Integrating Visual and Energy Criteria for Optimal Window Design in Temperate Climates

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INTEGRATING VISUAL AND ENERGY CRITERIA FOR OPTIMAL WINDOW DESIGN IN TEMPERATE CLIMATES

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ABSTRACT

Building codes and certifications require maximal building performance in different aspects. However, focusing on achieving a single purpose can prevent obtaining additional ones. This work aims to help building designers balance energy and visual performance design criteria. Correct window size selection is part of early design stage decisions that influences total building performance. The study is based on temperate climates, but procedures can be applied to different locations.

Large numbers of techniques have been used to optimize building features for one objective. However, it is not common to find an integrative approach to visual and thermal aspects of window design. The difficulty to achieve many goals resides in high degrees of complexity introduced when many building features must be considered in an infinite number of possible design solutions. Multi-objective optimization techniques start to be applied in building science. Nevertheless, choosing adequate acceptance criteria presents additional dilemmas. Different assessment criteria applied to a single problem can lead to diverse valid solutions.

A brief review was made of commonly used energy consumption and visual comfort and performance criteria. The study was made through whole-building computer simulations of a standardized test room. The influence of window size variations on energy consumption, visual performance and visual comfort was examined. The window-to-wall-ratio (WWR) of the facade prototypes varied from 10% to 100% in 10% steps. Energy consumption and visual comfort criteria for acceptance were defined based on the review. A graphical optimization method was used to select a range of recommended window sizes for different orientations.

This provided a solution space with “compromise sizes” satisfying both energy and visual aspect objectives. However, unprotected windows cannot meet all these criteria. This makes the provision of sun-protecting elements necessary. A selection procedure based on design needs is detailed. When various related criteria are applied using adequate values, the variety of acceptable solutions is increased, but too many can limit it. Clear acceptance ranges and objectives that can be translated to decisions have to be conceptualized beforehand.

INTRODUCTION

Windows characterize energy consumption and visual comfort patterns in buildings. Choosing their size is among many fundamental early stage decisions. Therefore, determining optimal characteristics for building performance is essential. Multiple aspects must be considered at once in order to accomplish project objectives. Even though, most research efforts are dedicated to find optimal properties of a single element for one purpose only. Multi-objective optimization starts to be applied in building science, considering several variables at once. However, appropriate evaluation criteria must be considered beforehand.

Applying different assessment measures to a single aspect of the same problem can lead to diverse valid solutions. Additional new criteria are then needed to define a solution [1]. Daylighting systems have been evaluated through indicators involving illuminance and glare [2]. However, assigning importance values to each visual factor and their interaction with energy consumption requires further exploration.

Whole-building computer simulation was used to examine window size variations and their energy consumption, visual performance and visual comfort patterns for temperate climates. A solution space is defined, and results are examined different design criteria. A method is shown on how to use them in order to define a “compromise size” from the solution space.

AVAILABLE VISUAL AND ENERGY EVALUATION CRITERIA

Energy

Energy use can be measured on site and is of economic interest for building operation. It is usually expressed in terms of energy units (kWh or GJ) per unit area per time unit. It quantifies consumption of heating, cooling, lighting and ventilation. The goal is to select the least energy-consuming system. Other methods include evaluating adaptive thermal comfort [3] and the degree-days method [4].

Visual performance and comfort

Discomfort due to visual effects is reported more frequently than discomfort by thermal effects. This is due to the time delay in experiencing the latter [5]. Visual performance and comfort criteria will be divided into illuminance-based and glare-based criteria.

-Illuminance-based criteria serve to evaluate if a lighting setup provides the amount of light needed to carry out a task, usually in the horizontal plane. Examples include the daylight factor, range of useful illuminances, and illuminance uniformity (understood here as the ratio between maximum and minimum illuminance in a space) [6]. Suitable values for different activities are provided in various standards.

