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Shadowing and blocking effect optimization for a variable geometry heliostat field

P. Cádiz[1*], M. Frasquet[1], M. Silva[1], F. Martínez[1], J. Carballo[1]

[1]*CTAER, Solar Departament, Paraje Retamares s/n, 4200, Tabernas – Almeria (SPAIN)*

Abstract

Optimization software is currently a key tool when designing heliostat fields. Shadowing, blocking, atmospheric attenuation, spillage and cosine effect losses can be hugely minimized with proper use of this tool, so they are widely used in this field of work. However, variable geometry is a ground breaking concept that is only recently been researched, and existing optimization software for conventional heliostat fields perform poorly when applied to this new concept, due to the fact that they do not use the advantages that it provides. The code here presented explores this idea to fully exploit the capabilities of variable geometry heliostat fields.

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1. Introduction

Optical efficiency is the relationship between the energy that hits the receiver and the total available solar energy. Improving this efficiency allows the size of the solar field to decrease, reducing costs. Solar field represents roughly 40% of the total cost of a central receiver power plant [1], so the final cost of generated power can be lowered significantly by placing the heliostats optimally according to optical efficiency. The position with maximum efficiency is not stationary, and varies with sun position, so traditional stationary heliostat fields are placed in such a way as to achieve the best efficiency integrated over the year.

* Corresponding author. Tel.: +34-678-815-786
E-mail address: pablo.cadiz@ctaer.com

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However, variable geometry allows the definition of an optimal configuration of the heliostat field for each individual instant the plant is operating, instead of having to settle for a single configuration for its entire operating life like conventional stationary geometry. With this in mind it is possible, at least theoretically, for the heliostat field to set up its geometry so that it minimizes losses according to sun position at all times, thus improving its performance greatly compared to conventional fields. The most common procedure has been to rotate the entire field so that cosine effect losses are minimized. This may not be the optimal way if shadowing and blocking effect losses are also considered. [2]

This paper presents results of a developed code that optimizes azimuthal distances between heliostats for a given time, focusing on accurate calculations of shadowing and blocking effect losses. To describe its advantages, three fields are compared. A traditional stationary field, a variable geometry field using the simple technique of rotating the whole field simultaneously, and a field where all azimuthal distances are optimized.

These characteristics could be defined thanks to the experience acquired by the CTAER in the construction of its Tabernas facility. The experimental facility built by CTAER in Tabernas (Almeria) is the first and only one of its kind, and has made it possible to go from theoretical concept to as-built reality [3] with everything this implies [2].

2. Variable geometry. Shadowing and blocking problem.

The instantaneous efficiency η is calculated as the product of the instantaneous efficiency terms, as seen in equation (1), where η_{cos} represents cosine efficiency, η_{sb} is shading and blocking, η_{itc} is the interception of sun rays at the aperture, η_{aa} is the atmospheric attenuation, and η_{ref} is the heliostat reflectivity.

$$\eta = \eta_{\text{cos}} \cdot \eta_{\text{sb}} \cdot \eta_{\text{itc}} \cdot \eta_{\text{aa}} \cdot \eta_{\text{ref}} \quad (1)$$

Out of these efficiency terms, the cosine factor is the one with the most weight in the final result, followed by mirror reflectivity. The cosine factor varies with the angle of incidence, that is, the angle between the solar vector and the normal to the heliostat surface. It varies close to symmetrically, with noon being the optimum point, when the field's axis of symmetry is aligned with solar azimuth. Given these facts, it is easy to assume that if the field rotates following solar azimuth, cosine effect losses are reduced to a minimum and thus, the optimum point is maintained throughout the year.

However, comparing the performance of a static field against a rotating field, it becomes clear that this approach is not the optimum. Cosine effect losses are indeed lower on a rotating field, but the increase in shadowing and blocking losses outnumbers the performance gained from cosine effect, and the overall performance is hindered. Tables 1 and 2 show the comparison between these two fields.

Table 1. Instantaneous performance comparison between stationary and rotating fields at 4pm, 21st July.

