The contributions of the **simulation paper** are

1. A definition and list of simulation approximations and a mechanism to identify performance problems from differences between measured and simulated data.
2. Specific evidence of limitations of whole-building simulation tools (in particular EnergyPlus) for use to simulate actual operating conditions.

Gaps:

Previous research only mentions project specific approximations and does not provide a mechanism to identify performance problems (1). Previous research mentions limitations of simulation tools but does not provide specific evidence for those limitations. (2).

Validation:

Qualitative evidence for the mechanism to determine performance problems based on assumptions is given through examples that show the ability to characterize differences as performance problems or assumption based differences (assumptions eliminate false positives) (1). We show specific instances of identified software limitations that circumvent the accurate modeling of the real building (2).

Domain:

These contributions apply to the HVAC domain in non-residential buildings for the task of performance evaluation based the comparison of measurement and predicted data for engineers that evaluate building performance.

Simulating building energy performance for comparison with measured performance

1 Abstract

Building energy performance is often unknown or inadequate given design goals. One concept to evaluate building energy performance is to compare measured with simulated performance data. This paper describes key tasks on how to simulate building energy performance for a comparison with measured data. We describe use of BIM (Building Information Models) to generate whole building energy simulation models, detail specific simulation models of four case studies, provide model simplifications and point out limitations of simulation tools. Previous research provides only project-specific simulation approximations; thus, we developed a generic list of approximations and a mechanism to use approximations to identify performance problems from differences between simulated and measured data. We base our research on a case study research method that provides real-life context of energy performance problems, existing design simulation models and limitations of simulation models. Based on these case studies we provide specific evidence of limitations of current whole building energy performance simulation tools (in particular EnergyPlus). Existing research does only mention some software limitations and does not provide specific evidence for them.

2 Introduction

Building energy performance problems are a well-known issue today (Mills et al. 2005). Several studies show that HVAC (Heating, Ventilation and Air Conditioning) systems in buildings do not operate as predicted during design because of performance problems and inappropriate approximations during design (Scofield 2002; Piette et al. 2001; Persson 2005; Kunz et al. 2009). These studies indicate an untapped potential to reduce energy consumption of buildings and highlight the gap between design and actual energy performance of buildings.

We compare simulated with measured building energy performance data in order to identify performance problems. The first criterion of simulating building energy performance is the selection of an appropriate simulation tool. Simulation models that are used for the comparison with measured data are typically either on a component (e.g., Xu et al. 2005) or on a building (e.g., Holst 2003) level. Detailed whole building energy simulation tools enable the simulation across different levels of detail from component to building level. A comprehensive list of available simulation tools references 382 exiting building energy software tools (US DOE 2010). These tools cover different simulation areas, have different focus, and cover one or more levels of detail. The selection of a simulation tool that is suitable for a comparison with measured data is a difficult task based on this large number of available tools. Crawley et al. (2008) compare the 20 major whole building simulation tools in detail, but mention the difficulty to compare tools due to inconsistent documentation and different formats that describe feature specifications.

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 assumptions, simplifications, or approximations on project-specific instances. Existing literature mentions specific simulation approximations (e.g., Mergi 2007), but does not provide a comprehensive list of simulation approximations.

We chose a case study based research method to provide 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 energy simulation models and of simulating energy performance. Based on the first two case studies we developed hypotheses for a formal definition of approximations, a formal representation, and a comparison methodology. We prospectively validate these hypotheses with two later case studies and compare them to the methods used in practice to illustrate the power of our approach. Multiple case studies of different building types and different HVAC systems provide more generality for our results compared to single case studies. Three of the case studies have been completed recently while one is about 30 years old. One case study focuses on natural ventilation only, two have a mixed natural and mechanical ventilation system and one has a mechanical ventilation system. The 30 year old building has a traditional HVAC system whereas the other three have more innovative systems. Three case studies had existing design simulation models versus one did not have an existing model due to its age.

We developed an 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. This methodology builds on and extends three areas: measuring building energy performance, simulating building energy performance and comparing the resulting measured and simulated data. Data acquisition systems in real-life buildings archive the measured data. Detailed whole-building energy performance simulation tools produce the simulated data for this comparison. This paper focuses on simulating building energy performance as necessary for the EPCM, whereas two related papers provide details on measurements and on the comparison process of measured and simulated data. Maile et al. (2010a) discuss measurement data sets, measurement assumptions, and data acquisition systems in this context. The comparison paper (Maile et al. 2010b) elaborates on the actual comparison task of the methodology by describing the difference phases of this process. The latter details existing performance assessment methods and relates EPCM to them. It provides results from the prospective validation of the methodology and discusses its limitations.

The goal of the methodology (Figure 1) is to identify performance problems. A person that we call performance assessor that could either be a commissioning expert and/or an energy simulation expert performs the tasks of the methodology. The EPCM consists of three major steps: preparation, matching, and evaluation step. In this paper, we discuss key tasks of the EPCM related to simulation of building energy performance (chapter 3).

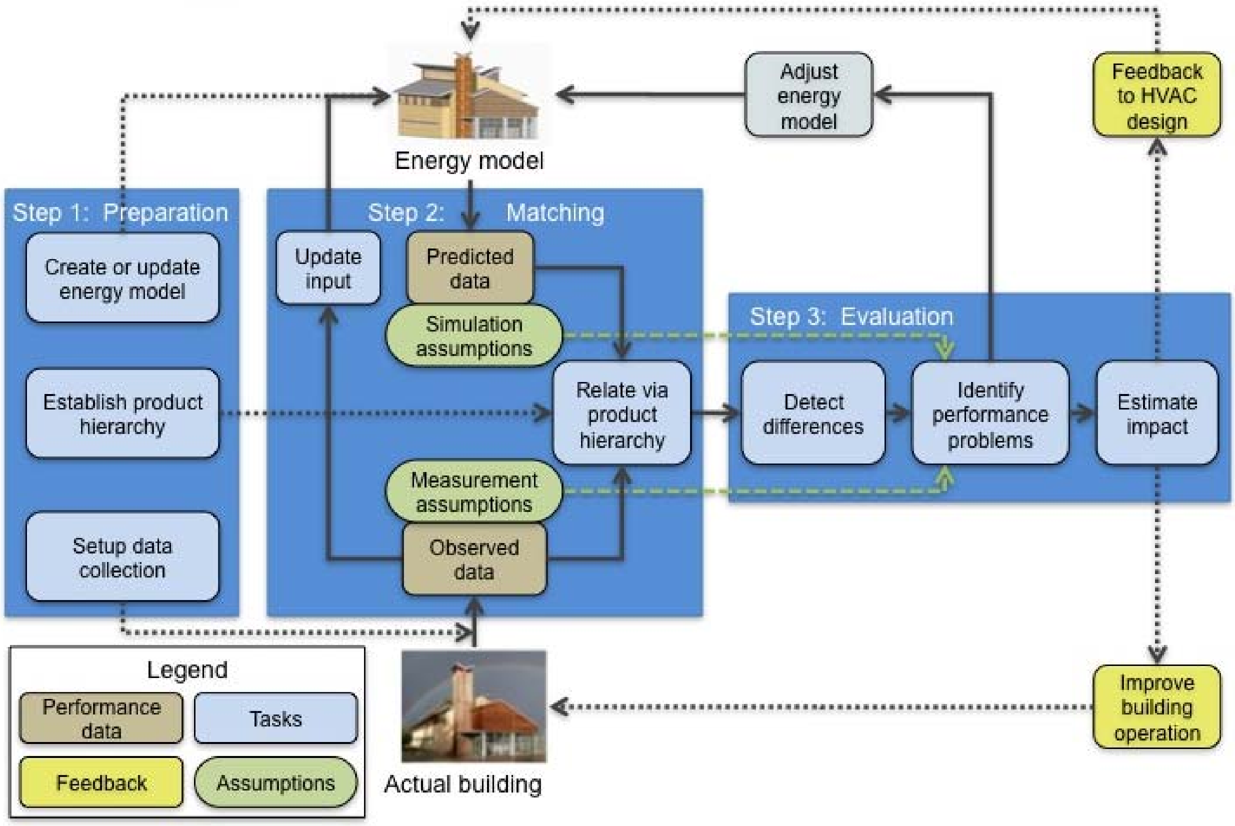

Figure 1: Overview of Energy Performance Comparison Methodology

The preparation step includes creating a new energy model or updating of an existing design energy model (see section 3.1), setting up of a data acquisition system and establishing a product hierarchy of the building components.

