METHODOLOGY TO PRIORITIZE AND OPTIMIZE PASSIVE DESIGN STRATEGIES IN CONCEPTUAL DESIGN PHASE

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ABSTRACT
The purpose of this study is to devise a step-by-step process/method to quickly incorporate passive design strategies in the conceptual design phase in architectural practice. This study explores the potential capabilities of Sefaira, a cloud-based software platform for performance-based design, to achieve this purpose. The ultimate aim of the study is to determine what passive design strategies have the most impact on building energy consumption and daylight potential, prioritize them in decreasing order of impact, and devise a method for architects to make quick and impactful design decisions while developing conceptual designs hence integrating this process into their workflow.

INTRODUCTION
Since the advent of the green building movement and the emergence of various building rating systems like LEED and Living Building Challenge in combination with stricter building codes, building performance simulation has become an integral part of the AEC industry. But these performance simulations are usually intended to be used to check compliance with the building code, design the mechanical systems, or achieve a credit in a building rating system, most of which occurs after the designs have been developed by the architects. This results in losing out on valuable opportunities in the early stages of building design to optimize passive design strategies like orientation, massing, window size and placement, and shading, which are known to have a significant impact on the energy and daylight performance at minimal additional cost in case of new buildings unlike bigger and better HVAC systems.

Traditional architectural practice involves using rules of thumb and personal experience to decide which passive design strategies work the best for their designs. Although the power of these rules gained through years of experience cannot be underestimated, it should be accepted that they have limitations owing to the uniqueness of each building in terms of its micro-climate, context, usage, or form. As a result, they might often lead to sub-optimal designs and are not flexible enough to provide insight into which strategy has the highest impact on performance. In other words, they are intended to be prescriptive rather than performance-based. Even building codes are adding performance-based pathways over the past few years as they’re more flexible and more results-driven than prescriptive compliance suggesting a change in the traditional architectural practice.

In typical architectural practice, the design process moves very fast in the early design phases. It is also during these early phases many important design decisions are made which also have a great impact on performance and are difficult to change later. But toggling between applications to run performance simulations of one design at a time might not be the most efficient way to integrate the same into the workflow. Architects want to understand which design decision affects the building performance the most and hence need to be focused on, what are the biggest opportunities and constraints, how their design options compare, what are the optimal parameters for the most effective strategies, what is the responsiveness of the design to various passive strategies, what are the synergies and trade-offs among strategies, and even get some of their specific questions regarding a particular strategy answered. At these early stages of design, absolute performance estimates are not needed as much as the relative performance of various design options to determine optimal solutions. It is also worth noting that daylight performance and occupant comfort weigh in as equally important factors along with energy performance for clients. Also important to the architects is an effective way to present these results to the client in a persuasive manner. Hence what they seek for is easy-to-use and quick performance analysis methodology and tool(s) that can potentially become an integral part of the design process to achieve all of the above without deviating much from their usual workflow, and ultimately position themselves in the green building market by aiming to achieve increasingly stringent performance expectations like those by LEED or ambitious targets like 2030 Challenge.

OBJECTIVE/ GOAL
Objective
The overarching objective of the study is to devise a methodology for architects to use energy and daylight performance analysis tools in the conceptual phase of building design to take maximum advantage of the
benefits of passive building design (design approach that uses natural elements, often sunlight, to heat, cool, or light a building). Since daylight is usually considered as critical as energy use in building types like offices and schools more than any other building type, a new office building in Minneapolis is chosen as the subject of study to demonstrate the methodology described in the later section.

Before going forward with integrating any performance analysis tools into the workflow, it is important to set a goal that is intended to be achieved as a result of the analysis, like 2030 Challenge for energy performance, LEED credit for minimum and maximum daylight levels, meeting ASHRAE standard 90.1 etc., or even just achieving a very narrow objective like optimum window to wall area ratio.

