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Quick design analysis for improving building energy performance

N. Brown^{a,b*}, M. S. Ubbelohde^{a,c}, G. Loisos^a, S. Philip^a^a*Loisos+Ubbelohde, 1917 Clement Ave, Bld 10A, Alameda, CA 94501 USA*^b*California College of the Arts, 1111 8th St, San Francisco, CA 94107 USA*^c*University of California, Berkeley, 130 Wurster Hall #1820, Berkeley, CA 94720 USA*

Abstract

A building's overall energy performance may be understood as the variation of its energy balance and the extent to which additional heating or cooling energy is needed to maintain comfort. Different characteristics of a building impact the energy performance in ways that vary over time. Transmitted solar gain, for instance, might be an asset at one moment and a liability at another. Architects, designers, and builders often want to know how well a building can be expected to perform in this regard, and they are interested to know what improvements might be the most effective to reduce overall energy use. Many projects lack the budget required for an extensive energy analysis, which is a common approach for answering such questions, while often energy-efficiency guidelines do not address project specific performance issues related to the interactions of site, program and design.

Quick analysis tools currently available tend to be inflexible and generic, and thus of limited use in giving design teams feedback about a specific design proposal. This paper presents a cost-effective analysis technique that assesses envelope and internal load characteristics (eg, transmitted solar gain, heat gain/loss of thermal mass, heat gain from equipment, etc) of a building design in terms of their relative benefit or liability to overall conditioning loads. Using data from the energy simulation of one design alternative, the tool presents overall performance of each building characteristic as well as a detailed visualization of performance over all 8760 hours of a typical year. The cumulative ranking provides a prioritized list for overall building performance improvements, and the detailed data visualization suggests specific time periods on which the design team should focus.

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*Corresponding author.

Tel.: +1-510-521-3800; fax: +1-510-521-3820.

E-mail address: nathan@coolshadow.com.

1. Introduction

Energy consultants have an opportunity to influence building design through analysis of energy performance and also through expertise in recommending potentially high-performing design alternatives. Large projects tend to have the budget to hire specialized consultants to analyze the proposal as it progresses through design phases in addition to the energy simulation required by code. Small projects may benefit from the experience of energy experts in recommending design alternatives, but these projects rarely have a budget for design analysis beyond that which is required for energy code compliance.

1.1. Typical Quick Analysis Tools

We present here an example of the kind of quick analysis tool that consultants might use on a small residential project with limited time and budget. A small residence is modeled in a Building Energy Performance Simulation (BEPS) program, such as EnergyPro [1] or eQUEST [2]. These simulation platforms are simplified representations of thermal characteristics and behavior in buildings. They are commonly used programs in industry and have many default settings available to use instead of having to define characteristics from scratch for a particular project. The modeler will define the geometry of the project, again making decisions that simplify the model for expediency. Once the model is running, the consultant may test a number of “energy efficiency measures” (EEMs) to identify potential design modifications for their impact on energy use. The consultant may then produce a report with graphs including energy by end use (Fig. 1a), and energy by EEM (Fig. 1b).

