A STRATEGY FOR ENERGY PERFORMANCE ANALYSIS AT THE EARLY DESIGN STAGE: PREDICTED VS. ACTUAL BUILDING ENERGY PERFORMANCE

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ABSTRACT

Developments in information technology are providing methods to improve current design practices, where uncertainties about various design elements can be simulated and studied from the design inception. Energy and thermal simulations, improved design representations and enhanced collaboration using digital media are increasingly being used. 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 improve building performance. The purpose of this research was to investigate the potential of these programs to perform whole building energy analysis during the early stages of architectural design, and compare the results with the actual building energy performance. The research was conducted by simulating energy usage of a fully functional research laboratory building using two different simulation tools that are aimed for early schematic design. The results were compared with utility data of the building to identify the degree of closeness with which simulation results match the actual energy usage of the building. Results indicate that modeled energy data from one of the software programs was significantly higher than the measured, actual energy usage data, while the results from the second application were comparable, but did not correctly predict monthly energy loads for the building. This suggests that significant deviations may exist between modeled and actual energy consumption for buildings, and more importantly between different simulation software programs. Understanding the limitations and suitability of specific simulation programs is crucial for successful integration of performance simulations with the design process.

KEYWORDS

building performance analysis, simulated vs. actual energy usage in buildings, architectural design

INTRODUCTION

Building performance simulation tools are increasingly used for analysis of the energy performance of buildings (Augenbroe et al. 2004, Aksamija 2009, Aksamija 2010, Wetter 2011, Aksamija 2012). Building energy simulation is a powerful method for studying the energy

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performance of buildings and for evaluating architectural design decisions, as well as choices for construction materials and methods. Complicated design issues can be examined, and performance of different design strategies can be quantified and evaluated. Currently, there are many building performance simulation programs with different user interfaces and different simulation engines that are capable of these analyses (Crawley et al. 2008).

Simulation and energy analysis are essential to designers in developing effective forms and components for their buildings. Building energy simulation is an analysis of the dynamic energy performance of a building using computer modeling and simulation techniques. There is a wide range of simulation tools available that help predict various aspects of building behavior, such as energy performance, acoustical performance, fire movement, structural performance, life-cycle assessment, etc.

Energy performance simulation tools allow designers to:

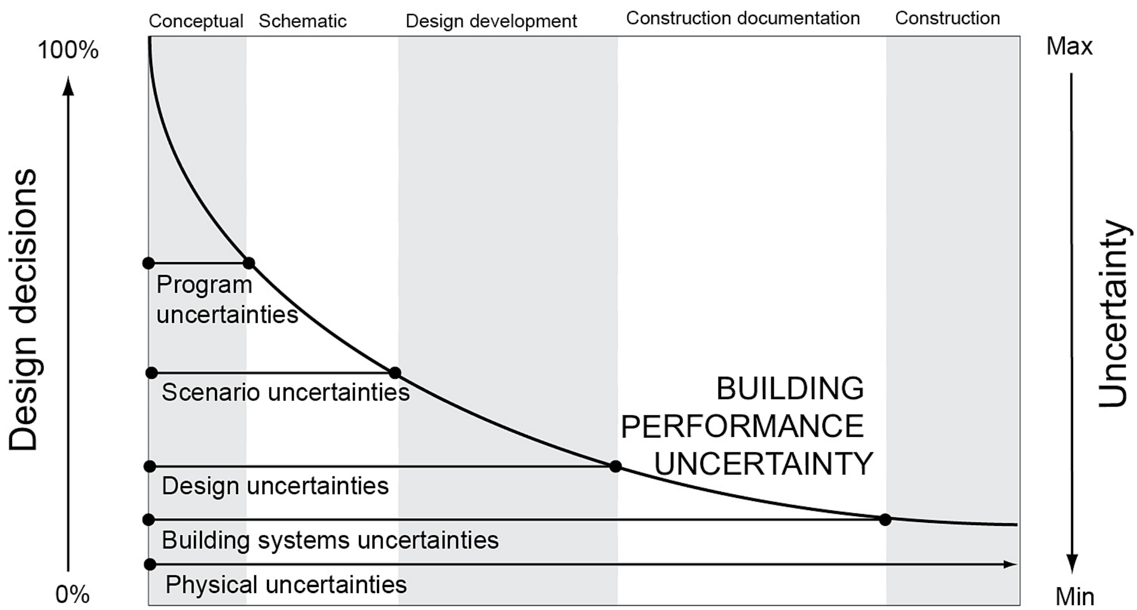
- Predict thermal behavior of buildings in relation to the outdoor environment.
- Simulate the impact of daylight and artificial light inside buildings.
- Estimate the size/capacity of equipment required for thermal and visual comfort, and the associated energy usage for their implementation.
- Calculate the effect of various building components on each other and predict resulting conditions.
- Check for compliance with energy codes.
- Consider the building as a single integrated system.