-Glare-based criteria are meant to assess visual comfort in a space. A comprehensive account of glare indexes and evaluation methods is detailed by [7]. Each measure is specific to a particular situation, such as luminance ratios [8]. Regarding natural light, a widely used measure is the Daylight Glare Index (DGI). A value of 22 is assigned to the evaluation “just acceptable”. Other methods include the daylight glare probability (DGP) [9].

Dynamic evaluations involving the above criteria require statistical measures such as averages but these can mask severe occurrences of an indicator [10]. For yearly evaluations, it is usual to add the number of hours a certain condition (border, extreme or average) is met.

METHOD

Location and test room description

Computer simulations were made using EnergyPlus for a fictional office module located in Amsterdam, the Netherlands. The IEA Task 27 model [11] was used as basis. It consists of a hypothetical room (dimensions 3.5x5.3x2.7m) with a single external wall. The U-value at the opaque section of the external wall follows NEN 2916:2004 (0.32 W/m2K). Slabs and internal walls are assumed adiabatic. Visual properties and thermal load conditions follow the IEA Task 27 model. A single opening is placed on the centre of the external wall, providing view at all times. WWR of the opening varied from 10% to 100% in 10% steps. Glazing for all window sizes was double pane clear (U-value at centre 1.7 W/m2-K), without any shading device. Evaluations were made for the four main orientations.

Mounted ceiling lamps provided a lighting density of 4x50W. They were controlled through a two-zoned dimmer. Lamps would supplement natural light if levels fell below 500lx at the working plane (0.8m from the floor). Daylight illuminance was measured at two sensor points, located at the centre of each lighting zone. P1 was the sensor closer to the window, while P2 closer to the back of the room. Glare was measured at P2, looking directly to the window.

Criteria used for optimization

The desired boundaries for the solution space are given below, detailing their yearly evaluation. Letters in italics refer to the notation used in equations (3.1) to (3.4).

a) Combined yearlong energy consumption (*En*) of heating, cooling, ventilation and artificial lighting had to be minimized.

b) Illuminance at P2 (*E*) had to be equal to or exceed 500lx for a minimum of 50% total occupancy hours. A value of 500lx is required in many standards to perform office tasks.

c) Illuminance uniformity, *U*, (Ep2/Ep1) had to be equal to or less than 3.5 for a minimum of 50% total occupancy hours. There is higher tolerance to daylight contrast than from artificial lighting.

d) Daylight glare when looking directly to the window from P2 (*G*), had to be equal to or less than DGI 22 [12] for a minimum of 50% total occupancy hours. Only this viewing direction was considered.

e) For this study, a solution was considered into the solution space if it accomplished illuminance criteria and at least one visual comfort criteria.

Compliance of a given criteria during all occupancy hours is unity. The above criteria can be stated as follows:

$$\text{Minimize} \quad En \tag{3.1}$$

$$\text{Subject to} \quad E \geq 0.5 \tag{3.2}$$

$$G \geq 0.5 \tag{3.3}$$

$$U \geq 0.5 \tag{3.4}$$

RESULTS

Figure 1 presents energy consumption and visual comfort for the analyzed cases. Stacked bars represent energy consumption detailed by heating, cooling, artificial lighting and ventilation. Curves represent percentage of occupancy hours for uniformity, glare and illuminance criteria. The graphical optimization method used is as follows: a shaded region covers the area below 50% occupancy hours. Curve points outside this area represents a given visual criteria being met. These results are valid for a single opening, placed in the centre of the facade.

In terms of energy consumption, larger window sizes for South increase cooling demand, while for North heating demand. East and West orientations have the highest overall energy consumption. Least energy use was observed at 30% WWR for North, and at 20% WWR for South, East and West orientations.