The matching step relates simulated and measured HVAC data. Starting points are measured performance data from the actual building and simulated data from the corresponding whole-building energy simulation model. The assessor performs an updated energy simulation with measured boundary conditions (e.g., Outside Air Temperature) with a designated software tool. By correlating simulated and measured data, the assessor creates data pairs with related measurement assumptions or simulation approximations (see section 3.3).

In the evaluation step, the assessor uses the established data pairs to detect differences between them and identify performance problems. The assessor uses a simple statistical characteristic (mean squared error) to detect differences of data pairs. He adjusts the simulation model based on identified performance problems to reflect the actual behavior in the model. He estimates the impact on thermal comfort and energy consumption based on these performance problems and uses his results to either improve the building operation or provide feedback to the HVAC design.

The following sections detail the tasks of the methodology related to simulation: Creating and updating of the energy simulation model, discussing simulation uncertainty, simulation approximations and their classification, and the use of these approximations in context of the EPCM. Since an energy simulation model is a key aspect of the EPCM we describe the process of creating a model either from design documentation or updating an existing model (section 3.1). Preferably, the assessor uses an existing model to provide the link to design; otherwise, he establishes a new model based on design documentation. We discuss previous work about uncertainty of simulation results and highlight the difficulty to quantify uncertainty within complex simulation models (section 3.2). Furthermore, we define the terms assumption, simplification and approximation in section 3.3. We broadly summarize assumption and simplification as approximations. We provide a list of approximations we developed based on literature review and the case studies. We categorize these approximations and describe a mechanism to use these approximations in context of EPCM. Both a comprehensive list and a mechanism to use assumptions to identify performance problems are gaps in existing literature.

Based on the difficulty to select an appropriate whole building simulation tool, we define requirements for simulation tools used in context of EPCM and discuss how a preselected number of comprehensive whole building energy simulation tools fulfill these requirements (chapter 4). We describe HVAC systems, available energy models, and limitations of the developed simulation models for each case study (chapter 5) and discuss the effects of those limitations. We summarize the limitations of software tools in general (chapter 6), provide recommendations based on these findings (chapter 7), and mention possible future research areas (chapter 8).

3 Simulation tasks of the Energy Performance Comparison Methodology

This chapter describes the tasks related to simulating building energy performance for the EPCM. In particular, we describe the task of creating a new and updating an existing energy performance simulation model, discuss error margins in simulation results, and elaborate on the role of simulation approximations.

3.1 Create or update an energy simulation model

An important part of the EPCM is a detailed energy performance simulation model. In 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. One of the major preparation tasks involves the creation or update of an energy simulation model. We describe the complete process of creating an EnergyPlus model (Figure 2) first, since the assessor can use a simplified version of this process to update an existing model. If two-dimensional architectural drawings are the starting point for our energy simulation model, the assessor first needs to create a BIM (Building Information Model) in a CAD tool. This BIM must contain detailed geometry, material assemblies (in particular material type and thickness), spaces, and thermal zone assignments. Thermal zones are an agglomeration of one or more spaces with similar 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. All of the mentioned data are required for energy simulation as described by Maile et al. (2007). The assessor exports this BIM to IFC (Industry Foundation Classes) (buildingSMART 2010) format within the CAD tool. It is essential hereby that the export is based on spaces and includes space boundaries. These space boundaries describe boundary surfaces between spaces as needed for thermal simulation.

Bazjanac (2005) details space boundaries, their definition, and importance. IDFGenerator converts the resulting IFC file into IDF (Input Definition Format, data input format for EnergyPlus) format. IDFGenerator includes GST (Geometry Simplification Tool) and uses predefined 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 material definitions). This IDF file also contains simulation specific parameters, such as convergence tolerances or simulation time period. GST/IDFGenerator also supports creation of partial IDF models (by spaces and floors). This is an additional benefit in using this process during the comparison to encapsulate parts of the building.

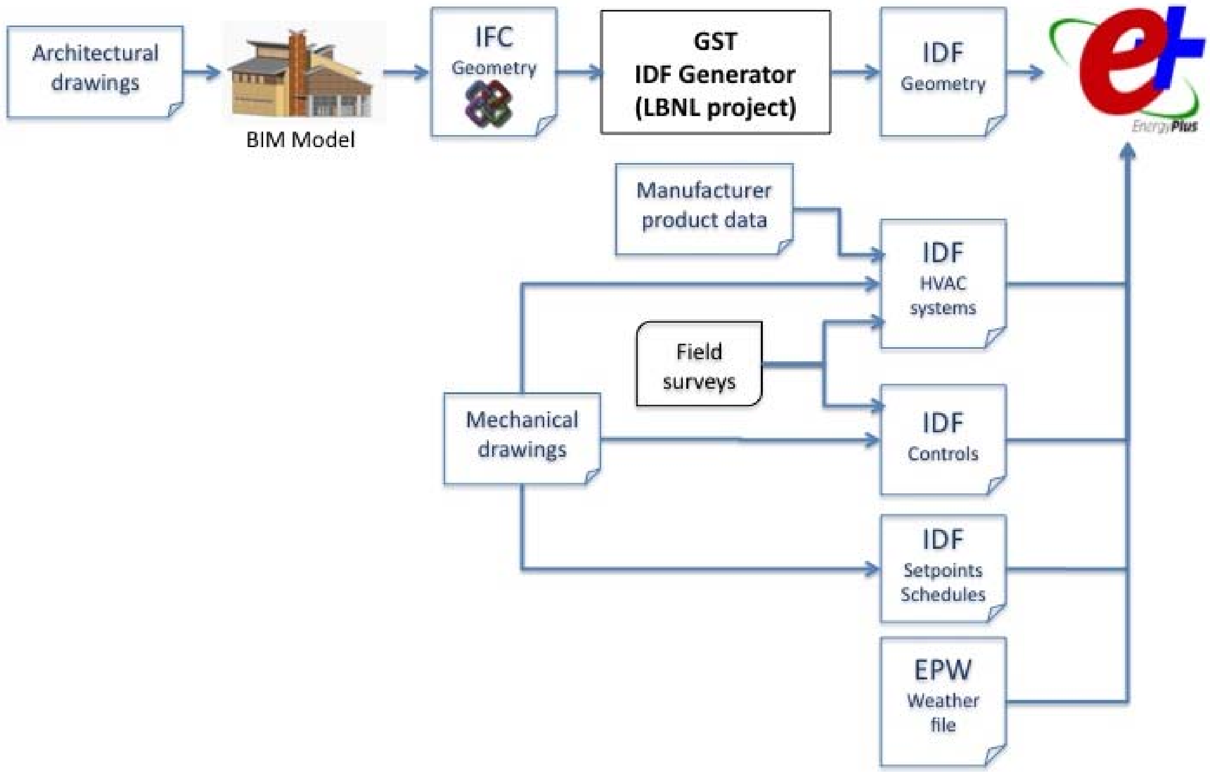

Figure 2: Creation of an EnergyPlus simulation model

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 of HVAC system topologies and HVAC component parameters. He also gathers missing component data (necessary for EnergyPlus objects) from manufacturer product specifications or field surveys. This task is currently tedious due to the missing 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.

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 control sequences (as established during design) and updated control sequences (as determined during field surveys). This differentiation is important because we want to establish a comparison between the original design model and actual operation as well as learn about specific control sequence changes. The reasons and more importantly the implication of these changes may not be known and may need further investigation within the methodology to determine the implications. While creating the model, it is important to anticipate possible links of the model with measured data to establish the consistent groups of set points for example. This would allow to simply replacing schedules with measured data rather than regroup spaces/zones and set points. Finally, the assessor needs to update a weather file to complete the data set needed for the EnergyPlus simulation. We use the EnergyPlus macro language (IMF, Input Macro Format) (EnergyPlus 2009) to integrate these different IDF files to allow easier manipulation of these possibly large text files. The authors developed a macro-based spreadsheet that allows defining zone and system level parameters and runs a visual basic macro in the background that automatically generates corresponding EnergyPlus macro files (IMF, Input Macro Format). An EnergyPlus preprocess (EPMacro) converts this set of macro files into a complete IDF file that can be used for the simulation (Figure 3). As new comprehensive graphical user interfaces become available, this process of creating EnergyPlus models will become easier and less time consuming.

