Internal loads are on a regular schedule (SFFB, GEB, Y2E2, SCC)
41. Splitting of HVAC systems does not have major influences on the results (SCC)
42. Dedicated pump configuration is simplified with a headered (parallel) pump configuration (Y2E2, SCC)

This list of simulation AAS is the first formal compilation of AAS for BEPS based on literature and four case studies. The formalization of these AAS is a first step towards understanding the implications and effects of the AAS. A compiled table that adds anticipated effects to each AAS can be found in Maile (2010). These anticipated effects support the assessor in evaluating simulation results. The second step is to minimize these AAS (and thus limitations) in the use, development, and input of BEPS models. We discuss further research areas based on this AAS list in section 8.4.

3.4 Process to identify performance problems from differences

In context of the EPCM, we used AAS as means to identify performance problems from differences between measured and simulated data. We have defined a process (Figure 4) to identify performance problems based on the concept of Ganeshan et al. (1999) that "assumptions can be identified as one of the reasons for discrepancies between observed and predicted behavior" (p.2.). This process starts with a graph of data pairs. The first decision is whether the data pair graph shows a difference. We used the simple characteristics root mean squared error (RMSE) and mean bias error (MBE) to provide an indication of differences. The RMSE gives an overall assessment of the difference, while the MBE characterizes the bias of the difference (Bensouda 2004). If a difference is identified, the assessor refers to the AAS to either explain the difference or to identify the difference as a performance problem.

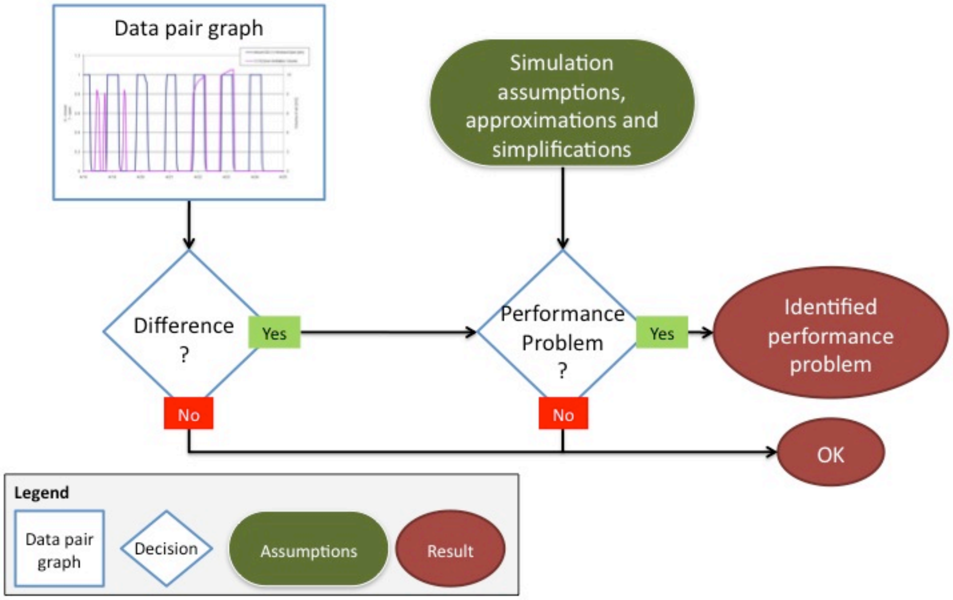

Figure 4: Process for using simulation AAS to detect performance problems from differences between pairs of measured and simulated data

An example of how AAS are used to identify performance problems is shown in Figure 5. While the simulated supply air temperature of an air-handling unit is constant, the measured supply air temperature varies about three degrees below and above this constant line. Even with added error margins of the measured data, this indicates a difference between the measured and simulated data. This difference can be explained by the model assumption that implements a simplified control strategy in the simulation model. The actual control signal based on supply air temperature, humidity, and outside air temperature shows more fluctuation than the simulation model, which uses only supply air temperature (AAS no. 31) as the basis for control. These different control strategies are reflected in the corresponding temperature measurements. This model assumption explains the difference, and thus this particular data pair instance does not indicate a performance problem.

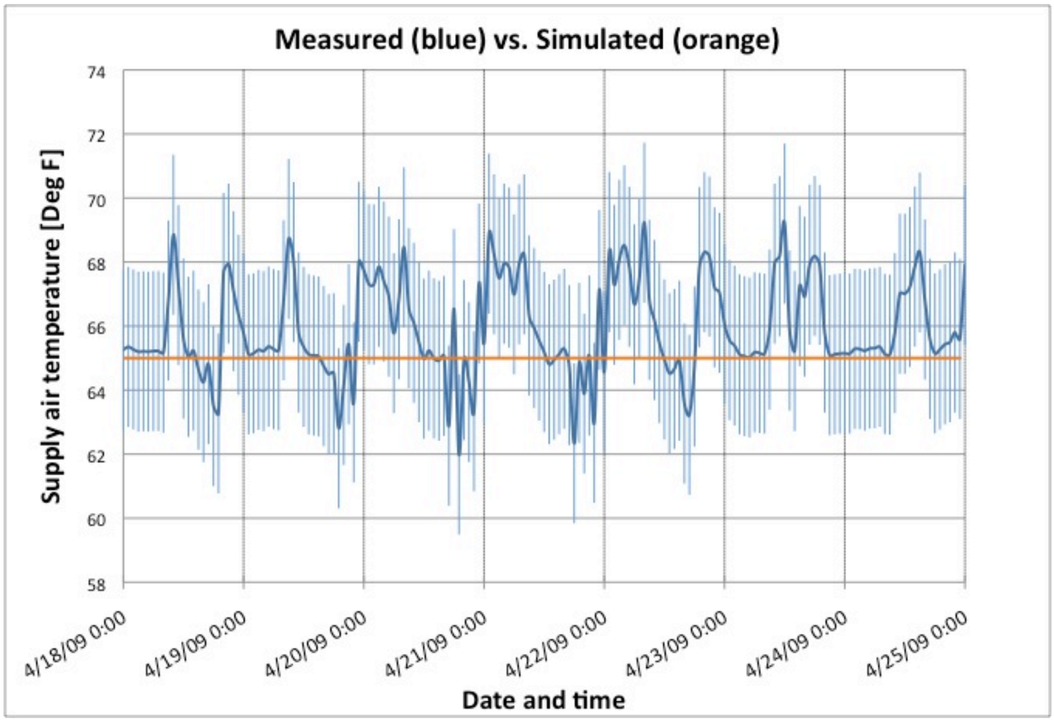

Figure 5: Comparison example showing supply air temperature of an air-handling unit measured (blue) and simulated (orange)
(Error margins of the measured data are illustrated in light blue.)

4 Selection of EnergyPlus as appropriate BEPS tool

A key component of the EPCM is the simulation tool used to create the simulated results. In this section, we first discuss the requirements for a simulation tool for use with the EPCM and thus during building operation. After establishing these requirements, we evaluate a list of BEPS tools based on these requirements. At the end of the section (4.3), we explain our selection of a BEPS tool based on the defined requirements and tool evaluation.

4.1 Requirements for BEPS tools for use during building operation

Maile et al. (2007a) argue that BEPS models, while usually created for design, are also applicable during the operations phase of a building. However, there are two important differences between these phases: the level of detail of input data and the availability of measured input data. These two differences lead to the following requirements for a BEPS tool to be used for detailed simulations during operation:

- High level of detail of input data
  - Ability to import detailed input data (geometry, HVAC, and controls)
    - Ability to semi-automatically import geometry data
    - Ability to model detailed and complex HVAC configurations
    - Ability to model detailed control strategies

    - Ability to adjust HVAC component equations
    - Ability to simulate at a small time scale
    - Ability to model complex geometry
    - Ability to consider feedback from HVAC systems
- Input of measured data
    - Ability to automatically import detailed measured input data
    - Ability to "override" simulated data with measured data (to support partial models)

The level of detail of a BEPS model increases with design stages, possibly resulting in a very detailed model at the final design stages. One reason for the increase of detail is that more information about the building is generated during design and finalized during construction. For example, during conceptual design the simulation expert may aggregate most of the office spaces into one combined office zone (depending on orientation and other influences) that is served by the same HVAC system, uses the same zone level components, and has similar internal loads. During later stages of the design process, similarities of these aggregated zones may change due to the increased level of detail and design changes; thus spaces that were similar in the early design stages and contained in one zone may be different and aggregated in different zones. In particular, at the operations stage, ducting and relationships among HVAC components are known (assuming they are documented accurately) and this enables the modeling of the actual building in greater detail. For a comparison with actual data, it is important to represent the building with the same level of detail, to enable a one-to-one matching between measured and simulated data.

