Visual Quality Assessment of Building Energy Performance Simulation Models

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Abstract

The increasing usage of building energy performance simulation (BEPS) tools creates a growing number of simulation models of different quality and level of detail. Today stakeholders receiving simulation results are mostly focusing on building level metrics such as total energy consumption, unmet load hours and uncomfortable hours. However, these metrics do not provide any insights on its quality and the wide range of input data in a BEPS model. To address this problem, we developed a set of visual aids that quickly show key aspects about the behavior of a BEPS model. We illustrate this concept in a prototypical implementation.

Introduction

Pervious work has been focused on assessing energy performance of buildings and BEPS models with key performance indicators (e.g., Alwear and Clements-Croome 2010). At the building level, these performance indicators typically provide an assessment of how well the building operates given those indicators (e.g., annual building energy intensity). Besides performance indicators, benchmarking is a concept to illustrate how a given building is performing in comparison to some predefined standardized values (like energy standards or building type averages). These indicators mostly focus on the energy and thermal performance of a building. At the building level, thermal performance is typically reported in unmet load hours and uncomfortable hours (e.g., ASHRAE 55-2004). Dashboards (e.g., Tom 2008, O'Donnell et al 2013) that aim to visually and quickly convey how well a building is performing use the same indicators. These indicators work well for both existing buildings as well as for the BEPS model of a building. However, these indicators illustrate only a very small subset of potential variables of a BEPS model. Large areas of the simulation model data are hidden and may or may not behave as wanted or intended.

Besides the similarities between the real building and the simulation model, there are also important differences such as the level of detail input data is defined in (Volk et al. 2014). A single zone model to evaluate some early design concepts is a totally different model compared to a detailed model that defines a zone for every space in the building. While the zoning is a key aspect about the BEPS, it also influences other types of data such as internal loads and/or HVAC systems. Building level indicators can provide no insights on the level of detail.

BEPS models contain a sizable set of input data (Maile et al. 2007), ranging from geometry definitions, material properties, internal loads, HVAC component and system data. It is difficult to oversee all aspects of the large data set during the process of creating and using a simulation model. There are only anecdotal reports about issues or problems with the input data of simulation models. More common are the description of issues with simulation tools or the modelling approach (e.g., Ahn et al. 2016). Maile et al. (2012) describe assumptions often made in simulation input and mention some typical errors. According to Arnold et al. (2005) it is also possible to 'tweak' a model to achieve a desired result.

Based on these indicators and the authors experience with BEPS (over a decade), simulation models do contain data errors, data guesses, workarounds and shortcuts that can remain unnoticed by focusing on building level data. Similar to the functional tests in context of commissioning real buildings (e.g., Xiao and Wang 2009), BEPS model need a way to be checked or verified. Our visual assessment is based on this notion of the functional test to ensure that components do perform. For example, ensuring that a chilled water pump is running during the annual simulation ensures that chilled water can be supplied to the building model.

Combining these existing assessment concepts and developing an advanced set of visual aids that provide more insights into a simulation model is the promise of this paper. A prototypical implementation of these visual aids is done based on the data model SimModel (O'Donnell et al. 2011) and the simulation front end Simergy (Digital Alchemy 2016).

In the next chapters, we investigate the data quality, data sources and potential for errors as well as typical errors in different categories of the simulation model. Based on the context to assess model quality, we illustrate different visualization techniques. Furthermore, the authors detail the implementation process of the prototype that uses these visualization techniques and provide initial practitioner feedback. We describe two use cases that show the power of this approach. Finally, we conclude the paper and discuss its findings and further research.

Common data errors in BEPS models

Simulation engines such as EnergyPlus (DOE 2016) do have an extensive error reporting for inconsistent or incomplete simulation models. Besides these engine errors typically also warnings are issues that indicate data irregularities that may or may not be important for a simulation model. While errors mostly block a simulation from completion, warnings highlight model issues that indicate a definition that may not be ideal. There are graphical user interfaces that provide additional validation rules that can be performed before a simulation is even initiated (e.g. Maile et al. 2015). The building level metrics do also provide model feedback. The focus of this paper is the quality assessment as another layer for model checking. These different layers are illustrated in Figure 1.