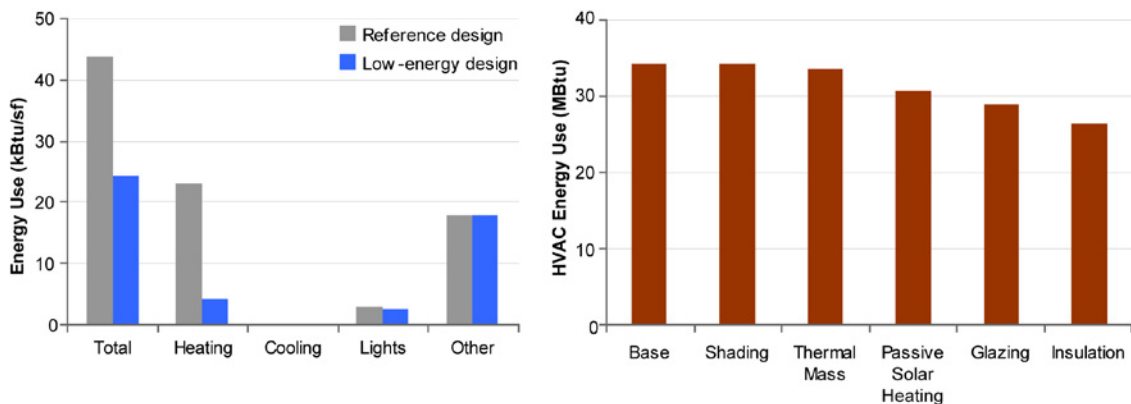


Fig. 1. (a) Example of energy end use graph shown in a typical quick analysis report; (b) Example of EEM graph shown in a typical quick analysis report; in this case, the report was assessing the effects of increasing shading, adding thermal mass, reconfiguring windows for passive solar heating, substituting more insulative glazing, and increasing insulation.

These graphs show something about the building in question: half of total energy use of a reference design is heating, and lights and other loads (equipment) account for the other half. They also show an estimate of building energy use and energy use intensity (EUI) that can be compared to benchmarks. The EEMs show that particular changes to the model had varying impacts, of which the addition of insulation had the biggest beneficial impact. Further analysis might combine EEMs into suites where multiple measures are applied to each simulation. With the budget limitations of a small project, the scenarios studied in this example are considered separately.

However, when design alternatives are tested through scenarios, they can only be understood through scenarios. In the design process, designers are continually considering which directions to pursue next, whether in initial design stages making decisions about massing and orientation, or in late design stages thinking about material specification and construction details. Typical quick analysis reports as described above can be problematic in that the analysis outputs are assessments of a finite set of alternatives. While patterns may be gleaned after looking at enough scenarios, each round of analysis is confined to the scenarios in question. For instance, the example graph above shows that using a different glazing product will improve performance. But will changing glazing area benefit the project? Would it be beneficial to add nighttime insulation over the windows rather than specify expensive glazing? These questions could be tested in further scenarios, but at the cost of further analytical iteration by the consultant. Furthermore, each subsequent test would similarly give information about only that tested scenario or suite.

The need for a quick analysis tool implies that the quality of the tool will be compromised relative to its counterpart, say the comprehensive analysis tool. In the example presented above, the compromises result in a tool that we characterize as:

- Inaccurate (relies heavily on default values and simplifications)
- Inflexible (relevant for only the scenarios studied)
- Crude (outputs tend to be summarized and not fine-grain)

1.2. Proposal for a New Quick Analysis Tool

The development of the Quick Analysis Tool arose out of our work with a client specializing in construction of customized homes using a standardized structural and building envelope system. The flexibility of the construction system was a potential boon to architects and owners, since it provided the economic benefits of mass production without constraining design. Our client found they were able to deliver very different projects using their system (Fig. 2). However, assessing the energy performance of these building became a challenge since each required new geometry to be input from scratch, and budget constraints allowed only a single BEPS iteration.



Fig. 2. Four client projects that were analyzed using the quick analysis tool. (clockwise from top left) Borrego Springs, CA, Amagansett, NY, Douglas City, CA, and Globe, AZ

We sought to develop a tool that would better meet the needs of analysis for small projects such as those pictured above. With the needs of these projects in mind, we defined the qualities of this tool as follows:

- The process required to build the BEPS model should be efficient.
- The analysis performed using the BEPS model should be automated and quick.
- Results should allow users to understand macro and micro performance, indicating overall performance and also the specific performance of envelope and internal load characteristics over time.
- The report should provide actionable suggestions for improving energy performance.

In addition to a description of the tool as designed, below we also present a case study of the Douglas City residence (lower right in the figure above) to demonstrate its utility for a project. While the quick analysis tool may be used to give feedback at multiple stages in the design process, the case study shows feedback that was given at a late stage of design.

2. Methods

Our goals for the quick analysis tool required a set of methods that would produce reliable, detailed output as well as intelligent synthesis of the outputs. This eliminates many rules of thumb and simplified BEPS platforms available, such as those mentioned above. Rather, we focused our development effort on efficiently getting information into a robust BEPS platform, and then automatically processing detailed outputs from the simulation.