However, past research on the utilization of simulation tools during the architectural design process indicates that despite the increase in number of available tools in the last decade, some architects and designers find it difficult to use these tools, since they are not compatible with the working methods and needs, or the tools are judged as complex and cumbersome (Gratia and de Herde 2002, Punjabi and Miranda 2005). To remain competitive, design professionals must weigh the value of information gained through simulation tools against the invested time and resources, and against the value of comparable information that might be gained through other means.

In order to evaluate and optimize building performance, different analysis cycles should be part of an integrated design process. Tools and applications that support integrated design and analysis from the earliest stages of the design can aid the decision-making process (Aksamija 2012). Figure 1 shows the impact of design decisions on actual building performance and relationships to project stages, as well as uncertainties about building components that are present during the different stages of the design.

As early as the conceptual phase, the analysis should focus on design aspects such as climate information, orientation, passive strategies, programming and building massing. Then at the schematic stage, the analysis should explore shading methods, solar access, and building envelope design options. During the design development stage, optimization of shading devices, daylight and glare studies, detailed energy performance studies, thermal analysis and optimization should take place. It is important to note that these types of studies have the greatest impact on building performance if they are conducted early in the design process (conceptual, schematic and design development phases). They should not be performed during the construction documentation phase, since their impact on building performance is too small to justify analysis at this stage, and the cost of design changes is typically prohibitive. Therefore, simulation tools and applications that can be used in early stages of the

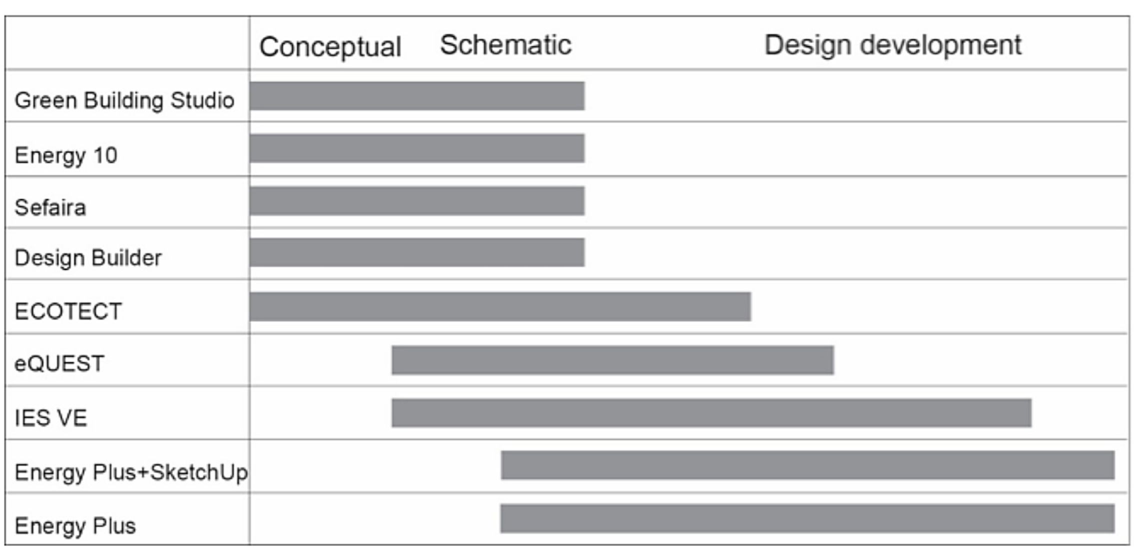
Figure 1: Design decisions and effects on building performance uncertainties in relation to different stages of the architectural design process.



design process are important for energy-efficient design, decision-making and investigations of design strategies that can be used to improve the overall building performance.

Figure 2 shows several building performance analysis tools and applications, and their applicability to different design stages. For example, during the early stages of the design process (conceptual and schematic design), tools such as Green Building Studio, Energy 10, Sefaira, Design Builder and Ecotect are applicable. During the schematic and initial design development stages, tools such as eQuest, IES VE, and EnergyPlus with OpenStudio plug-in for SketchUp are applicable. During the design development stage, EnergyPlus is the most

Figure 2: Energy and environmental analysis software applications in relation to design stages.



useful energy modeling tool, since its robustness allows for detailed calculations and optimization of building systems.

But, how are these different applications used in architectural design? A recently conducted survey investigated utilization of building performance tools in architectural practice, particularly comparing these following simulation programs: ECOTECT, HEED, Energy 10, Design Builder, eQuest, DOE-2, Green Building Studio, IES VE, Energy Plus and Energy Plus-SketchUp plug-in (OpenStudio) (Attia et al. 2009). With 249 responses, the survey ranked the utilization of tools and investigated requirements for potential future improvements of these applications. Findings indicated that Ecotect is currently most widely used (156 users), followed by eQuest (123 users), EnergyPlus-SketchUp (81 users) and EnergyPlus (81 users), IES VE (60 users), Energy 10 (57 users), Design Builder (54 users), DOE-2 (48 users), HEED (45 users) and Green Building Studio (27 users).