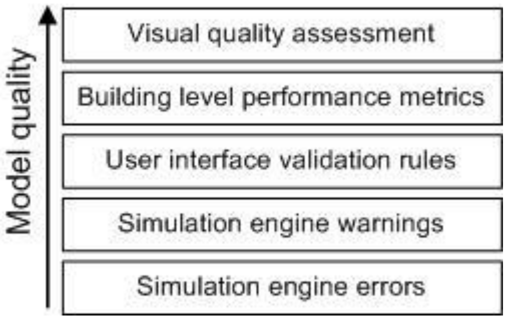

Figure 1: Different levels of model checking

To understand the common issues and possible error sources of the different data categories, we discuss their typical source, typical errors and likelihood of errors.

Building geometry

Starting with geometry data, there are various existing mechanisms to verify and check the correctness of geometry data. Depending on the source of the geometry, it is possible to run specific geometry rule checkers. For example, the IFC (Industry Foundation Classes) (buildingSMART 2016) data model forms the basis for several such model checkers. Simulation engines (e.g. EnergyPlus) do have various reports and export formats that enable visual or numerical verification of the geometry. While there are typically errors in the geometry definition (Maile et al. 2013), due to the numerous existing possibilities to verify geometry data, we do not include this aspect in our investigation.

Material properties

Several standards and energy codes define material properties and complete material layer sets for different building elements (e.g., bSa and OGC 2010), which are most often used in BEPS models. Using those predefined material layer sets, reduces the number of possible errors in this area. However, there is still a potential to select incorrect materials to get overwhelmed with the number of different materials in a given building model. Often the focus is shifted to other issues once the material properties are set. Visual feedback to verify that input data are correct seems useful for material properties.

Internal loads (zonal definitions)

Similar to the material properties, internal loads are typically defined by corresponding standards (e.g., ASHRAE 90.1-2016) for most of the usage types of buildings. Feedback on those internal loads per zone and floor area are given in most simulation report sets and should be enough to detect outliers at the intensity level. However, it is mostly unclear how many different unique definitions for internal loads are used in a simulation model. Do the modelers use the same occupancy for the complete office building or does he/she differentiate between corridor, atria, meeting room and offices?

Besides the internal loads, other definitions at the zone level such as infiltration or sizing parameters are treated the same way. Neglecting data such as infiltration may not be directly visible in simulation reports. This is important since infiltration can have a significant influence on the model behavior (Hand 2011). Therefore, feedback about the level of detail of zonal definitions is very useful.

Zonal equipment

Zonal components and their properties are less frequently defined in standards and mostly need to be defined by the modeler independently. The potential likelihood of error as well as the meaningfulness of these data is difficult to capture. To investigate the zonal equipment behavior, unmet load hours are typically used to illustrate if an equipment can meet the load in each zone.

System equipment

At the system level the modeler has even more flexibility in term of topology, types of components and parameters. While unmet load hours provide some indication of the performance of systems, its focus lies on the zone and not the system. This creates an additional need for indicators that can provide insight on how well a system is performing in its context of the simulation model. For both the zone and system level equipment an overview illustrating the gains and losses would provide a better understanding of the dynamics of a given building model.

Outside air

A special topic in the system context is the outside air. Buildings require the intake of fresh outside air for its occupants. Errors in this area can influence the results of a model dramatically and is furthermore related to infiltration and natural ventilation. An indicator for outside air is also useful to ensure all aspects of the fresh air are properly defined and working.

Schedules

Schedules are defined in several places in the BEPS model and may come from various standards. Misalignment of schedules for operating hours or temperature setpoints can often cause problems in the simulation model. Visualizing the alignment of schedules could bring great insight into simulation models and their timing.

Research methods

We used the following research tasks to develop our visual model assessment:

1. Literature review of the state of the art of energy performance indicators, thermal comfort indicators, energy dashboards, and common data errors.
2. Categorization of simulation input data and summary description of typical errors, sources of data and error potential.
3. Development of a set of visual aids based on the review and our modelling experience
4. Initial feedback from practitioners on the first set of visual aids
5. Development of a prototype
6. Test of the prototype with two use cases

Visual assessment concepts

This chapter describes each visual guide, its specific context and the specific error/issue it is addressing.

Energy performance indicators

Energy performance indicators have long been used as a key parameter for BEPS. Usually energy consumption per area (intensity) is used. These relative energy consumption values are also the basis for energy codes and consider the type of building as well. Nowadays, the relative energy performance is displayed on a green/yellow/red colored bar indicating how good the performance of a building is relative to a specific standard or predefined range (see Figure 2).