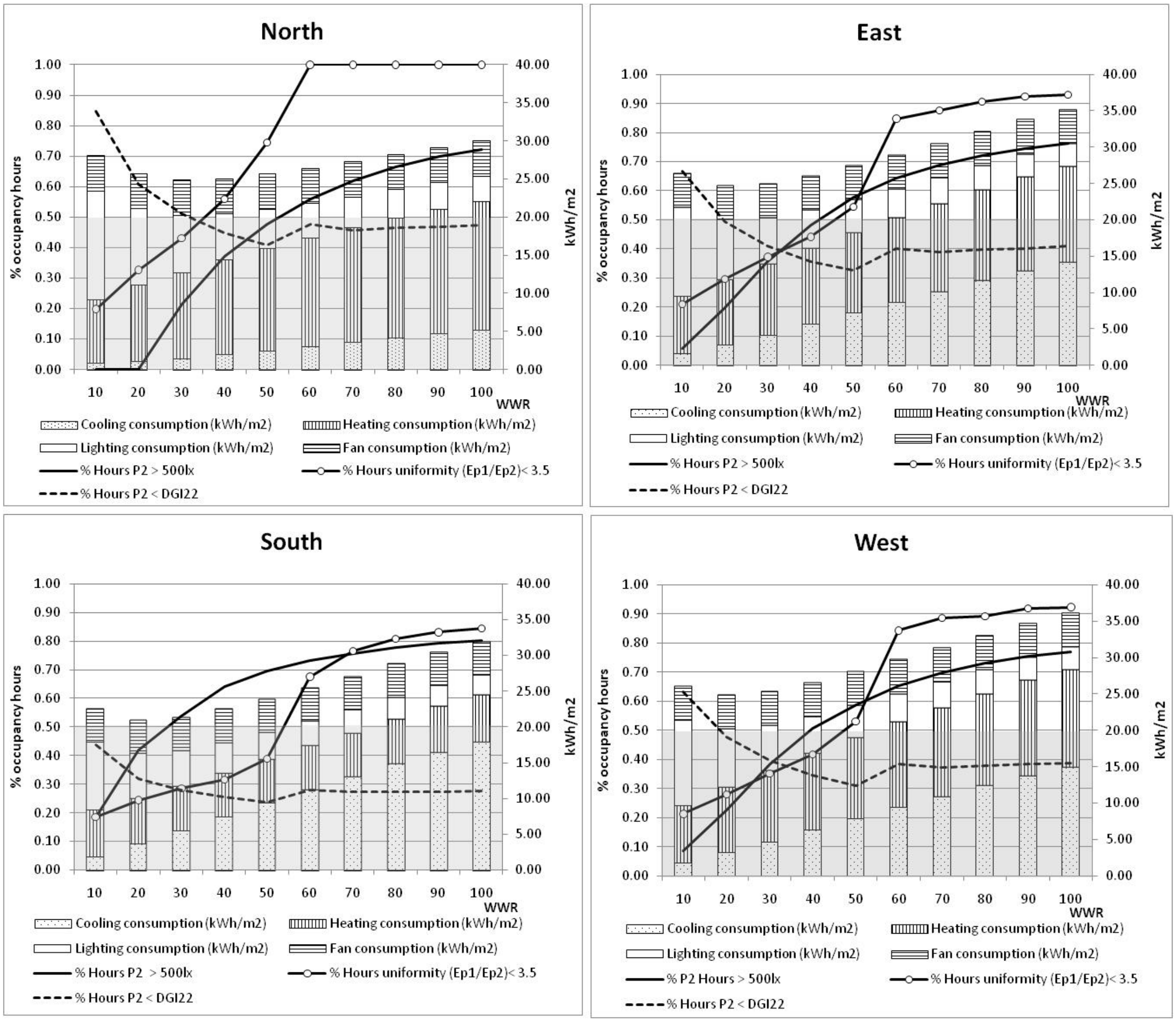

Figure 1: Energy consumption, visual performance and comfort for variable window-to-wall-ratio (WWR) of a hypothetical test room. Location: Amsterdam, the Netherlands. The four main orientations are shown. Unshaded areas on the graphs represent visual criteria being met.

However, window sizes with least total energy consumption are among the worst regarding visual aspects. Even though all visual criteria had equal importance values, illuminance performance at P2 was deemed a requisite to be met as it is stated in many standards. Window sizes achieving one of the two visual comfort criteria at P2 were found in the following window size range. For North: 50 to 100% WWR, for South: 60 to 100% WWR, for East and West: 50 to 100% WWR.

