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Proposal and analysis of different methodologies for the shading and blocking efficiency in central receivers systems

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ABSTRACT

Nowadays, there are many simulation codes aimed at the simulation of the solar field performance and the optimization of the layout of central receivers systems. These codes should obtain fast and accurately the different efficiency factors of the solar field at different sun positions (representative of the yearly operation). Among these factors, the shading and blocking efficiency is maybe the most demanding one regarding the computational effort.

In this paper four non-conventional methodologies are presented for the calculation of the shading and blocking efficiency. The codes have been developed with the ambition of decreasing the computational time without a significant accuracy drop. For that reason, they are suitable for optimization tools. Additionally, a new methodology for the determination of the subset of heliostats with potential for shading or blocking is presented.

The performance of the methodologies is evaluated by means of a study of the errors and computational times, which are compared to those reached by a conventional Monte-Carlo ray tracing reference simulation. Results indicate that the proposed methodologies, particularly two of them, present good accuracy and a significant decrease of the computational time. The causes of the main errors of each methodology are also discussed.

1. Introduction

This paper focuses on the study and simulation of the optics of solar tower systems, also called central receiver systems (CRS).

CRS consist of a large array of heliostats, individual mirrors with dual axis tracking systems, which concentrate solar irradiation onto a receiver located on the top of a tower. These systems have potential to supply solar thermal energy onto the absorbing surface of the receiver in a wide range of power and temperature levels. The applications of this technology are related to the generation of electricity or heat for industrial processes (Lovegrove and Stein, 2012).

Simulation tools are necessary since they allow the design and optimization of this kind of facilities; from an economic point of view, the heliostat field represents around 50% (Kolb et al., 2007) of the plant's total cost and causes about 47% of the annual power losses (William and Micheal, 2001).

The earliest simulation tools for CRS appeared in the late 1970 s. Nowadays, in the technical literature many codes may be found. Among them, the following can be highlighted: MIRVAL (Leary and Hankins, 1979), SOLTRACE (Wendelin, 2003), TONATIUH (Blanco et al., 2005), SENSOL (Relloso and Domingo, 2006), HLFD (Yu et al., 2012), DELSOL3 (WinDELSOL) (Dellin et al., 1986), HELIOS (Biggs and Vittitoe, 1979), UHC (Lipps and Vant-Hull, 1980), HFL-CAL (Schwarzbözl et al., 2009).

These simulation codes, their advantages and disadvantages and fields of application were analyzed by Kiera (1989), Monterreal (2000), Pitz-Paal and Schwarzbözl (2000) and Garcia et al. (2008). The first five codes use Monte-Carlo ray-tracing method, while the rest of them use the convolution technique.

Some of them are able to determine the best heliostat field layout to maximize the optical efficiency, which can be expressed as follows:

$$\eta_T = \eta_{cos} \cdot \eta_{ref} \cdot \eta_{s\&b} \cdot \eta_{at} \cdot \eta_{int} \quad (1)$$

where η_{cos} represents cosine effect efficiency, η_{ref} reflectivity of the heliostats, $\eta_{s\&b}$ shading and blocking efficiency, η_{at} atmospheric attenuation efficiency and η_{int} interception efficiency.

To achieve the layout, the codes must determine these efficiency values of all the heliostats in the field at different instants of the year. According to Walzel et al. (1977) at least 40 sample

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Nomenclature

Latin letters

a_s	solar azimuth angle, rad
CRS	central receiver systems
D	diagonal of the heliostat, m
RMSE	root mean square error
h_s	solar altitude angle, rad
J	day number
Nc	number of calculation points
Nr	number of reflected rays
Ns	number of shaded rays.
$\boldsymbol{S_o}$	the unit vector from the center of the heliostat pointing to the center of the sun
T	center of the target

Greek letters

ϕ	latitude, rad
δ_s	solar declination angle, rad
ω_s	solar hour angle, rad

points must be used to capture the location's daily and seasonal variations.

Since the computational effort is high, some of the mentioned codes divide the heliostat field into a certain number of cells or sectors, from which some representative heliostats are selected to perform the calculations. Other codes perform the calculations heliostat by heliostat.

Among the efficiency factors, the shading and blocking efficiency factor requires great computational effort. It is a geometric loss. Shading losses are due to the reduction of the heliostat's useful area, owing to its partial shading caused by its neighboring heliostats or the tower. Besides, blocking losses result from the reduction of the heliostat's useful area, due to the fact that part of the reflected radiation does not reach the receiver, being blocked by its neighboring heliostats. Both are usually combined into a single efficiency factor.

