7th International Building Physics Conference

IBPC2018

Proceedings

SYRACUSE, NY, USA

September 23 - 26, 2018

Healthy, Intelligent and Resilient
Buildings and Urban Environments

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Pareto Optimality Analysis for Evaluating the Tradeoff between Visual Comfort and Energy Efficiency

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ABSTRACT
Architectural designs are increasingly driven by both sustainability and health, which requires evaluating the tradeoff between visual comfort and energy consumption. Lack of daylight leads to poor visual comfort and health issues but reduces heat gains, while excessive daylight may lead to over-illumination, glare, and high heat gains. Identifying the tradeoff between multiple criteria is an intricate process that requires skill and experience, especially when dealing with complex phenomena such as visual comfort. In order to facilitate this process, this paper provides two contributions: (1) the description of a new single-valued visual comfort measure, and (2) the application of the Pareto optimality analysis method. Pareto optimality analysis consists of comparing different design options in terms of the tradeoff between multiple criteria, which is a method that is rarely used in architectural design albeit its many advantages. For the Pareto optimality analysis, single-valued performance metrics are required. The energy performance metrics such as annual heating and cooling loads are single-valued quantities that, nowadays, can be calculated and measured easily. Daylight performance, however, is a complex multi-dimensional phenomenon. While previously developed daylight and glare performance metrics have their merits, they are not readily applicable to Pareto analysis. In this work, a new light metric called Effective Glare and Light Measure (EGLM) is developed to address the current limitations. The EGLM metric is defined as a weighted sum of several normalized performance metrics to end up with a single-valued measure of visual comfort. Two software programs, DIVA-for-Rhino and EnergyPlus™, are used to calculate the time-dependent visual performance data and energy consumption, respectively. A script is then used to post-process the data. Several case studies are presented to illustrate the method with various building orientations, window-to-wall ratios, overhang depths, and glass visibility transmittance.

KEYWORDS
Pareto Optimality, Daylighting Analysis, Glare, Energy Efficiency

INTRODUCTION
Daylight has consistently been an essential component of architecture and the primary source for illuminating the interior environment. The benefits of using daylight in buildings range from savings in energy consumption and enhancing occupant health and comfort to improving outside views, and design aesthetics (Reinhart, 2014). While admitting daylight within a building has many known benefits, there are some disadvantages associated with transferring too much light into a space. These problems include occupants' visual and thermal discomfort and waste of cooling energy. Careful design is required to adjust these effects. As such, it is beneficial to apply methods helping designers to predict the tradeoff between criteria as much as possible during early design stages. Using Pareto optimality analysis is a quantitative and rigorous way of predicting this tradeoff (Hunt et al., 2007). However, this method requires single-valued metrics for all design criteria. This explains why this method is extensively used in engineering design, which generally involves design criteria that are easily quantifiable.

Architectural design is a discipline that involves qualitative metrics, one of them being aesthetics, which explains the unpopular use of Pareto optimality analysis. The premise of this paper is to demonstrate that Pareto optimality analysis can be used in architectural design when dealing with quantifiable criteria such as visual comfort and energy consumption. The method is used to compare the performance of different design alternatives corresponding to variations of several design parameters including building orientation, window-to-wall ratio, overhang depth, and glass visibility transmittance.

Energy performance metrics are generally straightforward since they are based on annual heating and cooling loads, which can be added to provide the annual energy consumption as a single-valued quantity. Visual comfort, however, is a complex phenomenon quantified using various intricate performance metrics that evaluate the level of illuminance and glare (Reinhart, 2014). A number of metrics have been adapted to evaluate the sufficiency of illuminance within a space, including, Daylight Factor, Daylight Autonomy, and Useful Daylight Illuminance (Reinhart, 2014). These metrics, however, have a number of drawbacks as they are either climate-independent, excessively simple, or multi-valued. As for glare, a number of metrics have been developed, including, CIE Glare Index, Unified Glare Rating System, Daylight Glare Index, and Daylight Glare Probability (Wienold and Christoffersen, 2006). These metrics, however, are either only applicable to artificial lighting or are metrics that measure glare at a given time as opposed to during a period of time such as the whole year. Therefore, a new visual comfort metric, called the Effective Glare and Light Measure (EGLM) is developed specifically for the purpose of architectural design driven by the tradeoff between visual comfort and energy consumption.