A “critical region” was observed for electric lighting consumption, occurring when reductions on electric lighting energy caused by daylight were less than 5% from the previous case. For North orientation, this was seen from 70% WWR. For South, East and West this was observed from 60% WWR.

The solution space is delimited by the intersection between compliance with at least one visual comfort criteria, compliance with illuminance criteria and start of the critical region.

The window size range is then for North: 50 to 70% WWR, for South: 60% WWR, for East and West: 50 to 60% WWR.

Higher-level information needs to be introduced to choose a single window size that also accomplishes other project objectives. If such additional objectives can be satisfied by a window size within the solution space, a "compromise" can be reached. For example, larger windows respond to improved views. Smaller windows respond to privacy, concerns on energy consumption, etc.

As an example, a designer wants to give the most views to the North, but keep energy consumption minimal. From the results, the solution space for that orientation comprises window sizes between 50 to 70% WWR. For most views, the designer can choose 70% WWR, as this is the upper limit in the solution space without wasting lighting energy.

DISCUSSION

Optimizing window size only for low energy consumption, results in an internal environment not meeting any visual acceptance criteria. This translates to an office environment dominated by high electric lighting usage. Window sizes optimized exclusively for visual comfort produce large heating or cooling energy consumption patterns. The inclusion of diverse visual comfort criteria enabled selecting more alternatives. For example, the glare acceptance criterion was not met by any alternative. However, including uniformity allowed other valid solutions to be accepted. It can also be discussed that measuring glare according to the accepted DGI formulas is not realistic, as it implies a user viewpoint directed towards the window year round.

It was also observed that the solution space, for this particular configuration and climate type, has limited window size options. The prototype already has high performance elements optimized for energy savings (insulation thickness, lighting control and luminaire zoning). Shading elements were not included in this study. This implies that adding too many criteria can limit excessively the solution space.

Differences in energy consumption between the window size using least total global energy and the smallest window size in the solution space are as follows: for North 3.25%, for South 21%, for East 11% and for West 13%. Except for South, this means that a relatively small increase in energy consumption can translate to a more acceptable space in terms of visual comfort, meeting illuminance requirements. Nevertheless, the increase in window size for South can be justified as an investment on visual comfort and views for higher acceptance and productivity from users. Shade elements can bring down this energy consumption.

The results also show that architectural propositions not providing visual control are problematic. Therefore, a careful design is needed that takes into account climatic elements such as glazing type and shade.

CONCLUSIONS

Window size is important in defining total energy consumption and overall visual comfort and performance. However, by itself is not enough to provide both low energy consumption and be an efficient visual system. More elements need to be taken into account from the earliest design stages. These include but are not limited to shading devices, adequate glazing types and adaptable personal visual comfort. Optimized building design requires that design teams set tolerance amounts to achieve compromise for each indicator. Multi-objective optimization methods can introduce additional complexity to the design process, but help reduce decision uncertainty.

From the results, it can be seen that optimizing window size for a single objective can hinder attaining additional ones, while failing to meet performance standards and comfort recommendations. Combining two suitable and clear objectives produces an acceptable environment in terms of visual comfort, performance and energy consumption.

The definition of “compromise sizes” includes a set of trade-off solutions found in the intersection of different criteria such as energy consumption, illuminance performance and visual comfort. Selecting a final size depends on additional project objectives set to meet user expectations. A larger variety of design elements can enrich options within the solution space. However, further research must be made to assign corresponding weight to visual performance and comfort criteria.

This paper presented an example of a trade-off selection procedure. It also presents a case where not all criteria can be met and a sample procedure on deciding acceptance for such cases. The solution space satisfies visual legal requirements, uniformity and is close to using the least energy. Objectives have to be clear in order to translate them to criteria, and in turn, show designers the range of solutions from which they can choose.

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