1.1 Research Purpose and Objectives

The intent of this work was to conduct a comparative analysis research on conceptual Whole Building Energy Analysis (WBEA) programs, which are applicable to early design stages. The purpose is to inform designers and engineers about the potential for integrating simulation programs with the design, which would yield accurate predictions about the building performance from the earliest stages of the design process. This is an essential aspect in the design of high-performance buildings, and improvement of 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, as discussed in the previous section. However, integration with the design process and BIM technologies are newer concepts, which are still being investigated (Aksamija and Mallasi 2010, Aksamija 2012). In essence, WBEA is the process of analyzing a building's energy performance by calculating how well the building's form, systems, and envelope perform under the surrounding environmental conditions. Software tools that integrate graphical results with context-sensitive guidance are likely to have the most appeal for architects and designers. 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 later design stages, when majority of the project details have been finalized.

When a building is modeled for the same climate in different simulation programs, the outputs of simulation runs are 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, Maille et al. 2007). This is a major issue for successful integration of performance simulations with the design process, especially for early stages of the design. In the conceptual and schematic design phases, design decisions can have a significant impact on the overall building performance and its energy usage (such as building massing, geometry, orientation, window-to-wall ratio, shading strategies, etc.). Therefore, the objectives of this study were:

- To conduct literature review and identify current research efforts relating to integration of building performance simulation programs with design process, and relationships between simulated and measured energy performance in buildings.

- To investigate properties and applicability of two different software programs, which are suitable for early stages of architectural design process (Vasari/Green Building Studio and Sefaira).
- To model a building similarly in these 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, and identify which simulation tools are better suited for early stages of the design.

1.2 Methodology

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. This can be achieved by integrating BIM technologies with energy simulations, however, most BIM-based WBEA software are new or still in beta versions. Therefore, this study was conducted to test two different software programs by modeling the energy usage of an existing building, and comparing to the actual building performance data.

Different simulation programs may have different software architecture, different algorithms to model building and energy systems, and require different user inputs even to describe the same building envelope or HVAC system components. For this study, the research methodology was to identify a recently designed and constructed existing high-performance building, and to model the identical inputs for building systems, environmental conditions, control strategies, and material components in different software programs. Simulations were completed using Vasari/Green Building Studio (GBS) and Sefaira, both of which have been specifically developed for early conceptual design.

2. LITERATURE REVIEW

There are existing studies that compare modeling capabilities of different building performance simulation programs (Maile et al. 2007, Crawley et al. 2008). Different tools have different modeling features and methods for describing the building and its systems, as well as calculation methods. But, regardless of the type of simulation tool, it is necessary to validate results and understand the capabilities of modeling software programs. For example, the Building Energy Simulation Tests (BESTEST) were developed to standardize methods for testing building energy analysis computer software (NREL 1995). The methodology prescribed by BESTEST has been adopted by the ANSI/ASHRAE standard method for testing and evaluating building performance analysis tools (ASHRAE 2001). Existing research exists that reviews validation of several building energy simulations programs using this method, comparing results from the studied software programs to analytical solutions developed for test cases (Neymark 2002).

One of the primary methods for investigating the validity of energy modeling and building performance simulation results is by comparing the modeled results to actual building performance data (Ryana and Sanquist 2014, de Wilde 2014, Fumo 2014). A recently published literature review by de Wilde suggests that there is often significant differences between predicted energy performance of buildings and actual measured energy use (2014). It suggests that there are three main types of performance gaps: 1) between initial predictions and measurements, 2) between computational models and measurements, and 3) between predictions and performance certificates in legislation. It also states that the current literature on the energy performance gap suggests various causes for the mismatch between predicted and measured energy usage in buildings, which can be grouped into three categories:

- Causes related to the design stages (such as modeling inputs not closely resembling the real conditions, building occupancy schedule, equipment loads, etc.)
- Causes related to construction stage (such as building elements and systems not being constructed as intended)
- Causes related to operational stage (such as building systems not being properly commissioned).

But how big are these discrepancies? 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, Fowler and Rauh 2008, Turner 2008, Turner and Frankel 2008, Newsham et al. 2009, Widener 2009, Scofield 2009, Stoppel and Leite 2013). The common performance measure that was used in these studies is the Energy Use Intensity (EUI) parameter (kBtu/ft^2 or kWh/m^2). It is calculated by adding energy usage for all building systems on an annual basis (for heating, cooling, ventilation, lighting, hot water needs, equipment), and normalizing by the building's gross area. This allows comparison among different buildings of similar types, and is commonly used to compare predicted to actual energy consumption. But, it does contain limitations since it does not distinguish between buildings with differing occupant density, usage patterns or process loads.