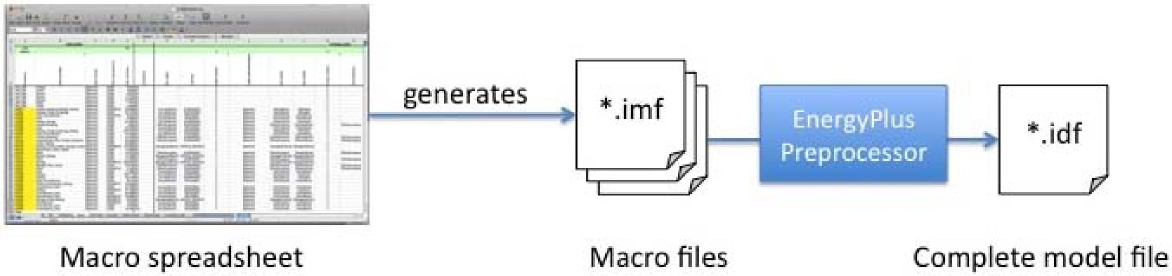

Figure 3: Macro process to generate complete EnergyPlus model file

The second and preferred process to obtain a necessary EnergyPlus model is through updating of existing models. The easiest scenario is an existing EnergyPlus model that may need some smaller adjustments to reflect the latest design changes. It is important to keep as-built changes out of the original model since within the process we want 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 existing energy simulation models other than EnergyPlus. Due to its widespread usage, DOE-2 models are often available. In this case a DOE-2 Translator (EnergyPlus 2009) provides some semi-automated support to convert this model into EnergyPlus syntax (Figure 4). It supports geometry (spaces and surfaces), schedules, material and constructions, but does not convert any HVAC data. Two of the case studies included an existing DOE-2 model that we used as basis for an EnergyPlus model.

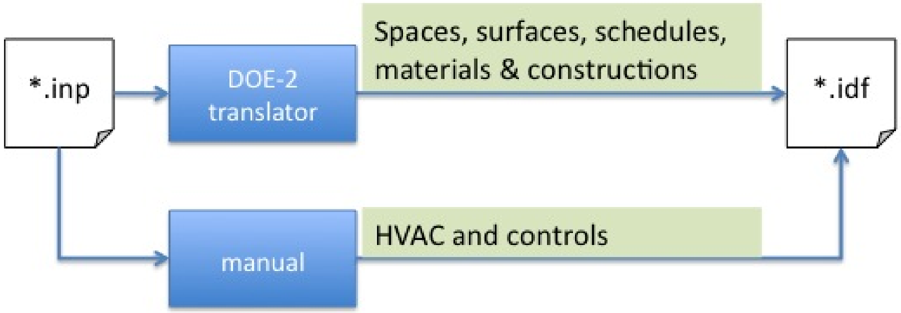

Figure 4: Process of using DOE-2 translator to generate an EnergyPlus input file

3.2 Error margins in simulation

In context of EPCM, error margins or uncertainty of simulation results are based on the uncertainty of input parameters. Uncertainty can be determined internal or external to the building simulation tool. The uncertainty of result parameters can be determined internally if the equations of the simulation are known and straightforward. Appendix B of the International Performance Measurement And Verification Protocol (IPMVP Committee 2002) gives an example of how to determine uncertainty in this case. The authors of this protocol use a linear regression model to prediction energy consumption. Corrado and Mechri (2009) discuss different probabilistic representations of uncertainty for different input parameter types. They also apply these probabilistic representations to a rather simple model. With the complexity of a simulation model, the uncertainty increases (Trcka and Hensen 2009). For whole building simulation tools, it is difficult to determine the uncertainty or error margins of results, due to the complexity and extensive number of equations and their underlying numerical mechanisms. De Wit and Augenbroe (2002) perform a “crude” uncertainty analysis for a natural ventilated building by developing a project-specific model within an uncertainty toolbox that propagates the uncertainty internally. For external assessment of uncertainty various types of sensitivity or uncertainty analysis can be performed. Hopfe (2009) provides an overview of existing techniques to determine uncertainty externally. Existing research that determines external uncertainty focuses on design models a specific subset of parameters. To apply these external techniques to determine uncertainty for detailed energy simulation models based on all input parameters is a significant effort and was out of scope of this research.

In general, simulation results can be only as accurate as its input (Corrado and Mechri 2009). The same applies for the error margins of input versus output. The result of a calculation can at best be as accurate as the accuracy of its input parameters. Maile et al. (2010a) discuss error margins and uncertainty of measurements in detail. In the context of EPCM we apply a simple approach to quantify the uncertainty of simulation results that is we assume that uncertainty is the same for a specific simulation data point as for the related measurement data point.

3.3 Role of simulation approximations

There are a number of concepts around simulations such as approximations, assumptions, and simplifications. An approximation is defined as an inexact representation that is adequate given its purpose. A simplification is a reduction of complexity. An assumption is an unproven starting point. Since both a simplification and an assumption are an inexact representation, we generally summarize assumptions and simplifications as approximations. Simplifications and assumptions are present in every simulation, since a simulation always is a reduction of a real life physical process or processes. In particular, for building energy simulation certain physical processes are not fully understood, such as 3-dimensional heat transfer. Therefore, most simulation tools approximate the heat transfer calculation by using a 1-dimensional approach. One exception is the 2-dimensional heat transfer algorithm for base slabs in DOE-2 developed by Bazjanac et al. (2000). The 1-dimentional approach is a simplification compared to the 2-dimentional approach. We further differentiate between model and user assumptions and simplifications. Model assumptions and simplifications are embedded in the model whereas user assumptions and simplifications describe a particular choice a user makes about certain aspect of a model. These approximations if contained in the model or specified by the user are usually not well documented and depend on arbitrary decisions of users (Bazjanac 2008). Documenting these approximations is the basis for their use within the EPCM and provides more transparency about important details of the simulation model.

In context of the EPCM, we use approximations as concept to identify performance problems from differences between simulated and measured data. This mechanism (Figure 5) uses data pairs as starting point. The first decision is if the data pair graph shows a difference. We select a simple mean square error statistic to characterize differences based on the type of data point (see Maile et al. 2010b). Once a difference is identified, approximations are used to decide to either explain this difference or identify the difference as performance problem.

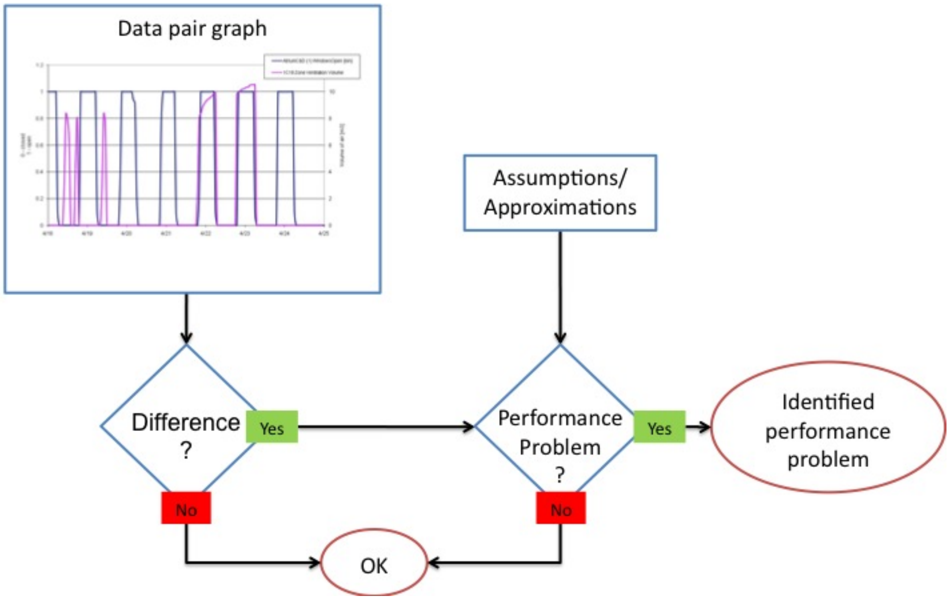

Figure 5: Mechanism to identify performance problems

Ganeshan et al. (1999) indicate that "assumptions can be identified as one of the reasons for discrepancies between observed and predicted behavior." We developed a generic list of approximations for simulation based on existing literature and applied it to each of the case studies. Table 1 shows an example for each category and Appendix A contains the full list we developed. The table includes the relationship between the approximations and the corresponding component level. We define the following categories for the approximations and assign them to the component level at which they typically occur:

- Model simplification

A model with reduced complexity compared to another model (e.g., simple versus detailed natural ventilation in EnergyPlus)

- Model assumption

A model that is based on an unproven aspect (e.g., constant component performance over time)

- User assumption

A user chooses a particular model input that is unproven (e.g., specific occupancy schedules)

- User simplification

A user reduces the complexity of an aspect of a model (e.g., one simplified geometric zone versus a detailed geometry model)

Table 1: Generic list of measurement approximations (partial list)

Approximation	Component Level	Category
Assume proportional relationship between valve position and load	Valves	Model assumption
Cp pressure values are representative of actual (no method to determine those values from wind tunnel tests)	Façade	Model assumption
Airflow model assumes bulk air flow	Zone/Node	Model simplification
Infiltration is typical	Zone	User assumption
Heat gains from lights are assumed to appear as zone loads	Lights/Zones	User assumption
Perimeter/Core zone modeling versus zone type modeling	Zone/building	User simplification

An example of how approximations are used to identify performance problems is shown in Figure 6. While the simulated supply air temperature of an air-handling unit is constant, the measured supply air temperature varies about 3 degrees below and above this constant line. Even with added error margins this indicates a difference between the simulated and measured data. This difference can be explained by the simulation assumption that ignores the pressure influence in the simulation model. The actual control based on pressure and supply air temperature thus shows more fluctuation than the simulation models that does only use supply air temperature as basis for control.

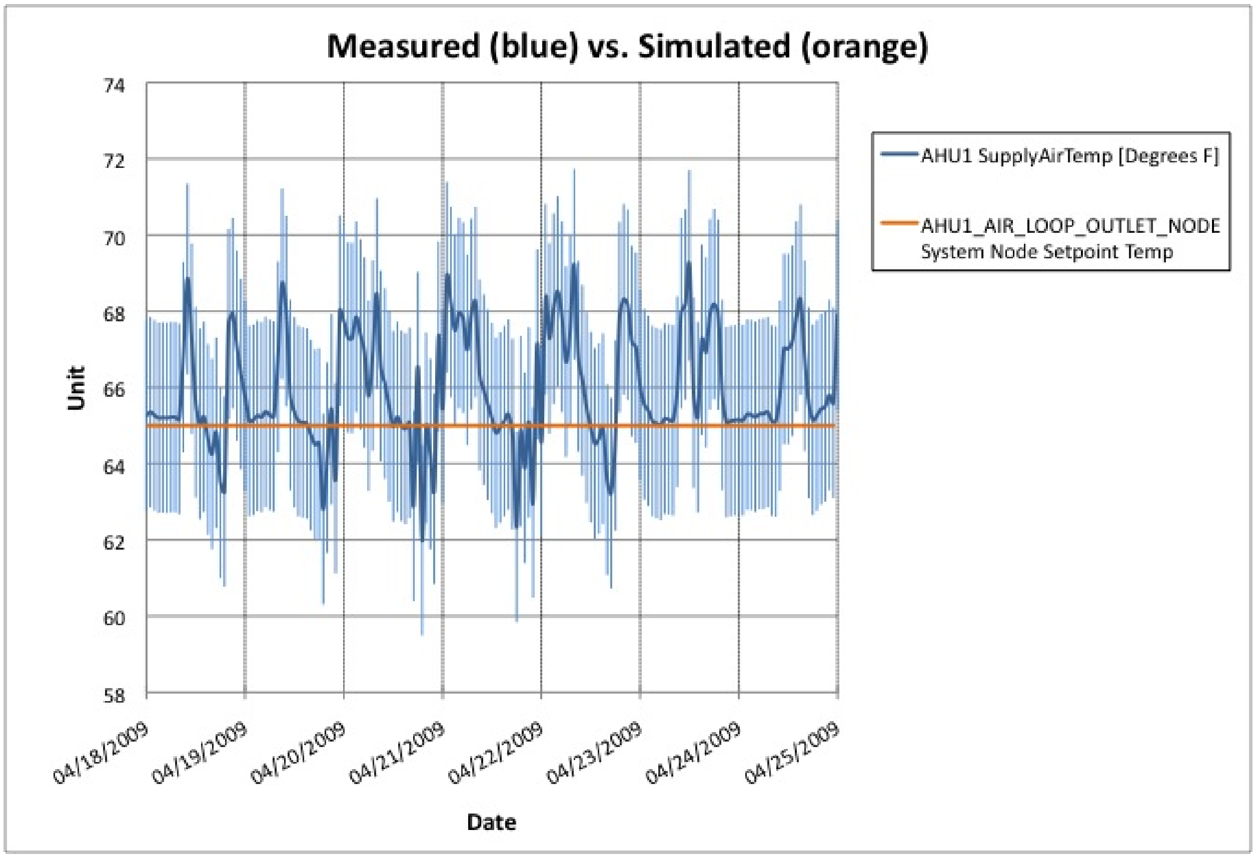

Figure 6: Comparison example showing supply air temperature of an air-handling unit measured (blue) and simulated (orange). Error margins of the measured data are illustrated in light blue.

4 Selection of an appropriate whole building energy simulation tool

One key component of the EPCM is the simulation tool used to create the simulated results. In this chapter, we discuss the special requirements for a simulation tool for use with the EPCM. After establishing these requirements, we evaluate a list of comprehensive whole building energy simulation tools based on these requirements. In section 4.3, we detail our selection of an energy simulation tool based on the defined requirements and tool evaluation.

4.1 Requirements for energy simulation tools for use during operation

Maile et al. (2007) argue that energy simulation tools, while usually created for design, are also applicable during the operation phase of a building. However, one important difference between different design stages and the operation phase of a building is the level of detail of the simulation. The level of detail progresses with the design phases. For example, during 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. This increase in level of detail issues two requirements on the corresponding software tools. The level of detail of a tool needs to include the highest level as needed during operation of a building. The tool should provide a flexible component architecture to allow increasing the level of detail of input from early design phases to the operation phase.

With this high level of detail, data exchange between tools in particular between CAD and energy simulation tools becomes an important aspect. 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 input of data increases the effort even more dramatically if various versions and modifications of a model are needed. Since BIMs contain those data we define BIM based geometry import as another requirement.

With the increasing complexity of the geometry of buildings, the simulation tool needs an appropriate geometric model. We formulate this requirement with the need for multisided planar polygons. More complex geometry such a curved surfaces can be approximated with those multisided polygons.

For the comparison of simulated results with measured data, the simulation tool needs an integrated simulation. That means that we require the feedback from the HVAC system response to the space or zone. Without this feedback the tool does not account for undersized systems and the resulting space temperature (and other space parameters) do not show the effects of such.

Another requirement for use of simulation modeling tools during operation is the ability to import measured data. In particular, the technical ability to import measured data with acceptable accuracy is needed. For example, does the tool functionality include the import of 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 tools 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 adjusting 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.

An important aspect of a simulation tool is its supported system topologies. 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, from air, hot and cold water to steam and electricity. Some tools focus specifically on air systems and provide little functionality on the waterside.

We define the ability to link to control design tools as another requirement for simulation tools. While none of the case studies included the previous use of such a control design tool, this functionality will become important in the future. With a separation of control algorithms and energy model, both can be tested more comprehensively and independent from each other.

Maile et al. (2010a) argue for the need for a one-minute resolution for measurements. We require the same resolution for simulation tools.