Most studies that evaluate the performance of daylighting systems and shading devices such as blinds, overhangs, louvers, light shelves, and dynamic glass fall short of providing an effective approach to the tradeoff analysis when evaluating the building performance with multiple criteria. For instance many studies have evaluated the performance of electrochromic glass (Lee and Tavil, 2007) without quantitatively analyzing the tradeoff between light levels and energy efficiency. Similar work that focus on glazing and shading devices have the same limitation (Ochoa et al., 2012).

The paper includes three sections. The first section describes the development of the new visual comfort metric, some of its variations, and its application in the Pareto optimality analysis method using a single office room with a window on the South façade as a case study. The performance of a given design in terms of visual comfort and energy consumption is quantified using the simulation software DIVA-for-Rhino (Solemma, 2017) and EnergyPlus™ (DOE and NREL, 2017). The second section presents results of practical applications of the method on the case study problem for various design alternatives corresponding to various values of building orientation, window-to-wall ratio, overhang depth, and visibility transmittance. The method is compared to the traditional way of comparing alternatives without the Pareto optimality analysis to illustrate its practicality. The third section includes a discussion of the method, its limitations, and the design opportunities that it provides.

METHODS

The Pareto optimality analysis method consists of visualizing the performance criteria of different design alternatives on a two- or three-dimensional graph when dealing with two or three criteria, respectively. In this paper, the first criterion consists of minimizing the annual energy consumption of the building of interest as the annual heating and cooling loads. The annual energy consumption is a single-valued quantity measured in mega-Joules (MJ). The second criterion consists of maximizing visual comfort in a room of interest.

Development of the Effective Glare and Light Measure (EGLM)

The EGLM metric is defined as a weighted sum of two additional metrics. i.e., the Effective Light Measure (ELM) and the Effective Glare Measure (EGM), as follows:

$$\mathrm{EGLM} = \beta\,\mathrm{ELM} + (1-\beta)\mathrm{EGM}$$

where β is a user-defined weight between 0 and 1.

Development of the Effective Light Measure (ELM)

Illuminance, measured in lux, is the amount of light that falls on a given surface area (Lechner, 2008). The Illuminating Engineering Society of North America (IESNA) recommends target values of illuminance for various tasks, including for instance, an average of 400 lux for office tasks and 1000 lux for laboratory work (Rea and IESNA, 2000). These target values are then converted into target ranges, such as 300 to 500 lux for office tasks. An illuminance below or above these recommended ranges puts unnecessary strain on the eyes and induces fatigue, among other issues. Unlike artificial lighting, daylighting varies constantly during the day as it depends significantly on the climate, seasons, and the weather. As a result, maintaining the desired illuminance level at all times is virtually impossible, and the goal is then to maximize the number of hours in the recommended range. In this paper, the illuminance spectrum is divided into five ranges defined as follows: Range 1 between 0 and 100 lux is undesirable, Range 2 between 100 and 300 lux is acceptable, Range 3 between 300 and 500 lux is desirable, Range 4 between 500 and 1000 lux is acceptable, and Range 5 above 1000 lux is undesirable. Using five ranges, as opposed to only three, provides the increased resolution needed to capture the difference between architectural design alternatives. Using five ranges, the Effective Light Measure (ELM) is defined as a weighted sum of the normalized numbers of hours when the illuminance is within a predefined range, which can be written as follows: $\mathrm{ELM} = \sum_{i=1}^{5} \alpha_i \frac{N_i}{N_{total}}$, where α_i is a user-defined weight for range i, with $\sum_{i=1}^{5} \alpha_i = 1$, N_i is the number of hours in range i, and N_{total} is the total number of working hours in a year. The user-defined weights, α_i, are subjective and are currently defined as 0.1, 0.2, 0.4, 0.2, and 0.1 for ranges 1 to 5, respectively.