2.1. Thermal Model

In order to build an accurate thermal model of the house, we selected EnergyPlus [3] as the BEPS platform. EnergyPlus provided a few key advantages for this study:

- subhourly calculation and explicit heat transfer reporting, allowing comparison between system loads and space loads at every timestep
- accurate representation of thermal mass effects [4]
- ability to explicitly control model geometry through Open Studio [5] for Google SketchUp [6], and build up a set of standard assumptions through a text editor

The first step in the process was to obtain a checklist of items from the client, including drawings of the design to be analyzed, characteristics of the envelope, and internal loads. This checklist helps to streamline the communication process prior to building the model. An EnergyPlus model is then constructed from this information. For characteristics not immediately known by the design team, such as occupant schedules, a set of standard assumptions are used, based on the ASHRAE energy efficiency standard for low-rise residential buildings [7] and/or residential energy use surveys [8]. Rather than modeling a specific HVAC system, the model is configured to report the system loads that would need to be met at each timestep in order to maintain a thermostat at a given temperature. The model is also configured to output heat flux for major envelope and internal load characteristics studied in the analysis:

- infiltration
- ventilation (according to design intent)
- conduction through inside wall surface

- conduction through inside floor surface
- conduction through inside ceiling surface
- conduction through windows
- transmitted solar gain
- lighting power
- equipment power

In addition, subgroups of components are identified by name. For example, if there are two distinct wall assemblies, it can be helpful to design teams to understand the impact of each wall type. Windows facing different orientations can be analyzed separately. Object names of each type are identified by a unique name that will allow results to be differentiated by type.

This tool requires only a single thermal model of the design at one point in time during the design process. However, it can also be helpful to show how the design performs relative to a conventional case (a known normative design). The case study presented here uses characteristics defined by the Title 24 energy code [9] as the conventional case, but other cases may use a conventional building based on other standards or local construction practices.

2.2. Calculation of Load Factors

We chose to look at the performance of the design characteristics in terms of annual load factors that indicate the aggregate annual contribution of each to potential HVAC load. Load factors are calculated for each building characteristic and for each subgroup of components using custom post-processing scripts. For each timestep in the simulation (typically a 15 minute interval), the heat flux to the space from each component is multiplied by the heat flux to the zone by the system. Heat loss from the space is counted as negative. Table 1 shows an example of this calculation. The resulting load factors provide a quantitative assessment of the impact of particular components on HVAC load; note that when the heat flux from a component is assisting the HVAC system, the load factor is positive. When the heat flux from a component occurs at a time when the system has the opposite sign (eg, there is heat loss from the floor at a time when the system is providing heating), the load factor is negative, indicating that the given component is fighting against the HVAC system.

Table 1. Example calculation of load factor at a particular timestep

	HVAC: 100 W (heating)	HVAC: -100 W (cooling)
Floor Conduction: 100 W (gain)	10,000 W ²	-10,000 W ²
Floor Conduction: -100 W (loss)	-10,000 W ²	10,000 W ²

2.3. Report

Once these load factors have been calculated, they are presented in a report in a variety of ways. First, the annual sum of load factors is calculated for each building characteristic. This identifies which characteristics are impacting HVAC loads the most over the course of a typical year, allowing the design team to prioritize improvements. Second, the HVAC load and load factors are presented as an annual visualization. This visualization allows the design team to gain insight into building performance and helps them develop strategies that are specific to the design. Last, a series of recommended alternatives

for performance improvement is provided based on priorities identified by load factors. Each of these report elements is discussed more thoroughly in the case study below.

3. Case Study

The building selected for this case study is a residence containing approximately 220 m² floor area, located in Douglas City, CA. The house consists of a single floor containing most of the living area and a small, partly subterranean basement was located below the main floor. Most of the glazed openings face south and are shaded by overhangs (Fig. 3 and 4). The house is designed to be off the grid. The architects deployed multiple sustainable strategies and were looking for analysis to test how the strategies were working. They also were interested to discover where modifications would be most effective.