**Broader Goal**

For this demonstrative study, the broader goal is to explore the tradeoffs between daylight and glare, test the potential of a well day-lit building using just passive design strategies to achieve 2030 Challenge, and also question the rules of thumb. Good daylight could possibly lower lighting energy by using proper daylight controls, as well as lower cooling energy by avoiding the heat produced by the electric lights that can now be turned off due to better daylight. But higher glazing can also lead to more unwanted solar gain in the summer thus increasing cooling energy use, and also cause more heat loss thus increasing the heating energy use in the winter. Also, more glazing leads to more glare unless proper shading techniques are in place. These interactions vary a lot depending on the climate, context, building shape and other factors which is why rules of thumb might not work in all cases if their basis could not be justified well. Hence, analyzing these interactions provides an opportunity for well-designed glazing to simultaneously improve daylighting, enhance occupant comfort, and reduce energy use, operating cost, and maybe even mechanical system size.

**Specific Goals**

The specific goals in the order of priority are: 1) Maximize well-lit space/ Spatial Daylight Autonomy/ sDA (>55% floor area) to earn points under LEED v4, 2) Minimize glare/ Annual Sun Exposure/ ASE (<10% floor area) to earn points under LEED v4 if possible, or at least keep it within manageable limits which in itself is a challenging task since ASE and sDA move in the same direction, and 3) Lower energy use to meet 2030 challenge (<27 kBTU/sf/yr) since the fundamental design moves to address the first two goals often have a significant impact on energy use. The terminology/ metrics used for each is described in the next section.

**TERMINOLOGY**

**Dynamic Daylighting Metrics**

Dynamic daylighting metrics are location-based and annualized. The USGBC codified two of these metrics in LEED v4: Spatial Daylight Autonomy (sDA) and Annual Sun Exposure (ASE).

**Spatial Daylight Autonomy (sDA)** describes how much of a space receives sufficient daylight. Specifically, it describes the percentage of floor area that receives at least 300 lux for at least 50% of the annual occupied hours.

**Annual Sun Exposure (ASE)** describes how much of space receives too much direct sunlight, which can cause visual discomfort (glare) or increase cooling loads. Specifically, ASE measures the percentage of floor area that receives at least 1000 lux for at least 250 occupied hours per year.

**2030 Challenge**

The current (year 2015) performance target of the 2030 Challenge requires all new buildings, developments and major renovations to be designed to meet a fossil fuel, GHG-emitting, energy consumption performance standard of 70% below the regional (or country) average/median for that building type. In the case of an office building in Minneapolis, the current target Energy Use Intensity (EUI) would be 27 kBTU/sf/yr based on the regional average.

**SOFTWARE FUNDAMENTALS**

One of the few software available for early stage performance prediction is Sefaira Architecture. It has the capability to provide real-time feedback in SketchUp or Revit (the platforms that most architects use for 3D visualization in early stages of design) on both energy and daylight metrics and hence chosen to demonstrate the methodology described in the next section. It is worth noting here that the focus of this study is not on the potential of a particular software itself but rather on the applications of the methodology discussed in the later section to the architectural practice. Hence any software that could propagate the latter would be equally applicable.

Sefaira requires four main inputs – modeled geometry in SketchUp or Revit, occupancy type, location, and building properties that can be adjusted manually or based on common baselines like ASHRAE and Part L – to produce four main outputs – energy use intensity (EUI) compared against 2030 Challenge benchmark, energy segments (heating, cooling, lighting, appliances), percentage floor area with glare per the LEEDv4 ASE metric, and percentage of floor area that is well-lit per the LEEDv4 sDA metric. The Real Time Analysis Plug-in calculates energy use using Sefaira’s Fulcrum engine which is based on ASHRAE’s radiant time series method of calculation (Bruning, 2012).

Daylighting is calculated with Radiance (providing backwards ray-tracing), and DAYSIM (layering climate data onto the analysis). The biggest advantage of Sefaira is that it does not need the designers to leave their native CAD environment and change their design process while performing energy and daylight...
analysis, hence integrating the latter into the already existing work flow (Sefaira, 2015).

METHODOLOGY

Base Case Shoebox Model
A simple four-story rectangular shoebox office building located in Minneapolis, Minnesota is chosen as the base case with properties as shown in Figure 1.