Furthermore, the simulation tool should include a mechanism to simulate all components and strategies the building employs or at the least provide a mechanism to account for components that cannot be modeled due to missing functionality

4.2 Existing whole building energy performance simulation tools

There exist a large number of simulation tools concerning energy in buildings today. US DOE (2010) publishes a comprehensive list of the available tools. Crawley et al. (2008) detail the functionality and differences of 20 major building simulation tools. Based on this report and our experience we provide a summary table (Table 2) that shows which tools provide the outlined requirements we set forward for the EPCM. It also includes specific components of the case studies and their availability in each tool. We preselected the following simulation tools that consider the whole building (not just specific aspects of it) and have a comparable functionality with EnergyPlus:

- EnergyPlus (EnergyPlus 2010)
- eQUEST (eQUEST 2010)
- TRNSYS (TRNSYS 2010)
- ESP-r (ESP-r 2010)
- IDA ICE (IDA ICE 2010)
- TRACE (TRACE 2010)
- IES (IES 2010)

Table 2: Simulation tool evaluation based on requirements

	EnergyPlus	eQUEST (DOE-2)	TRNSYS	ESP-r	IDA ICE	TRACE	IES
Supports high level of detail	X	X	X	X	X	X	X
User adjustable component equations	-	-	X	-	X	-	-
BIM based geometry import	X (IFC)	-	-	-	X (IFC)	X (gbXML)	X (gbXML)
Multisided polygons	X	X	-	X	X	-	?
Integrated simulation (feedback to space temps)	X	-	X	X	X	X	X?
Automated routines to import measured data	Partial	-	-	X	-	-	-
Overriding of system variables	Some	Some (input functions)	X	X	?	-	-
HVAC system flexibility	X	-	X	X	X	-	?
Complete water side simulation	X	X	X	X	X (partial)	X	X
Links to other control tools	X	-	-	-	-	-	-
Time step	1 min	1 hour	0.1 sec	1 min	< sec	1 hour	1 hour

	EnergyPlus	eQUEST (DOE-2)	TRNSYS	ESP-r	IDA ICE	TRACE	IES
(min)							
Specific components							
Natural ventilation	X	X (very simple)	X	X	X	-	X
Active beams	X	X	X	-	-	-	X
Radiant slabs	X	X	limited	X	X	-	X
Evaporative cool tower	X	-	-	-	-	-	-
Roof spray	-	-	X	-	-	-	-
Server rack	-	-	-	-	-	-	-

4.3 Selection of EnergyPlus

Based on these requirements for the simulation tool, we selected EnergyPlus as the simulation engine for the case studies. In particular, the ability to create partial geometry models from the BIM geometry and directly link to control design tools are two requirements that none of the above mentioned tools entails. In addition, the availability of specific HVAC components or strategies (e.g., natural ventilation) in EnergyPlus compared to other tools made this selection valid. Lastly, the ability to simulate based on a one-minute time step is another reason why we selected EnergyPlus for this study.

5 EnergyPlus simulation models of 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 energy simulation models as well as specific simplifications and limitations of each model.

5.1 San Francisco Federal Building

5.1.1 HVAC system

The section of the building we investigated at during our performance evaluation was naturally ventilated, thus no mechanical equipment was present besides the windows (manually operable and automated operable). The floor in question is above the lower mechanically ventilated floors and below the remainder of naturally ventilated floors (Figure 7).

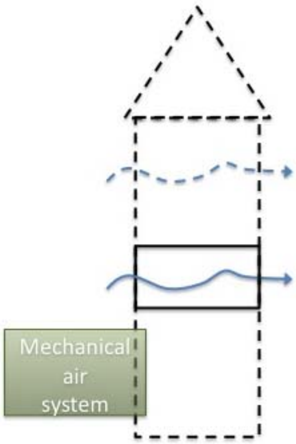

Figure 7: SFFB HVAC schematic

5.1.2 Design Energy model

An existing design EnergyPlus model (Carrilho da Graca et al. 2004) was used as basis for a more detailed EnergyPlus model for this comparison. Adjustments mostly due to more detail were made to the geometry in particular the sinus wave shaped ceiling was approximated with higher detail. EnergyPlus provides an advances AirFlowNetwork module (based on COMIS) (EETD 2003) that is based on nodal airflow calculations. This AirFlowNetwork required pressure coefficients (so-called Cp-Values), which describe how wind reacts to the façade. Wind tunnel test data performed during design provided these values.

5.1.3 Modeling simplifications

The main simplification within this model is the partial geometry of the building. The section is on the 6 floor of the building. The vertical boundary to the not modeled part of the 6th floor was defined as adiabatic assuming no major difference between the two floor elements in terms of temperature. The floor surface boundaries on top and bottom were interlinked in EnergyPlus. For the most part of the model, this equals the adiabatic assumption, since most spaces are full height and thus the temperature difference between both spaces (which in fact are the same) is zero. This simplification leaves out influences of the lower and upper floors and effect of neighboring sections on that floor. While it is relative unlikely that major temperature differences exist between floors that are naturally ventilated, a possible temperature difference between the lower floor (5th floor), which is mechanically air-conditioned, is not known. The effect of airflow in neighboring sections of the 6th floor is unknown and may vary depending on the 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 no measurements did detect those.

5.2 Global Ecology Center

5.2.1 HVAC system

The HVAC system at GEB contains several innovative features (Figure 8). A so-called cool tower in the lobby entrance area aims to cool the lobby in the summer through natural convection based on sprayed evaporating water 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 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 were necessary for lab exhaust. The second floor is fully naturally ventilated except 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.

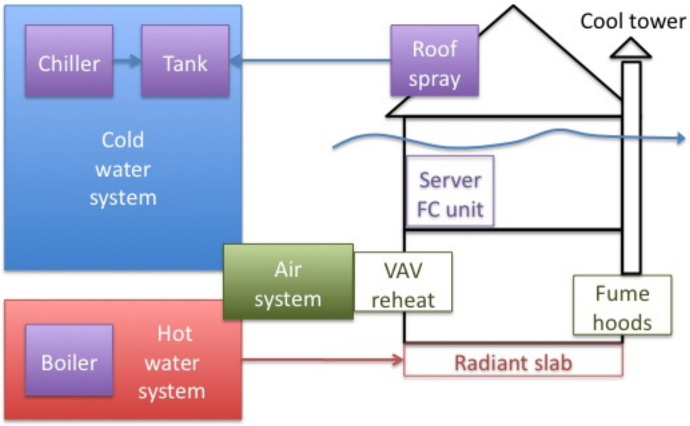

Figure 8: GEB HVAC schematic

5.2.2 Design Energy model

A DOE-2 model was created 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 the DOE-2 model into EnergyPlus input format.

5.2.3 Modeling simplifications

The innovative HVAC system at GEC was difficult to model in EnergyPlus at the time of the project. Since multiple components are not available as EnergyPlus objects, including an evaporative cool tower (was added later) and roof spray system. These missing components need to be modeled with workarounds (Figure 9) in order to include them into the model. Our model simplifies the roof spray system with a district chilled water object and ignores the cool tower in the lobby. The district cooling simplification excludes the roof spray from the evaluation. Thus problems with these two components cannot be detected while applying the EPCM. To enable evaluation of the remainder of the chilled water loop components, the measured supply water temperature is used as supply water temperature set point to recreate the conditions that the roof spray provides.

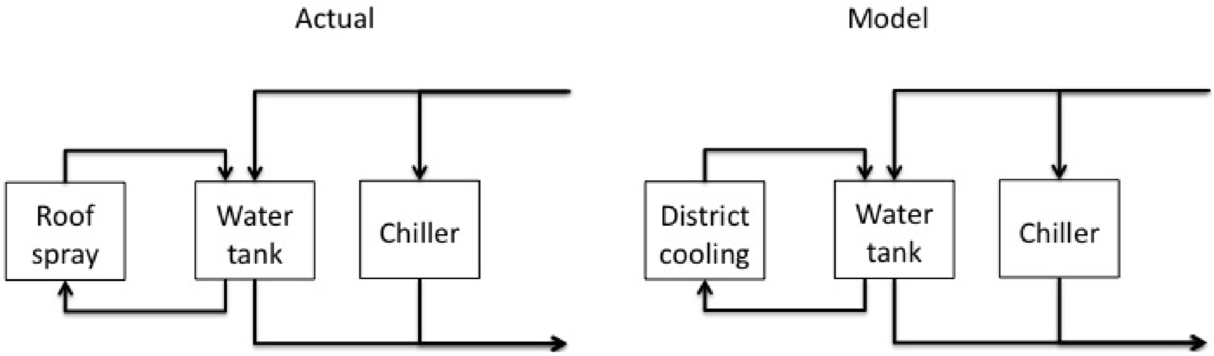

Figure 9: GEB Roof Spray simplification (on chilled water supply side)

5.3 Y2E2

5.3.1 HVAC system

Y2E2 contains a so-called hybrid system, a combination of mechanical and natural ventilation (Figure 10). Three main air-handling units that are 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 that 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 natural return path for air. The atria also support natural ventilation through automated windows around the perimeter. Offices on the north side of the building contain radiators for heating. They do not have a connection to 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 at the necessary temperatures for specific research. Finally, a server rank cools the server room to the necessary requirements. The entrance lobby area has an additional radiant floor for heating in the winter.