This increased level of detail compared to the typical detail of BEPS models at early design stages requires the ability of the BEPS tool to capture such a high level of detail. This high level of detail is required for all types of input data: geometry, HVAC, and controls. To achieve this high level of detail, data exchange between CAD tools and BEPS tools becomes an important issue. While the effort of the initial creation of the energy model depends greatly on the amount of data one needs to manually import, the manual import of data increases this effort even more dramatically if various versions and modifications of a model are needed. Since BIMs contain those data, we have defined import of BIM-based geometry as a requirement. Bazjanac (2001) states that a BIM-based geometry input can reduce the modeling effort for geometry by 70-80%.

The requirement for a high level of detail also applies for HVAC systems and system topologies that are supported by a BEPS tool. BEPS tools that are more flexible can support more real-life buildings than tools that provide a rather stringent system topology. A tool should cover all common system types, including air, hot and cold water, steam, and electricity systems. BEPS tools with discrete HVAC components are more flexible in their HVAC topologies than BESP tools that have predefined HVAC systems.

In addition, the need for detail poses requirements for the representation of controls in BEPS tools. Typically, three levels of control strategies are available in BEPS tools: simplified, equation-based, and realistic (with time delays). Simplified control strategies are based on a predefined set of strategies, where the user can specify set points and reference nodes, but cannot change underlying equations. Equation-based control strategies allow the user to define these equations, providing a high level of flexibility. Realistic control modeling is usually possible with the use of separate tools to design control strategies (such as Matlab/Simulink, etc.) that also consider time delay of controls and smoothing of control signals. To use those external design control tools, a link between BEPS tools and design control tools is necessary.

Furthermore, the simulation tool should include a mechanism to simulate all HVAC components and strategies employed for a building, or at least provide a mechanism to account for components that cannot be modeled due to missing functionality. Ideally a BEPS tool allows the user to adjust existing component equations to allow for flexibility or at least provides component models with different levels of detail. This is particularly important to enable the evaluation of new and innovative HVAC components or configurations.

Besides the level of detail of the model structure and data, the time resolution is also important. Maile et al. (2010a) argue for a one-minute resolution for measurements. Thus, we require the same resolution for BEPS tools.

Simulating energy performance at this high level of detail also requires two additional functionalities: representation of complex geometry and feedback of underperforming HVAC systems to space conditions. With the increasing complexity of the geometry of buildings, the simulation tool needs an appropriate geometric model. We formulated this requirement with the need for multisided planar polygons. More complex geometry, such as curved surfaces, can be approximated with the use of multisided polygons.

The feedback from the HVAC system response to the space or zone must also be provided at the required level of detail. Without this feedback, the BEPS tool does not account for undersized systems, and the resulting space temperatures (and other space parameters) do not show the effects of such. Since an undersized HVAC system will have an effect on the space conditions in the actual building, the BEPS tool needs to consider this effect as well. Integrating system and zone simulation allows accounting for these system deficiencies (Hensen and Clarke 2000; Trcka and Hensen 2009). Thus we require an integrated simulation of HVAC systems and spaces, including the necessary feedback from systems to zones.

Another requirement for use of simulation modeling tools during operation is the ability to import measured data. In particular, one needs the technical ability to import measured data with acceptable accuracy. For example, does the tool functionality allow importing one-minute measured data as input for a space temperature set point, and does it provide automated routines to accomplish this import? An additional requirement is the tool's ability to integrate measured data into the simulation process. For example, does the tool allow overriding specific water temperatures of the main water loop? This kind of overriding allows one to adjust the simulation model to its specific environment and allows easier creation of partial models. Partial models of a building allow focusing on a specific aspect of the performance by isolating, for example, a subsystem and defining adiabatic boundaries around it.

4.2 Existing whole building energy performance simulation tools

Today a large number of BEPS tools exist for assessing energy in buildings. U.S. DOE (2010a) has published a comprehensive list of the available tools. Crawley et al. (2008) detail the functionality and differences of 20 major BEPS tools. Out of 20 major BEPS tools, we preselected the eight tools that contain more than the average number of HVAC components (18) and system types (36). We used this average criteria, since a BEPS tool needs to account for at least half of the typical HVAC components and system types to represent all components and systems in an actual building. Based on this report and our experience, we provide a summary table (Table 3) that shows which tools meet the outlined requirements we set forward for the EPCM. It also includes specific HVAC components that were found in the case studies and notes their availability in each tool.

Table 3: BEPS tool evaluation based on requirements for use during operation
("X" indicates full support, "P" indicates partial support, and "–" indicates no support)

Functionality	**EnergyPlus**	**eQUEST**	**ESP-r**	**IDA ICE**	**IES <VE>**	**HAP**	**TRACE**	**TRNSYS**
A. BIM-based geometry import[1]	X	X	X	X	X	P	X	P
B. User-configurable HVAC systems[1]	X	X	X	X	X	X	X	X
C. Air loops[1]	X	P	X	X	X	X	X	X
D. Fluid loops[1]	X	X	X	X	X	X	X	X
E. Discrete HVAC components[1]	X	-	X	X	X	-	-	X
F. Simplified controls	X	X	X	X	X	X	X	X
G. Equation-based controls	X	-	X	X	-	-	-	X
H. Links to other control tools	X	-	-	-	-	-	-	X
I. User adjustable component equations	-	-	-	X	-		-	X
J. Time step (sec)[1]	60	3600	60	< 1	60	3600	60	.1
K. Multisided planar polygons[1]	X	X	P	X	X	-	-	-
L. Integrated simulation (system feedback to spaces)[1]	X	-	X	X	X	X	X	X
M. Automated routines to import measured data	P	-	P	-	-	-	-	-
N. Overriding of system variables	P	-	X	P	-	-	-	X
Specific HVAC components								
O. Natural ventilation (pressure buoyancy driven)[1]	X	P	X	X	X	-	-	X
P. Natural ventilation (via pressure network)[1]	X	-	X	X	X	-	-	X
Q. Active beams	X[2]	-	-	X[1]	X	-	-	X[3]
R. Radiant slabs[1]	X	-	X	X	X	-	-	X
S. Evaporative cooling tower	X[2]	-	-	-	-	-	-	-
T. Roof spray	-	-	-	X[4]	-	-	-	X[4]
U. Server rack	-	-	-	-	-	-	-	X[5]

4.3 Selection of EnergyPlus

Based on these requirements for the simulation tool, we selected EnergyPlus as the simulation engine to use in the case studies. We note that none of the other tools mentioned above incorporates two of our requirements: the ability to create partial geometry models from IFC-based BIM geometry (functionality A) and the ability to directly link to

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[1] Based on Crawley et al. (2005) and Crawley et al. (2008).
[2] (U.S. DOE 2010c)
[3] (Fong et al. 2010)
[4] (Esmore 2005)
[5] (Mackay 2007)

control design tools (functionality H). In addition, the availability of specific HVAC components or strategies (e.g., natural ventilation, functionality O and P) in EnergyPlus compared to other tools made this selection attractive. Lastly, the ability to simulate based on a one-minute time step (functionality J) is another reason why we selected EnergyPlus for this research.

5 EnergyPlus and its AAS in case studies

Maile et al. (2010a) provide a brief description of the four case studies focusing on their measurements and data acquisition systems. Here we focus on the HVAC systems of the case studies and their BEPS models, as well as specific limitations and AAS of each model. We also briefly discuss the creation of geometry models for each case study. These examples show that documenting limitations of a specific EnergyPlus model with AAS provides a better understanding of the representation of each particular model. These AAS have an effect on the differences between measured and simulated data, which are described for each issue. While some of these effects result in explainable differences in data pairs, others simplify the HVAC model in a way that excludes specific components or aspects of the building from the assessment.

5.1 Case study 1: San Francisco Federal Building (SFFB)

5.1.1 HVAC system

The section of the building we investigated during our performance evaluation was naturally ventilated; thus no mechanical equipment was present besides the windows (manually operable and automatically operable). The floor in question is located above the lower mechanically ventilated floors and below the remainder of the naturally ventilated floors (Figure 6).

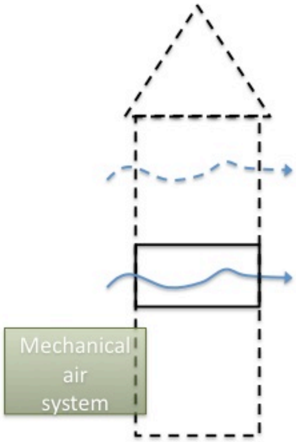

Figure 6: SFFB HVAC schematic

5.1.2 Design BEPS model

An existing design EnergyPlus model (Carrilho da Graca et al. 2004) was used as the basis for our EnergyPlus model for this assessment. We adjusted the building geometry to incorporate more detail; in particular the sinus wave shaped ceiling was approximated with higher detail than in the existing model. EnergyPlus provides an advanced AirFlowNetwork module (based on COMIS (EETD 2003)), which uses nodal airflow calculations. This AirFlowNetwork required pressure coefficients (so-called Cp-Values), which describe how wind reacts to the façade. Wind tunnel test data collected during design provided these values (Rauscher et al. 2002).