- Location – Minneapolis, MN
- Shape - Rectangular
- Aspect ratio – 2.67 (160’/60’)
- Floor to ceiling height – 13’
- No. of stories – 4
- Orientation – 0 degrees (elongated on east-west axis)
- WWR North – 65.4%
- WWR South – 65.4%
- WWR East – 23.1%
- WWR West – 23.1%
- Stil height North – 3.5’
- Stil height South – 3.5’
- Stil height East – 9’
- Stil height West – 9’

Figure 1 Base case shoebox model

The envelope properties, and HVAC, lighting and appliance efficiencies are set to the ASHRAE 90.1-2013 baseline for climate zone 6 as available in the Sefaira for SketchUp Plugin (shown in Figure 2).

No surrounding buildings are considered for this demonstrative study for simplicity but context is certainly a very important aspect to determine optimum design parameters for real buildings.

Parameters under Study
The parameters chosen to be investigated in this study are passive design strategies that have an impact primarily on daylight performance. A range of values for each of these parameters is set based on a general understanding of an architect’s design limits for the particular building type. Parametric analysis is performed within this range for each of the passive strategies to investigate their individual effect on energy and daylight performance. In all cases, building floor area is kept constant as architects usually work with a fixed space program. The parameters and their respective range of values are listed in Table 1.

Table 1
Parameters and respective ranges

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aspect Ratio</td>
<td>1-6 (min. depth 40’)</td>
</tr>
<tr>
<td>Floor to Ceiling Height</td>
<td>11’-15’</td>
</tr>
<tr>
<td>Number of Stories</td>
<td>2-9 (min. depth 40’)</td>
</tr>
<tr>
<td>Orientation</td>
<td>0-180 degrees</td>
</tr>
<tr>
<td>Shading Projection - East</td>
<td>0-100%</td>
</tr>
<tr>
<td>Shading Projection - West</td>
<td>0-100%</td>
</tr>
<tr>
<td>Shading Projection - North</td>
<td>0-100%</td>
</tr>
<tr>
<td>Shading Projection - South</td>
<td>0-100%</td>
</tr>
<tr>
<td>WWR - East</td>
<td>0-90%</td>
</tr>
<tr>
<td>WWR - West</td>
<td>0-90%</td>
</tr>
<tr>
<td>WWR - North</td>
<td>10-90%</td>
</tr>
<tr>
<td>WWR - South</td>
<td>10-90%</td>
</tr>
<tr>
<td>Stil Height - East</td>
<td>3’-9’</td>
</tr>
<tr>
<td>Stil Height - West</td>
<td>3’-9’</td>
</tr>
<tr>
<td>Stil Height - North</td>
<td>0.5’-3.5’</td>
</tr>
<tr>
<td>Stil Height - South</td>
<td>0.5’-3.5’</td>
</tr>
</tbody>
</table>

Step 1: Individual Parametric Analysis

Local sensitivity analysis (Tian, 2013) is used to analyse the base case model individually for each parameter over its respective range of values while maintaining all other parameters the same as the base case, to determine the percentage change in energy use, percentage of well-lit floor area and percentage of floor area under glare from the worst to the best case. This step helps the architects understand which parameter change has the highest potential to impact performance and must definitely be considered while making any design changes to avoid resulting in a worst performing case, and which ones do not matter much and hence can be left to aesthetic creativity in the later stages of the design. This step can also be used by itself if a particular design change is being investigated separately instead of optimizing the design holistically.

Step 2: Prioritization of Parameters

The parameters are now arranged in the decreasing order of priority based on their sensitivity to changes in percentage of well-lit floor area by determining the percentage improvement of the best case over the worst case within the range of values for each parameter. For example, for aspect ratio parameter as shown in the results section, the best case is 49% well-lit floor area (aspect ratio 2) and the worst case is 29% (aspect ratio 6), so the percentage improvement of the best case over the worst case is (49%-29%)/29% = 69% (Figure 19).
Step 3: Base Case Optimization

Once the parameters are prioritized, the base case model is then optimized in that order of parameters for the maximum percentage of well-lit floor area, each time building on the best case of the previous parameter optimization, similar to the sequential search optimization method (Christensen, 2004). The percentage of floor area under glare is also kept under check at each step to make sure that it does not increase over the best case of the previous step.

Step 4: Final Output Analysis

The last step is to analyze the improvement in the final outputs (percentage of well-lit floor area, percentage of floor area under glare, and EUI) of the ultimate best case over the base case. This step also involves exploring the possibility of using daylight controls to reap the benefits of adequate daylight to decrease energy use thereby achieving the 2030 Challenge.