Field	Cosine effect (CE) efficiency (%)	Shadowing effect (SE) efficiency (%)	Combined effect (CE*SE) (%)
Stationary	0.542	0.762	0.413
Rotating	0.956	0.623	0.595

Table 2. Annual performance comparison between stationary and rotating fields.

Field	Cosine effect (CE) efficiency (%)	Shadowing effect (SE) efficiency (%)	Combined effect (CE*SE) (%)
Stationary	0.8079	0.8765	0.7081
Rotating	0.9566	0.8372	0.8009

The annual performance results show that indeed, a rotating field is the better solution. The small increase in shadowing effect losses is not enough to obscure the huge increase in cosine effect performance.

The instantaneous performance results confirm that late in the day (in this case at 4pm) shadowing effect becomes a problem for rotating fields.

The source of this problem resides in low sun elevation. A common configuration in central receiver solar field designs is the radial staggered layout. This distribution, where the heliostats alternate positions, each group of three forming equilateral triangles, has been shown to provide good field density without high losses [4].

In a conventional field with a staggered geometry, the lowest losses from shading and blocking are at solar noon on any day of the year, where the axis of symmetry coincides with the solar.

In a rotating field, the axis of symmetry is always aligned with the solar azimuth so the percentage of shading could be expected to be constant and lower all day long. However, as seen in Figure 2, performance very early and very late in the day drops significantly because the sun is so much lower in the sky at those times that a staggered layout cannot avoid shading. In fact, losses are aggravated.

The code here presented aims to maintain the much better cosine effect performance of a rotating field, while at the same time avoiding the shadowing and blocking problem at low sun elevation.

3. Azimuthal optimization

A proposed solution to this problem, presented in this paper, is to use optimization techniques to derivate the azimuthal distances between heliostats, so that a compromise between cosine effect and shadowing and blocking losses is achieved. These azimuthal distances are calculated each time for a number of specified days and hours throughout the year. In this optimization, 7 days per month have been chosen (days 1, 4, 6, 11, 16, 21 and 26 of each month), and 13 hours of sunlight are assumed (from 6am to 6 pm, both included)

3.1. Heliostat positioning

Because of the nature of variable geometry fields, heliostats are positioned so that radial distances are fixed (heliostats move on top of rails around the tower) and only azimuthal distances can be varied. The optimization process uses radial distances and number of heliostat in each radius as inputs. In each radius, a heliostat is positioned so that its azimuth is the same as the sun azimuth. From there, azimuthal distances of the remaining heliostats are optimized, its constraints set up in such a way as to maintain a minimum distance and avoid collision.

To reduce the number of variables to optimize, a sensible approach is to assume the symmetry of the field.

3.2. Cosine effect

The calculation of cosine efficiency is simple using the Law of (specular) Reflection. The dot product of the directions of sun and heliostat (or facet) normal direction is related to the angle of incidence.

$$\cos = \cos\theta_i = d_{sun} \cdot d_n$$

3.3. Shadowing and blocking

Shadowing and blocking losses are calculated geometrically, assuming the heliostats as rectangles in space. The process includes two parts.

First, the four vertices of the target heliostat are projected into a plane which is perpendicular to the sun's vector. Then, the neighbors of the target heliostat are also projected, and the useful area is calculated. This area is the projected back again to the target heliostat.

Then, with shadowing losses calculated, the process is repeated for blocking. Neighboring heliostats are projected into a plane containing the target heliostat and blocking is calculated this way, removing the appropriated portions of area from the target heliostat. The remaining area is the shadowing and blocking effect performance.

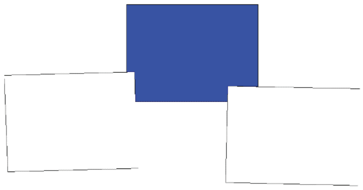

Fig. 1. Example of a blocked heliostat. Useful area represented in blue.

3.4. Results

The following results have been obtained using a 113 heliostat field, and its variable geometry equivalent. That is, when optimizing the azimuthal distances, the radial distances and the number of heliostat per radius are the same as in the fixed (or rotating) field.

