FACADE OPTIMIZATION USING PARAMETRIC DESIGN AND FUTURE CLIMATE SCENARIOS

Elliot J. Glassman and Christoph Reinhart
[1]Harvard Graduate School of Design, Cambridge, MA/ WSP Built Ecology, New York, NY
[2]Massachussets Institute of Technology, Cambridge, MA

Contact information: elliot.glassman@post.harvard.edu

ABSTRACT

New links between parametric design software, energy simulation tools, and optimization algorithms allow for the customization of individual building components or whole building form in order to reduce anticipated energy use. These optimization methods are of particular interest in studying design problems where an energy conserving measure may act beneficially in one season but detrimentally in another if not properly sized, such as a static shading device. Other possible applications for optimization include generating new building forms based on performance criteria or gaining maximum energy savings for the least amount of initial investment.

Given that one can anticipate that a site's climate is going to substantially change over the coming 70 years, any claims regarding the climate responsiveness should be considered with care. In fact, in this paper it is shown that the optimal facade solutions vary as ambient conditions change over time. This paper deminstrates this effect and then asks the question of how claims of climate responsiveness can actually be upheld in this context.

INTRODUCTION

Optimization in building design is an interesting point of study because of the integrated nature of energy performance. Energy use in buildings is a factor of the heat loss and gain through the opaque and glazed assemblies of a building envelope, internal loads from occupants, lighting, and equipment, and the performance of the building's mechanical systems that provide heating, cooling, and lighting.

These factors are all interconnected and affect one another. Some of them reinforce each other, but some are inversely related. For example, using daylighting to cut reliance on artificial light can reduce the electricity used to power the lighting, and additionally reduce cooling loads induced by the waste heat created by lighting fixtures (Bodart & De Herde, 2002). Yet, increasing window area for better daylighting will increase heat transfer through envelope, since even the best performing glazing units do not possess that same thermal resistance of a sufficiently insulated opaque assembly.

Finding the right balance for a particular situation would allow the designer to provide the solution that provides sufficient daylighting potential while maintaining a window to wall ratio that provides a good thermal performance.

Optimization is also possible in terms of building components. Sizing a static shading device correctly around window openings is critical to ensure that the shade has the best possible influence on the energy use of a building. The shading of windows is meant to reduce cooling loads in buildings by blocking the sun to prevent unwanted solar heat gain in cooling season. Yet, it would be beneficial during heating periods to allow passive solar heat gains to reduce the energy used for heating. Overshading can lead to exclusion of these beneficial solar gains. Therefore, an optimized shading device would be sized to exclude the direct solar gains when they are not wanted, but permit them when they would be advantageous (Jorge, Puigdomenech, & Cusido, 1993).

Conceptually, using parametric tools that allow variable geometry in conjunction with simulation software and optimization algorithms can allow the designer to find the best performing solutions to design questions within the context of performance.

There are emerging tools available that allow a 'live', parametrically controlled digital model to be connected with a simulation program. These tools are fairly simple to use and allow designers to conduct these performance evaluations within a software interface they are already familiar with.

For example, common tool used in many design schools and professional practices for parametric design is the Grasshopper add-on program which operates with the Rhino 3-D modeling software by Robert McNeel and Associates. Grasshopper is a graphical algorithm editor that allows users to create a logic tree containing functions and parameters that generate geometry. Any changes made to the parameters affects the resulting geometry (McNeel, 2010).

There have been various plug-ins developed for Grasshopper that connect the Rhino geometry to simulation software. The Geco plug-in allows the digital model to be analyzed by Autodesk's Ecotect program (Frick & Grabner, 2011). Similarly, the Diva for Rhino tools provide Grasshopper components that provide daylight analysis through Radiance and thermal analysis through Energy Plus (Reinhart, Niemasz, & Sargent, 2011).

