A VISUALIZATION ENVIRONMENT FOR ANALYSIS OF MEASURED AND SIMULATED BUILDING PERFORMANCE DATA

James O'Donnell[1&2], Tobias Maile[1], Kevin Settlemyre[3] and Philip Haves[1]
[1]Lawrence Berkeley National Laboratory,
Berkeley, CA, 94720 – U.S.A.
[2]School of Mechanical and Materials Engineering, University College Dublin,
Belfield, Dublin 4, Ireland
[3]Sustainable IQ, 38 Sunset Road, Arlington, MA 02474 – USA

ABSTRACT

Conventional visualization and analysis of data stored in Building Automation Systems (BAS), Energy Management Systems (EMS) or outputs generated by simulation tools is confined to limited graphical and customization capabilities of the originating software or spreadsheets. As a consequence, there is a currently no generic, life-cycle and interoperable tool for analysis of both predicted and measured building performance data.

This paper presents a new BIM-based life cycle visualization environment for analysis of measured and simulated building performance data through synchronized display of multi-context and multivariable time-series data complemented by summary reporting data. A demonstration of the visualization environment focuses on a performance analysis scenario using data from a base case simulation and one design alternative.

INTRODUCTION

A recent increase in available energy performance data from buildings as provided by measurement systems and generated by Building Energy Performance Simulation (BEPS) tools has led to large data sets (Maile, 2010). Performance analysts who are trying to analyze these data struggle with the quantity of data as well as the lack of easy-to-use data visualization tools.

Current software tools that plot performance data typically focus on a specific data type or a specific type of analysis. Most require data in a specific format (e.g. (Friedman & Piette, 2001; Mazzarella et al., 2009) or focus on data from a specific source. One example of the latter is measured data from data loggers (PG&E, 2013). Often engineers use generic visualization software and develop custom routines to support their current analysis needs, for example Seidl (2007). Other analysis tools are just very difficult to use (Isakson & Eriksson, 2004; O'Donnell et al., 2004). Only one of these tools supports both simulated and measured data. Maile et al. (2011) describes a software tool that is capable of displaying simulated and measured data, but this tool lacks the ability to import data structures, has a limited set of data graphs available and does not support the definition of reusable data graph templates. Displaying a combination of measured and simulated data within the same graph is particularly difficult since measured performance data are often irregular, with false readings, gaps and duplicate values (Maile et al., 2011).

Besides these data challenges and tool limitations, the increase in available data also leads to the need for a more defined management structure for all available data points. Most tools do not provide an adequate mechanism for organizing data – one exception is the data warehouse structure proposed by Keller (2008).

Furthermore, there is currently an absence of an interoperable and generic building lifecycle tool for analysis of both predicted and measured building performance data. Limited graphical and customization capabilities of Energy Information Systems (EIS), Building Automation Systems (BAS) and spreadsheets typically restrict visualization and analysis scenarios. As a result, it is difficult for end users to display data in different contexts (for example relative humidity for a zone context or air outlet temperature for a cooling coil), work with large volumes of data or create data management infrastructures for use over multiple design alternatives and multiple projects.

To address these shortcomings the authors have developed a new visualization environment for analysis of measured and simulated building performance data across the building life cycle, with a particular emphasis on synchronized display of multi-context and multivariable time-series data complemented by summary reporting data. This environment uses a defined structure (building object hierarchy) with implementation using a data model (O'Donnell et al., 2011). The paper first describes this building object hierarchy as well as the SimModel that enables context-based analysis. The paper continues by explaining interoperable data analysis and the developed data visualization methodology. The paper also demonstrates an initial application of the visualization environment using predicted data from the BEPS outputs for a base case and one design alternatives for an example building located in Chicago, USA. This demonstration uses a current beta version of Simergy, a current freeware tool (LBNL, 2013).

CONTEXT BASED ANALYSIS

All performance evaluations require a context. Current performance analysts are familiar with analysis contexts that include building energy use intensity, supply temperature for an AHU context, Coefficient Of Performance (COP) for a chiller context and many others. This work recognizes conventional performance analysis contexts and categorizes them as building objects (see Figure 1).