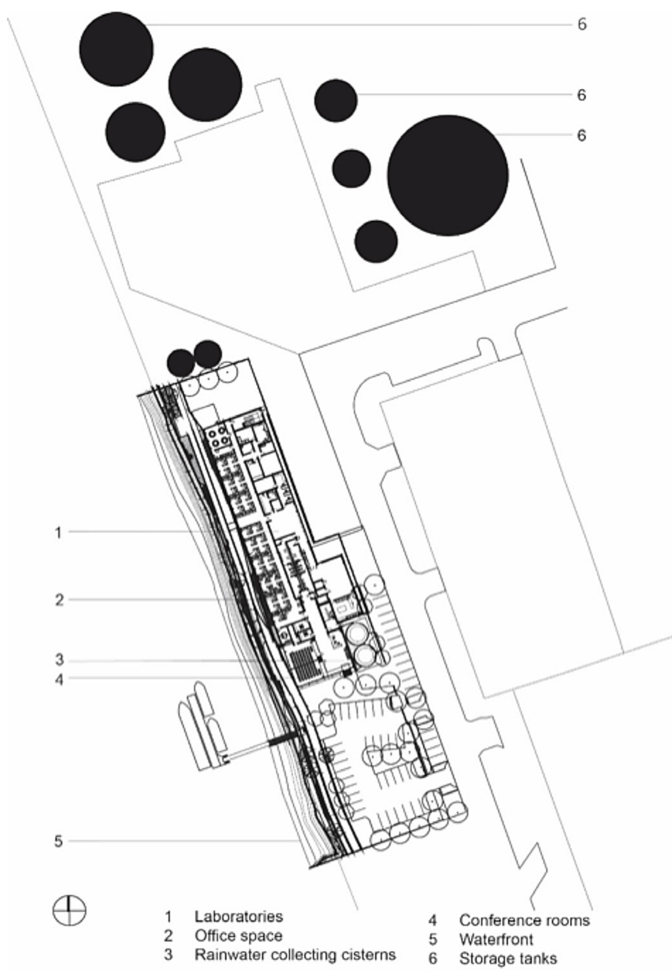
Results of studies that investigated predicted vs. actual energy performance of large data sets of buildings suggest that significant variation among individual buildings may exist (Diamond et al. 2006, Turner 2008, Turner and Frankel 2008, Widener 2009). For example, Turner and Frankel conducted a study of 121 LEED certified buildings, and their findings indicate that the average predicted annual energy savings of 25% (compared to energy code baseline buildings) was close to the actual measured savings of 28% (2008). However, they found significant variation among individual buildings, where over half of the buildings differed from the design predictions. Specifically, over 30% performed significantly better and 25% performed significantly worse.

There is ongoing research that aims to identify key issues that need to be addressed in order to reduce this gap between simulated and measured energy performance (Korjenic and Bednar 2012, Ham Golparvar-Fard 2013, Katunsky et al. 2013, de Wilde 2014). For example, one of the investigated approaches is to use dynamic simulations and precise input data, where the input data is coming from measurements of energy usage for each part of the HVAC system and equipment (Korjenic and Bednar 2012, Katunsky et al. 2013). This approach has been investigated for commercial office buildings and industrial buildings. Another method is to use digital and thermal imagery to analyze existing buildings and develop spatio-thermal models, which can be used to detect deviations from simulated data and improve simulation accuracy through model calibrations (Ham Golparvar-Fard 2013). This approach has been applied to residential and educational buildings. However, both of these methodologies are only applicable to existing buildings and determination of retrofitting design strategies to improve their energy performance. It is much more challenging to address these issues during the design process of new buildings. The literature suggests that the performance gap for new buildings can only be bridged by a broad, coordinated approach that combines model validation and verification, improved data collection for predictions, improved forecasting and change of industry practice (de Wilde 2014). It is necessary to expand collection of data, provide deep insights into individual cases, apply validation and verification to energy prediction methods, and investigate applicability of different tools and software applications and their accuracy. Therefore, the following case study provides an in-depth analysis of simulated vs. actual energy usage for a specific building, specifically investigating results of two software programs that are aimed for early architectural design and their correlation to actual, measured data.

3. 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 3).

Figure 3: 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. Locating them adjacent to the industrial neighborhood, with its reduced opportunities for fresh air, was a practical response to the site.

On the other hand, natural ventilation for the office spaces was considered highly desirable. By facing the waterway, 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 4 shows natural ventilation and shading strategies.