Seemingly, this newly enabled integration of parametric design, energy simulation tools, and optimization algorithms opens up a new realm of possibility to create a variety of new forms and optimized components that are generated to provide maximum environmental performance. But the designer must consider the changes to the external and internal environment that will alter the conditions that the design was originally optimized for. These changes will impact the way that the building ultimately performs and may prove to be problematic over the long term.

There could be changes to the context in which a building is situated. Contextual shading may change over time as development or redevelopment occurs on neighboring plots. Shading from adjacent buildings in urban context will affect the amount of solar radiation a building receives.

Changes in climactic conditions could also invalidate the underlying assumptions used in an optimization. While some yearly variation in weather can be expected, more dramatic changes in temperatures are anticipated due to global warming. This will alter the amount of heating and cooling degree hours as demonstrated by Figure 1, which is based on the A2 climate scenario developed by the Intergovernmental Panel on Climate Change (IPCC).

This warming will expand the length of the shading period required. A form that has been generated to self-shade during the original cooling season while allowing solar radiation to enter to the building in heating season would be a less effective shape as the climate got warmer. Similarly, a static shading device optimized to perform under one set of assumptions would conceivably not provide enough shading under a climate change scenario.

Changes in internal loads could also affect the energy balance that would be used in an optimization based on feedback from an energy simulation. In recent years, improvements in lighting efficiency have dropped the amount of waste heat contributed by the operation of lighting systems. A further reduction in internal heat gains is anticipated for office buildings once widespread adoption of cloud computing becomes a reality, possibly reducing gains from equipment loads substantially (Johnston, 2011). Occupancy changes from one type to another over

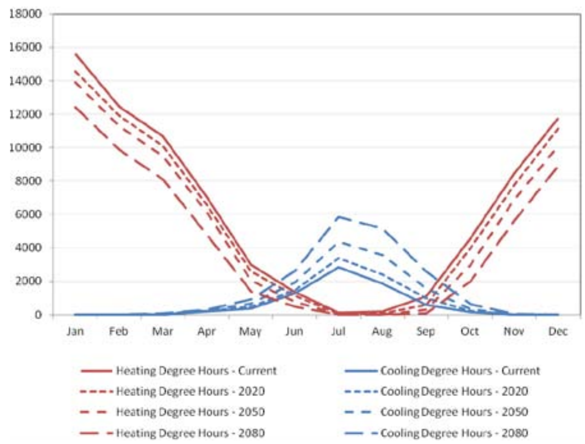

Figure 1 - Change in annual heating and cooling degree hours over time, Boston, MA

time could likewise alter the performance of an optimized design.

The questions that this manuscript will address are how drastically these possible changes will alter the optimized solution, what decisions designers and clients can make to ensure long term energy efficient performance, and even how one decides what constitutes the most optimized solution in the first place.

METHODOLOGY

The method presented optimizes a set of variables in a building facade to find the most suitable solution for a favorable energy balance. The study then explores how the most optimized solution may change in future climate scenarios.

Using Rhinoceros and Grasshopper, a model was created of four zones of a theoretical office building; each of the zones facing one of the four main cardinal directions. Each zone was 4.5 meters deep, the approximate maximum depth of a perimeter zone that is most affected in terms of temperature and daylight by the properties of the facade (Corney, 2010). The zone also possessed 4.5 meters of exterior facing facade and was 3 meters tall. There were no exterior obstructions assumed for the purposes of the study.

The geometry of the zones was then connected to a custom Grasshopper component called Viper developed by Jon Sargent as part of the Diva environmental performance plug-in for Rhino (Reinhart, Niemasz, & Sargent, 2011). Viper conducts a thermal analysis of the Rhino model components using Energy Plus based on a TMY climate file, the occupancy type, and the thermal properties assigned to the construction elements of the model (Sargent, 2011). In this model, the interior partitions, floor, and ceiling of the zone were made to be adiabatic surfaces. The facade was assumed to be a brick construction with a 6" CMU back-up wall, with extruded polyurethane insulation in between the masonry layers. The window units were assumed to be a double glazed window with a low-e coating and an air layer in between the glazings.