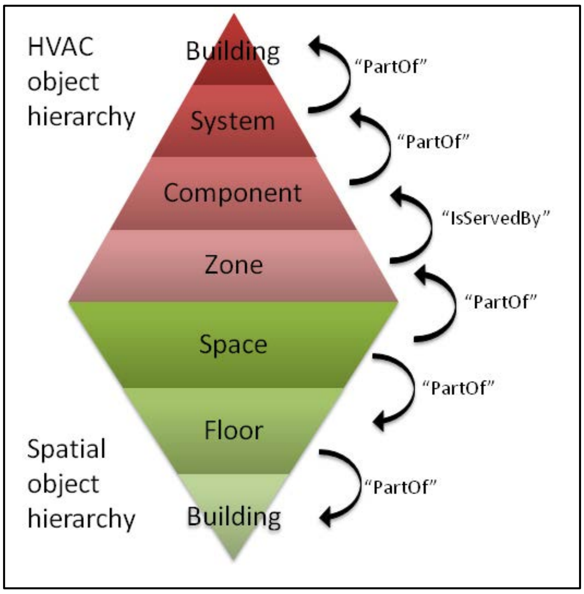

Figure 1: Building object hierarchy image (Maile et al., 2012)

For an individual building, the full category list of building objects includes building, floors, spaces, zones, HVAC systems, and HVAC system components. The applied object-based convention maintains consistency by associating performance categories such as "utility consumption" and "energy end-use breakdown" with the building. An individual building object may have any number of performance evaluations associated with it.

Due to the potential for a large data sets for a given building (e.g., 2,231 data points measured at one minute intervals for one building (Garr et al., 2012)), a formal representation is needed to organize these data points. Such a representation would link building objects so that reasoning about differences between measured and simulated data becomes possible. O'Donnell (2009) combines the geometrical and system perspectives into one tree structure that is focused on the zone object. The relevant HVAC hierarchy is connected to each zone, which leads to duplicate instances of HVAC systems and components and does not account for relationships among components of different HVAC systems. Maile et al. (2011) combines the two perspectives into a pyramid representation as shown in Figure 1. This representation eliminates duplicate instances of objects but it is difficult to represent in this view visually in a software context. These two perspectives are primarily linked through zones (here thermal zones) and spaces. This zone-space relationship is a "PartOf" relationship, as are most of the other relationships illustrated in Figure 1 (buildingsystem, system-component, building-floor, floor-space, zone-space), except the component-zone relationship, which is classified as an "IsServedBy" relationship. In addition, a number of other relationships are contained within the building object hierarchy (Maile et al., 2012).

Figure 2 illustrates a partial building object hierarchy for an example building. The tree on the left shows the HVAC hierarchy and the one on the right shows the spatial hierarchy.

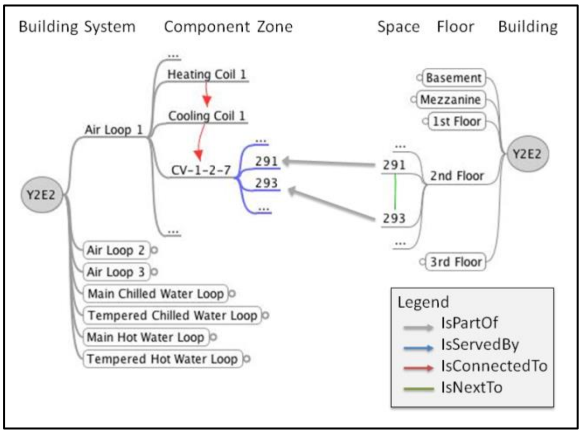

Figure 2: Example of a building object hierarchy

A BEPS model typically directly contains these relationships between building objects or they can be derived from other relationships. In EnergyPlus, each zone is part of a building and indirectly linked to neighboring zones through connected surfaces objects. The concept of a floor as an agglomeration of spaces is missing in EnergyPlus. However, the HVAC components are part of a specific HVAC system with a branch structure that connects HVAC components and includes direction of flow. In addition, the HVAC components on the zone level link to their related zone objects.

Furthermore, formalized concepts for topological relationships contained in interoperable data models such as Industry Foundation Classes (IFC) or SimModel support modeling of distribution systems (like HVAC). Supported representations include explicit port types, such as air-inlet or chilled water outlet, and connections of pipes and ducts. The alternative is to include port definitions as part of an object definition and connections through a referencing mechanism between ports. Ports are explicitly linked to the elements they serve and connection elements are linked to the ports they connect. SimModel concepts go beyond their counterparts in IFC, as IFC does not support ports on zones or spaces. Applications may in turn easily establish direction of flow based on these concepts.