RESULTS AND DISCUSSION

Step 1: Individual Parametric Analysis

Aspect Ratio

The depth of daylight penetration remains the same for a particular window head height and hence daylight does not penetrate far enough in deeper buildings. But as the building gets thinner (increasing aspect ratio), daylight penetrates from either sides of the building gradually covering the entire floor area and exceeds the well-lit limit (1000 lux) after a certain point causing glare.

Floor to Ceiling Height

As the floor to ceiling height increases, the head height of the windows also increases, resulting in deeper daylight penetration and higher glare.

Number of Stories

Since the aspect ratio is kept constant, the depth of the building decreases with increasing number of stories. The explanation on the depth of daylight penetration is the same as that for aspect ratio parameter.

Orientation

A building with its longer side oriented along the east-west axis is expected to have the highest percentage of well-lit floor area (as expected with a rule of thumb). But a slight deviation from a perfect east-west orientation results in the highest well-lit floor area and lowest glare in this case probably due to some self-shading effects.

Vertical Shading Projection – East

Proceedings of BS2015:
Vertical shading on the east reduces the glare caused by low angles of the sun in the early hours of the day, and thereby increases the well-lit floor area.

**Vertical Shading Projection – West**

![Figure 8 West Shading Parametric Analysis](image)

A greater percentage of occupied hours in a typical office fall in the late afternoon when the sun is in the west than in the early morning when the sun is in the east. Hence west glazing poses a higher risk of annual glare than east glazing, making west shading more effective in mitigating glare when compared to east shading.

**Horizontal Shading Projection – North**

![Figure 9 North Shading Parametric Analysis](image)

The sun path is inclined towards the south, hence north glazing only sees indirect daylight that doesn’t cause glare. So shading on the north does not serve any purpose in terms of daylight.

**Horizontal Shading Projection – South**

![Figure 10 South Shading Parametric Analysis](image)

The south face of the building sees the maximum amount of direct sun as the sun path is inclined towards the south hence resulting in maximum glare. As a result, south shading is very effective in mitigating glare and increasing the well-lit floor area.

**Window to Wall Area Ratio (WWAR) – East**

![Figure 11 East WWAR Parametric Analysis](image)

Since the head height is kept constant while increasing WWAR, the depth of daylight penetration remains the same but the glare dominates in east and west orientations due to low sun angles. Useful daylight is admitted through the part of the glazing higher in the wall contributing to the well-lit floor area while the part of the glazing placed at view range of the user usually contributes to glare due to direct sun. In addition, the glazing below the desk height is neither useful for daylight nor for view. This could explain why the well-lit floor area and floor area under glare remain constant after reaching a certain WWAR.

**Window to Wall Area Ratio (WWAR) – West**

![Figure 12 West WWAR Parametric Analysis](image)

The explanation of the results is similar to that for WWAR on the east orientation. The percentage of floor area under glare is more for the west exposure than the east as more occupied hours in an office fall late in the afternoon when the sun is in the west than in the early morning when the sun is in the east.

**Window to Wall Area Ratio (WWAR) – North**

North glazing is not affected by glare since there is no direct daylight through it, but that also results in under-lit spaces due to inadequate daylight. Hence the percentage of well-lit floor area increases with increasing WWAR on the north. But the amount of
glazing below the desk height does not contribute to useful daylight thereby rendering higher WWARs useless in improving the well-lit floor area further.

The head height determines how deep the daylight penetrates into the space. Since direct light causes glare, the deeper direct light penetrates, the higher is the glare potential thereby reducing the well-lit floor area. Hence greater head height (due to greater sill height) leads to higher glare and lower well-lit space.

**Window Sill Height – East**

South glazing is important for good daylight as the sun is oriented to the south most of the day, due to which low WWAR on the south results in under-lit spaces. Useful daylight is admitted through the part of the glazing higher in the wall (eg. clerestory windows) contributing to the well-lit floor area while the part of the glazing placed at view range of the user usually contributes to glare due to direct sun. In addition, the glazing below the desk height is neither useful for daylight nor for view. This could explain why the well-lit floor area peaks at a certain WWAR and then drops down to remain constant.

**Window Sill Height – West**

The explanation of the results is similar to that of the window sill height on the east face of the building.