In order to determine the shading and blocking efficiency, given the huge amount of heliostats in a heliostat field, it is essential to previously determine the subset of heliostats with potential for shading and blocking each one of the heliostats in the field. That makes it possible to significantly reduce the required computational effort and the simulation time.

For example, HELIOS considers that the heliostats with potential for shading and blocking the analyzed one are the n heliostats closest to it, regardless of the sun position or other factors. The value of n usually ranges between 4 and 34, although it can be modified by the user. The code uses the same subset of heliostats for optimization at different instants and days of the year.

In order to later determine the shading efficiency, the vertices of the involved heliostats, considering they are rectangular sheets, are projected onto a plane perpendicular to the main direction, using orthogonal cylindrical projection along the main direction. Consequently, such projections become parallelograms.

In the case of the blocking efficiency, the vertices of the involved heliostats are projected onto a trigonometric sphere whose center coincides with the center of the target and is the projection center. Afterwards, in order to simplify the calculations, the heliostat projection obtained on such sphere is considered to be flat and have straight sides. Hence, heliostat projections will be, in general, trapezoids.

On this basis, shading and blocking calculations are similar. The analytical method described in Manson (1974) is used to determine whether there is overlap and if so, the overlapped surface is determined by analytical means. The procedure is based on decomposing the quadrilaterals into rectangle trapezes, determining all possible combinations between them without repetition and finally determining the common area between them in pairs.

It is not clear, however, what happens if several heliostats shade and/or block the analyzed one, nor how to determine the shading caused by the tower.

In Besarati and Yogi Goswami (2014) the subset of heliostats with potential for shading the analyzed one is determined. This is done by means of a circle drawn from the top view of the heliostat field, with its center at the analyzed heliostat and its radius set to be $R = 2.5D$ for dense fields, and the projection of the main direction onto the horizon plane. The selected heliostats are those which are located in the half-circle that is closest to the sun and to the projection of the main direction. Thus the code selects three heliostats, although that number can be modified.

This method has the disadvantage that the radius does not depend on the sun altitude. If it is high, too many candidates will be selected. By contrast, at instants immediately after the sunrise or before the sunset, when the sun altitude is low, generally too few candidates will be selected.

In that work it is also indicated that, for blocking calculation, the procedure is analogous although operating with the horizontal projection of the reflected ray at the center of the heliostat. Moreover, it is indicated that if the heliostat layout was in polar form, the above calculations are not necessary, selecting directly the two closest heliostats in the row adjacent to the analyzed heliostat and the one that is two rows over.

Afterwards, the method described in Sassi (1983) is used to determine the shading and blocking efficiency itself.

Belhomme et al. (2009) propose a method based on the projection of the spheres circumscribed about the heliostats onto a plane perpendicular to the main direction, using orthogonal cylindrical projection, along the main direction in the case of shading, and along the direction of the reflection in the case of blocking. In the event that the projections of such spheres intersect (in the described projection they are circumferences) it will be necessary to check the shading between the facets. This checking is performed by projecting the vertices of the analyzed heliostat's corresponding facet, using the above mentioned projection, onto the plane defined by the facet of the heliostat shading and/or blocking it. According to Gottschalk et al. (1996), the Separating Axis Theorem is used to check whether there is overlap.

Thereafter, since this is a ray-tracing code, the interaction between the incident rays and the reflected rays is checked, applying them to the analyzed facet, with the face with potential for respectively shading it and blocking it.

Sassi (1983) proposes a simpler method, which considers the heliostats to be flat rectangular sheets with the same size and orientation. In this way, it is enough to project the center of one of heliostats onto the plane defined by the other heliostat, using orthogonal cylindrical projection, along the main direction in the case of shading, and along the direction of the receiver in the case of blocking. Once this is done, it will be clear if there is overlap, comparing the abscissa and the ordinate of the center of the projected heliostat, respectively with the heliostat width and height in their true size. The center of the not projected heliostat is assumed to coincide with the origin of a Cartesian system x and y.

For the calculation of the shading and blocking efficiency, the horizontal sides of the analyzed heliostat are divided into the same number of equal parts, and the length of the vertical stripes overlapping in each division is determined.