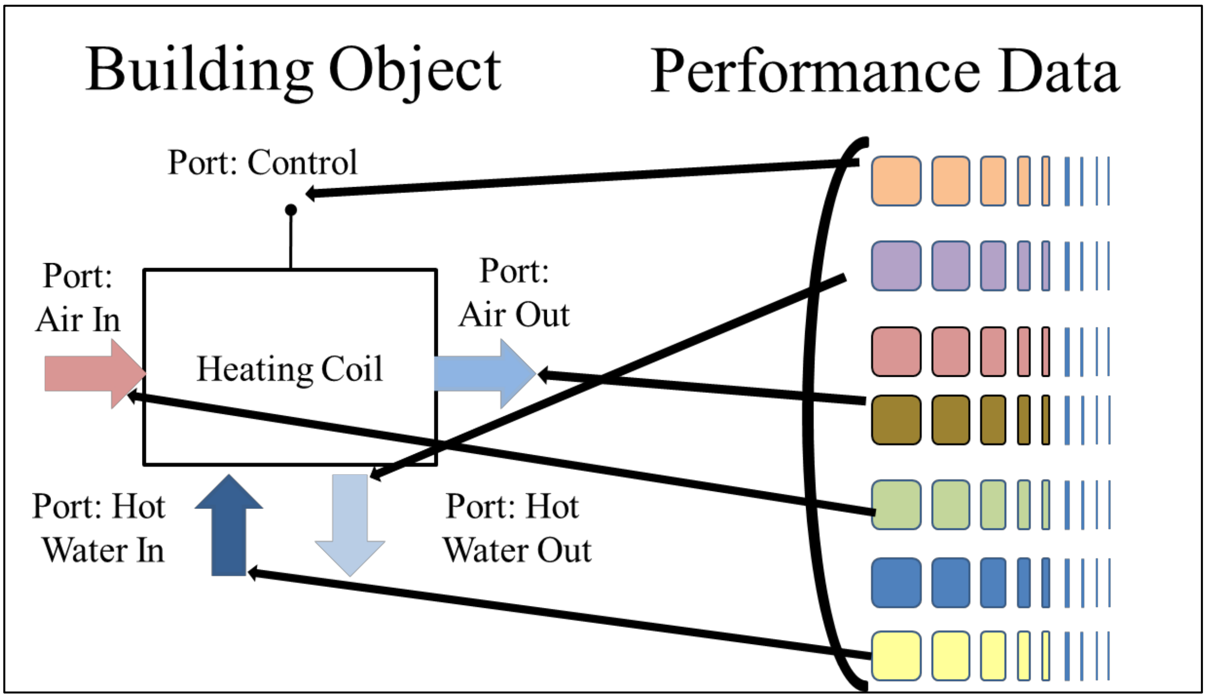

Figure 3: Conceptual representation of automated linking of performance data with a building object to support context based performance analysis

Context-based analysis can leverage significant benefits from explicit port definitions by establishing explicit links between individual streams of time series data and identifiable ports (Figure 3). With such links available, performance analysis solutions can define analysis techniques independently of a given building (Granderson et al., 2012; Schein et al., 2006) and associate individual analysis methods with the appropriate objects in a generic building object hierarchy. For a specific instance of a building object hierarchy, i.e. a given building, the solution only requires explicit links between the data and the ports in order to facilitate automated analysis. This approach far surpasses traditional bespoke solutions that heavily rely on manual data manipulation.

As a result, an automated solution must base itself on an appropriate interoperable life cycle data model and SimModel fulfills these required interoperable and functional criteria (O'Donnell et al., 2011).

INTEROPERABILE ANALYSIS

Robust and mature life cycle data models of buildings include all objects required by a building project as well as objectified relationships between objects. Of which IFC is presently an ISO/PAS standard (ISO, 2013) for the architecture, construction and facilities management domain but is missing some key entities for the purposes of simulation and performance analysis. Instead, the authors propose to use SimModel, which has an architecture that is very closely aligned with IFC, as the interoperable life cycle data model for performance analysis.