The variable parameters of the facade within the Grasshopper environment were the number of layers of two inch extruded polyurethane insulation in the wall, the window to wall ratio, and the projection length of a fixed overhead shading device. The range of insulation layers was from 0 to 5; 0 layers offering no insulative value beyond what the masonry wall would provide, and 5 layers offering an additional R-value of 50 on top of the masonry wall. The variable window to wall ratio options ranged from 10% to 80% of the facade. The overhead shading device could project out from the face of the facade anywhere from 0.01 meters to 3 meters.

The Galapogos evolutionary solver algorithm contained within Grasshopper (Rutten, 2010) was then used to find the optimized solution to these variables for each of the four zones in three different locations with different climates. The three locations used were Boston, MA, Fairbanks, AK, and Phoenix, AZ. The optimized solution was defined in two ways: the least costly solution over a ten year period as a total of initial investment and energy costs, and the solution that produced the least amount of carbon emissions in the same ten year period as a total of the embodied carbon and carbon emissions due to energy use. The results of the two criteria for the optimized solutions were then compared.

The optimization process was then run for the same locations with anticipated weather files for the years 2020, 2050, and 2080. These future weather files were generated using a 'Climate Change World Weather Generator' tool developed at the University of Southampton. The tool takes a typical meteorological year (TMY) baseline climate file containing current hourly data and morphs the data into new weather files for the specified year, taking into account the anticipated effects of climate change (Jentsch, Bahaj, & James, 2010).

The morpher is based on the HadCM3 global circulation model used in assessment reports by the IPCC. The IPCC's Special Report on Emissions Scenarios (SRES) outline six climate change scenario families entitled A1Fl, A1B, A1T, A2, B1, and B2. The default scenario used by the weather file morpher is A2 scenario which is the assumption used for the purposes of this study.

In an additional optimization exercise, a similarly structured Grasshopper model was created that looked at an optimized solution across the entire period from the 'current' year 2010 to the year 2080. Four Viper components, each containing a different year's climate file for the same location, were used. The energy results between the years were linearly interpolated with Grasshopper domain and range components.

Therefore, this study produces solutions for five different time frames, which will hereafter be referred to as 'Current', '2020', 2050', '2080', and '2010-2080'. The results were then compared to see how drastically the optimized solutions would vary given the differences in the external environmental conditions presented by climate change and increases in the price of energy.

Cost based optimization

The Grasshopper model used researched cost values of materials and energy in the calculations for the optimization. The cost based optimization model sought to find the least costly solution as a total of the initial cost of the facade assembly and the ten years of energy costs resulting from its performance.

The installed cost of the materials used were based on prices found in RS Means Building Construction Cost Data on a per square foot basis (RSMeans, 2011). The quantity of each material used in the façade construction was automatically calculated for each solution generated by using components in Grasshopper. Then the model used those quantities to find the total construction cost of the facade.

Assemblies such as windows that included the pricing for both the frames and glass were listed in RS Means. However, the overhead projection devices are complex assemblies that are not listed in the construction cost data. Therefore, an approximate price was provided from a survey of multiple manufacturers that provide such shading products to provide a reasonable value. The actual costs of the shades can vary greatly because of the number of design, hardware, and materials options. For the purposes of the study, it was assumed that aluminum projections will be used. The cost assumptions are listed in Table 1.

Table 1 Material Costs

MATERIAL	UNIT COST
4" Face Brick	\$12.05/sf
2" Extruded Polystyrene Insulation (per layer)	\$1.48/sf
6" CMU Back Up Wall	\$5.24/sf
Glazing (Double pane, aluminum frame, low-e)	\$38.90/sf

Overhead Aluminum Sun Shades	$45.00/sf

The energy prices for electricity and natural gas were found for each of the three locations on the website of the US Energy Information Administration and used as a baseline for the energy costs (EIA, 2011).