Fig. 3. Douglas City residence, plan

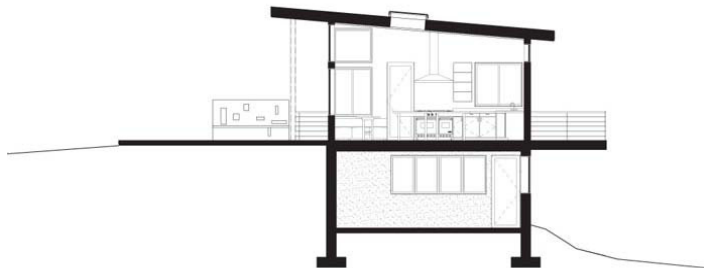


Fig. 4 Douglas City residence, section

3.1. Load Factor Summary

The load factors calculated for the Douglas City residence are graphed in Fig. 5. Load factors that on the whole increase demand for HVAC are shown in red, and those that on the whole decrease demand are shown in green. As described above, a second model was simulated in the process to describe the performance of “conventional” building characteristics defined by a Title 24 prescriptive envelope. This conventional case was not constructed as a compliance model; rather, it is meant to assess the performance of the design with normative materials and no shading. The load factors for the conventional case are shown in gray. For the Douglas City residence, the load factor associated with window conduction heat gain and loss was the most significant negative factor, followed by infiltration. The results were more exaggerated but similar for the conventional construction.

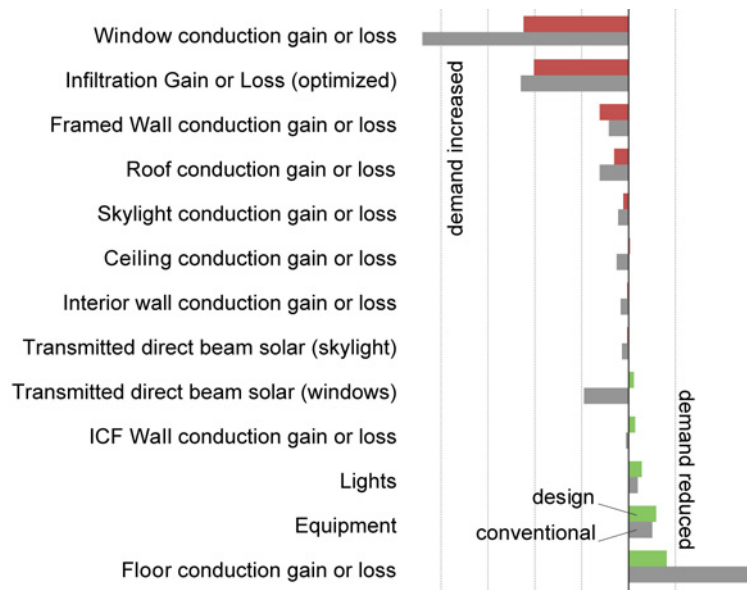


Fig. 5. HVAC load factor summary

3.2. Load Factor Visualization

In addition to a summary of load factors, the load factors are also presented in detail for all 8760 hours of the year. This helps the design team to understand how the building performance varies over time, and may as a result indicate potential energy efficiency measures that had not been identified by the annual performance. The load factors are graphed in a rectangular plot with day of the year on the horizontal axis, and time of day on the vertical. Note that in the conventional case, HVAC energy is used for heating primarily during night hours from November through May, and energy is used for cooling during the afternoon from June through October (Fig. 6). The design case under study will require significantly less cooling than the conventional case such that the need for mechanical cooling can be called into question.

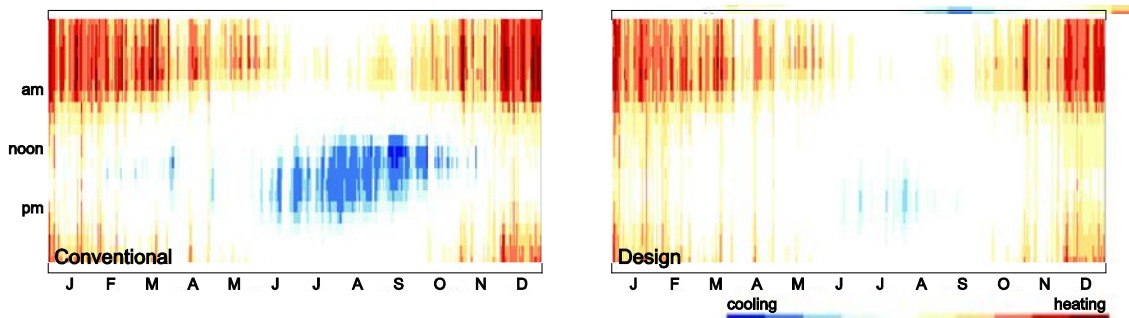


Fig. 6. HVAC Load hourly visualization of conventional case (left), and design case (right)

