Whole Building Energy Analysis: A Comparative Study of Different Simulation Tools and Applications in Architectural Design

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ABSTRACT

With the expanding interest in energy-efficient building design, whole building energy simulation programs are increasingly employed in the design process to help architects and engineers determine which design strategies save energy and are cost-effective. The purpose of this research was to investigate the potential of these programs to perform whole building energy analysis, and compare the results with the actual building energy performance. The research was conducted by simulating energy usage of a fully functional building using Vasari/Green Building Studio (GBS) and Sefaira, which are aimed for early architectural design process. The results were compared with annual utility data of the building to identify the degree of closeness with which simulation results match the actual energy usage of the building. The results indicate that the energy modeling results from Vasari/GBS are much higher than the actual, while results from Sefaira are comparable to actual building energy usage (slightly higher). It is crucial to understand the limitations of different tools in order to successfully integrate building performance analysis in early stages of the design process, as well as capabilities of different software programs for modeling different energy-efficiency design strategies.

Introduction

With the increasing demand for more energy-efficient buildings, the construction industry is faced with the challenge to ensure that the energy performance predicted during the design is achieved once a building is in use. Energy simulation tools are increasingly used for analysis of energy performance of buildings (Augenbroe et al. 2004; Aksamija 2009; Aksamija 2010; Wetter 2011; Aksamija 2012). Today, there are many building performance simulation programs with different user interfaces and different simulation engines that are capable of these analyses. The intent of this paper is to document the comparative analysis research conducted towards conceptual Whole Building Energy Analysis (WBEA) through the software programs such as Vasari/Green Building Studio (GBS) and Sefaira, which are applicable to early design stages. Next stage of the research is to also compare more robust simulation programs that are applicable for later stages of the design process, such as eQuest and EnergyPlus, which was not included in this paper. The intent is also to inform designers and engineers about the potential for integrating simulation programs with the design, which would yield accurate predictions about the building performance. This is an essential aspect in design of high-performance buildings, and improving the design decision-making process (Aksamija and Abdullah 2013). Given the significant variety of such simulation tools, it is crucial to understand limitations of the tools and the complexity of simulations. Prior to conducting this research, our objective was to find an efficient and beneficial method of seamlessly integrating WBEA into the design process.

The notion of calculating building's energy usage as a "whole" is not a new concept—there are existing simulation tools that have been around for the last two decades. However, integration with the design process and Building Information Modeling (BIM) technologies are newer concepts that are still being investigated (Aksamija and Mallasi 2010; Aksamija and Abdullah 2013; Moon et al. 2011; O'Donnell 2013; Punjabi and Miranda 2005). In essence, WBEA is the process of analyzing a building's energy performance by calculating how well the integration of that building's form, systems, and envelope perform under the surrounding environmental conditions. It is equally important to consider a life cycle cost analysis during this process in order to make educated financial decisions and have a successful building design. The "conceptual" aspect of WBEA is the attempt to integrate WBEA into earlier phases of design in order to allow all parties working on the project to make the best informed design decisions prior to more detailed design and additional months of labor. By integrating WBEA into the conceptual phase, the intent is that the amount of time and money saved will increase significantly. This can be achieved by integrating BIM technologies with energy simulations. These integrated early analyses help make more informed decisions in the conceptual design phase when changes are least expensive. An added advantage is that the conceptual model can be used to form the basis of a more advanced model as the design develops. However, most BIM-based WBEA software programs are new or still in beta versions. Therefore, this study was conducted to test several different software programs by modeling the energy usage of a building with several energy-efficiency design strategies (use of natural ventilation, radiant system, geo-exchange system, light-shelves, daylight occupancy sensors) , and comparing that the results to the actual building performance data.

There is an ongoing dialogue about modeled vs. actual energy performance in buildings. Previous studies that investigated discrepancies between simulated and actual energy usage in buildings indicate that these gaps can be substantial, and in the range from 10 to 30% (Diamond et al. 2006; Scofield 2009; Stoppel and Leite 2013). It is clear that much work needs to be done to better align energy modeling accuracy with actual building performance outcome if this method, as currently implemented, is to effectively serve the design community in delivering high performance buildings. The wide variability of energy modeling accuracy on an individual project basis implies significant flaws in any life-cycle energy savings comparisons undertaken by the affected projects. There is a clear need for better data on actual building use characteristics to better correlate modeling inputs with building use characteristics (Frankel and Turner 2008). The next several sections outline the methodologies and results in detail.