SimModel or Simulation Domain Model is a new, interoperable XML-based data model for the building simulation domain (O'Donnell et al., 2011). SimModel provides a consistent data model across all aspects of the building simulation process, thus preventing information loss as changes occur to the building over time. The model accounts for new simulation tool architectures, existing and future HVAC and low energy systems, components and features. In addition, it is a multi-representation model that enables integrated geometric and Mechanical, Electrical and Plumbing (MEP) simulation configuration data. The SimModel objects ontology moves away from tool-specific, non-standard nomenclature by implementing an industry-validated terminology aligned with the latest version of IFC (buildingSMART, 2013).

Post-processing of simulation output is most important as simulation engines may generate enormous amounts of output data. SimModel output mappings therefore reflect the breadth and depth of present output formats and output requests contained in EnergyPlus. The chosen approach stores a set of inputs created from a number of reusable library entities that enable a user to recreate identical outputs for a particular model. After a given simulation run, SimModel stores a link (URL) to simulation outputs with simulation run data as opposed to explicitly storing output data within a model instance. To ensure consistency when rerunning simulations, simulation configurations data is also structured and stored for re-use.

VISUALIZATION ENVIRONMENT

The Simergy results visualization environment currently enables users to leverage simultaneous displays of results from single or multiple simulations for any of the available output variables in EnergyPlus (See et al., 2011). The results environment also provides the framework for visualizing results at a number of other stages in the building lifecycle and can support:

- Weather data from an on-site weather station
- Actual building performance data
- Optimization analysis results that inform design
- Assisted calibration analysis to transition the design energy model to one used during operations
- Visualize results for operational „what if scenarios' to quantify their potential influence.

The results environment is key component of the Simergy user interface (Figure 4). Conceptually, it complements predefined reports as generated by EnergyPlus by allowing users a more granular analysis of results. In order to do so, the results visualization environment design focuses on four main features that are annotated in Figure 4.

1) - Ribbon - The Results Environment ribbon includes high level data through Results Sets, Results Screen and Views. Here the user can control the data that they will be working with in terms of predefined sets of views (Results Screen), saving sets of customized views for later use on a given project or for use on other projects, and the configuration of the results view field which allows one to twelve Result Screen configurations.

2) – Available Output Variables and Selections – This portion of the Results Visualization workspace comprises of three subsections where one can view, filter and select output variables associated with the Results Sets. In future versions of Simergy the **Available Component Tree,** which represents the building object hierarchy, will allow users to select a component in the „Tree' and will filter the output variables in the Available Output Variables table to display the variables only associated with that component. The **Available Output Variables Table** displays the output variables available for the Results Sets selected. The **Output Variable Selection Table** stores user chosen output variable selections from the Available Output Variables Table and are displayed in a Results View. For an active Results View a user can add, select or delete Output Variables. This feature enables enormous flexibility in terms at the highest level of data granularity.

3) – Results Reporting Area – The major remaining portion of the workspace was designed to contain one to four configurable Results Views that are selectable from the view configuration icons in the ribbon. Current results view options vary from four identically sized to a single larger Results View. In order to multi-contextual comparisons, heighten understanding and problem solving, each Results View may contain information ranging from a single output variable for a single Results Set to a group of output variables that can plot against two y-axes.

4) – Results View Controls – Each Results View has its own set of controls that enable creative flexibility in terms of chart or graph, chart type, time step type and zooming. Graphing options include five graph categories of column chart, line, surface, area and range charts that are easily interchanged on an individual Results View basis. Further frequency selections range from timestep to run period and enable even further analysis flexibility. .

Name	Area	Alternative
Outdoor Dry Bulb	Environment	Baseline Design
Outdoor Dry Bulb	Environment	Design Alternative 1
Outdoor Relative Humidity	Environment	Baseline Design
Outdoor Relative Humidity	Environme	Design Alternative 1
Outdoor Wet Bulb	Environment	Baseline Design
Outdoor Wet Bulb	Environment	Design Alternative 1
Plant Loop Cooling Dem...	CHW LOOP -	Baseline Design
Plant Loop Cooling Dem...	HW LOOP - 1	Baseline Design
Plant Loop Cooling Dem...	CHW LOOP -	Design Alternative 1
Plant Loop Cooling Dem...	HW LOOP - 1	Design Alternative 1
Plant Loop Heating Dem...	CHW LOOP -	Baseline Design
Plant Loop Heating Dem...	HW LOOP - 1	Baseline Design
Plant Loop Heating Dem...	CHW LOOP -	Design Alternative 1
Plant Loop Heating Dem...	HW LOOP	Design Alternative 1
PlantLoopCoolingDeman...		Baseline Design
PlantLoopCoolingDeman...		Design Alternative 1
PlantLoopHeatingDema...		Baseline Design
PlantLoopHeatingDema...		Design Alternative 1
Pumps:Electricity		Baseline Design
Pumps:Electricity		Design Alternative 1
Time Not Comfortable S...	THERMAL ZON - 1 - 1 (...	Baseline Design