Figure 2: Energy intensity show in a colored bar

Thermal comfort

Reporting thermal comfort is also a well-established concept. PPD (Predicted percentage dissatisfied) together with PMV (Predicated mean vote) is used as an indicator that illustrates the percentage of dissatisfied people given specific indoor conditions (Peeters et al. 2009). ASHRAE 55 defines minimum requirements for comfort. The indicator, hours not comfortable are typically illustrated in colored bars. A very uncomfortable example is displayed in Figure 3.

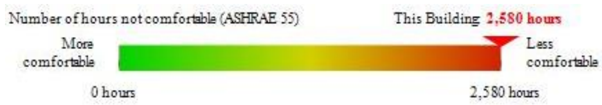

Figure 3: Unmet load hours illustrated in a color bar

Unmet load hours

Often unmet load hours are also used as an indication on how well the building can maintain predefined temperatures and thus it is also an indirect indicator for thermal comfort. This is the first variable that also provides some indication of the quality of the BEPS. If the model is not setup well, unmet load hours will occur more often. Typically, reports differentiate between unoccupied and occupied hours with a focus on occupied hours. It is either displayed as a numeric value or a colored bar (see Figure 4).

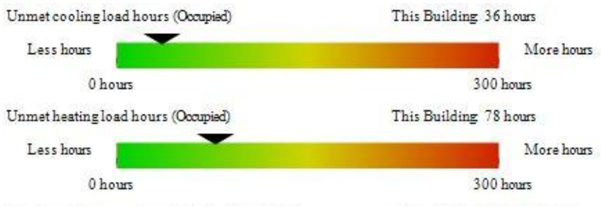

Figure 4: Uncomfortable hours illustrated in a color bar

To further improve this representation, we used a XY plot of humidity ratio over operative temperature. With the overlaid comfort box, it is clear which points are inside or outside of the comfort range (see Figure 5).

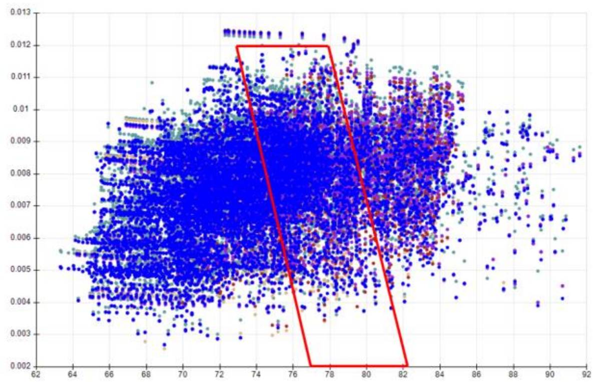

Figure 5: XY plot: Humidity ratio over operative temperature

Setpoint and load achievement

Like unmet load hours at the zonal level, setpoint achievement is a more generic term to describe how well a specific setpoint is met. To provide a better insight on when those are occurring, we developed an area chart that illustrates the different categories such as system heating, system cooling, zone heating and zone cooling monthly.

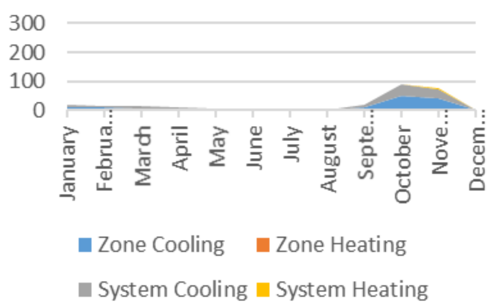

Figure 6: Unmet setpoint hours at the zone/system heating/cooling level

This graph provide insight on the overall amount of unmet setpoint hours, but also a better understanding of the period of the year as well as the category. Based on different availability of reports, we used unmet demand as well as the temperature different between the actual temperature and the temperature setpoint at system nodes as indicators. For example, Figure 6 illustrates a cooling issue both at the zone and system level in the autumn.

Operating hours

This metric can provide two insights into the BEPS model. First, it shows if all pumps and fans are running. Secondly, the amount of run hours over the period of the year. Like the graph for setpoint achievement, we developed a monthly area chart with different categories for fans and pumps.