Purpose and Objectives

Building performance simulation tools that integrate graphical results with context-sensitive guidance are likely to have the most appeal for architects. In contrast, engineers need software tools that can be used in both the conceptual design stage, when little is known about the building; as well as in the final design stages, when majority of the project details have been finalized. Software programs that combine simplified input wizards with detailed simulation tools have the most potential to meet these differing needs at various stages of the design process.

When a building is modeled for the same climate in different simulation programs, the performance of the building shown as the output of the simulation run is expected to be similar. However, different software programs may exhibit a significant difference in output for the projected energy usage of a building (Agami 2006; Maile et al. 2007). The objectives of this study were:

- To investigate properties and applicability of several different software programs (initially Vasari/GBS and Sefaira, as well as eQuest and EnergyPlus).
- To model a building similarly in all the software programs by closely mapping the input parameters.
- To compare the results of simulations with measured utility data and identify discrepancies.
- To document the findings of the study.

Modeling Methodology

Different simulation programs may have different software architectures, different algorithms to model building and energy systems, and require different user inputs even to describe the same building envelope or HVAC system component. For this study, the research methodology was to identify a recently constructed existing building, and to model the identical inputs for building systems, environmental conditions, control strategies, and material components in all software programs. Also, simulation settings were kept the same or as close as possible, such as the time step and calculation algorithm. Initial simulations were completed using Vasari/GBS and Sefaira, which have been specifically developed for early conceptual design. Simulations in eQuest and EnergyPlus are currently in progress, and will be reported at later stages of the research.

Comparison of Energy Simulation Tools

Vasari/GBS

Vasari/GBS is one of Autodesk's design software that integrates conceptual modeling with WBEA, allowing the designers to make important design decisions in earlier phases of the project. It is still in beta version, but it is becoming increasingly used by design professionals due to its dynamic and integrated features, as well as automated modeling capabilities that reduce time and effort needed during the conceptual design. The apparent benefit of this tool is that BIM-based design information and geometry can be used for energy analysis during the earliest stages of the design process. It supports performance-based design via integrated energy modeling and analysis features. GBS is a web-based energy modeling software that can be used for early design decision-making, and allows for data exchange between BIM design programs and energy modeling engine. GBS differs from Vasari slightly, where the parameter settings can be altered post-simulation without creating a new project. Another difference is that GBS offers a more detailed list of component and condition parameters to change for the design alternatives, such as construction methods and building systems (R-value of the building envelope, type of glazing, sizing of HVAC equipment, etc.). The GBS simulation results were evaluated under ANSI/ASHRAE Standard 140-2004 (Autodesk, 2013). Vasari/GBS use DOE-2.2 for energy analysis engine.

Sefaira

Sefaira is a web-based sustainability analysis platform specifically built for conceptual design. Sefaira is targeted towards architects, engineers, consultants and building designers. It performs whole-building analysis of energy use, carbon and renewable energy potential allowing designers and architects to explore different design options. The software runs simulations on a specified geometry from a SketchUp model, and produces results that the designer is able review, compare, and manipulate in a web-based interface. Sefaira uses the radiant time series (RTS) method as the core of their proprietary energy simulation engine.

eQUEST

eQUEST is a publicly-available, easy to use building energy analysis tool, which provides results by combining a building creation wizard, an energy efficiency-measure wizard and a graphical results display module with an enhanced DOE-2.2 derived building energy simulation program. The building creation wizard walks a user through the process of creating a building model. Within eQUEST, DOE-2.2 performs an hourly simulation of the building based on inputs that describe its construction, occupancy patterns, equipment load, plug loads and lighting loads, as well as heating and cooling systems. eQUEST allows users to create multiple simulations and view the alternative results in side-by side graphics.