5.1.3 Usage approximations, assumptions, and simplifications

The vertical boundary to the non-modeled part of the 6th floor was defined as adiabatic, assuming no major difference between the two floor elements in terms of temperature (AAS no. 21). The floor surface boundaries on top and bottom were interlinked in EnergyPlus. For most parts of the model, this adiabatic assumption seems reasonable, since most spaces are full height, and thus the temperature difference between the two spaces (which in fact are the same) is zero. While it is relative unlikely that major temperature differences exist between floors that are naturally ventilated, it is possible that an unknown temperature difference could exist between the modeled floor and the lower floor (5th floor), which is mechanically air-conditioned.

The main approximation within this model is the partial geometry of the building that assumes that boundary walls are adiabatic (AAS no. 30). The selected section is on the 6th floor of the building. The effect of airflow in neighboring sections of the 6th floor is unknown and may vary depending on wind direction and speed. These uncertainties about the influences of processes that are close to the instrumented section of the building could not be quantified, since there were no measurements to detected them.

A simplification embedded in this EnergyPlus model is the representation of the sinus waved ceiling. Since EnergyPlus does not allow for curved surfaces, this ceiling was simplified using rectangular planar surfaces (AAS no. 7).

5.2 Case study 2: Global Ecology Building (GEB)

5.2.1 HVAC system

The HVAC system at GEB contains several innovative features (Figure 7). A so-called evaporative cooling tower in the lobby entrance area aims to cool the lobby in the summer through natural convection based on the use of sprayed water evaporating in this tower. The lobby also features large glass doors that can be opened during the summer to provide a transitional space between outside and inside. In the winter, a radiant slab heats the lobby. The first floor is mechanically cooled and heated by the main air handler, with an additional fan coil unit cooling at the zone level. This main air handler has an economizer and is single ducted. In addition, fume hoods are installed where necessary for lab exhaust. The second floor is fully naturally ventilated, except for the mechanically cooled server room. The hot water system is a typical system with two boilers, whereas the chilled water system uses a chiller and a night sky spray connected to a chilled water tank as source of cooling energy. The night sky spray evaporates water into the air on the roof during sufficiently cold nights to cool the water naturally.

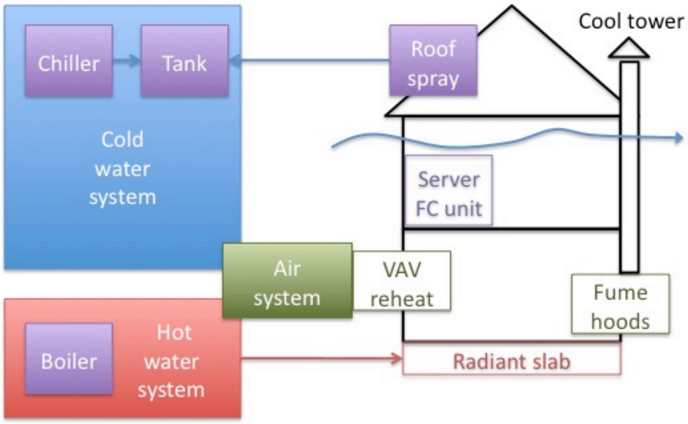

Figure 7: GEB HVAC schematic

5.2.2 Design BEPS model

A DOE-2 model was created by the designer during design of the building. We created the EnergyPlus model based on this DOE-2 model with the help of the DOE-2 Translator (see section 3.1). This translator automatically converts parts of a DOE-2 model into EnergyPlus input format.

5.2.3 Usage approximations, assumptions, and simplifications

The innovative HVAC system at GEB was difficult to model in EnergyPlus at the time of the project, because multiple components were not available as EnergyPlus objects, including the evaporative cooling tower (which was added in a later version of EnergyPlus) and the roof spray system. These missing components needed to be modeled with workarounds to include them into the model. Our model simplified the roof spray system with a district chilled water object (AAS no. 5; Figure 8) and ignored the cooling tower in the lobby (AAS no. 32) due to the missing availability in EnergyPlus. The district cooling simplification excluded the roof spray from the evaluation. Thus, problems with these two components cannot be detected using the EPCM. To enable evaluation of the remainder of the chilled water loop components, the measured supply water temperature was used as the supply water temperature set point to recreate the conditions that the roof spray provides.

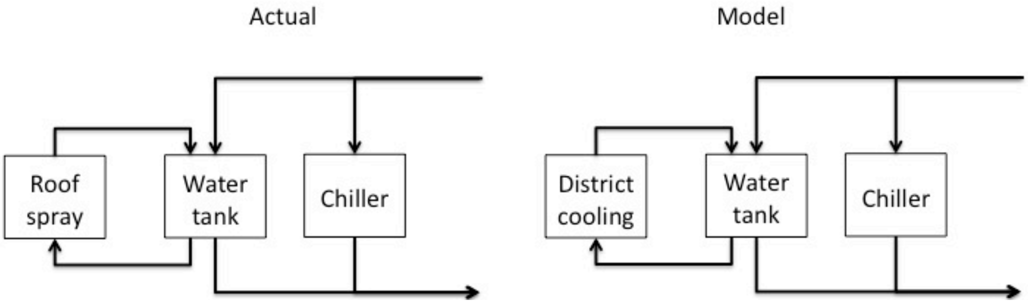

Figure 8: GEB roof spray simplification (on chilled water supply side)

5.3 Case study 3: Yang and Yamazaki Environment and Energy Building (Y2E2)

5.3.1 HVAC system

Y2E2 contains a so-called hybrid system, a combination of mechanical and natural ventilation (Figure 9). Three main air-handling units that use 100% outside air with heat recovery serve the building. The offices on the upper three floors are served via constant volume thermal boxes that are connected to active beams, which provide some additional cooling and (if necessary) heating. The basement floor includes variable volume thermal boxes for the lab areas, as well as fume hoods and other components to exhaust air. Air that is not explicitly exhausted through those components in lab and restroom areas is moved through plena into one of the four atria. Thus, the atria are used as a natural return path for air. The atria also support natural ventilation through automated windows located around the perimeter. Offices on the north side of the building contain radiators for heating. They do not have a connection to the forced mechanical air system. Both hot water as steam and chilled water come from Stanford's Cogeneration plant and are distributed throughout the building. Fan coil units serve mechanical, electrical, and data rooms with redistributed and optionally cooled air. Furthermore, so-called environmental rooms have special HVAC components that provide the necessary cooling or heating capacity to keep the rooms within a small bandwidth of the temperatures necessary for specific research. A server rack cools the server room to the necessary requirements. The entrance lobby area has an additional radiant floor for heating in the winter.

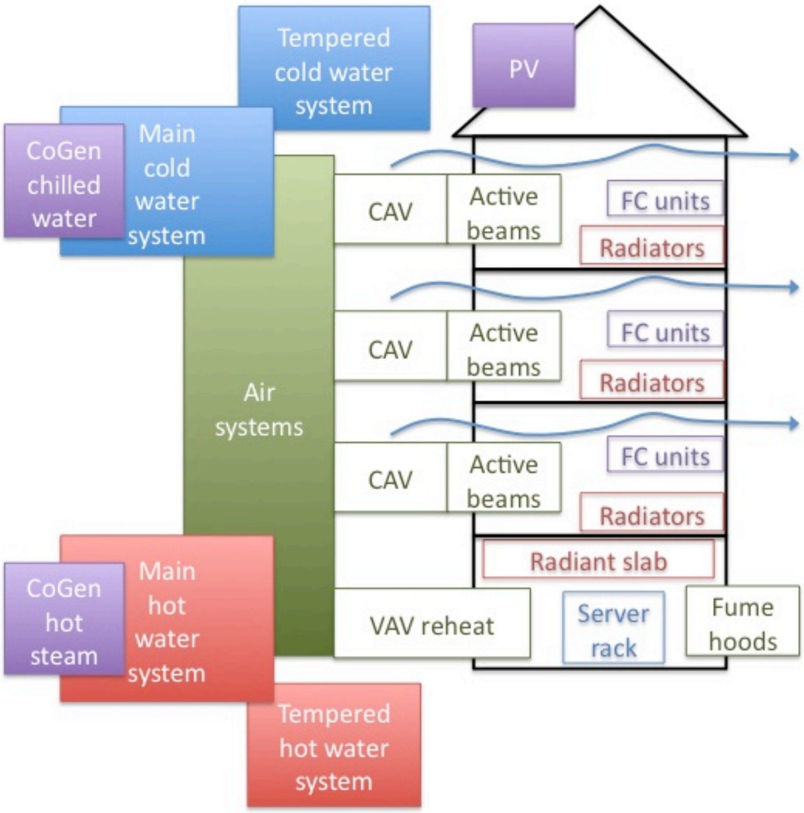

Figure 9: Y2E2 HVAC schematic

5.3.2 Design BEPS model

The BEPS model was done in eQUEST in two different versions; one that corresponds to the ASHRAE 90.1 baseline, and one that reflects the proposed design. We based our initial EnergyPlus model on the original design eQUEST model to provide the link to design, and we used the DOE-2 translator (see section 3.1) to convert parts of the eQUEST model. The creation of a CAD model was a challenge due to inconsistent architectural drawings. One specific aspect of the geometry model is modeling the plena. We modeled plena through which return air passes as separate zones but included the remainder plena within the slab construction.