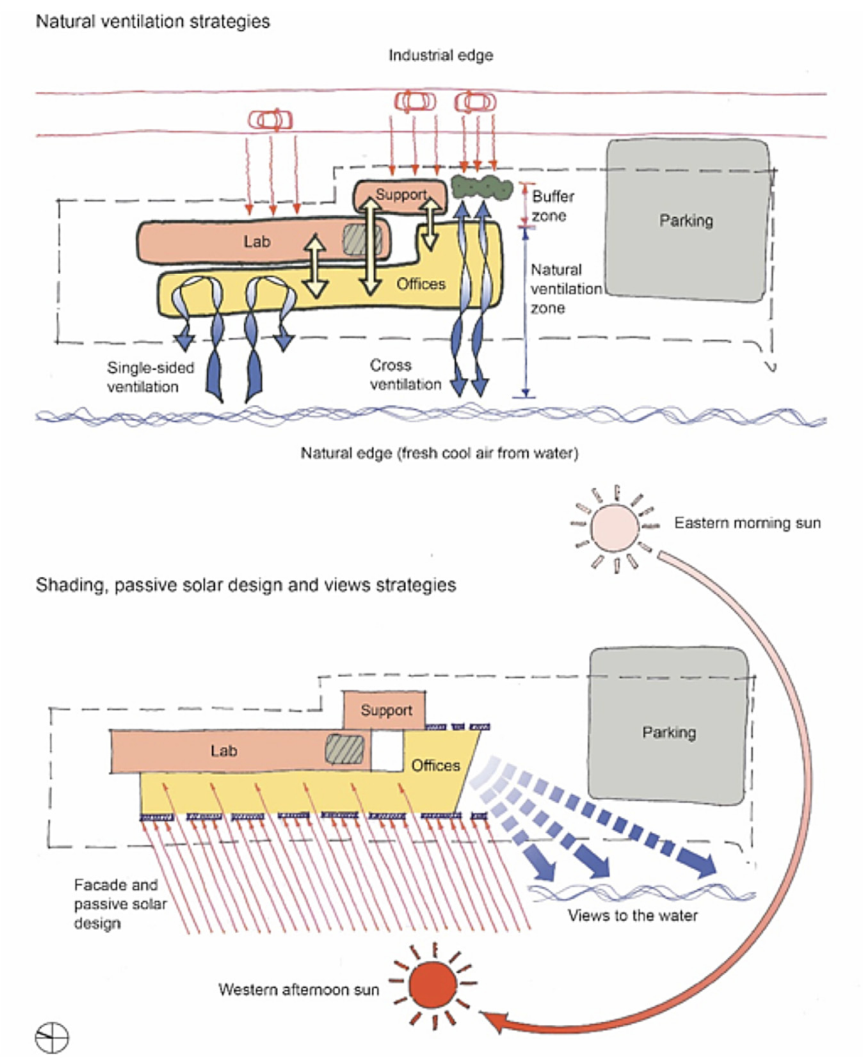
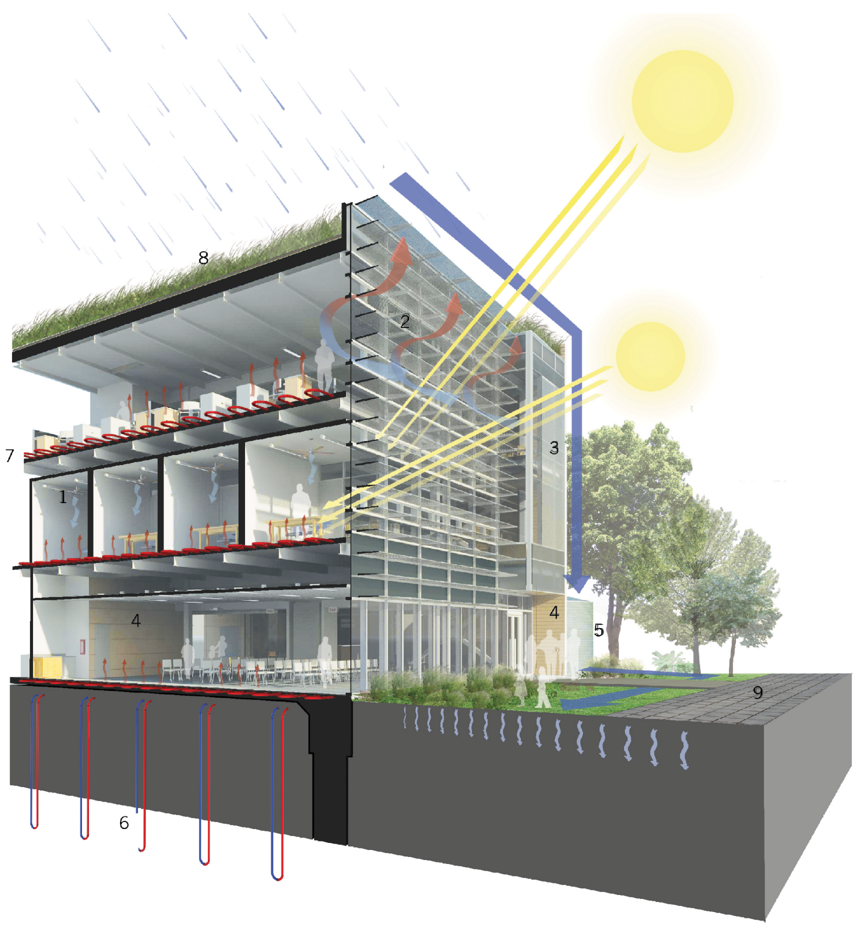


Figure 4: Passive design strategies for shading and natural ventilation.