Development of the Effective Glare Measure (EGM)

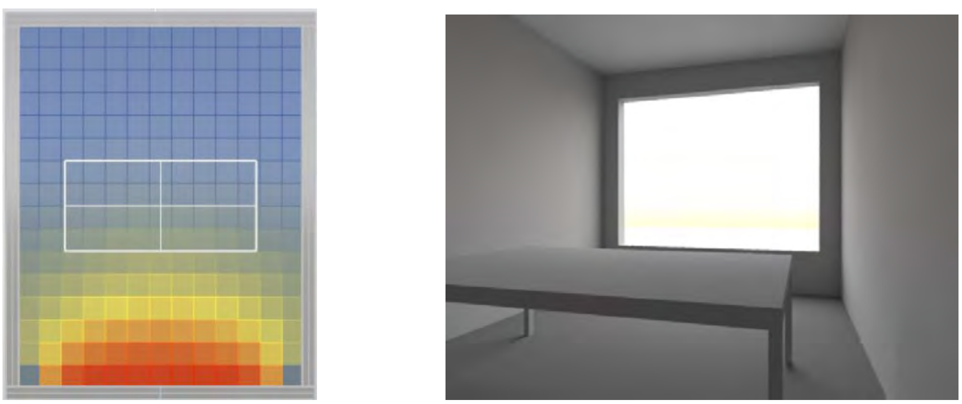
Glare depicts the contrast in brightness between different objects in one's field of vision and one way to quantify it is with the instantaneous measure called the Daylight Glare Probability (DGP). The DGP defines the probability that a person is disturbed by brightness distribution throughout the space (Wienold and Christoffersen, 2006). The DGP is a number between 0 and 1 to be minimized. Wienold (2009) proposes several ranges as follows. Range 1 corresponds to imperceptible glare with a DGP below 0.35, Range 2 is perceptible glare between 0.35 and 0.40, Range 3 is disturbing glare between 0.40 and 0.45, and Range 4 is intolerable glare above 0.45. The Effective Glare Measure (EGM) is defined as a weighted sum of the normalized numbers of hours when the DGP is within a predefined range, which can be written as follows: $\mathrm{EGM} = \sum_{j=1}^{4} \gamma_j \frac{N_j}{N_{total}}$ where γ_j is a user-defined weight for range j, with $\sum_{i=1}^{4} \gamma_i = 1$, N_j is the number of hours in range j, and N_{total} is the total number of working hours in a year. The user-defined weights, γ_j, are subjective and are currently defined as 0.5, 0.3, 0.15, and 0.05 for ranges 1 to 4, respectively.

Pareto optimality analysis

It is assumed that a set of design alternatives are analyzed in terms of visual comfort and energy consumption. The Pareto optimality analysis corresponds to plotting the corresponding values of all design alternatives on the two-dimensional graph. In this paper, the horizontal axis is the annual energy consumption to be minimized and the vertical axis is visual comfort to be maximized. As a result, the best design alternatives are those closest to the top-left corner of the graph.

Case study

As shown in Figure 1, the room of interest is a rectangular office, 4.26-m long, 3.35-m wide, and 3.00-m floor-to-ceiling height with a window. The work table is placed at the middle of the room such that the user is facing the window. The baseline design of the office has the window on the South façade, a window-to-wall ratio of 50%, no overhang, and a glass visibility transmittance of 80%. The point where horizontal illuminance is simulated is at the center of the table. The glare sensor is located 1.4 meters from the floor facing the window to represent the position and orientation of the person sitting at the desk. The weather of Anderson, South Carolina is used for all simulations, which corresponds to a mild climate with approximately equal heating and cooling loads. A standard heat-pump HVAC system is considered for heating and cooling the building with lower and upper setpoint temperatures of 24ºC and 22ºC. The R-values of the exterior wall and window are 17 and 3.5, respectively, and the interior walls, floor, and ceiling are considered adiabatic to represent the effect of an interior office of a multi-story building. DIVA-for-Rhino and EnergyPlus^{TM} are used to simulate the illuminance, glare, and energy consumption over the entire year, 10 hours per day from 8:00AM to 6:00PM.