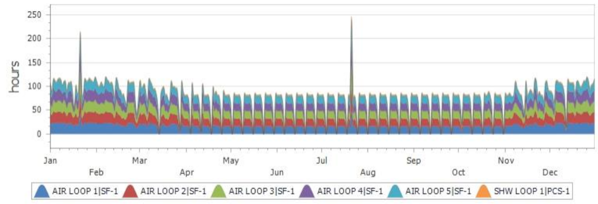

Figure 7: Operating hours in area charts

Material properties (U-Values)

While materials can have a wide spectrum of properties, depending on which physical phenomenon are considered in a simulation. The most relevant characteristic of a material in the thermal simulation context is its U-Value (or R-Value). The U-Value represents the overall heat transfer coefficient for assemblies of materials. Showing the average U-Values for each type of building element on a sketch of the building, provides valuable insights of the material characteristics used (see Figure 8). This summary helps to identify property errors, but can also highlight current weak areas that can still be further improved.

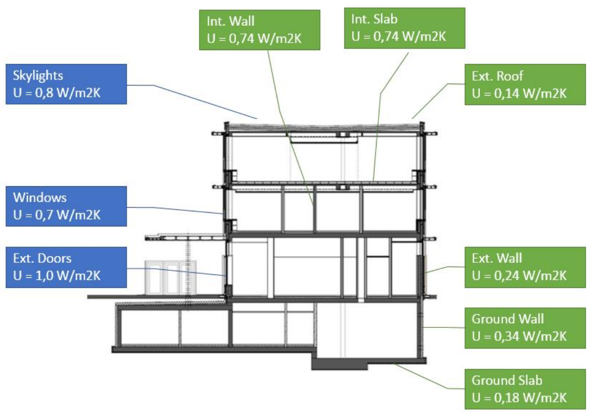

Figure 8: U-Values feedback at the type of building element level

Level of detail

With more and more ways to exchange and import geometry data into BEPS tools, the level of detail of simulation models also increases. It seems logical that the level of detail in a simulation model should be consistent. It is useful to know which data areas are at a different level. The first difficulty here is how to represent the level of detail in a simulation model. For data that is related to zones, we defined unique instance variable per area. E.g., the indicator for zones is determined by the number of zones divided by the building floor area. Similarly, the number of infiltration objects is established and divided by the building area. These values allow a quick assessment within the model but also across simulation models. Therefore, a comparison between these values within a model is needed and realized with a so-called tree-map. It can be easily seen, if internal load data is defined with less detail than the actual geometric definition of the zones. This indicator also shows commonly discussed variables such as infiltration. Figure 9 illustrates that the infiltration is defined with less detail compared to internal loads and the zoning (bigger areas indicate more detail).

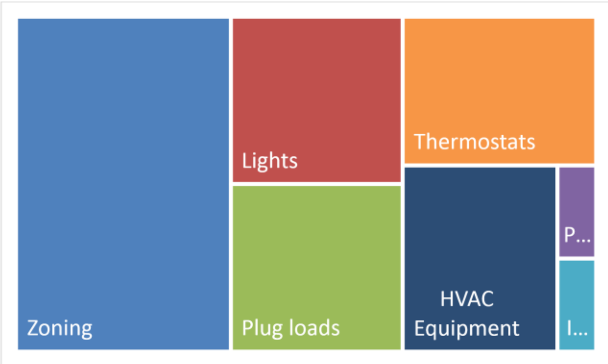

Figure 9: Level of detail shown in a tree-map.

Outside air indicators

Another big influence on comfort and energy consumption is the amount of outside air that is drawn either mechanically or naturally into a building. Thus, an indicator about mechanical (fresh and return), natural and infiltration is illustrated by an area chart (see *Figure 10*).

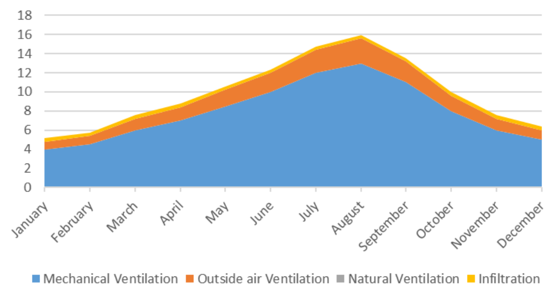

Figure 10: Ventilation area plot to provide context of outside air with mechanical ventilation and infiltration

Energy flow

While energy flow in every simulation model is unique, it is important to understand the largest contributor to energy in a model. Sankey diagrams provide a promising way to get more insights into the energy flow within a building but are relatively difficult to implement in a generic manner. Thus, we developed a simplified energy balance by showing the energy input and output of the simulation model side by side (see Figure 11).