**Window Sill Height – North**

North glazing only receives indirect light and is not exposed to direct light. Hence the placement of the window in the wall does not affect the well-lit floor area or the floor area under glare as long as the WWAR remains constant.

**Window Sill Height – South**
The explanation of the results is similar to that of the window sill height on the east and west faces of the building. The glare caused by deeper penetration of direct light can be mitigated by using appropriate exterior and interior shading devices (which is more difficult on the east and west orientations than the south due to lower sun angles).

Step 2: Prioritization of Parameters
The bar chart in Figure 19 shows the percentage improvement in well-lit floor area, floor area under glare and EUI of the best case over the worst case in each parameter range arranged in the decreasing order of percentage improvement in well-lit floor area. Orientation and number of stories are the biggest players affecting the amount of well-lit space followed by aspect ratio, floor to ceiling height and WWAR-North.

Step 3: Base Case Optimization
The base case is optimized in the order of parameters determined in Step 2. In each parameter range, the option with maximum well-lit floor area is chosen to proceed to the next parameter optimization, while making sure that the floor area under glare does not exceed that of the previous optimization (in fact Figure 20 shows that it reduces at each optimization step). The optimized parameters in comparison to the original base case parameters are shown in Table 2. The architect can choose to end the optimization process at any intermediate step based on intended degree of optimization as long as the most effective parameters are optimized.

Step 4: Final Output Analysis
The bar chart in Figure 20 shows the progressive improvement of the well-lit floor area (46% to 80%) and the area under glare (54% to 8%) over the course of the optimization.

Although the EUI does not appear to vary significantly when the benefits of daylight are not considered, the use of daylight controls involving automatic blinds and continuous dimming of electric lights reduces the EUI from 31 kBTU/sf/yr of the baseline to 24 kBTU/sf/yr of the optimized case with daylight controls (29 kBTU/sf/yr without daylight controls) as shown in Figure 21, thereby achieving the 2030 Challenge (target EUI of 27 kBTU/sf/yr) using just passive design strategies. It can be noted that the use of daylight controls increases the heating load due to the reduction in heat produced by the electric lights, but it also decreases the cooling and lighting loads substantially with lower electric lights usage thereby reducing the overall EUI.
CONCLUSION

The results of the optimization indicate that the order of priority of the parameters produced the desired result by achieving all three goals set earlier – achieving 2030 Challenge, gaining LEED points for maximizing sDA beyond 75% and minimizing glare below 10%. Also the biggest players affecting daylight, namely, orientation, number of stories, aspect ratio and floor to ceiling height are also the ones that are usually expected to do so (among the parameters chosen for this study), hence reaffirming their importance. Some parameters do not seem to agree with rules of thumb mostly because each building is unique based on its climate and context.

Although the results of the methodology are highly dependent on the specific base case chosen, it can be safely admitted that such process should also work for different climate, surroundings/context and base case properties. The order of priority of parameters would be different for a different climate depending on whether it is heating dominated or cooling dominated and also the exact geographic location. Surrounding buildings and context would play an important role in determining the optimum parameters as those would affect shading and daylight. A different set of base case properties could result in lower or higher sensitivities to each parameter but the overall order of priority should be the same for the same physical form of the building.

This study is intended to produce relative and approximate results rather than absolute results, as it is applicable to the conceptual design stage where exact design inputs are not available (Hopfe et al., 2005). Hence the rigor of the software is not the primary concern as much as its processing speed for quick results as long as it’s based on reliable engines. This methodology is used as an indicator to the designer on which of their design interventions are the most effective to attain their goals. Since this paper is application-oriented rather than software-oriented, any software that is explicitly designed for conceptual stage performance analysis and can successfully implement the methodology could be appropriate. A validation study is not included in this paper as most of the previous published research (Hygh et al., 2012) on sensitivity analysis in building performance prediction is focused primarily on sensitivity to changes in energy use while this paper is mainly focussed on sensitivity to changes in well-lit floor area.

In conclusion, this paper discusses one way of setting goals and devising a methodology that is specific to achieving those. Different set of goals require different methodologies, but the ultimate objective of this paper is to promote the use of similar methodologies and tools that architects could integrate into their workflows without losing much time and effort.

REFERENCES