Similarly, the individual load factors can be graphed in the same visualization space. Looking at conductive heat gain and loss through the windows, we note that this factor is problematic during winter nights as well as summer afternoons in the conventional case, and that it is problematic in winter nights in

the design case (Fig. 7). A common recommendation for improving performance is often to reduce window area or improve the u-value of the window assembly. However, this load factor analysis shows that the issue is only apparent during winter nights. The team is then free to address this problem with a finer grain or dynamic solution such as insulated shades deployed during cool nights rather than addressing the situation with a more overall, expensive or static architectural solution.

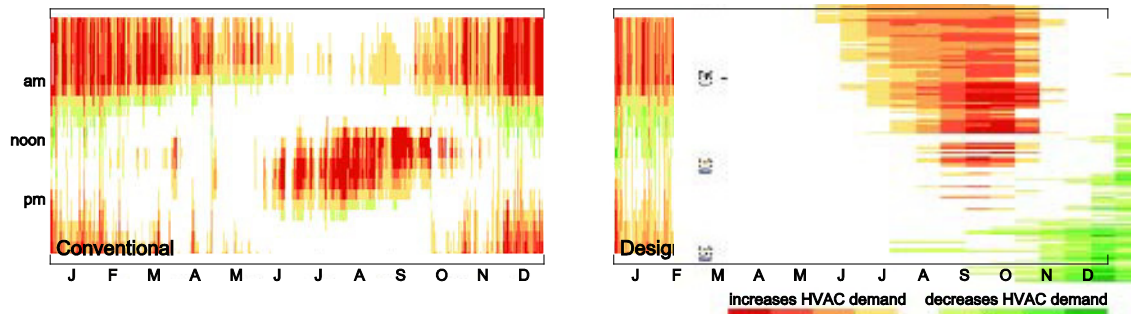


Fig. 7. Window conductive heat gain/loss hourly load factor visualization of conventional case (left), and design case (right)

Looking at the impact of transmitted solar gain, we see that the shading strategy of the design case is much more effective compared with the conventional case (Fig. 8). While transmitted solar gain is still helping in the mornings throughout most of the year, its negative impact during summer afternoons has been nearly eliminated.

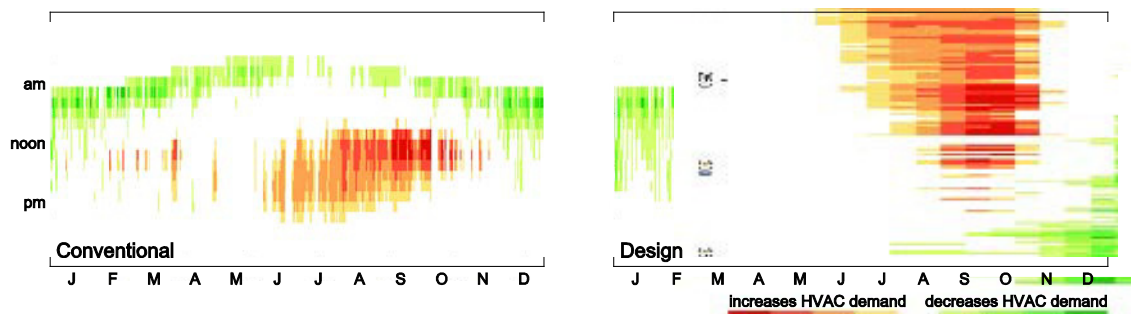


Fig. 8. Transmitted solar gain hourly load factor visualization of conventional case (left), and design case (right)

3.3. Interpreting Results and Providing Recommendations

Large negative load factors indicate areas to prioritize for improvement. Note that the conductive heat transfer through windows was the largest negative factor. This means that the conductive heat transfer through the window assembly was often increasing system demand, for instance by allowing heat loss at a time when the system was heating the space. On the other hand, heat transfer from the floor and from internal equipment had positive load factors, indicating that those components were generally reducing reliance on the HVAC system. The windows perform better in the design compared to conventional construction, because glazing with a lower U-value was used in the design compared to conventional.