EnergyPlus

EnergyPlus is one of the most advanced, publicly-available building energy simulation programs, whose development begun in 1996 with funding from the U.S. Department of Energy. While the program borrows what was effective from BLAST and DOE-2, it contains a number of innovative features, including sub-hourly time steps, user-configurable modular HVAC systems that are integrated with a heat and mass balance-based zone simulation, as well as input and output data structures that can facilitate third party module and interface development. Graphical user interface has recently been developed and released for EnergyPlus (OpenStudio), and a software development kit has been developed to simplify the creation of applications that use simulation models. Although results from eQuest and EnergyPlus are not included in this paper, they are important in the overall research since these applications are more robust and would be valuable addition to the available body of knowledge on relationships between simulated and actual building energy performance data.

Case Study Building Description

The case study building that was used for this study is a research laboratory building located in Tacoma, Washington. The facility is primarily used for studying and analyzing water samples, but is also used for educational activities. Its area is 51,000 ft^2 (4,740 m^2). The program includes laboratories, offices, conference rooms, an exhibit center, a cafeteria, and related building services. The building is located on a long and narrow site along the industrial waterfront of the Thea Foss Waterway. The geometry of the site led to a narrow building design, oriented roughly north and south (Figure 1).

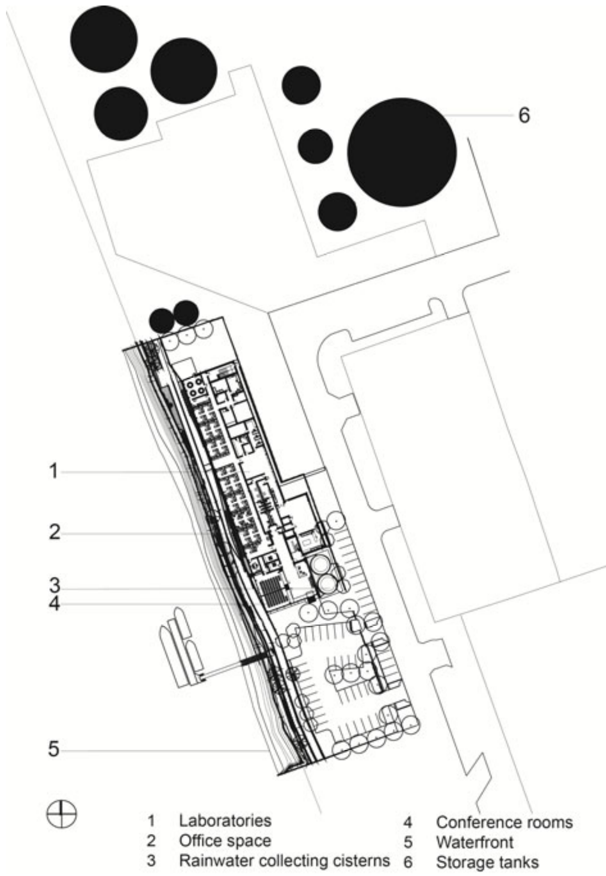

Figure 1. Building site and typical floor plan.

The building design used passive sustainable design strategies, which were strongly influenced by the site's orientation. The major programmatic elements are grouped into two zones: a laboratory zone facing inland and an office zone along the waterway. Because of the programmatic requirements of the research activities, the laboratories required mechanical ventilation.

On the other hand, natural ventilation for the office spaces was considered highly desirable. By facing the waterway—a source of fresh air—the offices benefit from natural ventilation. The office spaces on the north end of the building, with the laboratories to the east, use single-sided natural ventilation. At the south end of the building, where the offices have west and east exposures, natural cross-ventilation is provided. Operable windows in the west and south facades allow occupants to control the amount of natural ventilation. Landscaping was used to create a buffer zone to the east of the offices, keeping out air and noise produced by the neighboring industrial activities. Solar orientation was also a factor in the design of the west and south facades. The glazed curtain wall on the south facade uses horizontal shading elements to block midday sun, while providing unobstructed views to the water. Figure 2 shows natural ventilation and shading strategies.