The methodology used in the model to anticipate future energy price increases from this baseline follows the methodology developed in a previous paper (Holmes & Reinhart, 2011) that used the average of several scenarios from Energy Modeling Forum's 2009 report. This report, referred to as EMF-22, looks at projected increases in the cost of electricity and natural gas over time. There are actually ten different cost models used in EMF-22, each corresponding to different target levels for green house gas emissions. For the purposes of this study, the values for the increases in seven of the complete scenarios (ADAGE, EPPA, IGEM-NDO, IGEM-UDO, MiniCAM-Base, MiniCAM LoTech, MRM-NEEM) were averaged together in order to obtain a single middle of the road projection.

The EMF-22 report gives the price increases as a nationwide average. The percentage of increase for each interval was calculated, then multiplied by the base energy price for each location from the EIA statistics. The EMF-22 report gives the projected price increases in 10 year intervals; Grasshopper domain and range components were used to linearly interpolate between the time periods to find estimated costs in the intervening years.

The EMF projections also only extended as far as 2050, so the same projected increase from 2010 to 2050 was used to extrapolate the total increase from 2051 to 2090 with the years in between similarly interpolated.

Carbon based optimization

The carbon optimization model found the solution that produced the lowest total of kg/CO2 between the embedded carbon in the materials and the carbon emissions produced from the generation of electricity used in the building.

The University of Bath's Inventory of Carbon & Energy (ICE) was used as a reference in order to calculate the embedded carbon of the materials. ICE lists over 200 common building materials and the kg of CO2 produced for each per kg of the material created (Hammond & Jones, 2008). Using the figures for density of the materials per cubic meter also contained within the ICE survey, the Grasshopper model automatically calculated the quantities of materials being used in a given façade solution and then tabulated the embedded carbon.

The ICE survey provided a number for the embedded carbon of a window assembly, but the overhead shades again presented a challenge in assigning a value since they are not listed in the survey. Additionally, the embedded carbon of aluminum can vary greatly depending on the percentage of recycled content in the material used. Therefore, the amount of carbon embedded in the overhead shades was calculated based on manufacturer supplied data on the percentage of recycled content and material use intensity per square foot of overhead projection.

The embedded carbon material assumptions taken from the ICE of kg CO2 per kg of material are listed in Table 2. In order to facilitate comparison, the calculated values of embedded carbon per square meter are also provided in the table. These figures take into account the densities of the materials which were also obtained from the ICE survey and the volume of material used per square meter of facade.

The Viper component can provide the carbon emissions resulting from the site energy usage of electricity and heating gas. The component automatically looks up the values based on the two letter state abbreviation in the name of the climate file. Finding the total carbon emissions from a particular design was simply a matter of multiplying these outputs by the number of years in the study period. For the '2010-2080', the carbon emissions were linearly interpolated between the results of the simulated years.

Table 2 Embedded Carbon of Materials

MATERIAL	EMBEDDED CARBON
4" Face Brick	0.52 kg CO2/kg 89.8144 kg CO2/m2
2" Extruded Polystyrene Insulation (per layer)	2.7 kg CO2/kg 3.977 kg CO2/m2
6" CMU Back Up Wall	0.074 kg CO2/kg 9.022 kg CO2/m2
Glazing (Double pane, aluminum frame, low-e)	279 kg CO2/m2
Overhead Aluminum Sun Shades	1.77 kg CO2/kg 17.34 kg CO2/m2

As a side note, although current carbon emissions data for each location is available, it is unknown how about the ways in which future energy generation methods may change the amount of emissions that are produced for each kWh of energy generated. Therefore, the carbon emissions values are less reliable in later scenarios as the future will hopefully bring cleaner energy production methods and greater reliance on renewable energy sources.

RESULTS

Figure 2 shows the results for the southern zone and western zones in the Boston climate over time, optimized once for cost and once for carbon. The results were indicative of the general trends found in all the locations for all orientations.