The western facade consists of an aluminum rainscreen system 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. The south facade consists of a curtain wall with fixed exterior horizontal sunshades, and fritted glass. On the east and north facades, a 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 5: Building systems and sustainable design approaches.



1 Operable windows and fans
2 Fixed horizontal shading elements
3 Fritted glass
4 Salvaged wood
5 Rainwater collecting cisterns
6 Geo-exchange wells
7 Radiant floors
8 Green roof
9 Permeable pavers

HVAC systems include a radiant heating and cooling system in the floors, vertical geo-exchange wells, and a heat-recovery system in the laboratories and office spaces (Figure 5). Other energy-efficiency and sustainability strategies include vegetated roofs, stormwater collection, water reuse, use of recycled and reclaimed materials, as well as a measurement and verification system that tracks actual building performance and informs users of real-time energy use. During the design process, the modeled energy consumption showed that the EUI for this facility would be 81 kBtu/ft^2 (256 kWh/m^2). This indicated that energy savings would be 36% compared to an ASHRAE 90.1 baseline building's EUI of 123 kBtu/ft^2 (388 kWh/m^2). The building was completed in 2010, and achieved LEED Platinum certification by the U.S. Green Building Council.

4. ENERGY MODELING

The building design incorporated several advanced design methods, as discussed in previous section. Table 1 shows the modeling capability of such design features by the studied energy simulation tools.

Table 1: Summary of modeling capabilities of investigated energy simulation tools.

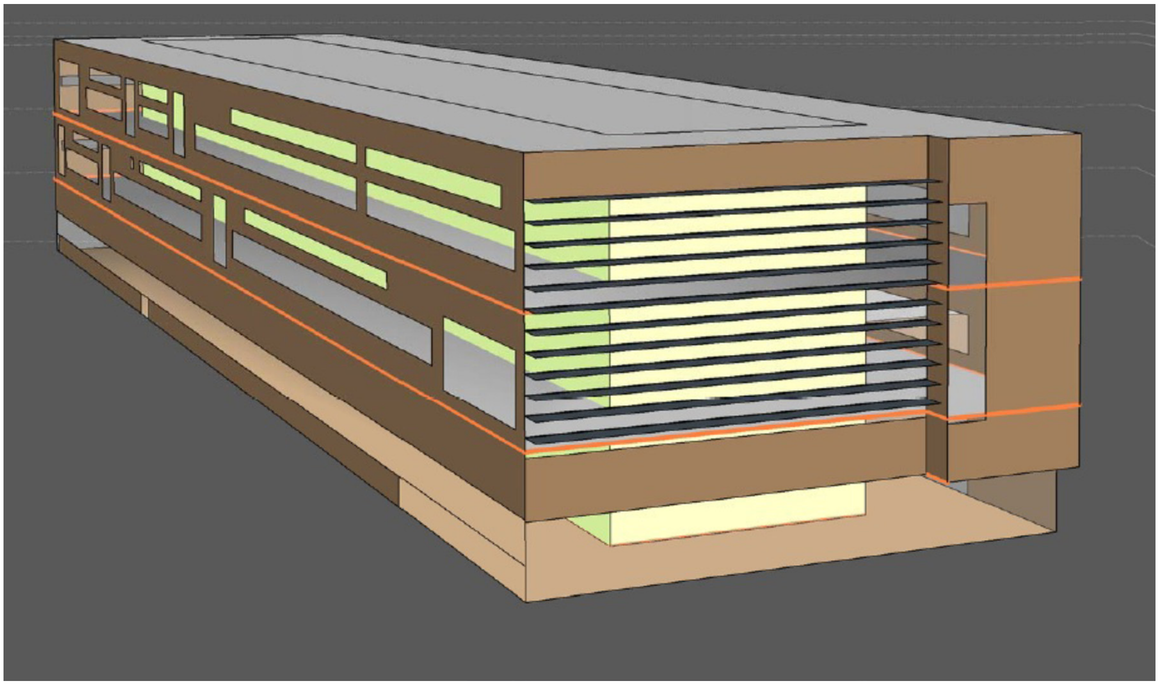
	Vasari/GBS	Sefaira
Natural ventilation	Yes	Yes
Radiant heating and cooling	No	No
Light-shelves	Yes	Yes
Occupancy sensors	Yes	Yes
Heat recovery system	Yes	Yes
Vertical geo-exchange wells	No	Yes

4.1 Energy Modeling with Vasari/GBS

Vasari/GBS is one of Autodesk's design software tools 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 an 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.). Vasari/GBS use DOE-2.2 for its energy analysis engine.