The western facade consists of an aluminum rainscreen with punched high-performance windows, and automated exterior blinds. Similar to venetian blinds typically used for interiors, the closed blinds prevent solar heat gain within the building during afternoon hours. South facade consists of a curtain wall with fixed exterior horizontal sunshades, and fritted glass. On the east and north facades, rainscreen facade system with corrugated metal panels was used. The overall window-to-wall ratio (WWR) for all four facades was low, around 32%. Glass selection was based on the orientation of the windows and the functional requirements of the interior spaces. The vision areas for all facades consist of double-glazed air-insulated glazing units with low-e coating. The opaque areas of the facades were designed for an average thermal resistance of R-19 hr-ft^2-F/Btu (3.36 m^2-K/W).

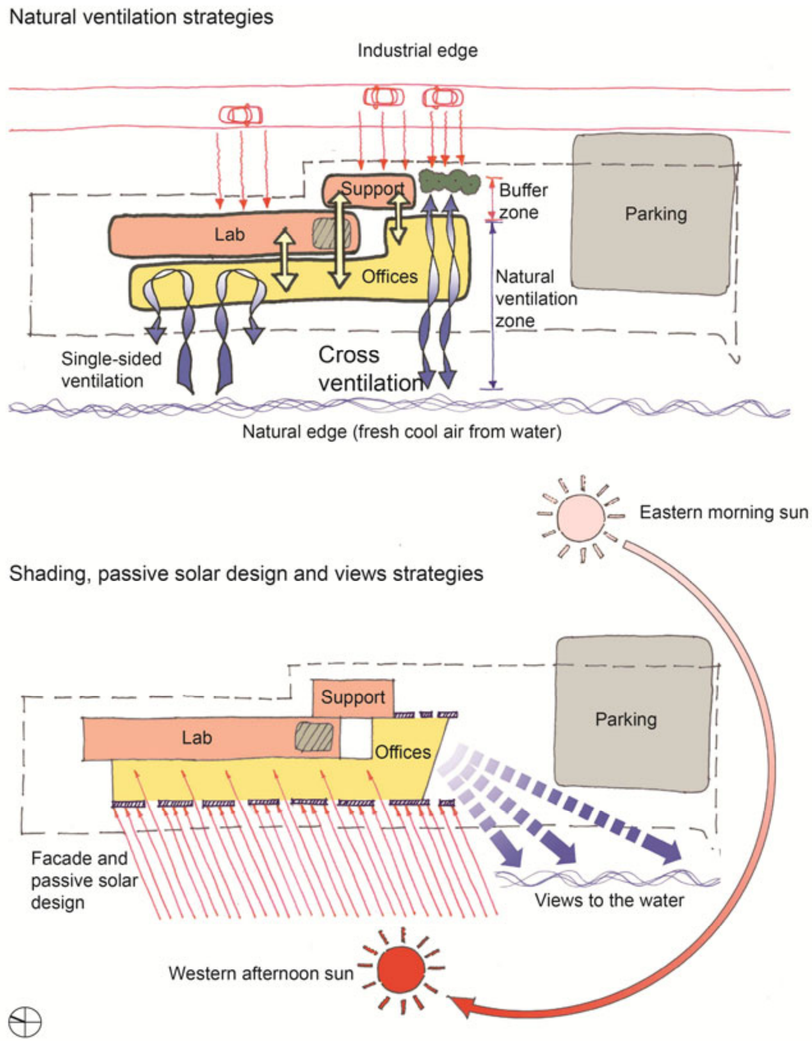

Figure 2. Passive design strategies for shading and natural ventilation.

HVAC systems include radiant heating and cooling system in the floors, vertical geo-exchange wells, and a heat-recovery system in the laboratories and office spaces (Figure 3). Other energy-efficiency and sustainability strategies include vegetated roofs, stormwater collection, water reuse, use of recycled and reclaimed materials, as well as measurement and verification system that tracks actual building performance and informs users of real-time energy use. The building was completed in 2010, and achieved LEED Platinum certification by the U.S. Green Building Council.