An important benchmark to note is the building with ideal performance – one where the HVAC system is never used. Since HVAC heat flux would be always zero in this case, the HVAC load factors would all

also be zero. While this case study shows that the floor was more helpful in the conventional model as opposed to the design, this is actually because the HVAC loads were larger. Therefore, while these positive load factors indicate which components are reducing HVAC demand, they also indicate a failure with another component that is creating the need for HVAC demand in the first place.

Recommendations for improvement are based on the most problematic load factors and vary by load factor type (Table 2). The tool distinguishes between HVAC loads that are mostly heating, mostly cooling, or balanced between heating and cooling. One or more recommendations are given for each building characteristic analyzed and are prioritized by the load factor corresponding to each characteristic. The design team may then consider options for adjusting the design accordingly. Since the recommendations are based on load factors and not on differential between two scenarios, the team may consider a number of options to address the problematic load factors.

Table 2. Actionable recommendations based on load factor prioritization for the Douglas City residence

Window Conduction Gain or Loss	<i>conductive heat loss through windows is increasing heating loads</i> > Specify a window with a lower U-value or use nighttime insulated window shades.
Infiltration Gain or Loss	<i>heat loss through infiltration is increasing heating loads</i> > This analysis assumes a tight building assembly. In order to ensure that performance is not worse, tight construction assembly is required (eg, ensuring gaps around window frame elements are sealed)
Wall Conduction Gain or Loss	<i>conductive heat loss through walls is increasing heating loads</i> > Increase the resistance of the wall assembly (add insulation and/or a radiant barrier). Consider adding thermal mass if there is a large day-night temperature variation.
Roof Conduction Gain or Loss	<i>conductive heat loss through the roof is increasing heating loads</i> > Increase the resistance of the roof assembly (add insulation and/or a second radiant barrier). Consider adding thermal mass if there is a large day-night temperature variation.

4. Results and Lessons Learned

One barrier to energy analysis on a small project is the effort and cost to build the input model. This process is dependent on the client's understanding and ability to provide the relevant information to begin the analysis. We found that working with a client on more than one project improved the efficiency and effectiveness of the use of the checklist. Likewise, as the tool was used and refined, generating the output from the model became more efficient as scripts were written and refined. Once the development of the tool was complete, most of the cost of providing this service is time spent constructing the BEPS model.

We found that the tool is successful at presenting a macro and micro view of performance. The annual load factors summarize the specific areas where the envelope is performing well, and the visualizations enable a detailed understanding of how the performance is changing over time. Likewise, the information generated for the design team is suggestive of multiple solutions. Since the core of the analysis focuses specifically on the interaction of the system and other building loads, the understanding of performance stems from the building as simulated. This proves to be more powerful than looking at one simulation relative to another slightly modified simulation. The information is open-ended to multiple design alternatives rather than closed to the single alternative being compared.

5. Conclusions

The strength of this tool lies in its quick deployment and analysis of the interaction between loads as a way to understand building performance. Loads from easily (and specifically) identifiable components are identified. The design team gains an understanding of how these components are interacting with the building to provide or remove heat over time, and whether this interaction is helpful or not. With the knowledge of how the design works, they can set about generating ideas for changes. For this reason, the tool is useful at any point in the design process when there is a design proposal that can be modeled, and the design team would find it useful to understand performance. This could be in an early stage of design when decisions are being made about massing and orientation of openings, to later in the process when construction assemblies are being specified.

Nevertheless, this is a quick tool and therefore has limitations. Because the tool is focused on the outputs from a single BEPS model, it won't help the design team assess a large range of options. Rather, it indicates promising directions to pursue from the design iteration studied. A second limitation relates to the identification of opportunities. The analysis uses HVAC load as a quantification of the undesirable generated for individual timesteps. This approach highlights the ways in which a building is not meeting its thermal needs at a moment in time. It is less clear how to improve performance dynamically. If the model shows that the building needs heating early in the evening, the analysis does not take into account presence or absence of solar gain earlier in the day that may or may not have been stored in thermal mass. This tool will indicate whether or not the thermal mass is helping or hurting at a particular moment in time, but it will not indicate if there is the opportunity to charge or discharge the mass at another time.

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