5.3.3 Usage approximations, assumptions, and simplifications

Due to the lack of a component in EnergyPlus to model directly supplied steam, we ignored the hot steam supply (AAS no. 32) and used only a hot water loop to serve the building (Figure 10). This simplification excludes the heat exchanger performance from a detailed evaluation. However, the efficiency of the heat exchanger was reflected in the difference of heating energy between measured efficiency (which includes the heat exchanger) and simulated efficiency (which excludes the heat exchanger).

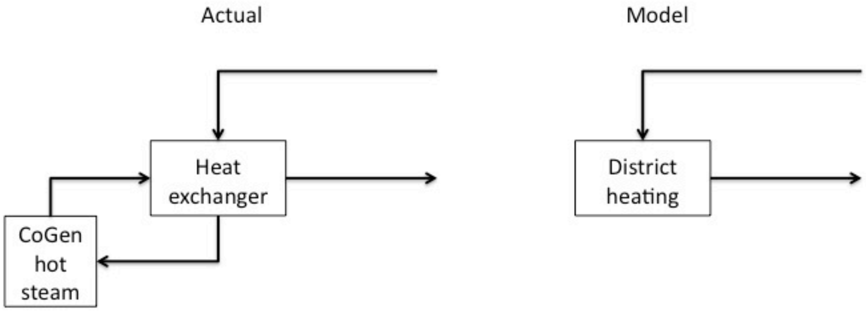

Figure 10: Y2E2 hot steam simplification

The interconnected two hot and chilled water loops that operate on different temperatures and serve different types of equipment also could not be modeled as such in EnergyPlus. EnergyPlus lacks a corresponding object to connect the two loops; thus our model contains two standalone loops (Figure 11). The consequence of this simplification (AAS no. 33) is a reduced water flow rate in the main water loop in the simulation compared to actual. In addition, the secondary loop's energy demand is not integrated with the main loop and may lead to different return temperatures in the main water loop.

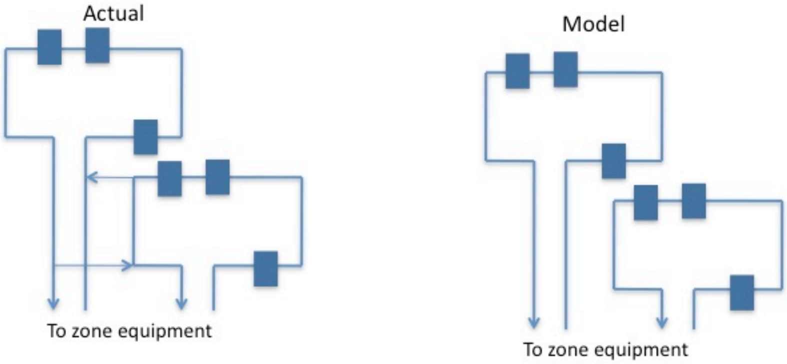

Figure 11: Y2E2 loop connection simplification

The air loop topology in EnergyPlus does not allow splitting of airflow into multiple exhaust flows. Because of this closed loop structure, the 100% outside air system cannot be modeled exactly as it is in the real building. At Y2E2 exhaust airflow splits between the atria and return air via the heat exchanger (AAS no. 27; Figure 12). The simplification in the model is to ignore the detailed return path through the atria, which influences the conditions in the atria as well as the exhaust airflow ratio of the heat exchanger. The exhaust airflow is smaller than the supply airflow in reality, but equal in the simulation model. Morrissey (2006) describes a similar configuration where EnergyPlus was not able to account for different return air paths.

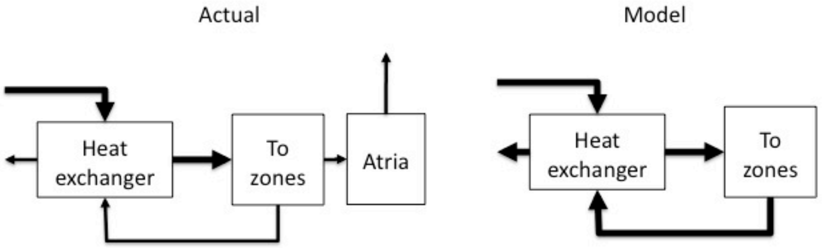

Figure 12: Y2E2 air loop topology simplification

The EnergyPlus structure does not include a two-stage zone equipment configuration. At Y2E2, supply air from the air-handling unit first branches into thermal boxes. For most of the building, these constant volume thermal boxes branch into multiple active beams. There is no support for this configuration in EnergyPlus. Thus, the active beams need to connect directly to the air-handling unit in the model (AAS no. 28; Figure 13). This direct connection ignores the thermal boxes completely. While it has little influence on the airflow, since active beams and thermal boxes in this configuration are all constant volume, additional heating and cooling at the thermal boxes in the basement needs to be included into separate supply branches. This simplification means that airflow rates at the thermal box level cannot be directly compared, since this level does not exist in the simulation. There is no effect on the system level, but at the zone equipment level, entering air conditions may vary, because the function of the thermal boxes has been combined into one of three supply branches (another limitation of EnergyPlus).

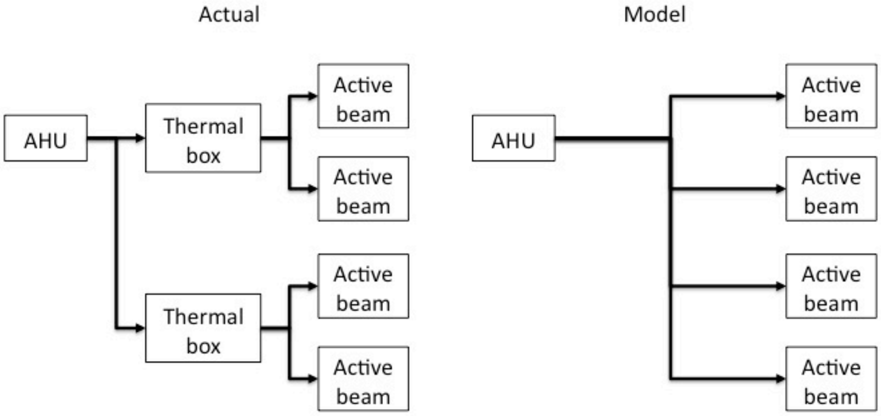

Figure 13: Y2E2 air loop branching simplification

Multiple different zone equipment components for one zone are another issue with the EnergyPlus model for Y2E2. For example, some conference rooms have both active chilled beam components and constant volume registers (AAS no. 29; Figure 14). Since EnergyPlus allows only one zone equipment component that is connected to an air loop, this configuration cannot be modeled directly in EnergyPlus. The workaround is to split the zone into two, with the corresponding single zone equipment components assigned to each part and use a so-called *air wall* component between the two zones. The air wall has assigned properties that allow heat transfer between the two zones (to mimic the one actual zone), and we defined additional airflow objects that exchange air between the two zones to create the same conditions in both zones. Depending on how well the model parameters capture the mixing between the two zones, there may be no effect on thermal parameters; however, the topology is different due to the additional zone.