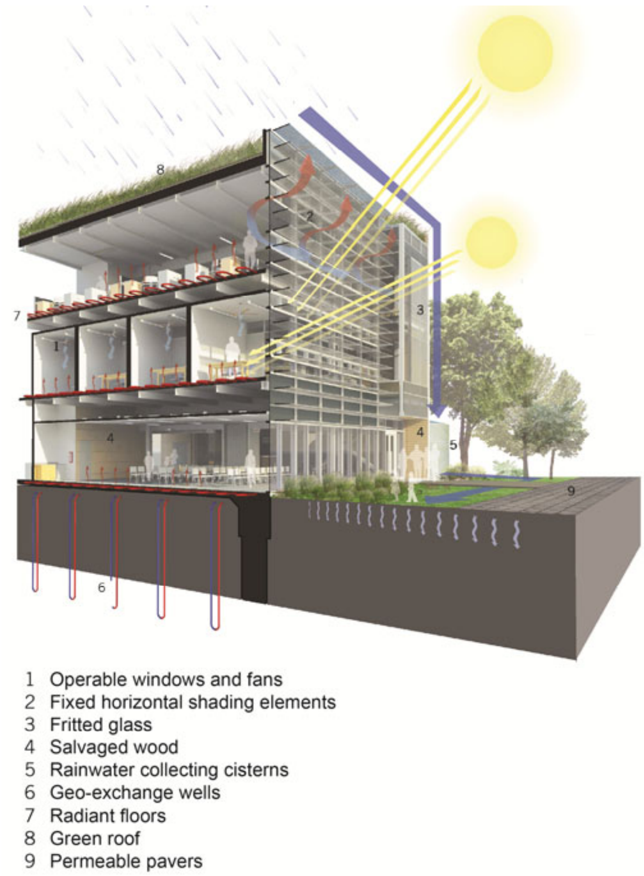

Figure 3. Building systems and sustainable design approaches.

Energy Modeling

The building design incorporated several advanced design methods. Table 1 shows modeling capability of such design features by the studied energy simulation tools.

Table 1. Modeling capabilities of energy simulation tools

	Vasari/GBS	Sefaira	eQUEST	EnergyPlus
Natural ventilation	Yes	Yes	Yes	Yes
Radiant heating and cooling	No	No	Yes	Yes
Light-shelves	Yes	Yes	Yes	Yes
Occupancy sensors	Yes	Yes	Yes	Yes
Heat recovery system	Yes	Yes	Yes	Yes
Vertical geo-exchange wells	No	Yes	Yes	Yes

Energy Modeling with Vasari/GBS

The modeling of the case study building began by modeling its geometry Vasari, as seen in Figure 4. Then, inputs for building's occupancy patterns, systems, equipment, lighting and plug loads were selected that describe the building in more detail. Cloud-based simulations were performed by using Autodesk's subscription to Autodesk 360, which prepares the model and uploads to Autodesk's servers for analysis. The data exchange was performed through the GBXML file schema. Changes to the model can be made, and different sets of simulations can be run fairly quickly. For the case study building, that was not conducted since the building is already built and occupied.

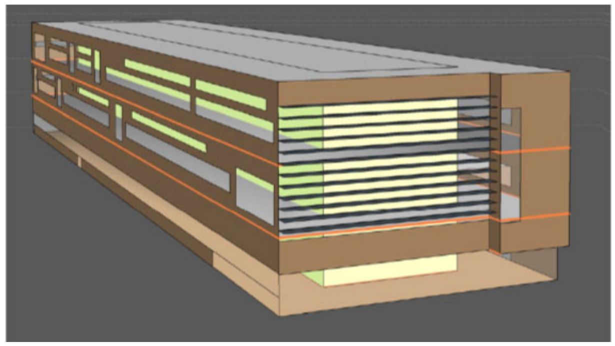

Figure 4. Energy model in Vasari.

Energy Modeling with Sefaira

In order to have an identical model to compare WBEA results to Sefaira, the Vasari model had to be imported into SketchUp. Before Sefaira can run a simulation, building components (i.e. walls, floors, roofs, and glazing) must be assigned as "entities" using the Sefaira Plugin for SketchUp. This is how Sefaira is able to assign values and understand the geometries in the in order to run simulations. Figure 5 shows the model coming from SketchUp and the overall results.