Name	Area	Alternative
Zone/Sys Sensible Coolin...	THERMAL 2 - 2 (...	Baseline Design
Zone/Sys Sensible Coolin...	THERMAL ZO - 2 - 4 (...	Baseline Design
Zone/Sys Sensible Heati...	THERMAL ZONE - 2 - 2 (...	Baseline Design
Zone/Sys Sensible Heati...	THERMAL ZONE - 2 - 4 (...	Baseline Design
Outdoor Dry Bulb	Environment	Baseline Design

Figure 4: Layout of the visualization screen in the Simergy Interface including access to context specific data

DEMONSTRATION

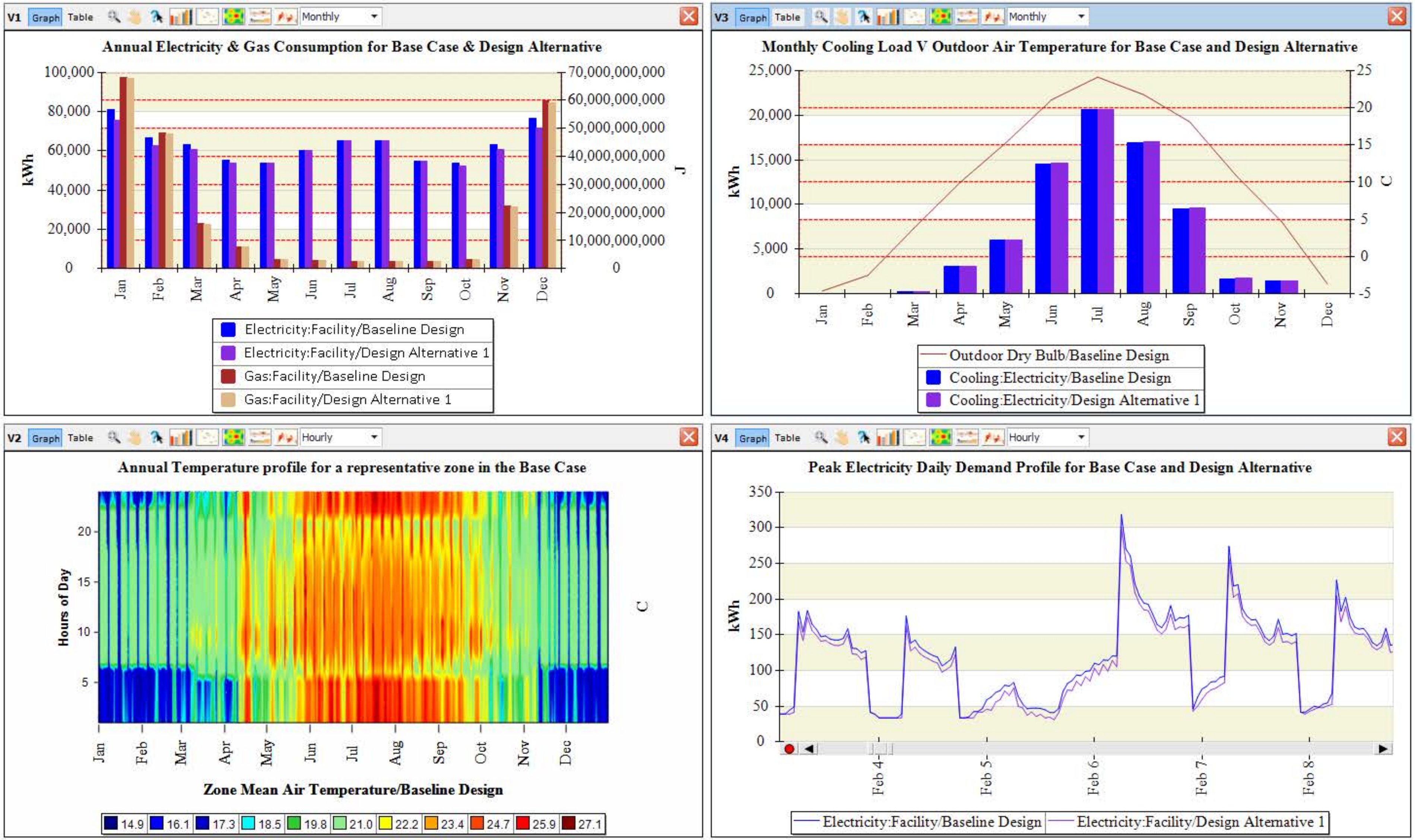

Figure 5: Example of results visualisation in Simergy Interface

An example implementation of this proposed visualization environment focus on a design scenario with a base case and one alternative. Due to current functional limitations of the software, import of measured data is not an available feature. When this functionality is available the tool will rely on a clean data set that has passed through a utility standard validation, estimation and editing process to ensure quality and consistency. Therefore, this demonstration leverages two distinct sources of simulation outputs to illustrate the practice of comparing two annual datasets.

In order to create a fair comparison of data, both simulation models used a predefined set of output requests from an existing Simergy library (this output set is stored in the SimModel format and can be reused on a given project or on other projects).

The design scenario focuses on the DOE reference building "RefBldgMediumOfficeNew2004_v1.3_5.0_5A_USA_IL_CHICAGO-OHARE" which is located in the Chicago area (DOE, 2012). The base case and design alternative differ in terms of the windows used: the base case uses double pane windows on all facades while the design alternative uses triple pane window on all facades.

Visualization of results incorporates simultaneous multi-context analysis of four different sub-contexts, one per quadrant of Figure 5. Starting in the top left hand corner of Figure 5 and working clockwise the contexts for analysis are as follows:

1. *Building*: an annual plot of monthly electricity and gas totals for based case and design alternative, displayed in a histogram
2. *Plant equipment chillers*: annual plot of monthly cooling load, displayed in a histogram, against outside air temperature displayed in a line graph for the base case and design alternative
3. *Building*: multi-day peak load electricity analysis for the base case and design alternative in a line chart
4. *Zone*: annual plot of hourly zone mean air temperature for a representative zone in the base case, displayed as a carpet plot.