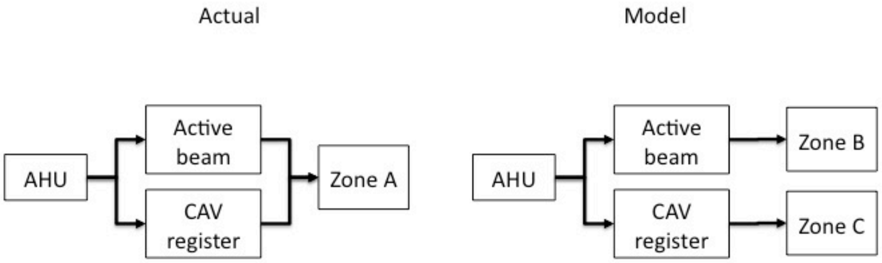

Figure 14: Y2E2 simplification of zone equipment component configuration

5.4 Case study 4: Santa Clara County Building (SCC)

5.4.1 HVAC system

The HVAC system of the Santa Clara County building consists of several air-handling units that are connected to a hot water loop and a chilled water loop (Figure 15). The hot water loop generates hot water via three boilers. The chilled water loop contains two chillers that are connected to a condenser loop that uses two cooling towers as sources for chilled water. Two identical AC units (one is redundant) serve the computer room and have their own separate chilled water loop with two evaporators. The main towers are served by three constant volume 100% outside air units with cooling, heating coils, and a heat exchanger. Other separate air-handling units that are also 100% outside air and provide heating and cooling as necessary serve medical spaces. The office and lobby area are served by air handling units with economizers and heating and cooling coils with a dual duct configuration. Specific air handling units serve mechanical and electrical rooms to provide cooling for these spaces.

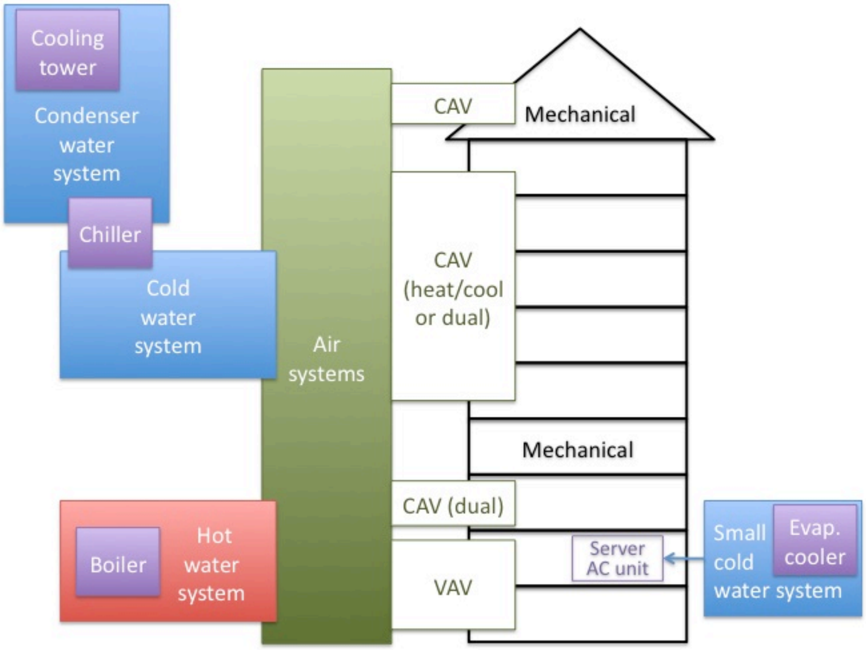

Figure 15: SCC HVAC schematic

5.4.2 Design BEPS model

Due to the age of the facility, no design BEPS model existed. Thus, we created a new EnergyPlus model based on existing documentation, following the process outlined in section 3.1. A particular challenge of the detailed CAD model and its conversion to IDF was the relative complexity of internal spaces across floors and the large number of columns embedded in walls in various geometrical configurations.

5.4.3 Usage approximations, assumptions, and simplifications

Since the HVAC systems at this facility are mostly typical systems, we could easily model them in EnergyPlus. The large supply fan units that serve the main towers are one exception. Their two-stage split of branches with additional coils in between cannot be reflected with more than three branches using EnergyPlus (Figure 16). The corresponding simplification is the use of two separate air-handling units (AAS no. 41). The effect of this simplification is the split of airflow into two equal systems, each with half the airflow. In addition, return air temperatures may be slightly different depending on the distribution of internal loads in the zones.

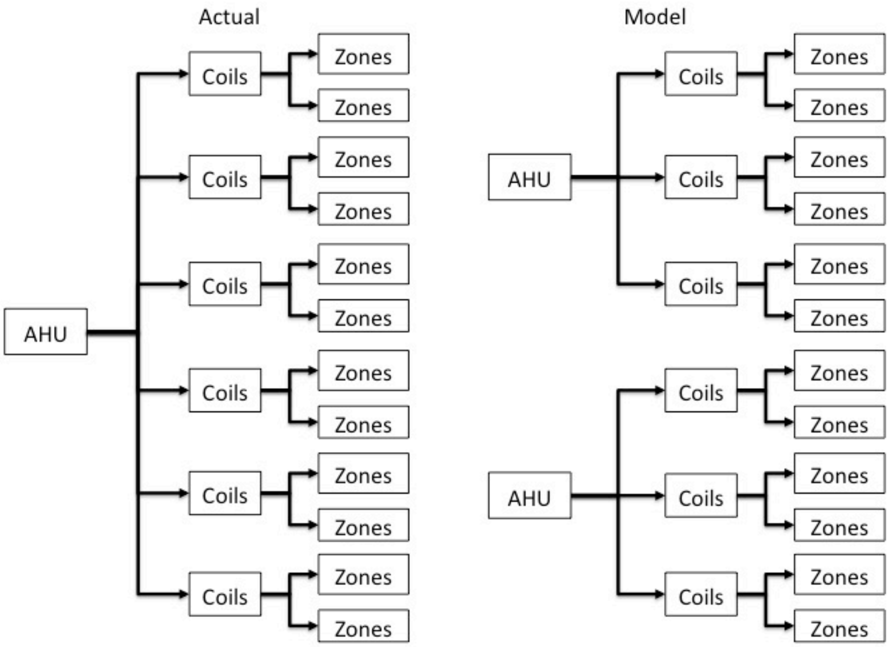

Figure 16: SCC HVAC air loop branch simplification

Another simplification of the EnergyPlus model is the pump configuration on the chilled water loop. While the actual building has a pump in series with each chiller, the model contains a series of two parallel pumps (represented with one EnergyPlus object) and two parallel chillers (AAS no. 42; Figure 17). Thermodynamically the effect of this different configuration is negligible; however, the control strategy of synchronizing the pumps with the corresponding chiller cannot be evaluated, since the link between the chiller and the pump gets lost in the EnergyPlus model.

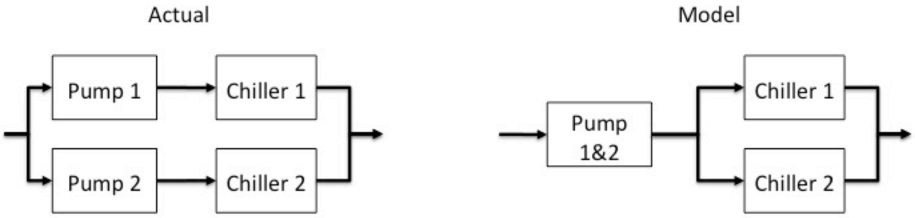

Figure 17: SCC chilled water loop pump configuration

6 Limitations of and recommendations for BEPS tools

Based on the limitations of EnergyPlus illustrated in section 5 for four case studies, we discuss the general limitations with BEPS tools in this section as well as corresponding recommendations. The recommendations specific for EnergyPlus apply to EnergyPlus V5.0 (U.S. DOE 2010e) despite its recent modifications and upgrades. To use BEPS tools during operation, further features are required (see 4.1), which have not been addressed in recent EnergyPlus or other BEPS tool developments. The major conceptual limitations of BEPS tools are inadequate geometric representation (section 6.1), inability to model innovative, unique, and unorthodox objects, systems and configurations (section 6.2), missing functionality to integrate measured data (section 6.3), inconsistent internal data models (section 6.4), inappropriate graphical user interfaces (section 6.5) and insufficient level of detail (section 6.6).

6.1 Inadequate geometric representation

Geometric models of BEPS tools are typically based on a one-dimensional heat transfer that leads to internal planar surface pairs that have to be parallel to each other (external surfaces typically do not have an opposite surface). This limitation may be adequate for simplistic buildings and designs that have only rectangular walls, but fall short for more complex geometry configurations. Figure 18 illustrates examples of complex wall configurations that cannot be adequately represented with the current geometry models in BEPS tools.