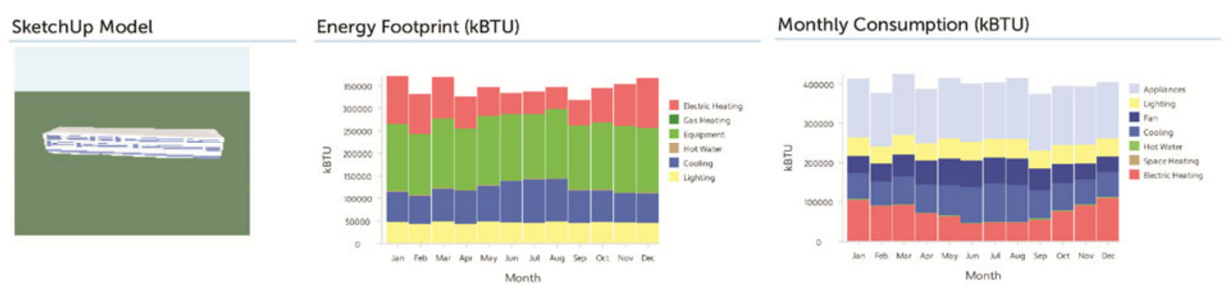

Figure 5. Energy model in Sefaira.

Building components are automatically organized into categories known as "entities". The user can manually select and change the "entities" if certain components are designated incorrectly. The SketchUp model file then must be uploaded on Sefaira's online site in order for WBEA simulation to be conducted, which was conducted for the case study building. The building parameters for space use, zones, HVAC systems, occupancy patterns and loads were then assigned, and simulations were run. Sefaira also offers an ability to create different design alternatives to investigate different design strategies and their effects on energy consumption, but that was not conducted for the case study building.

Comparison of Results to Actual Building Performance Data

Figure 6 shows actual energy usage for the case study building. This data was collected over a period of one year, from May 2012 to June 2013. The data was collected almost two years after the building occupation, in order to allow continuous operation of building systems and commissioning. Since the building is a research laboratory building, the energy usage is relatively constant due to equipment loads and cooling loads that are present during the entire year. The measured EUI for the building is 94 kBtu/ft^2 (321 kWh/m^2), and the total annual energy consumption is 4,774 MBtu (1,399 kWh).

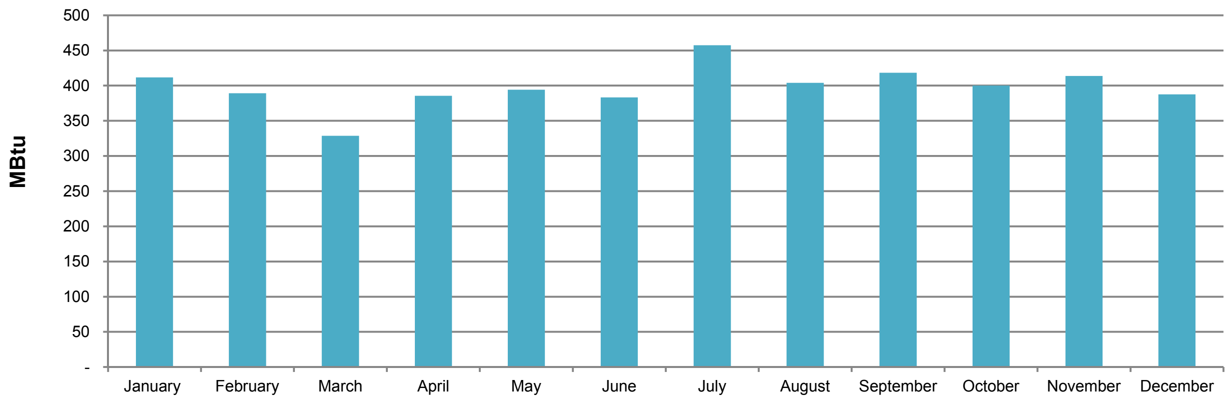

Figure 6. Actual monthly energy usage data for the case study building.

Figure 7 shows modeled annual energy usage results from Vasari/GBS. The graph shows total modeled energy consumption, as well as actual building energy performance. Comparing the total energy usage to the actual performance data, it is evident that modeled energy usage in Vasari/GBS is significantly higher than the actual energy usage. Simulation results from Vasari/GBS indicated that lighting loads would be a significant part of the overall energy usage for the building and that it would be constant throughout the year, which is not the case. The modeled EUI from Vasari/GBS for the building was 148 kBtu/ft^2 (505 kWh/m^2), and the overall annual consumption was 7,527 MBtu (2,206 kWh).