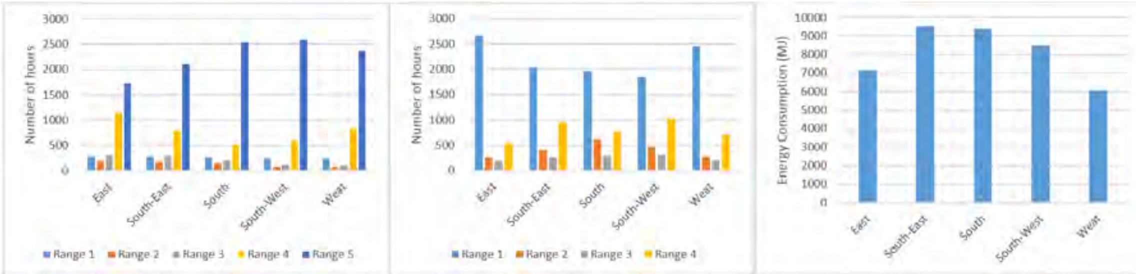
a) b)

Figure 1. a) Plan of view of the room of interest with window oriented towards South, table at the center of the room, b) Rendering of the room as simulated by DIVA-for-Rhino.

RESULTS

Effect of building orientation

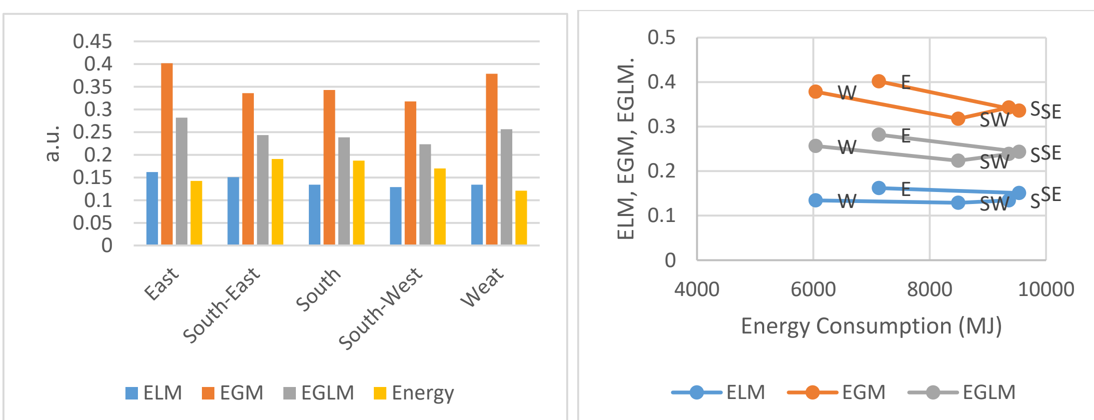
Five different building orientations are considered, i.e., East, South-East, South, South-West, and West. Figure 2 shows the results using the traditional method of visualization with three histograms, namely, the number of hours of illuminance in each of the five ranges, number of hours of glare in each of the four ranges, and energy consumption. The graphs include all necessary information to compare the five design alternatives. However, this method is fairly confusing and analyzing the tradeoff between alternatives in terms of visual comfort and energy consumption is virtually impossible.



a) b) c)

Figure 2. a) Number of hours of illuminance in each of the five ranges for each building orientation, b) Number of hours of glare in each of the five ranges for each building orientation, and c) Energy consumption for each building orientation.

Figure 3.a) shows the same results in a more compact manner by plotting the visual comfort metrics ELM, EGM, EGLM, and Energy on the same histogram. The information is easier to understand. However, the tradeoff is still difficult to extract. Finally, the same results are shown in Figure 3.b) using the Pareto optimality analysis method with the visual comfort metrics on the vertical axis and the energy consumption on the horizontal axis. Using this method, the tradeoff between the design alternatives can be easily identified since the best designs are those closest to the top left corner of the graph. Focusing on EGLM (grey curve), it is clear that the East and West orientation are significantly better than the other three building orientations. The selection of the final design alternative (either East or West) depends on the designer's preferences. The East orientation is best if visual comfort is preferred. The West orientation is best if energy consumption is preferred.



a) b)

Figure 3. a) ELM, EGM, EGLM, and Energy (in MJ divided by 50,000 for scaling), b) ELM, EGM, EGLM versus Energy (MJ)

Figure 4 shows the Pareto curves corresponding to the variations of three other design parameters, i.e., window-to-wall ratio, dimension of overhang, and glass visibility transmittance. Analysing each curve allows identifying the best design in terms of tradeoff between criteria.