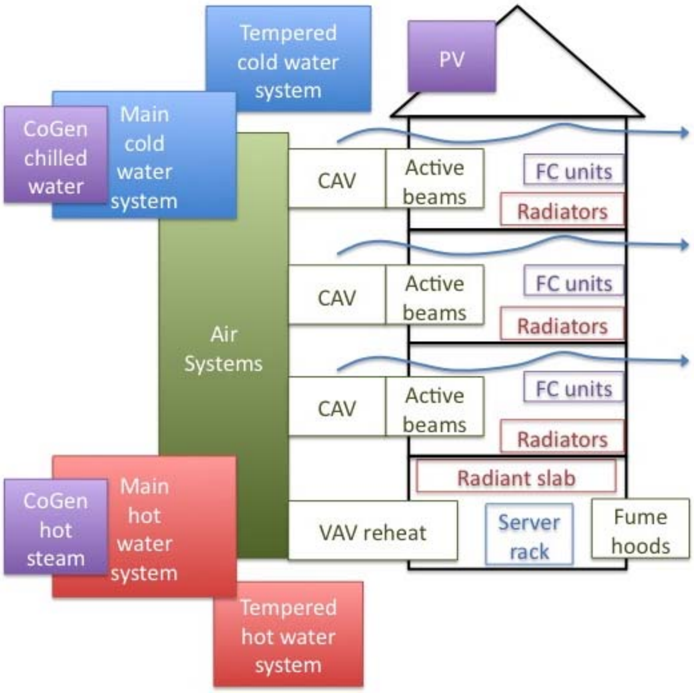

Figure 10: Y2E2 HVAC schematic

5.3.2 Design Energy modeling

The design energy model was done in eQUEST in two different versions; one that corresponds to the ASHRAE 90.1 baseline and one that reflects the corresponding design. We based our initial EnergyPlys model on the original design eQUEST model to provide the link to design and used the DOE-2 translator (see section 3.1) to convert parts of the eQUEST model.

5.3.3 Modeling simplifications

Due to a missing component in EnergyPlus to directly supply steam, we ignore the hot steam supply and use only a hot water loop to serve the building (Figure 11). This simplification excludes the heat exchanger performance from a detailed evaluation. However, the efficiency of the heat exchanger will be reflected in the difference of heating energy between measured (includes heat exchanger efficiency) and simulated (excludes heat exchanger).

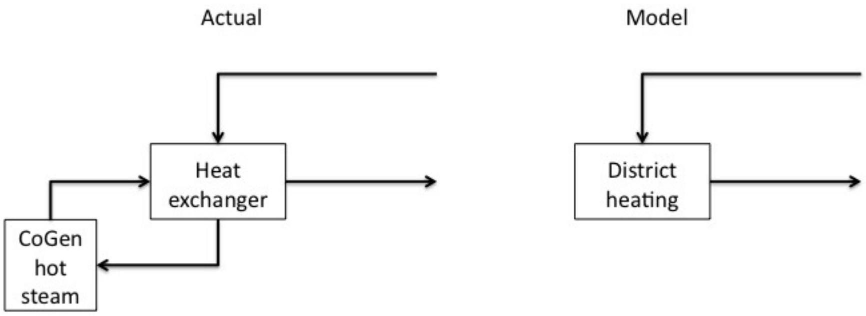

Figure 11: Y2E2 Hot steam simplification

The interconnected two hot and chilled water loops that operate on different temperatures and serve different types of equipment can also not be modeled as such in EnergyPlus. A corresponding object to connect the two loops is missing, thus the model contains two standalone loops (Figure 12). The consequence of this simplification is a reduced water flow rate in the main water loop in the simulation compared to actual. In addition, the secondary loops energy demand is not integrated with the main loop and may lead to different return temperatures in the main water loop.

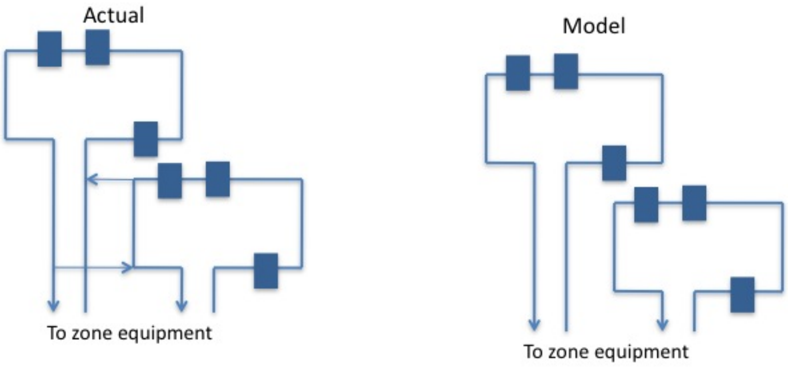

Figure 12: Y2E2 Loop connection simplification

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 the real building. At Y2E2 exhaust airflow splits between atria and return air via the heat exchanger (Figure 13). 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 is not able to account for different return air paths.

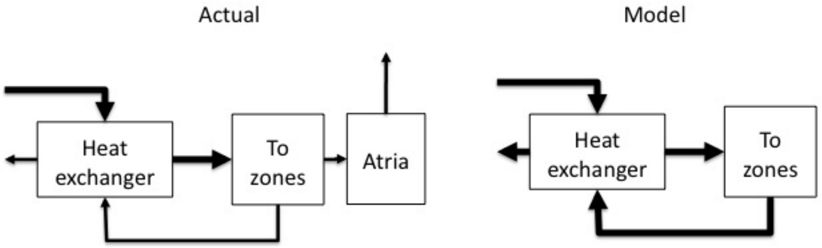

Figure 13: Y2E2 air loop topology simplification

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 (Figure 14). 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, additional heating and cooling at the thermal boxes in the basement need to be included into separate supply branches. This simplification leads to airflow rates at the thermal box level that cannot be directly compared, since this level does not exist in the simulation. There is no effect on the system and zone equipment level.

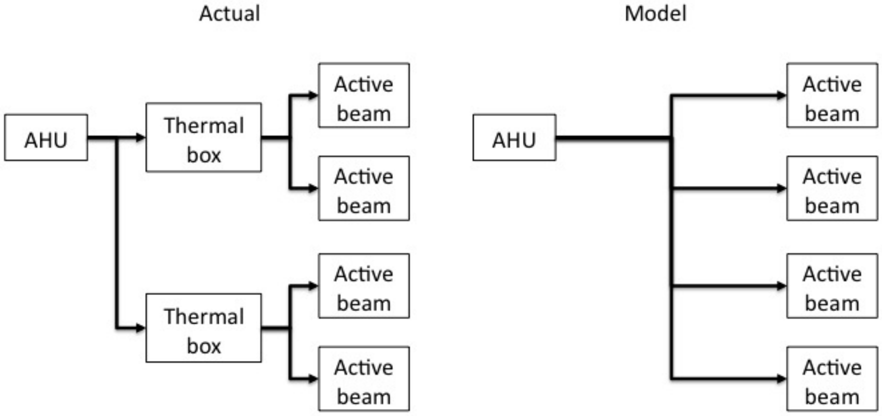

Figure 14: Y2E2 air loop branching simplification

Another issue with the EnergyPlus model for Y2E2 is multiple different zone equipment components for one zone. E.g., some conference rooms have both active chilled beam components and constant volume registers (Figure 15). Since EnergyPlus allows one zone equipment component that is connected to an air loop this configuration cannot be directly modeled 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 define 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.

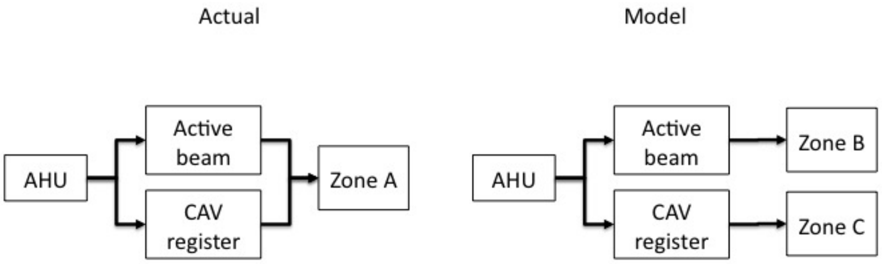

Figure 15: Y2E2 simplification of zone equipment component configuration

5.4 Main Jail North

5.4.1 HVAC system

The HVAC system of the Main Jail North consists of several air-handling units that are connected to a hot water loop and a chilled water loop (Figure 16). 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 source 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 cellblocks are served by three constant volume 100% outside air units with cooling, heating coils and a heat exchanger. Other separate air-handling units serve special cells (e.g., mechanical cells) that are also 100% outside air and provide heating and cooling as necessary. 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 in order to provide cooling for these spaces.