Figure 8 shows modeled annual energy usage results from Sefaira. The graph shows total modeled energy consumption, as well as actual. Comparing the total energy usage to the actual performance data, it is evident that the monthly energy usage data is close to the actual energy usage data, but there are some discrepancies for the monthly loads. Generally, the modeled energy consumption is higher than the actual energy usage during colder months. However, summer loads tend to be lower than the winter loads, which even for the temperate climate of Tacoma is typically not the case. The modeled EUI from Sefaira for the building was 95 kBtu/ft^2 (324 kWh/m^2), and the overall annual consumption was 4,821 MBtu (1,413 kWh).

Figure 9 shows summary of results, and comparison between modeled energy usage and actual energy usage data for different software programs. Modeled energy data from Vasari/GB is significantly higher than the actual data, while modeled energy data from Sefaira is close to the actual. Therefore, designers need to cautious about selection of appropriate tools for conceptual whole building energy analysis.

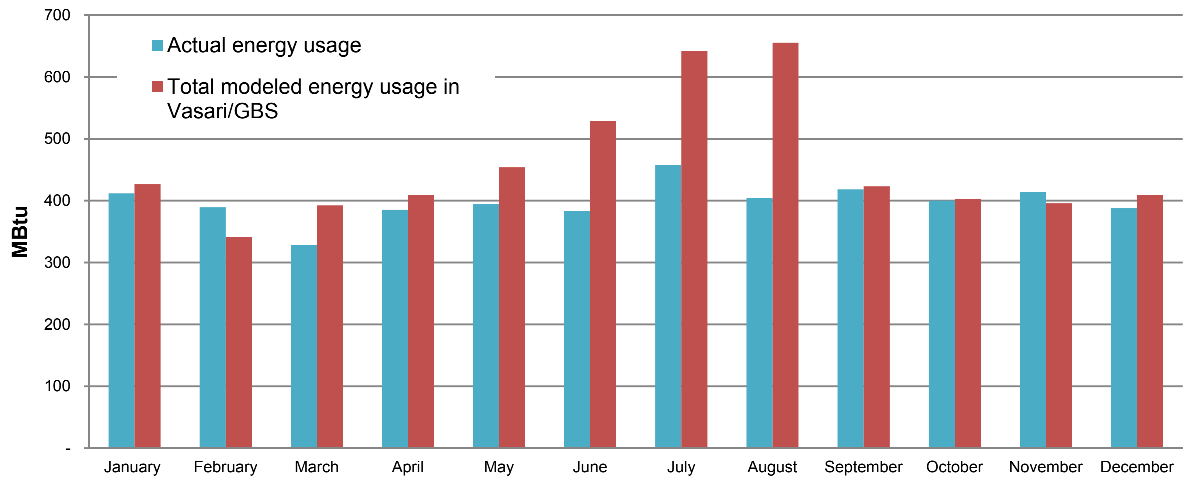

Figure 7. Modeled energy usage data from Vasari/GBS for the case study building.