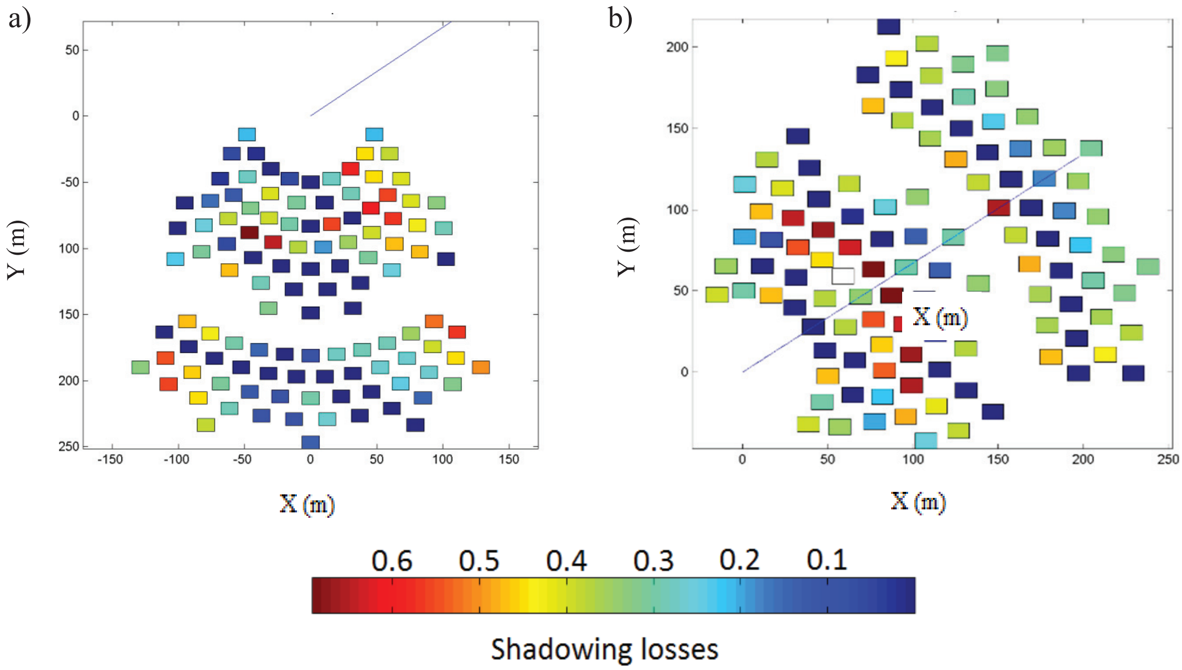

Fig 2. (a) Fixed variant of the 113 heliostat field, 4pm. (b) Rotating variant of chosen field, 4pm. Colors represent shadowing loses.

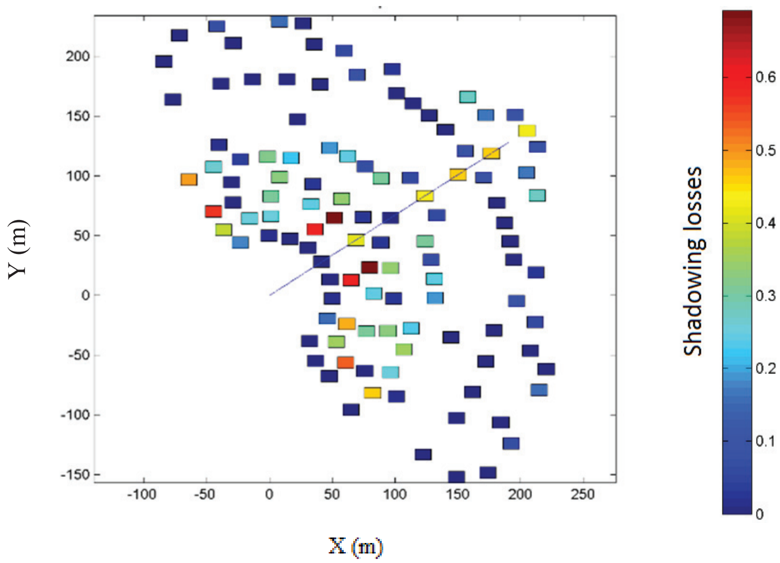

Fig 3. Optimized variant of the 113 heliostat field, 4pm. Colors represent shadowing loses.