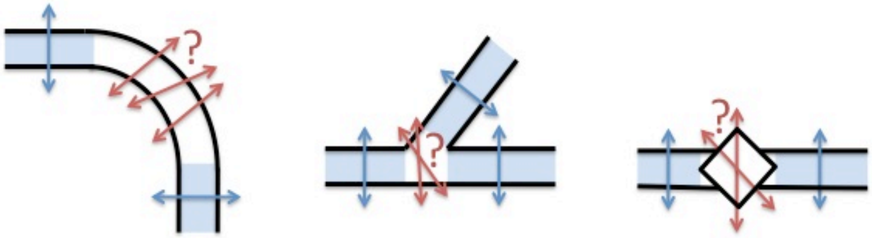

Figure 18: Examples of complex geometrical configurations
(curved wall, non-rectangular wall intersection, embedded column in wall; blue arrows indicate one-dimensional heat transfer while red arrows show where one-dimensional heat transfer is not defined)

The geometric representation of BEPS tools is based on the assumption that buildings do not have curved walls, complex embedded columns, and non-rectangular wall configurations. This assumption (AAS no. 12) is unrealistic given today's architectural designs. The geometric representation of BEPS tools is often referred to as thermal view of the building. This thermal view consist of only planar and parallel internal surfaces that are often approximated by placing both surfaces in the same plane, the middle plane of a wall, which creates incorrect volumes of spaces and surface areas. Since a HVAC simulation depends greatly on the volumes and areas due to the fundamental equations including those characteristics, the simulation results produced become unrealistic.

This inadequate representation creates the need for workarounds that are, however, not supported with this simplistic representation. This simplistic representation is also not compatible with geometry models of CAD tools that include significant functionality to model complex geometry. This inadequate representation forces users to make arbitrary decisions in preparing and executing BEPS models. While the simulation AAS concept allows documenting limitations of BEPS tools it cannot solve fundamental problems with BEPS tools.

Thus, we recommend new and more complex geometry models for BEPS tools that include more complex geometrical configurations (such as in Figure 18). At least, the addition of two-dimensional heat transfer specifically for columns and beams need to be addressed in future BEPS tools.

6.2 Inability to model innovative, unique, and unorthodox objects, systems and configurations

While the inadequate geometric representation of BEPS tools is a fundamental limitation, limitations of HVAC topology and simplified control representations are further reasons that hinder the ability to model innovative, unique, and unorthodox buildings and systems. This inability makes new, innovative, or just different components, systems and control strategies difficult if not impossible to evaluate. A promising, just emerging concept in the HVAC industry is component-based simulation based on equation-based languages such as Modelica (Modelica 2010). Such a component and equation-based simulation environment reduces time reduction for component model development significantly and increases flexibility to model innovative systems (Wetter 2009).

In the following subsections we discuss the specific limitations of EnergyPlus that limit the user to model innovative designs. These are the limited HVAC topology illustrated by the limitations of zone equipment configurations as well as water loop configurations, the simplified control representation within EnergyPlus, and missing HVAC component models.

6.2.1 Limited HVAC topology

While EnergyPlus is more flexible than tools such as DOE-2 and BLAST in its HVAC topology, there still exist numerous limitations in the EnergyPlus topology. To name a few, EnergyPlus requires closed loops, so hybrid systems where exhaust air flows in two different ways (through atria and exhaust ducts) cannot be modeled (see section 5.3.3). Water loops can only have one set of parallel branches on the supply and exhaust side. Thus, multiple splitting and mixing of water flow are impossible to achieve with the current architecture of EnergyPlus. To model specific loop configurations in EnergyPlus, workarounds become necessary, and comparisons of all variables within a loop become more difficult.

Like EnergyPlus, most simulation tools have limited flexibility with respect to HVAC topology. Either predefined HVAC system templates or relatively strict topology rules limit the ability of the simulation expert to model new and innovative HVAC system topologies. Thus, we recommend that future BEPS tools should support truly component-oriented topologies that allow any combination of components to be connected with each other. Without this improved flexibility, new and more innovative and complex HVAC systems cannot be modeled exactly, and questionable workarounds must be developed. Using BEPS tools during operation also requires more flexible HVAC topologies than the simplified topologies typically used during design.

Specific instances of HVAC topologies of the case studies that cannot be represented in EnergyPlus are configurations of air loop supply branches, of zone equipment components, and of connections between water loops.

6.2.1.1 Limited air loop supply branch configurations

Modeling of multiple off-branching on the supply side of air loops is also very limited; in particular, a two-step branching with integrated coils is only possible for up to three branches on the first step. Obviously this is a restriction of the HVAC topology and not adequate for the air loop structure at Y2E2 (see section 5.3.3) or SCC (see section 5.4.3). Both limitations introduce problems for one-to-one comparisons, because of differences in configuration between the simulation model and the actual HVAC system. These limitations may also cause effects on temperatures, in particular return temperatures. These topology limitations lead to the inability to model innovative HVAC system topologies (as demonstrated with the limitations at Y2E2).

6.2.1.2 Limitations with zone equipment components

In addition, modeling a thermal box serving a number of zones that have additional zone equipment components (e.g., at Y2E2; see 5.3.3) is not possible. EnergyPlus can only have a single zone equipment component as connection between an air loop and the zone. While this may be a reasonable simplification at early design stages, actual buildings (e.g., Y2E2) may have more than a single zone equipment component connected to an air loop. Space conditions may become difficult to simulate in situations where zone equipment configurations do not coincide between the modeled and actual configurations.

6.2.1.3 Limitation of water loop configuration

It is not possible to connect two or more water loops for multi-temperature usage in EnergyPlus. Developers removed this feature in version 2.2. The necessary separation of water systems is illustrated in Figure 11. In this case, water flow and potentially return water temperatures do not compare directly.

6.2.2 Representation of controls in EnergyPlus

EnergyPlus includes mainly simplified control objects. While control strategies provided in EnergyPlus have increased in number and complexity over the last years, they are still not flexible enough to accommodate many real-life control strategies. With more complex HVAC systems and the combination of systems, the control strategies become more complex and error-prone (Maile et al. 2007b). New additions to EnergyPlus allow a more flexible definition of controls; the first one is the so-called EMS (Energy Management System;Ellis et al. 2007) model that includes a number of new EnergyPlus objects, including functionality to insert user-defined equations. The second option is the link via Ptolemy II to generic simulation tools such as Matlab/Simulink (Wetter and Haves 2008). However, EnergyPlus does not provide controller objects that simulate the actual performance of a hardware controller.

Because of the increasing complexity of control strategies in buildings, a proper evaluation of control strategies between measurements and simulation can only be achieved if it is possible to represent the actual control strategy within the simulation model. An example of a complex control strategy is the control sequence of the radiant slab at Y2E2. This strategy depends on time of day, several temperatures within the concrete slab, and space air temperatures. It also changes the valve position by only a small percentage every ten minutes. It is not possible to model this control strategy with EnergyPlus' simple control objects. Since control strategies determine the goal a HVAC system tries to achieve, the comparison between measured and simulated data becomes difficult if the control strategy cannot be modeled in the simulation tool. A workaround for control strategies that are difficult to model given current functionality is to use measured or control data points directly as input for the BEPS simulation

(Maile et al. 2010). For example, if an air loop temperature set point cannot be determined accurately in the BEPS model, the archived control set point is imported into the simulation. While this eliminates differences between the model and the actual building correlated to this set point, the control strategy cannot be assessed, since it is taken directly from the actual building.

We recommend adding controller components that simulate the actual behavior of control hardware in EnergyPlus to simplify their use within the simulation. In addition, the EMS and Ptolemy functionality should be extended to increase the flexibility to more than just schedules (Ptolemy II link) and integrate controller types that can simulate realistic controller performance (EMS).

6.2.3 Missing HVAC components

Some new and innovative components are not available in EnergyPlus. While it is certainly difficult to keep up with all developments within a reasonable timeframe, the more important issue here is that there are no user-definable generic components that could be used to define a simplified version of a specific component. The effect of missing components varies from case to case.

One example of a component that is not available in EnergyPlus is a variable air volume (VAV) thermal box with cooling. The thermal boxes provided in EnergyPlus either have a heating coil or no coil at all. However, innovative systems use *VAV thermal boxes with cooling coils* that are not available in EnergyPlus. The lack of a representation for the cooling coil at the thermal box level requires a substantial change in the loop topology and makes a comparison very difficult.

Thermal constant air volume (CAV) boxes in EnergyPlus can have flow at the constant speed or must be off completely. At Y2E2, these boxes can have a reduced airflow rate during nights and are thus *two-speed CAV thermal boxes*. The lack of representation for these CAV boxes causes the airflow during nights to be below the actual (i.e., zero) and thus influences the modeled space conditions.

A representation of a heat exchanger that converts steam energy into hot water is also not available at this time in EnergyPlus. At Y2E2, such a *steam heat exchanger* is used to transfer energy from hot steam to hot water. The effect of a missing steam heat exchanger model is that the heat exchanger cannot be evaluated directly.