Figure 16: SCC HVAC schematic

5.4.2 Design Energy modeling

Due to the age of the facility, no design energy model existed. Thus in context of our project, we created a new EnergyPlus model based on existing documentation following the process as outlined in section 3.1.

5.4.3 Modeling simplifications

Since the HVAC systems at this facility are mostly typical systems, we could easily model them in EnergyPlus. One exception is the large supply fan units that serve the main cellblocks. Their two-stage split of branches with additional coils in between cannot be reflected with more than three branches with EnergyPlus (Figure 17). The corresponding simplification is the usage of two separate air-handling units (or AHU’s). The effect of this simplification is the split of airflow into two equal systems with half the airflow. In addition, return air temperatures may be slightly different depending on internal loads in the zones.

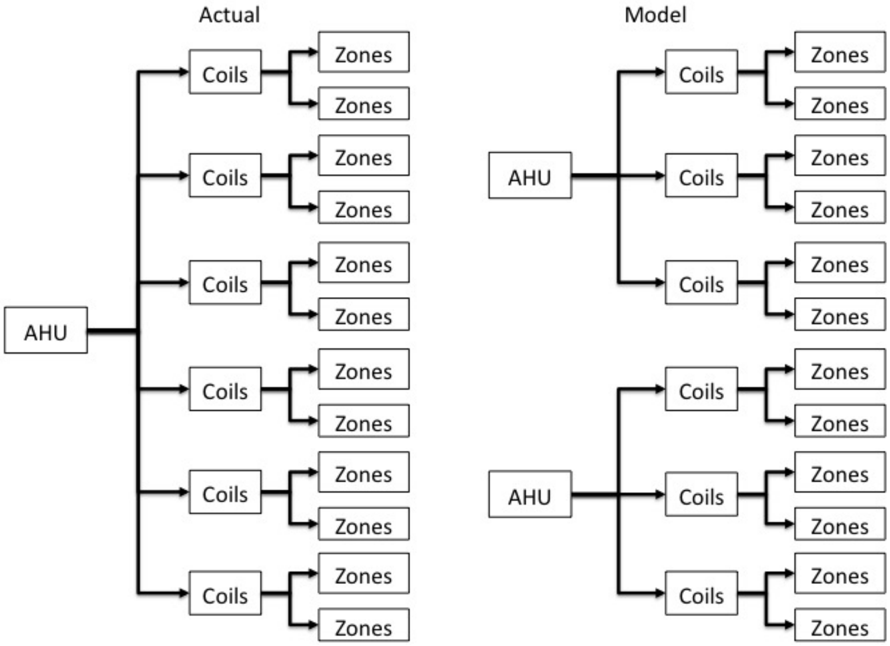

Figure 17: SCC HVAC air loop branch simplification

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 (Figure 18). Thermodynamically the effect of this different configuration is negligible, however, the control strategy that the pumps run in sink with the corresponding chiller cannot be evaluated since the link between chiller and pump gets lost in the EnergyPlus model.

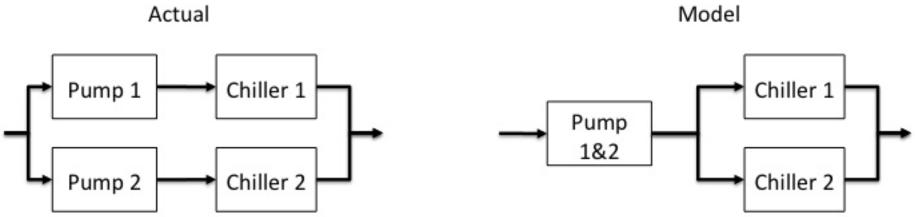

Figure 18: SCC chilled water loop pump configuration

6 Limitations of EnergyPlus

This chapter describes the shortcomings of today’s whole building energy performance simulation tools, in particular EnergyPlus, which we investigated during the case studies and provides evidence for these shortcomings if applicable.

6.1 Simplified controls

EnergyPlus includes only simplified control strategies. While control strategies 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 combination of systems, the control strategies become more complex (Maile et al. 2007) and more important in the overall picture of energy consumption in buildings. New recent 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 a possibility to insert user-defined equations. The second option is the link via Ptolemy II to generic simulation tools such as Matlab/Simulink (Wetter and Philip Haves 2008). Due to the increasing importance 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 concrete slab, and space air temperatures. It also changed 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 systems tries to achieve, the comparison between simulated and measured data becomes difficult if the control strategy cannot be modeled in the simulation tool.

6.2 Software architecture limitations

Some limitations of EnergyPlus are due to its architecture. For example, EnergyPlus does not include pressure within water systems in particular pressure losses. Most water loops in reality are operated based on pressure differences, thus it is difficult to reflect the same operation in water loops as in the actual building. Air loop pressure can be considered in EnergyPlus, but only for simple cases such as constant volume systems (fans). Air loop pressure simulation in EnergyPlus also require substantially more input objects. The effect of not considering pressure influence in the simulation can be seen in Figure 6.

6.3 Limited HVAC topology

While EnergyPlus is more flexible as tools like DOE-2 and BLAST in its HVAC topology, there still exist numerous limitations in EnergyPlus topology. To name a few, EnergyPlus required closed loops, so hybrid systems where exhaust air flows two different ways (through atria and exhaust ducts) is not possible to model (see section 5.3.3). Water loops can only have one set of parallel braches 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.

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 problem for one-to-one comparisons due to different configurations between simulation model and actual HVAC system. These limitations may also cause effects on temperatures in particular return temperatures.

6.4 Only one zone equipment component that connects an air loop to a zone

In addition, having a thermal box that serves 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, more detailed models (e.g., Y2E2) may have more than a single zone equipment component connected to an air loop. Space conditions may become difficult to simulate with zone equipment configurations do not coincide.

6.5 No combined water loops

It is not possible to connect two or more water loops for multi temperature usage. Developers removed this feature in version 2.2. The necessary separation of water systems is illustrated in Figure 12. In this case water flow and potentially return water temperatures does not compare directly.

6.6 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 *VAV thermal box with cooling coil*. The thermal boxes either have a heating coil or no coil at all. However, more innovative system may use thermal VAV boxes with cooling coil that are not available in EnergyPlus. This missing cooling coil at the thermal box level requires a substantial change in the loop topology and makes a comparison very difficult.

Thermal CAV boxes in EnergyPlus either can have flow at the constant speed or are off completely. At Y2E2, these boxes can have a reduced airflow rate during nights and are thus *two speed CAV thermal boxes*. These missing CAV boxes cause the airflow during nights to be below (be zero) the actual and thus influence the space conditions.

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 the hot steam to hot water. The effect of a missing steam heat exchanger model is that the heat exchanger cannot be directly evaluated.

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 required the development of a workaround with district hot water to ensure the conditions downstream are the same. Thus, the steam heat exchanger cannot be evaluated directly.

A chilled *roof spray* object as used at GEB is also not available in EnergyPlus. While such an object is truly specific, there is no similar object in EnergyPlus. With the missing roof spray object, it is not possible to evaluate its performance with measurements. Since the roof spray is a relatively new concept, the evaluation of this early installation would have been extremely useful for future projects.

6.7 Model warm-up

EnergyPlus uses the first day of a simulation period or design day as so-called warm-up period. The engine simulates this first day multiple times until either a convergence tolerance is meet or a certain number of attempts passed. 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 the comparison with measured data, this approach can lead to conditions on the first day that are different from the measured data due to long term effects. Especially on the space level this difference on the first day influences the results of the following days. It would be better to integrate measured data as basis for the warm-up. We discovered a workaround to force the space conditions of the warm-up day to be the same as 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 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. 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 a incorrect starting condition for the simulation, depending on a number of factors this incorrect starting condition may become less important over the course of time.