Table 3. Annual performance comparison between stationary, rotating and optimized fields. Power does not take into account thermal losses.

Field	Cosine effect (CE) efficiency (%)	Shadowing and blocking effect (S&BE) efficiency (%)	Combined effect (CE*S&BE) (%)	Power (MW)
Stationary	0.84	0.793	0.648	4.115
Rotating	0.952	0.776	0.739	4.420
Optimized	0.926	0.896	0.830	4.772

Azimuthal distances optimization yields 18 % more optical performance compared to a conventional fixed field. However, it should be noted that in terms of power this improvement is significantly lower, because the optimized field grants better performance improvement early and late in the day, when solar radiation is lower and thus, less power is generated. Power generated is 16 % greater than a fixed field and 8 % greater than a rotating one.

Against a rotating field, the optimized one sacrifices a 2.6 % in cosine efficiency to obtain a much greater shadowing and blocking efficiency. Heliostats are placed more separately to avoid S&B when sun elevation is low.

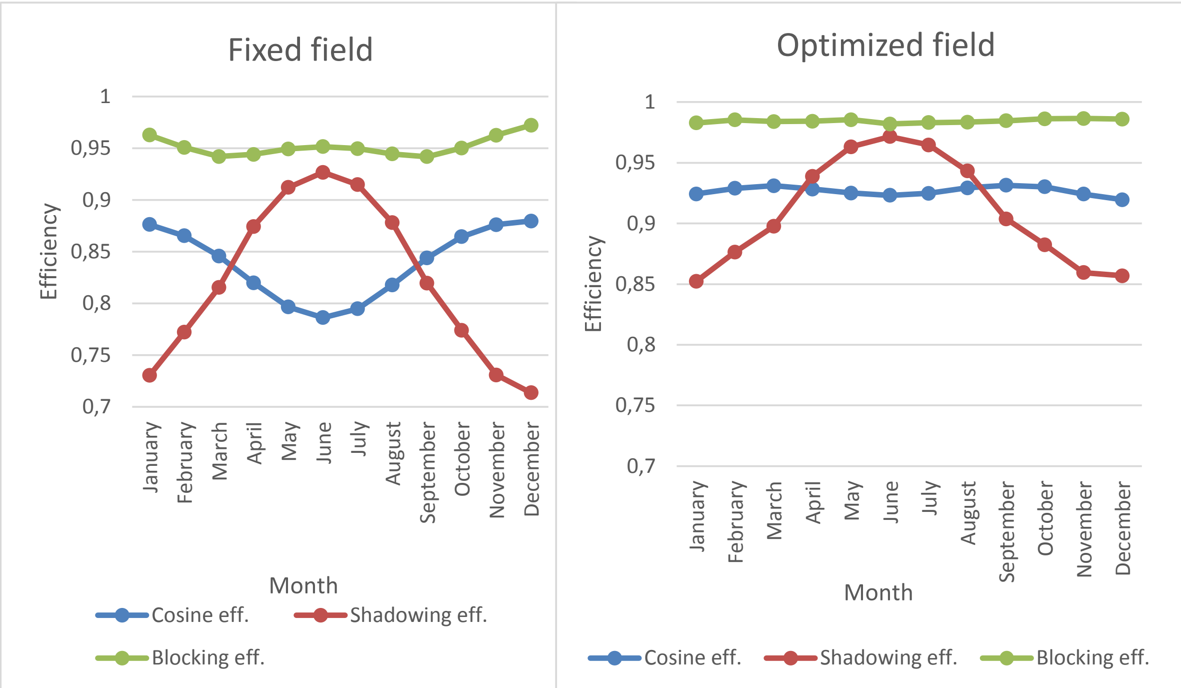

Fig 4. Annual performance comparison of an optimized field and a fixed field

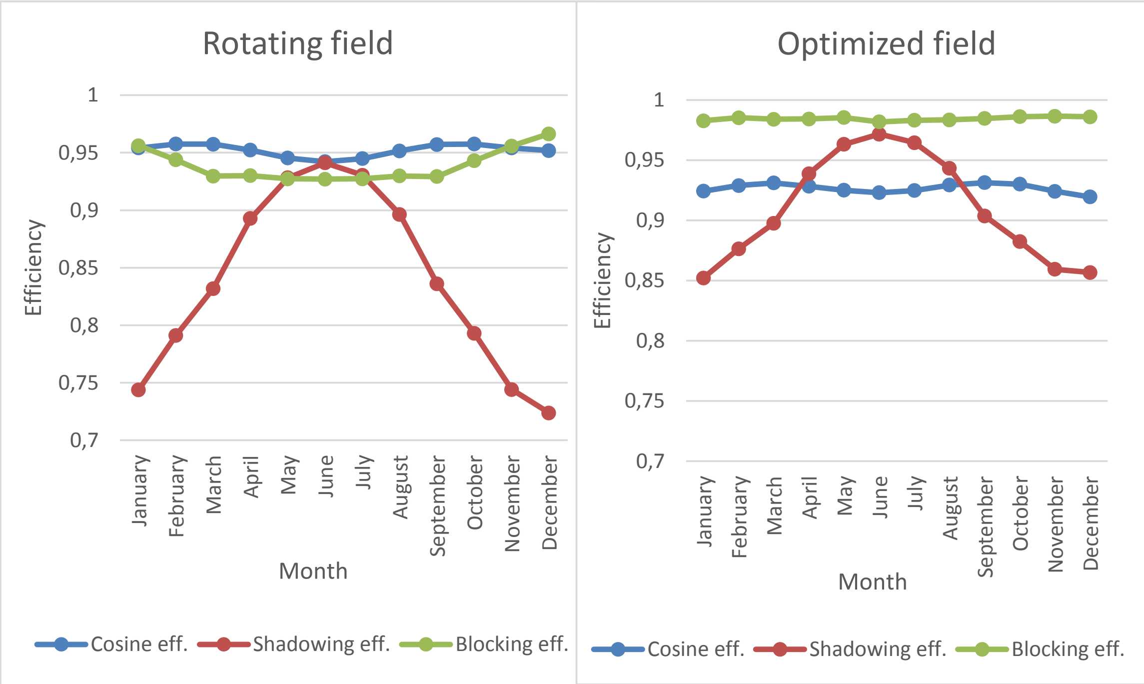

Fig 5. Annual performance comparison of an optimized field and a rotating field

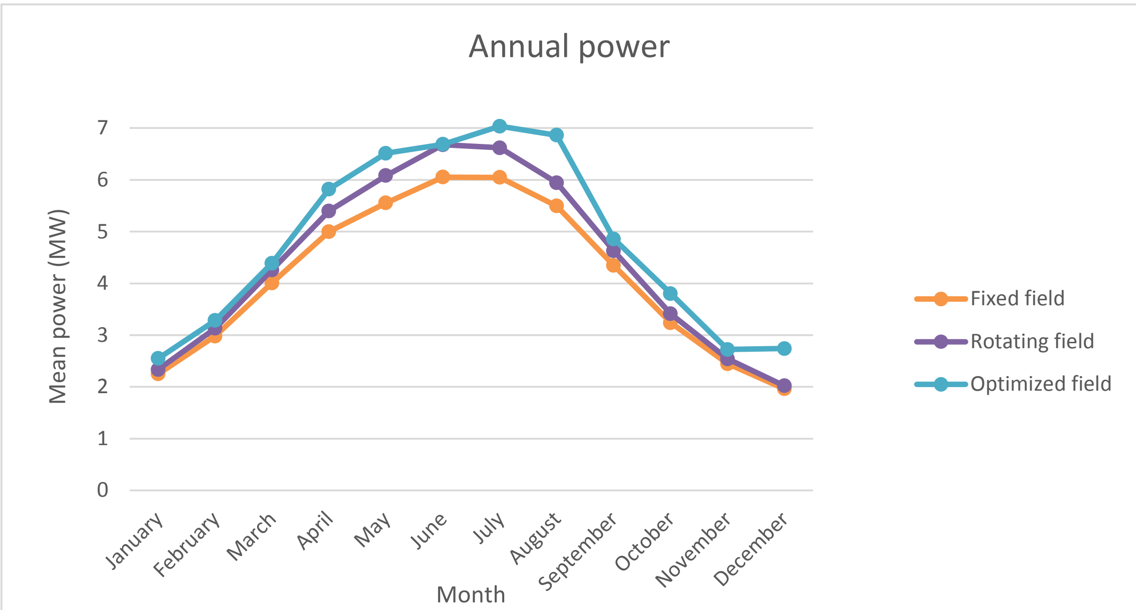

Fig 6. Annual power comparison. Only optical losses are taken into account.