While hot and chilled water district heating is available in EnergyPlus, *district steam heating* is not. Thus, it is not possible to model the steam supply at Y2E2. Together with the missing steam heat exchanger, this limitation requires the development of a workaround with district hot water to ensure the downstream conditions are the same. Thus, the steam heat exchanger cannot be evaluated directly.

A chilled *roof spray* object is also not available in EnergyPlus. While such an object is truly specific, there is no similar object in EnergyPlus. Without the roof spray object, it is impossible to evaluate the roof spray performance with the measurements such as at GEB. Since the roof spray is a relatively new concept, evaluation of this early installation would be extremely useful for future projects.

While these are specific examples of missing components in EnergyPlus, Table 3 summarizes whether other tools provide or lack these mentioned components. In general, simulation tool developers need to keep up with new developments of HVAC components to provide the simulation experts with the flexibility to test new components against older ones. A flexible software architecture that incorporates component libraries that allow adding of components between releases would dramatically improve the current situation and allow users to develop new component models if none exist. Using more detailed BEPS models requires the use of more detailed HVAC component models.

6.3 Limitations for a comparison with measured data

Besides the described limitations of EnergyPlus, we illustrate limitations that are apparent through comparisons with measured data. Specifically, we describe limitations on importing measured data, the consequences of the current model warm-up, and limitations of report variables.

Based on these limitations, we recommend better integration of measured data into BEPS tools. The ability to override any variable within the simulation environment with measured data would provide the functionality to test specific aspects of the simulation model versus actual measured values. For example, overriding air flow rates of fans with actual measured air flows would eliminate ambiguous differences between the measured and the simulated air flow.

6.3.1 Limited import of measured data

While it is possible to convert measured weather data into the weather data format as shown by Maile et al. (2010a) who describe the WeatherToEPW Converter tool that accomplishes this conversion, the integration of measured data with EnergyPlus is limited. It is not possible to override space temperatures, for example, to mimic a response of a system.

6.3.2 Model warm-up

EnergyPlus uses the first day of a simulation period or design day as a so-called warm-up period. The engine simulates this first day multiple times until either a convergence tolerance is met or a certain number of attempts has occurred. This is a reasonable approach for design simulations, since it provides a starting point that is consistent with the first day of the simulation. For comparison with measured data, this approach can lead to a situation where conditions on the first day differ from the measured data, due to long term effects. Especially on the space level, this difference on the first day influences the results for the following days. It would be better to integrate measured data as the basis for the warm-up. We discovered a workaround to force the space conditions of the warm-up day to be the same as the measured conditions. It uses a "duplicated" zone that is conditioned with an ideal system to the measured temperature in the building. For the first day of simulation, we mix the air of the two zones so that the conditions in the two zones are equal and correspond to the measured data. This workaround creates modeling overhead, because it doubles the number of zones and thus increases simulation time (about 1.5 times longer runtime, e.g., for Y2E2, 19 hours instead of 12 hours). It eliminates the need to adjust internal loads iteratively to create a similar starting point in the simulation model as provided by the measured data. Providing a specific function in the simulation tool that allows for a more flexible warm-up period based on measured data could provide a better starting point for the comparison. Insufficient model warm-up leads to the use of an incorrect starting condition for the simulation. Depending on a number of factors, this incorrect starting condition may become less important while time progresses in the simulation.

6.3.3 Report limitations

EnergyPlus makes available a large number of report variables, or resulting data points. Some data points cannot be reported directly and need to be derived from other report data. One example is the position of a valve. Often this position is available within the measurement data set as a control point, but the corresponding simulation data point is an air or water flow rate. Table 4 summarizes the variables for which no direct correspondence of measured and simulated data points is available. One can derive a data point either external to the simulation or within the simulation with the help of the Energy Management System (Ellis et al. 2007) in EnergyPlus.

Table 4: Measured variables without direct counterparts in simulation

HVAC system or component	Measured data point		Simulated data point	
	Variable	Unit	Variable	Unit
Atrium	Windows open status	Binary	Zone ventilation volume	m^3
Radiant slab	Radiant temperature set point	°F	-	-
Radiant slab	Night setback set point	°F	-	-
Air loop	Air flow	CFM	Air flow (for each sub loop)	m^3/s
Thermal box	Air flow (for each box)	CFM	Air flow (aggregated for multiple boxes)	m^3/s

6.4 Limitations of internal data models for interoperability

The internal data model of EnergyPlus is inconsistent and not a true object-oriented data model (for example it does not include inheritance). Specifically, various parameters need to be specified multiple times such as air or water flow rates. Connections between components through branches are also different for different loop types. The EnergyPlus components do not represent actual components, but contain functionality of multiple actual components such as combining a coil and its control. Thus, it is difficult to map objects, parameters, and characteristics for interoperability with other tools.

With the increase of detail for use of BEPS tools during operation, we recommend increasing the reliability of data exchange between software tools. Dramatic time savings (weeks versus hours) and reduction in the number of error sources (the effect of errors varies with the size of the BEPS model) will significantly improve the use of BEPS tools during operation. In particular, better interfaces between CAD tools, HVAC control design tools, data repositories, and BEPS tools are needed. Exchanging data between HVAC design tools and BEPS and the actual control system would provide a more comprehensive way to evaluate control strategies and reduce errors and differences among the different strategies used in different tools. Better integration of data repositories would allow easier and more comparative analysis of simulation results as well as comparison with measured data. Even more helpful would be an improved integration of measured data into BEPS tools; on a simulation functionality level as well as on a data level. Other BEPS tools have similar issues with internal data models, thus we recommend extending or adjusting internal data models of BEPS tools to truly object-oriented architectures that also relate better to actual components, systems, and buildings.

6.5 Graphical user interfaces

While no graphical user interface (GUI) for EnergyPlus exists that supports all major HVAC functionality, other BEPS tools have more advanced GUI's, but typically lack one or more of the following functionalities. A GUI should provide the ability to integrate tools and scripts that allow users to adjust certain routines and data transformations for a specific project. In addition, providing versioning functionality for the simulation models would support the user who is applying EPCM. Starting with the original design model, assessors will create a significant number of models that differ mostly only in small aspects from each other. Providing versioning functionality could help the assessor to maintain an overview of differences between models. In addition, a GUI should also allow for the use of partial models, so the assessor can focus on specific aspects of a building without specifying the detail of other parts of it. Enabling partial models would require creating adiabatic surfaces for the needed geometry and summarizing and simplifying geometry, HVAC systems, and components. Because of the current need to develop custom programming code that supports the energy modeler, we recommend the development of a comprehensive GUI for EnergyPlus and other BEPS tools, to increase the efficiency of model creation and updating.

6.6 Increased level of detail

As reported in this paper, EnergyPlus does not always support the modeling of HVAC systems to the level of detail needed for operation. This is a significant shortcoming and needs to be resolved. Besides increasing the level of detail of HVAC components and possible topologies, simulation tools should provide a range of HVAC components at different levels of complexity. This would enable the user to start with a simple component model at early design stages and increase the complexity and level of detail of the components over the course of design and into building operation. With increased detail, the need for interoperability to exchange data also increases, as well as the need to manage the input data, in particular the differences between different versions of BEPS models. Furthermore, increased detail also requires modeling a wider variety of HVAC components, as well as new HVAC components and HVAC system configurations, to match actual components and topologies more closely.

7 Validation of simulation AAS

The value of simulation AAS is in their use in the EPCM, allowing the selection of more appropriate BEPS tools, giving direction to their further development and allowing the construction of better BEPS tools. Through AAS that are specific to BEPS tools, the AAS support the selection of an appropriate BEPS tool for a given performance assessment scenario. The formalization of AAS highlights limitations of BEPS tools and thus can direct future development efforts to overcome those limitations. The documentation of AAS can also show fundamental problems with specific BEPS tools and thus trigger new developments of BEPS tools to advance the tool development.

The validation is based on the performance problems found at the Y2E2 case study. Detailed information about the performance problems is included in Maile et al. (2010b) and Kunz et al. (2009). The former paper includes a prospective validation of the EPCM with the Y2E2 case study. In context of this validation, AAS support the evaluation of differences between measured and simulated data. 41 differences between measured and simulated data could be explained with corresponding simulation AAS. From a total of 109 differences, these 41 (37.3%) could be eliminated as false positives by analyzing the simulation AAS. In section 3.3, we provide references from literature and the four case studies for each AAS as source. These sources indicate that the list of critical AAS is not specific to Y2E2, but applies to other case studies and is based on existing literature. Details about the reasons why we used the Y2E2 case study specifically for the validation is contained in Maile et al. (2010b).

The AAS within the EPCM are used as explanations for differences between simulated and measured data; however, a difference may be caused by other influences or may be a combination of issues. Future research should validate AAS to understand their effect better, specifically in a quantitative manner. This would inform the energy modeler about that the quantitative effect of a specific AAS and enable a better informed BEPS model creation even early in the design process.