6.8 Limited import of measured data possible

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

6.9 Report limitations

EnergyPlus has a large number of report variables or resulting data points available. Some data points cannot be reported directly and may 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. One can derive a data point either external to the simulation or within the simulation with the help of EMS.

7 Recommendations

Based on our experience with the case studies we recommend the following additions and changes to simulation tools in the future for developers of simulation tools. These recommendations are specifically related to the use of simulation tools during operation and within the context of the EPCM.

7.1 Improvements of simulation tools

Based on the limitations of simulation tools we discovered during this research, we recommend the following improvements of simulation tools: improvement of the validation of simulation tools, the integration of new and innovative HVAC components and HVAC system topologies, more detailed component models, and a better integration of measured data into simulation tools.

7.1.1 Improvement of validation of simulation tools

Since most of the tests for simulation tools are based on comparative tests between different simulation tools, we recommend validating results of simulation tools more rigorously with real-life buildings as done with these case studies. Only if the simulation tools are validated with data from real-life buildings, their ability to properly predict conditions in real buildings will improve.

7.1.2 Enable increased level of detail

As we reported in this paper, EnergyPlus does not always allow to model 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 the design into building operation.

7.1.3 Reliable and extended use of interoperability

We also recommend increasing the reliability of data exchange between software tools. Dramatic time savings and reduced error sources will significantly improve the use of simulation tools during operation. In particular, we need better interfaces between HVAC control design tools, data repositories, and simulation tools. Exchanging data between HVAC design tools and energy simulation as well as the actual control system would provide a more comprehensive way to evaluate control strategies and reduce errors and differences between 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 with measured data. Even more helpful would be an improved integration of measured data into simulation tools; both on a simulation functionality level as well as on a data level.

7.1.4 New and innovative HVAC components

Simulation tool developers need to keep up with new developments of HVAC components in order to provide the simulation experts with the flexibility to test new components against older ones. A flexible software architecture that would enable component libraries that allow adding of components between new releases would dramatically improve the current situation and allow users the development of new models if none exist.

7.1.5 New and more flexible HVAC topologies

The topology flexibility of most simulation tools is limited. Either predefined HVAC system templates or relatively strict topology rules limited the flexibility of the simulation expert to model new and innovative HVAC system topologies. Simulation tools should start to 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 need to be developed.

7.1.6 Versioning of simulation models

During the use of EPCM the assessor creates a potentially large number of different simulation models. New user interfaces need to provide a mechanism to deal with these different versions in an efficient manner, specifically enabling changes across multiple versions and highlighting differences between them. Raftery et al. (2009) use a version control system that is typically used for software development to version different text file based models. Such versioning functionality should be included in future graphical user interfaces of simulation tools rather than be based on text files.

7.2 Comprehensive User Interface

Due to the current need to develop custom programming code that support the energy modeler, we recommend the development of a comprehensive user interface to EnergyPlus and other simulation tools in order to increase the efficiency of model creation and updating. This user interface should provide the ability to integrate those little tools and scripts so the user can adjust certain routines and data transformations for his/her specific project. In addition, versioning functionality for the simulation models would support the user while applying EPCM. Starting with the original design model, the assessors will create a significant number of models that differ mostly only in small aspects from each other. Providing versioning functionality could help to keep an overview of differences between models. In addition, a new user interface should also include the use of partial models, so the assessor can focus on specific aspects of a building without the detail of other parts of it. Enabling partial models would require creating adiabatic surfaces for geometry needed and summarizing and simplifying geometry, HVAC systems and components.

8 Future research

This chapter describes possible future research based on the concepts in this paper.

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 provide beneficial to combine two or more simulation tools to enable a more accurate model. Trcka et al. (2007) describes the coupling of simulation tools as co-simulation.

Another similar approach enables communication during execution time with multiple other tools via sockets (Wetter and Philip Haves 2008). This approach allows more flexible use of tools that can model controls, such as Matlab or Simulink.

8.2 Integration of error calculations into whole building simulation tools

Due to 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 the error calculation in the tool, future research could also determine default error margins and statistical sampling methods to address the uncertainty of various input parameters better in the simulation.

8.3 Expert system based on assumptions

Future research could define possible consequences of specific assumptions and built an expert system that automatically determines differences between simulated and measured data.

8.4 Assumption list

The list of approximations (see section 3.3) is based on literature review and the four case studies. Future case studies and research may identify more assumptions. New HVAC component models, system configurations, and control strategies may require the definition of new approximations.

8.5 Detailed uncertainty analysis for simulation results

A detailed investigation of uncertainty of simulation results was out of scope of this research; however, future research could integrate uncertainty calculations either within the energy simulation tool or within the EPCM. Assessing uncertainty of measured and simulated data could provide a more reliable assessment of differences between them.

9 Conclusion

In this paper, we provide a generic list and categorization of simulation approximations we collected from literature research and experience with the case studies. Based on these generic approximations a specific list of approximations that is linked to the product hierarchy is used to identify of performance problems from differences between simulated and measured data. This list and the mechanism to use approximations to determine performance problems are new concepts.

We selected EnergyPlus as the most suitable simulation engine based on the requirements we developed for a comparison between simulation and measured data. Specifically, the ability to communicate with control design tools, to generate partial geometry models and the reasonable set of available HVAC components are key criteria that differentiate it from other tools. To properly transition design simulation tools into operation, energy performance simulation tools need further adjustments. We describe shortcomings and limitations of simulation tools (in particular EnergyPlus) and give our recommendations for future developments. Specifically the requirements for 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 time effort to generate or update simulation models.

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Appendix A List of simulation approximations

Table 3: Generic list of measurement approximations

Approximation	Component Level	Category
Infiltration is typical	Zone	Appropriate documentation
Wall constructions are built based on design	Assemblies	Appropriate documentation
Manufacturer data reflects actual performance	HVAC components	Appropriate documentation
Assume relationship between valve position and load is proportional	Valves	Model assumption
Dynamic effects of building heat flows are neglected	Building	Model assumption
Idealized models assume that the thermal box can reduce the flow rate to the design minimum value	Thermal box	Model assumption
Relationship between compressor heat and heat removed by the evaporator is proportional”	CoolingTower:Single Speed	Model assumption
Radiant energy falling on people will be convected to the surroundings	Baseboard heater	Model assumption
Outdoor air economizer will be closed for cooling	System sizing	Model assumption
PV array always operates on maximum power	PV array	Model assumption
Windows/solar collectors are always clean	Particular components	Model assumption
Component performance is constant (no degradation)	HVAC components	Model assumption
Cp pressure values represent actual conditions	Façade	Model assumption
Ducts are perfectly insulted	Ducts	Model assumption
Ducts have no air leakage	Ducts	Model assumption
Heat recovery efficiency is fixed (constant air flow rate)	Coil:Desuperheating	Model assumption
Temperature set point for a specific set of zones is identical	Zone	Model assumption
Infiltration loads are negligible or considered part of the ventilation loads	Zone	Model assumption
No air stream reheating is provided by the circulation fans or by the ducts.	Fans	Model assumption
Quasi-steady power prediction is constant and continuous over time step	PV array	Model assumption
Solar and transmission loads affect the perimeter zones only	Zone	Model assumption
View factor approximation is reasonable	Building elements	Model assumption
Control response is instantaneous	Controls	Model simplification
Response times of various HVAC system components and their controls are neglected	Controls	Model simplification

Approximation	Component Level	Category
Airflow model assumes bulk air flow	Zone/Node	Model simplification
Zone is well-mixed	Zone	Model simplification
Pressure drop is neglected	Air loop/Water loop	Model simplification
Assumptions embedded in component models are reasonable	Components	Model simplifications
Heat gains from lights are assumed to appear as zone loads	Lights/Zones	User assumption
Heat transfer between floors is ignored (partial models)	Zone/Floor	User assumption
HVAC topology workarounds do actually represent real system	HVAC system	User assumption
Internal loads represent actual building usage	Zone/Building	User assumption
Thermal subzones are somewhat arbitrary	Zones	User assumption
Perimeter/Core zone modeling versus zone type modeling	Zone/building	User simplification
Internal loads are on a regular schedule	Zone	User simplification
HVAC mode is simplified	All	User simplification
Surrounding shading objects (e.g., trees) are simplified	Shading	User simplification
The heating and cooling coils have an infinite capacity	Coils	User simplification