The modeling of the case study building began by modeling its geometry in Vasari, as seen in Figure 6. Then, inputs for the building's occupancy patterns, systems, equipment, lighting and plug loads were selected that describe the building in more detail. Cloud-based simulations are performed by using Autodesk's subscription to Autodesk 360, which prepares the model and uploads to Autodesk's servers for analysis. The data exchange is performed

Figure 6: Energy model of the case study building in Vasari.



through the gbXML file schema. Simulations are conducted, and results are returned directly to Vasari, allowing the user to visualize the basic results. Changes to the model can be made, and different sets of simulations can be run fairly quickly. For the case study building this was not conducted since the building is already built and occupied.

4.2 Energy Modeling with 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.

As a general overview, the process in this study was to first build the conceptual model in Vasari, as outlined in the previous section. 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 plug-in for SketchUp. This is how Sefaira is able to assign values and understand the geometries in order to run simulations. Figure 7 shows the model coming from SketchUp and the overall results.

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 website in order for WBEA simulations to be calculated, which was conducted for the case study building. The building parameters for space use, zones, HVAC systems, occupancy patterns and loads were

Figure 7: Energy model of the case study building in Sefaira.

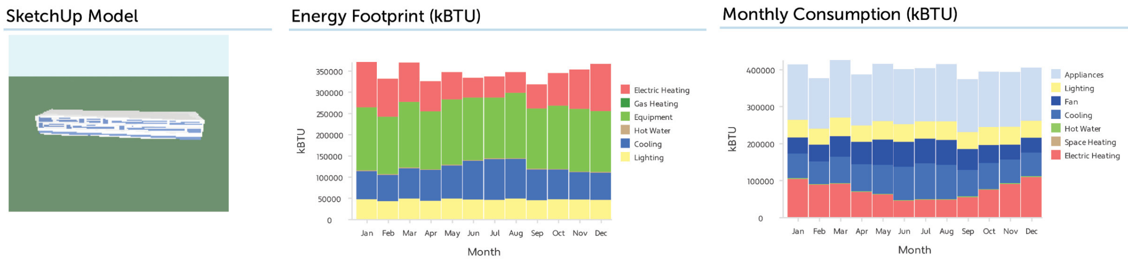
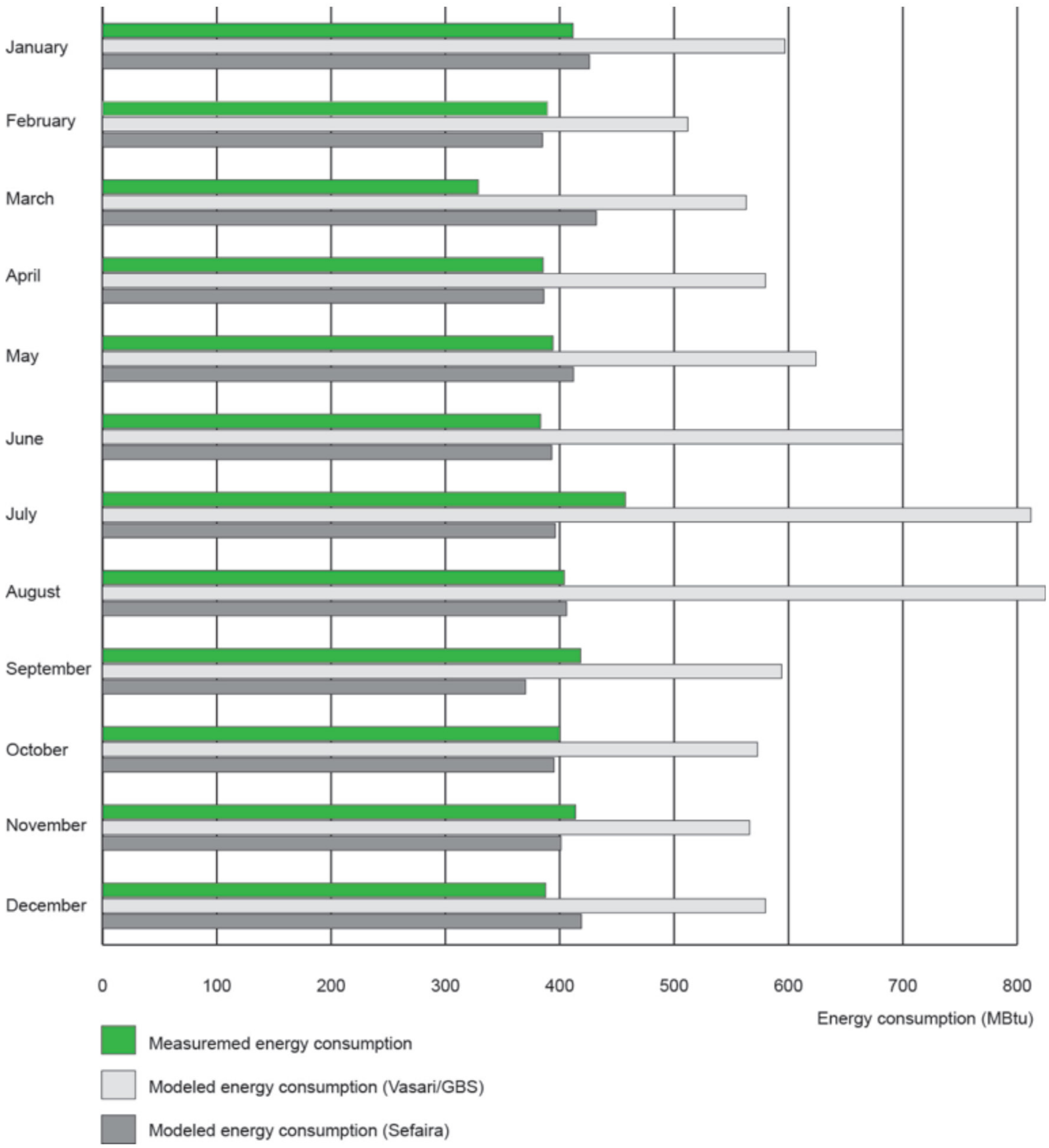