Figure 11: Energy balance of a simulation model

Schedules

Schedules are heavily used in simulation models to describe many time dependent and varying parameters. Conflicting schedules can cause strange simulation results behavior. Thus, we found that comparing schedules in carpet plots can show important differences (see Figure 12). One can quickly see that one of the lower schedules has a different weekly pattern compared to the upper one. Occupied hours versus operating hours across a building with different uses and systems can reveal differences that influence the results and behavior of a simulation model.

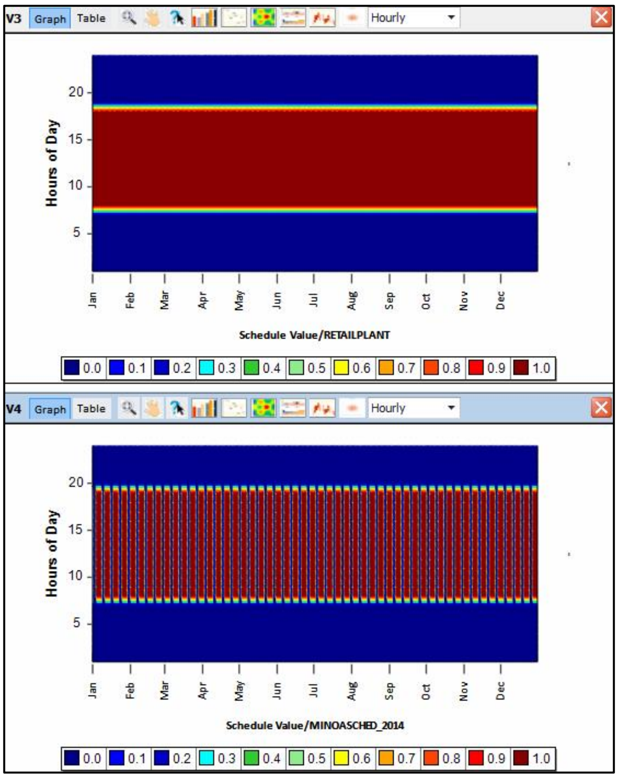

Figure 12: Carpet schedule plots

In this chapter, we illustrated all visual concepts that we use in our quick model assessment. In the following chapter, we describe the prototypical implementation of those visual aids.

Prototypical implementation of the visual aids

An implementation of the developed visual aids mainly depends on the result data from a simulation as well as the reporting and plotting environment. Since the focus of this study is on the visual aids rather than on the implementation, the authors build these visual aids on top of an existing data model and simulation tool. The data model used in called SimModel (O'Donnell et al. 2011) and the platform is Simergy (DA 2016).

Data model – SimModel

The data model used as a basis to extract and calculate the required data for the visual aids is SimModel. This simulation domain specific data model is object oriented and combines several other data models such as the IFC and EnergyPlus data model. It also contains a mechanism for linking result data to objects within the data model. Since for the development of this prototype EnergyPlus was used as a simulation engine, SimModel worked quite well as a data container.

Software platform – Simergy

The visual aids report was developed on top of the simulation software platform Simergy. Through Simergy access to the SimModel as well as the link to the result data was trivial and straightforward.

The object SimOutputRequest allows to request any report variable that EnergyPlus supports. This mechanism is used to get all report variables triggered and reported in the simulation. All report variables are saved in a SQLite database (SQLite 2016) and thus are easily accessible with the Simergy report environment (see Figure 13).

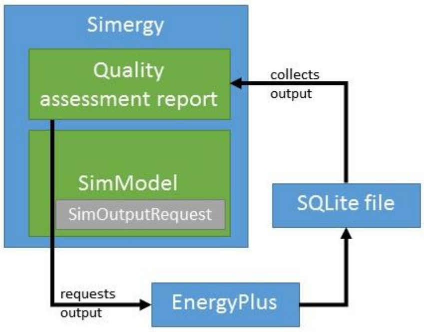

Figure 13: Data flow of the prototype

The most time consuming and challenging part of the implementation is the definition of these report variables. Most of the graphs need only simple calculations, to sum values or average values which is also supported in the Simergy environment.

Feedback and use cases

Feedback from the practitioners so far shows that these visual aids enable a quick assessment of BEPS models. Our intent is to get more formal feedback form practitioners.

We use two use cases to illustrate the power of the visual aids to detect inconsistences or errors in simulation models.