Figure 19 illustrates the occurrences of simulation AAS (for simulation AAS numbers, see section 3.3 or Appendix C in Maile (2010)) in the four case studies and literature. Most of the simulation ASS occur in more than one case study, are mentioned in existing literature, and are used to eliminate false positives in the validation case study. The AAS are ordered based on total occurrences and at least half of them have three or more occurrences. We used 42% of the AAS as false positives in our validation case study, but anticipate that even more AAS would be used in additional validation studies. 23% of the AAS show only one occurrence, but still were important for the particular case study.

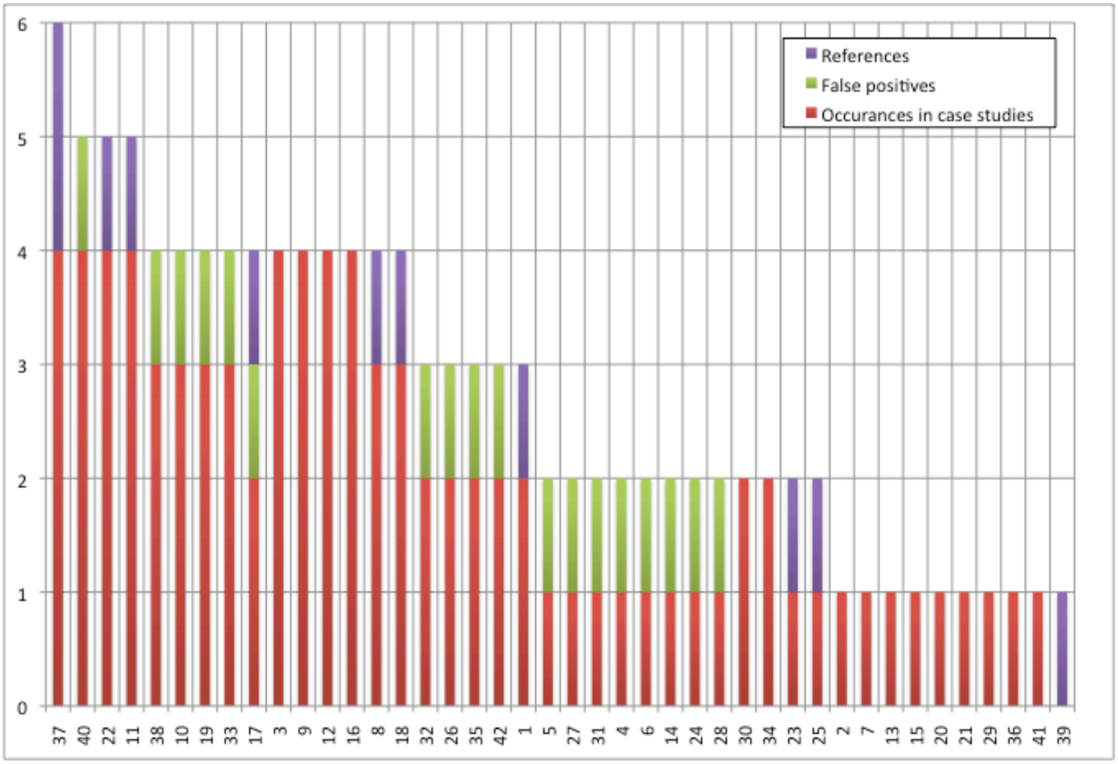

Figure 19: Occurrences of simulation AAS in case studies and literature

8 Limitations and future research

This section describes limitations of this research and discusses possible future research areas based on the concepts in this paper. In particular, we discuss emerging technologies in BEPS, an integration of error calculations into BEPS, possible expert systems based on AAS and our process for identifying performance problems, the limitations of the AAS list, and the possibility of detailed analysis of the accuracy of simulation results. This research is a further step towards the application of BEPS tools to predict the actual energy performance of buildings more accurately.

8.1 Emerging technologies in simulation tools

Some new developments within the context of simulation tools can be integrated into the methodology. In particular, while we selected and used a single simulation engine, it may prove beneficial to combine two or more simulation tools to enable a more accurate model. Trcka et al. (2007) describe the coupling of simulation tools as co-simulation research. Another similar approach enables communication among multiple tools during execution time via sockets (Wetter and Haves 2008). This approach allows more flexible use of tools that can model controls, such as Matlab or Simulink. Combining the functionality of two or more simulation tools would allow taking advantage of the strengths of these tools and helping to avoid their weaknesses. For example, the realistic simulation of controller signals in Matlab connected to EnergyPlus would eliminate the difference due to time delays (or the lack thereof).

8.2 Integration of error calculations into whole building simulation tools

Because of the complexity and large number of equations embedded in whole building simulation tools, it is practically impossible to perform an error calculation outside of a simulation engine (see section 3.2). Future research could integrate error calculations into whole building simulation tools, so users could specify error margins of input data and the tool would output error margins based on the input. In addition to providing the error calculation in the tool, future research could also determine default error margins and statistical sampling methods to better address the uncertainty of various input parameters in the simulation. For example the solar radiation measurements (direct and diffuse) have various effects on the performance of the building such as solar loads in spaces through windows but are often measured crudely. The propagation of the error margin of the solar measurements would help to understand the real influence of the accuracy of such a measurement. Though statistical sampling methods the actual variation in building use could be modeled more realistically than with constant values and regular patterns.

8.3 An expert system based on approximations, assumptions, and simplifications

Future research could define possible consequences of specific AAS and build an expert system that automatically determines differences between measured and simulated data. Automated detection of differences based on statistical criteria could highlight data pairs that show differences and simplify the performance assessor's task of finding data pairs that do not match. A second stage could use AAS to qualify these differences as performance problems and provide indications of related performance problems. Once both stages are mostly automated, the assessor could focus on the difficult data pairs and save effort in finding these pairs in the first place. Performance problems could be found more quickly and closer to their actual appearance. A quicker response time to find problems would enable faster assessment of building energy performance and faster feedback on the BEPS models and their AAS. This faster feedback would make a practical application more meaningful, since performance problems can be determined in a more timely fashion.

8.4 Identifying new approximations, assumptions, and simplifications

The list of critical AAS (see section 3.3) is based on literature review and the four case studies. Future case studies and research may identify more AAS. New HVAC component models, system configurations, and control strategies may require the definition of new AAS. In addition, the case study models are all based on EnergyPlus. The limitations of EnergyPlus may not correspond to those in other BEPS tools, and thus new AAS may need to be added to the list to account for specific concepts in other BEPS tools. The development of new assumptions and their anticipated effect as well as a hierarchy of AAS based on their anticipated effect would depend on future tool developments and typical modeling practice. The anticipated effect of each AAS is also an area of further research. The validation of these effects and more stringent descriptions would aid the development of an expert system.

8.5 Detailed analysis of accuracy of simulation results

A detailed quantitative investigation of accuracy of simulation results was beyond the scope of this research; however, future research could integrate accuracy calculations, either within the BEPS tool or within the EPCM. Assessing accuracy of measured and simulated data could provide a more reliable assessment of differences between measured and simulated data. Developing more accurate simulation results will reduce the number of AAS needed to document limitations and make the process of EPCM easier.

9 Conclusion

In this paper, we provide a list and categorization of critical simulation AAS we collected from literature research and experience with four case studies. These AAS describe limitations of BEPS models, in particular limitations of input data, use of simulation concepts, and shortcomings of BEPS tools (specifically EnergyPlus). This list and the process for using AAS to determine performance problems are new concepts and thus contributions of this paper. These simulation AAS enable a better assessment of differences between measured and simulated data.

We selected EnergyPlus as the most suitable simulation engine; based on the requirements we developed for a comparison between measured and simulated data. Specifically, EnergyPlus' ability to communicate with control design tools and to generate partial geometry models, as well as the reasonable set of available HVAC components, are key characteristics that differentiate it from other BEPS tools. To properly transition design BEPS tools into operation, these tools need further adjustments. We have described shortcomings and limitations of simulation tools (in particular EnergyPlus) and have given our recommendations for future developments. Specifically, requiring simulation tools to enable more data exchange would enhance the use of performance evaluation based on design models. In addition, improved data exchange would support reuse of design data more directly and reduce the effort needed to generate or update BEPS models. We have recommended that BEPS tools increase their level of detail to correspond to the level of detail of actual buildings. We have also discussed additional possible improvements to EnergyPlus related to comparing simulation data with measured data in terms of model warm-up, making more report variables available, and improving the functionality for importing measured data. We have discussed limitations of this research and future research directions. This research provides a step towards enabling prediction of actual building performance.

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