A number of observations are possible based on the displayed plots of Figure 5. There is a quantifiable difference in natural gas use between the two cases, a phenomenon that is most noticeable during winter heating months. Electricity use for the design alternative is also measurably different between the two cases but again during the winter time period with no meaningful difference during the summer cooling season. In fact there is a higher cooling load for the design alternative during the peak summer months. For a location like Chicago, conventional thinking might expect peak demand load during a peak summer time cooling event but the peak demand occurrence was actually during morning ramp up on a day in early February. This is most important as the peak demand load typically influences tariff for a period of 12 months. While the design alternative might have a slightly lower demand peak than the base case, it is immediately apparent that equipment scheduling needs adjustment to reduce this peak load occurrence. Furthermore, functional intent is of paramount importance during analysis. The carpet plot illustrates that zone conditions are acceptable for the majority of the run period but further investigation may be required for high zone temperatures during summer months

CONCLUSION AND FUTURE WORK

Performance analysis activities conducted through an interoperable life cycle BIM ensures performance evaluations over the entire BLC. This approach captures original design intent and updates this design intent to reflect any changes in the building. During operation, a performance analysis may then compare updated design intent with actual operation.

Furthermore, context based performance analysis can deliver significant efficiency improvements with respect to the quality of and time spent on performance analysis. These improvements are made possible through predefined automated calculations that remove much of the overhead associated with data acquisition and manipulation prior to analysis.

Over time this visualization environment will continue to evolve, especially with respect to the display of measured data. The key issue is that measured data is available in a non-homogenous format that inevitably requires pre-processing. Another area of future work will focus on customizable interfaces for different stakeholders and potentially access to other sources of data (O'Donnell et al., 2013).

ACKNOWLEDGEMENT

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