Figure 8: Comparison of actual and all modeled energy usage data.



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.

5. COMPARISON OF RESULTS TO ACTUAL BUILDING PERFORMANCE DATA

The actual energy usage data for the case study building 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 MWh).

Figure 8 shows a summary of results, and comparison between modeled energy usage and actual energy usage data for the two different software programs. Modeled energy data from Vasari/GB is significantly higher than the actual data, while modeled energy data from Sefaira is comparable (but does not match the monthly energy loads for the building). Table 2 shows comparison between the monthly modeled data and measured values, and Table 3 shows a comparison between the overall modeled and measured EUIs.

Table 2: Comparison of monthly modeled and measured energy consumption data.

Month	Vasari/GBS (MBtu)	Sefaira (MBtu)	Measured energy usage (MBtu)
January	597	426	412
February	512	385	389
March	563	432	329
April	580	386	385
May	624	412	394
June	700	393	383
July	812	396	457
August	825	406	404
September	594	370	418
October	573	395	400
November	566	401	414
December	580	419	388
Total	**7,527**	**4,821**	**4,774**

Table 3: Comparison of modeled and measured EUIs.

	EUI (kBtu/ft^2)	Change from measured EUI (percentage)
Vasari/GBS	148	+57%
Sefaira	95	+.01%
Measured	94	0

Comparing the modeled energy usage results from Vasari/GBS to the actual performance data, it is evident that the modeled energy usage in Vasari/GBS is significantly higher than the actual. 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 building design incorporated several advanced design methods for providing daylight (narrow building plate, daylight redirecting mechanisms such as light-shelves, occupancy sensors), which the modeling capabilities in Vasari/GBS cannot fully support. Therefore, it was found that modeled energy data from Vasari/GBS may not accurately portray the effects of advanced design strategies on energy consumption. 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).

Comparing the modeled energy usage results from Sefaira 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 lower than the actual energy usage for the majority of 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).

When we analyze monthly results, results from Vasari/GBS are higher than actual energy consumption for all months, and especially during summer season. Monthly results from Sefaira show variation compared to the actual data. For example, modeled results are higher than actual for January, March, May, June, November and December. During February, July, September and November are lower; and are comparable during April and October.

These results suggest that significant deviations may exist between modeled and actual energy consumption for buildings, and more importantly between different simulation software programs. The two investigated simulation programs are geared towards early stages of the architectural design process, and designers should be cautious in selecting and choosing the appropriate tools to investigate energy performance during the early stages of design process. Understanding the limitations and suitability of specific simulation programs is crucial for successful integration of performance simulations with the design process. Especially important are the early stages of the design process, since the design decisions at these stages can have a significant impact on the building performance. Therefore, it is necessary to select the tools and applications that have the ability to take into account passive design strategies (shading, building envelope treatment, daylighting, natural ventilation), as well as active design strategies (HVAC equipment) and occupancy/building operation inputs, and infer how combined energy-efficiency design strategies will influence building performance.

6. 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. Moreover, results have indicated that different simulation programs may provide different results, where some tools may predict significantly larger energy consumption and some tools may predict lower energy usage in buildings, compared to actual measured data. This is a major concern, since the design and construction industry may require performance-based design and delivery in the near future, where design professionals might be legally liable for the energy performance of the buildings that they design. This changing paradigm would require use of simulation and modeling tools from the earliest stages of the design, through design development. Therefore, 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.

Next step of 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. 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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