Use case 1: schedule inconsistencies

The first use case, the simulation model did show many unmet load hours. In this multifunctional model with one common HVAC system, the origin of these unmet hours was unclear. The schedule comparison revealed that the internal load the occupancy schedules were quite different. Running hotel, retail and office spaces all on the same HVAC system did cause times with insufficient conditioning. Thus, the comparison of the HVAC system schedule with the three different occupancy schedules did quickly show the origin of the problem.

Use case 2: operating hours

The second use case, a storage facility is modelled with typical core and perimeter zoning and moderate level and quality of the data definitions. After developing the first version of this model, results did not seem correct, so an investigation into the details was required. The operating hours graph (see Figure 14) quickly revealed that the hot water pump was not running throughout the year. A further investigation revealed that pump parameters were incorrect and conflicting.

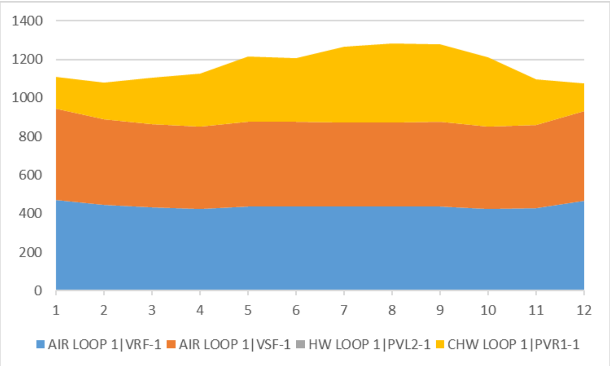

Figure 14: Operating hours of use case 1: the lack of operating hours for the hot water pump reveals an issue in the model

Use case 3: Inconsistent internal loads

The third use case is a large office building that was modelled at a very detailed level. Information about each space including their different functions (such as office, meeting or corridor spaces) were modelled. Due to a error in the model creation only one people definition was assigned to all zones. This mistake can be easily established through the detail tree map (see Figure 15). The small area of the people indicates the low number of instances.

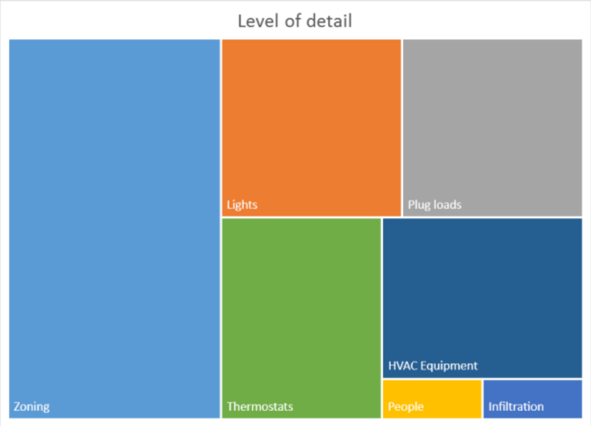

Figure 15: Level of detail of a large office building model

Conclusion

During this project, we detected a gap of data quality assessment in BEPS models. This work addresses this gap and aims to be a first step for easier simulation model debugging and assessment.

We successfully developed a set of visual aids to assess a given simulation model. The contribution is to provide visual indicators to results of BEPS models that significantly improve the understanding of the input data of a given model. We think that this assessment helps the modeler to debug his BEPS models as well as it helps the stakeholders to better understand and assess a BEPS model.

Future work

Additional feedback and testing

Performing a proper test with practitioners would enable us to show more evidence of the power of this concept of the visual aids.

Improvement of representations

While we spend significant effort to find meaningful visual representations on a given issue, additional visualization techniques may prove more effective. In addition, the combination of graphs with numerical values in the same context could also provide additional benefits and should be investigated in the future.

Sankey diagrams

We choose a simplified representation of the Sankey diagrams; further work is needed to automatically generate detailed Sankey diagrams automatically. These promise great insights into the energy flow of a building model.

Independent model assessment

Our prototypical implementation is based on a specific simulation data model, the EnergyPlus simulation engine as well as the Simergy environment, an independent model assessment tool could assess a wider range of models.

Extension of the graphs

Extending the operating hours graphs may prove to be useful to show not only the operating hours of flow moving devices, but also boilers, chillers and others. Another possible area of extension would be scatter plots for heating and cooling operation.

Interactive reports

Currently the visual aids are implemented as a static report with no direct user interaction. The ability to investigate an issue in more detail via user interaction with the graphs could be a powerful extension in the future.

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