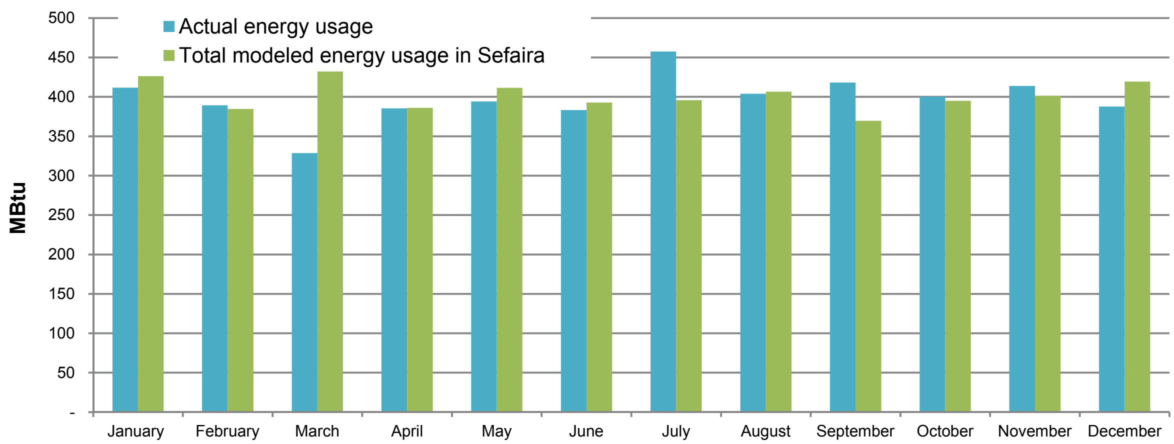

Figure 8. Modeled energy usage data from Sefaira for the case study building.

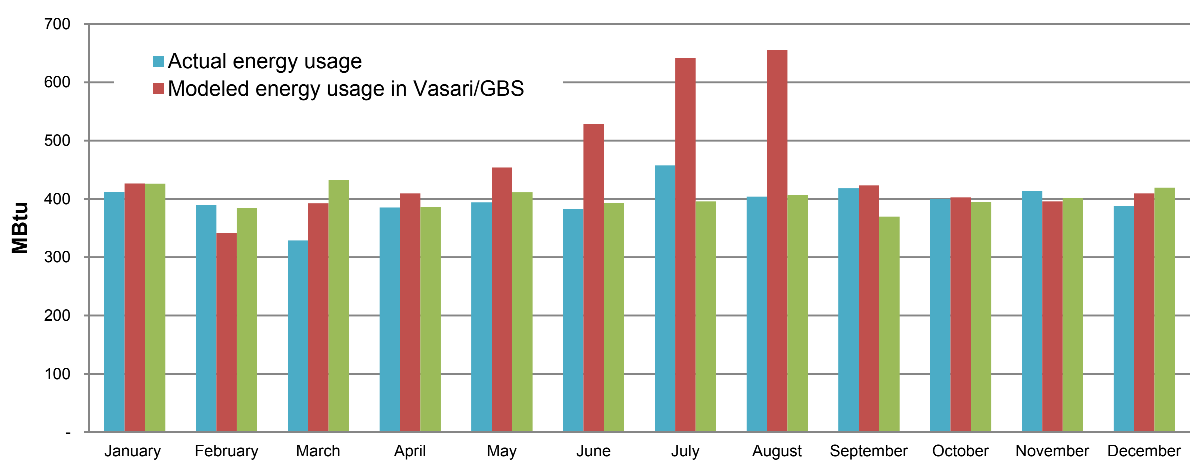

Figure 9. Comparison of actual and all modeled energy usage data.

Conclusion and Future Work

Design of energy-efficient and high-performance buildings requires that building performance and simulations tools are used and integrated with the design process. The purpose of this research was to document a comparative analysis of different simulation tools that are appropriate for early conceptual stages of the design process. We analyzed and simulated energy usage of a recently constructed and occupied building in two different programs aimed for early energy analysis (Vasari/GBS and Sefaira), and compared it to the actual measured energy usage. The results show that there may be large discrepancies between simulated results and the actual energy data. Specifically, the modeled results from Vasari/GBS were 63% higher than the actual data (mostly due to the inabilities of the software to take into account advanced lighting and HVAC system), while the modeled data from Sefaira was only slightly higher (1%), but did not follow the same monthly energy consumption pattern as the actual data (summer loads were lower than the winter loads). It is crucial to understand the limitations of different tools in order to successfully integrate building performance analysis in early stages of the design process. In addition, this study focused on one specific building, and it must be stated that some aspects can be generalized (such as inadequacies of the programs to take into account advanced energy-efficiency strategies), while some aspects are specific for this particular case study (such as lower modeled summer loads for a building with high equipment loads throughout the entire year).

The next step for this research is to extend the simulations and modeling, and complete energy models for the case study building in two additional software programs: eQuest and EnergyPlus. These two software programs are geared more towards the schematic design and design development stages of the design process. We will then compare the results to the actual building energy usage data, as well as results from Vasari/GBS and Sefaira. Those results will give us an insight into similarities and discrepancies between results coming from conceptual energy modeling tools, more robust modeling tools geared towards later stages of the design process, and the actual energy usage.

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