Namely, the results showed changes in the optimal solution over time and differences between the cost and carbon optimized scenarios for the same time frame. In the cost optimization, the energy conserving measures became more widely implemented as energy prices increased, even if the climate change moderated energy use from the current baseline, such as the case with the Boston and Fairbanks studies. In the carbon optimizations, there was less variation in the recommendations, but solutions were more directly indicative of the changes to climate. The changes to the sun shade sizes reflected the increased shading period and in some cases in the Boston study, the recommended level of insulation actully decreased slightly because of the more moderate temperatures.

Generally, the carbon optimized solutions use less energy on an annual basis than the cost optimized. The later period optimizations and long term solutions demonstrate a convergence between the cost and carbon recommendations. This convergence is demonstrated in the average annual energy usage in Figure 3.

The carbon optimized solutions have a higher initial investment; some of the overall cost is regained by savings in annual energy costs, but not all of it is recouped within the ten year period. As energy prices increase over time, the recommendations for the cost and carbon based optimizations begin to converge. Similarly, the long-term scenarios between the cost and carbon optimizations are more similar to each other.

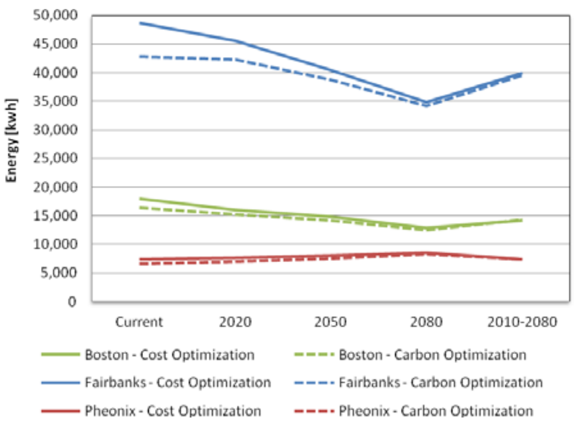

Figure 3 - Average Annual Energy Usage

In the long term '2010-2080' optimizations, savings aggregate to justify bigger expenditures in additional facade elements. For example, the window to wall ratio is usually larger than is suggested in the ten-year optimization scenarios, as the energy savings

Figure 2 - Sample of optimized results from study, the south and west facades in Boston, MA.

realized from daylighting aggregate to justify the added expenditure for a larger window, both in terms of that initial cost and embedded carbon.

In the cost driven optimization scenarios, the application of energy conserving measures such as additional insulation or shading devices is minimal. An additional investment is only warranted when the cost of energy it saves is greater than the cost of initial investment.

Ten year cost optimizations for each of the ensuing future climate scenarios (2020, 2050, 2080) all recommend increasing levels of insulation, even though the weather conditions are projected to become more moderate relative to the baseline climate in the case of Boston and Fairbanks. This is because the price of energy increases even as energy usage decreases, justifying the purchase of additional layers of insulation to save additional energy cost.

In the carbon driven optimization scenarios, the application of energy conservation measures is much more aggressive than in the cost based studies. The levels of insulation are appreciably higher and the shading devices are used much more liberally. This is due to the fact that the embedded carbon of the materials is much smaller relative to the carbon emissions from energy generation than the initial construction investments are to the energy costs.

There is generally less variation in the carbon optimizations, but it is easy to see the warmer climate has an effect on the proposed solutions. The southern shading devices get longer in each ensuing future scenario, reflecting the extended shading period. In Boston, the energy use decreases as the climate moderates, and therefore the recommended insulation levels actually decrease on some of the facades by 2080. In Phoenix, where the already hot climate gets warmer, the insulation and shading device sizes increase and the window sizes decrease in order to minimize solar heat gain.

DISCUSSION

Of all the three variables in the study, insulation is the factor that increases the most in the cost optimization due to its relatively low cost of procurement and installation. However, the practical reality is that insulation levels are hard to change once the walls are constructed. Barring a major renovation to the facade, the walls would not be opened to allow additional layers to be put in. Therefore, an owner may want to initially consider adding more insulation than would be apparently be warranted in a strict short term cost analysis as a hedge against energy future price increases over a long period. Indeed, the long term '2010-2080' scenario recommends very high insulation levels.