This mean power is defined as the mean of the power yielded by each field during each calculated hour. Please bear in mind that the fixed and optimized field have been evaluated for every day of the year, whereas the optimized field has not, and direct total power comparison is not possible.

4. Validation

The code has been developed using MATLAB, and it has been validated using both other commercial software and real data.

4.1. Software validation

Tonatiuh [5] is an open-source Monte Carlo ray tracer for the optical simulation of solar concentrating systems. It is incapable of optimizing, and has only been used to evaluate individual configurations.

NSPOC [6] is a tower solar power plant optimization software developed by Nevada Software. It has been modified so that it can be applied to variable geometry fields using a methodology equivalent to the code here presented. It has been used to validate annual optimizations.

4.2. Real data validation

The calculation of shadowing and blocking effect losses of the code has also been validated using CTAER facilities at Almeria, Spain. The 13 heliostat variable geometry field has helped collecting real data than has then been evaluated and contrasted with Tonatiuh, NSPOC and the Matlab code presented in this paper.

The heliostat field was moved so that significant shadowing was present in some heliostats. The shadows were measured in situ. Several different measures were taken, at different times of day.

Shadowing and blocking losses were calculated using the three pieces of software, and results were compared. Additionally, Tonatiuh and the code presented in this paper are also capable of representing the actual portion of the heliostat that is shadowed. The results from one heliostat are presented here as an example.

Table 4. Real data validation results for one heliostat

	Shadowing and blocking losses (%)
Real data	45.776
NSPOC	46.534
Tonatiuh	44.5279
Matlab code	44.131192

Fig. 7. Photograph of shadowed heliostat. CTAER Tabernas, Almería.

a b

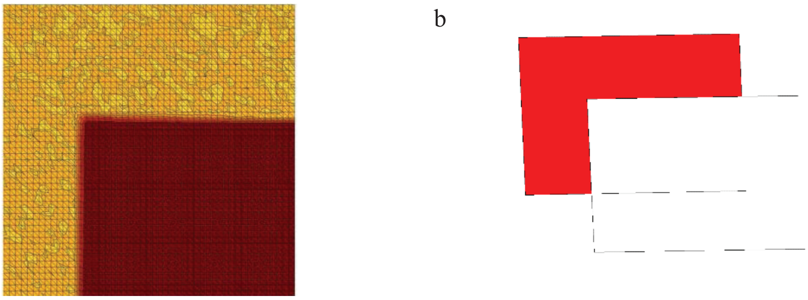

Fig. 8. (a) Shadowed area calculated with Tonatiuh. (b) Shadowed area calculated with Matlab code.

5. Conclusions

The results show that azimuthal distance optimization is a valid and sensible approach when defining the movement strategy of a variable geometry field. The developed code is able to hugely improve shadowing and blocking efficiency by sacrificing some cosine effect efficiency, spreading the heliostats.

In terms of power the improvement over a rotating field is not as high due to the fact that the gain in optical performance is greater when less power is generated due to lower radiation (early and late in the day). However, it should be noted that the cost of implementing this strategy in a variable geometry field is virtually zero, as it is merely a matter of positioning the heliostats in a certain way throughout the year.

The code is by no means perfect, and there is plenty of room for improvement:

- Spillage: Right now, the code calculates interception efficiency using simple Gaussians. Aberration effect is not considered.
- Run time. The function that deletes the portions of area that are blocked or shadowed is not optimized. This function could be modified so that maybe its precision is lowered but it takes less time to evaluate.
- Optimization technique. Several different algorithms may be considered to further reduce computational time.

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