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Calculation of the shadow-penumbra relation and its application on efficient architectural design

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Abstract

Shadow Dispersion is the effect by which any opaque object's shadow progressively becomes penumbra. This effect originates from a partial obstruction of the visibility of the solar disk. It allows diminishing solar gain in places where there is high radiation intensity, facilitating visual ergonomics and energy efficiency. Although architecture in the tropics offers a wide array of strategies for creating penumbras, *i.e.*, meshes, lattices, architectural fabrics, openwork walls and pergolas, there is no method for its design. Solar architecture literature simplifies the shadow projection phenomenon and always assumes sunrays as being parallel, but penumbra calculation does not allow for this simplification. In order to bridge this gap, calculating equations are deduced here and the tables needed to appraise suitable architectural areas not to block but soften sunlight are included. This paper defines the penumbra rate and shows its application on a building built in Medellin in 2006, designed for housing exhibitions of orchids, which depend on penumbra to survive. The work concludes by outlining the future possibilities of incorporating penumbra zones into the architectural design process. Other applications of the method are also mentioned.

Keywords: Penumbra; Gloom; Shadow; Shading device; Solar control; Shadow Dispersion

1. Introduction

In the tropics, permanent and moderate climatic conditions enable the construction of open buildings, highly permeable and able to establish tight bonds with the place they are in Mesa (2013). Shadow is more significant in this part of the planet than in temperate zones due to the lack of seasons, and because there is a higher intensity of incident solar radiation (Tzonis et al., 2001). Therefore, for many buildings and outside spaces located in the tropics, to have enough shadow is sufficient to offer human comfort conditions for many hours a day.

The balance between sunlight and shadow is a fundamental part in building design due to its strong effect on energy efficiency and thermal comfort. In higher scale projects such as urban planning, roads, squares and parks design, this is also a very important issue. In outdoor spaces and in any public space project, the energy efficiency aspect is less important since there is usually no air conditioning. Nevertheless, thermal comfort and visual ergonomics

Abbreviations: h, element's height; ld, limit distance; f, solar disk viewing angle; θz, zenith angle; e, solar elevation angle; d, penumbra zone width; x, element's size; lh, limit height; lx, limit size; PR, penumbra rate; s, element's projection perpendicular to the solar rays.

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precede the list of priorities to be fulfilled (Higueras, 2013). In turn, in a smaller scale objects' design, it is essential to take shadow calculation into account, which is a prerequisite for the correct dimensioning and distribution of any shading device (Olgyay, 1968; Salazar, n.d.).

The methods and instruments employed to calculate shadows are widely used and spread within the professional environment. In these methods, it is assumed that sunlight rays have an impact on the terrestrial surface as a set of parallel rays. The results obtained from these calculations suggest a drastic change between the shading zone and the sunny zone, with a clear limit between both regions. This is something that is never observed in real shadows, as it can be easily proven. It suffices to expose any opaque object to the sunlight to verify that any shadow is smaller than the object that projects it, and that the shading region edge – called penumbra zone – is clearer as the distance between the object and its shadow increases. None of those phenomena are taken into account when shadow calculations are carried out with analysis methodologies in which sunrays are considered parallel.

A false premise of parallelism does not always lead to an imprecision with effective consequences on the designed objects' solar performance. If it is a big size object, the imprecision of not considering the penumbra is unseen since the shading area is proportionally bigger. Nevertheless, for those cases in which architectural decisions tend to design elements whose dimension is just of a few centimetres, it is essential to consider sunrays as not being parallel.

Solar disk viewing angle and solar aureole are important concepts to improve solar concentration systems. Solar tracking, mirror design and absorber plane optimization cannot be done by applying the parallel solar vector assumption. The solar disk viewing angle has variations during the year, but these variations are not significant and if it is considered as a constant value, the accepted limit of the solar disk is 4.65 mrad (Buie et al., 2003a). The solar aureole presents higher variations originated in the scattering of the solar beam through the earth's atmosphere depending on local climate variations (Buie et al., 2003b). The radiant flux contained within the circumsolar region of the sky, including solar disk and solar aureole, is an important issue defining a pyrheliometer's acceptance angle. A 5° field of view is defined by the ISO-9060 to capture the sun and part of the circumsolar region because the total amount of direct radiant flux is found within this angle.

There are subtle evidences of the sunshape distribution variation on the shadow casting phenomena within architectural elements: during clearer days the shadows will be sharper and the penumbra zone narrower. In foggy days and during mornings in warm-humid places, the penumbra zone becomes wider and the shadow definition becomes less evident. The 5° magnitude does not have a particular significance in architectural design because the extent of the solar disk provides between 98% (extremely clear skies) and 90% of the direct insolation (Buie and Monger, 2004). From the designer's point of view, both conditions can be considered equivalent because the critical design condition arises when the sky is clearer, less energy comes from the aureole and the shadows have a better focus.

Database searching (including Science Direct, One File, Science Citation Index, Expanded Academic ASAP and Discovery Service) using "penumbra, shadow and architecture" as keywords did not find any relevant paper during the retrieval made in July 2014. Publications about penumbra in architecture refer to a characteristic of spaces lightened with diffused natural light. In computer graphic research the term "soft shadow" is also used, and describes computer techniques to increase realism in rendering algorithms (Kolivand and Shahrizal Sunar, 2013). Classic books on Bioclimatic Architecture, in which there is always a chapter completely dedicated to the principles of Solar Geometry, do not mention the shadow-penumbra relation either. Arzoumanian (1988), Baruch (1976), Koenigsberger et al. (1977), Lippsmeier (1969), Lan (1986), Olgyay (1968), Puppo and Puppo (1972), Szokolay (1977) and Yáñez (1988) works not only do not have the concept of penumbra, but also do not include any discussion about the consequences of assuming sunrays' parallelism when making solar control calculations.

The consequences of this gap are particularly important in sunlightning studies carried out for the tropics. Meshes, lattices, architectural fabrics, openwork walls and pergolas, are part of the formal tradition and repertoire for buildings in this part of the planet. The architectural enclosures made with these elements can form surfaces of many square meters, but they are often composed by fairly small-dimension elements repeatedly installed. They should not be designed without taking into account the penumbra effects they produce.

A successful design process is based on analysis and representation methods in which simplifications of the applied model do not distort the essence of the studied phenomenon. To calculate shadows from a large list of architectural elements, assuming sunrays as parallel, does not have practical consequences or prevent making good design decisions. On the contrary, if rays are considered as divergent, this would lead to an unnecessary complexity in the calculations since the conclusions would be ultimately the same as those from using simpler methodologies.

At the detail scale, things are very different. For small size objects, the proportion between shadow and penumbra reaches a balance. In such cases, assuming sunrays' parallelism implies ignoring an important phenomenon called Shadow Dispersion, which can have a major role in architecture for the tropics, and which offers great possibilities in the creation of energy efficient and visually comfortable spaces.

2. Objective

To incorporate penumbra zones into the architectural design process by developing the technical basis, deducing