The exterior shading devices are the most expensive component in the materials used on a per square foot basis. They are never recommended in the ten year cost optimizations, indicating that they do not save enough energy in the payback period to be economically justifiable. The overhead shades only appear in some of the long term cost optimizations.

However, it should be noted that the simulations may be over-penalizing the effect of the shading devices on interior illumination levels. The daylight analysis in Energy Plus relies on the split flux method for interior reflections of light that has been demonstrated to have some inaccuracies (Versage, Melo, & Lamberts, 2010). By underestimating the internal illumination level due to shading, the model assumes additional lighting energy use and associated cooling loads, hence reducing the energy cost savings that would monetarily incentivize the use of shades.

It would be interesting to see how the results may differ if future development in interconnecting these various programs would allow a more accurate Radiance based simulation to be performed in conjunction with the energy simulation. This would however likely require more extensive simulation times, especially for the optimization process which will run several simulations to find the best solution.

The overhead shading devices may be the easiest one of the three variables to change over time. It is the most accessible component and the shorter lifecycle of the aluminum shades may make upgrade to appropriately longer projections in the future easier. As an alternative to static shading, adaptable systems such as exterior Venetian blinds could be considered to adjust to changing conditions.

The recommended shading device sizes do not generally change on the east and west facades, and this is most likely due to the occupancy hours of the office typology. Additional shading is not required when the office is not occupied and the systems are not in operation.

Though the long-term view does offer more added protection from likely future changes, there are challenges in this approach, mostly due to the uncertain nature of future projections. For example, the study uses the A2 climate change model as its underlying assumption, which is just one of the possible scenarios outlined by the IPCC report.

There are also other numbers in this study in terms of energy costs or carbon emissions that may change over time. Future technologies may improve the energy performance of mechanical systems or offer easily added insulation value to the envelopes of existing buildings. Therefore, it can be hard to be deterministic in offering an optimized solution for the long term.

The facade solutions that offer better performance from an energy and carbon standpoint tend to be more expensive. Even the savings from energy costs may not make up the difference in the increased initial costs, especially in the short term. However, designers should look for cost offsets in reduced expenditure in mechanical systems that a more efficient envelope may allow.

Ultimately, question raised by this manuscript is not only a technical but also a philosophical one: Should our emphasis be on reducing the cost of resources or controlling our impact on the environment? The relatively low cost of energy in the United States now make investment in energy conservation measures less amenable to those seeking a quick return on investment. But as this study demonstrates, the ten year payback generally preferred by designers and owners for investments of this type may produce a solution less successful at coping with future changes.

CONCLUSION

The integration of parametric design software and simulation programs seemingly offers the possibility of building forms and components optimized for energy performance. However, as this study demonstrates, the subject of climate responsive design optimization is a great more complex than is generally presented by designers.

A facade optimized for a particular scenario will not remain the optimized solution as changes to the climate occur. The challenge for decision makers in the design stages is how to deal with the fact that the optimized energy solution changes over time. The physical parameters of a building can be hard to change.

The implications for design is that designers and the building stakeholders must try to predict and take into account likely changes to the external and internal influences on performance. Any design that claims to be 'optimized' for any environmental performance criteria will not be optimized for long if it only takes into account current conditions.

The advantage of the methodology presented in this manuscript is that it provides ways to go about incorporating climate predictions into the optimization model. Although there may be limitations in predictions or the current capacity of the simulation tools to provide the ideal analysis for every performance factor, this methodology will yield better results over the long term than a design only optimized for current conditions.

Such an analysis may help designers pinpoint where adaptable systems should be used to the extent which they are practical and cost effective. Taking into account multiple predictive scenarios will contribute to a robust design able to deal with a variety of conditions.

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