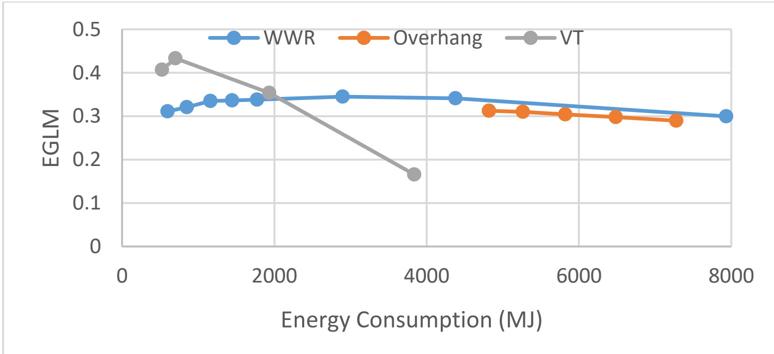


Figure 4. Pareto curves of three parametric studies: blue curve: WWR varies between 6% (lowest energy) and 40% (highest energy), orange curve: overhang depth varies between 0.5m (highest energy) and 1.4m (lowest energy), grey curve: glass visibility transmittance varies between 1% (lowest energy) and 60% (highest energy).

CONCLUSIONS

This paper shows the advantages of using the Pareto optimality analysis method to identify the tradeoff between multiple criteria in architectural design. This method, however, requires the use of single-valued quantities. Since visual comfort is a complex phenomenon that is generally quantified using multi-valued quantities, a new single-valued metric was developed in order to be readily usable in Pareto optimality analysis. Several case studies are presented to illustrate the benefits of the method. The single-valued metric is based on a weighted sum of additional metric, which are also based on subjective user-defined weights. The effect of the subjectivity of these weights will be studied as future work. However, this disadvantage is somewhat negligible compared to the benefits of using the Pareto optimality analysis method.

REFERENCES

DOE & NREL (2017). EnergyPlus (version 8.7.0) [computer software]. Available from https://energyplus.net.

Hunt B. J., Blouin V. Y., & Wiecek M. M. (2007). Modeling relative importance of design criteria with a modified Pareto preference. *ASME. J. Mech. Des.*, 129(9), 907-914.

Lechner, N. (2008). *Heating, cooling, lighting: Sustainable design methods for architects*. Wiley, Inc. Hoboken: New Jersey.

Lee, E. S., & Tavil, A. (2007). Energy and visual comfort performance of electrochromic windows with overhangs. *Building and Environment*, 42, 2439-2449.

Ochoa, C. E., Aries, M. B., Loenen, E. J., & Hensen, J. L. (2012). Considerations on design optimization criteria for windows providing low energy consumption and high visual comfort. *Applied Energy*, 95, 238-245.

Rea, M. S., & IESNA (2000). *The IESNA lighting handbook: Reference & application*. New York, NY: Illuminating Engineering Society of North America.

Reinhart, C. (2014). *Daylighting Handbook, Volume I*. United States: Christoph Reinhart. ISBN: 9780692203637.

Solemma, LLC. (2017). DIVA-for-Rhino (version 4.0) [computer software]. Available from: http://diva4rhino.com.

Wienold, J. (2009). Dynamic daylight glare evaluation. *Proceedings of the Eleventh International Building Simulation Conference.* Glasgow, Scotland.

Wienold, J., & Christoffersen, J. (2006). Evaluation methods and development of a new glare prediction model for daylight environments with the use of CCD cameras. *Energy and Buildings*, 38(7), 743-757.