

Ray Tracing Method for the Evaluation of Yearly Performance of a Solar Thermal Concentrator

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Abstract

A method for evaluating the yearly performance of a solar concentrator is presented. The simulation is achieved using the commercial forward ray-tracing tool Tracepro in conjunction with MATLAB. Ray tracing methods are often used to assess the performance of solar concentrators; however, most works on this area simplify the simulation process by considering only a handful of representative scenarios along the year, for example, summer and winter solstices for tracking studies or monthly average days for evaluating the annual average output of the system. The present method is able to achieve a year-long simulation on an hourly basis using MATLAB to setup each simulation within Tracepro via the Dynamic Data Exchange (DDE) protocol; for increased fidelity hourly irradiance data from Meteonorm is also taken into account. The simulation results showed that the proposed method is able to provide valuable data that can be used as input for broader studies, for example, annual dynamic simulations that consider site-specific energy demands.

Keywords: Ray-tracing, solar concentrator, Tracepro, annual simulation

1. Introduction

The ray tracing method is a novel tool applied for the evaluation of solar concentration systems. The method is based on the simulation of a large amount of sunrays in order to determine their distribution and intensity on optical bodies (Duffie and Beckman, 1980). The results are often used to optimize the geometry and orientation of said bodies in order to reduce optical aberrations caused by misalignments of the solar tracking system or to predict the amount of energy concentrated.

It can be found in the literature several works that applied this tool to evaluate the performance of solar concentrators. For example, in Hu et al. (2018) presented a new tracking method aimed to reduce the cosine loss effect on a central tower concentrator by means of a novel refractive body installed before the receiver. Similarly, this technique has been used to evaluate the performance of linear concentrators. An example is shown by Terrón et al. (2018), who evaluated a compound parabolic concentrator by establishing multiple positions to the Sun. Similar studies carried by Su et al. (2017); and Waghmare and Gulhane (2016) have also applied this technique to develop solar tracking strategies for parabolic trough concentrators. In the study described by Yeh, P. and Yeh, N. (2018), the ray-tracing method was used during computational simulation in order to increase the concentration ratio by optimizing the geometry of a curved Fresnel lens able to refract incident radiation onto a secondary concentrator. The method has also been applied in central tower concentration systems. An example is shown by Eddibi et al. (2017), where a novel heliostat field distribution is proposed in order to reduce geometric losses (blockage and shadows) by simulating the solar position at solstices and equinoxes.

A tool that allows these types of analysis is TracePro, an opto-mechanical simulation software. It has been used for the optical analysis of models used in some of the previously mentioned works (Hu et al., 2018; Su et al., 2017; Yeh And Yeh, 2018). To do this, the software evaluates the intensity associated with each beam that propagates through CAD models imported into the workspace. In addition, it has a Macro functionality, which

allows the software to be controlled by other applications using the Dynamic Data Exchange (DDE) communication protocol. This latter shares information between softwares through an item able to identify particular commands required by the program that establishes the communication. However, the application of this simulation technique has been limited for the optimization of novel optical systems (González, 2015).

As observed, the ray tracing method can be applied on different types of solar concentrators. However, the studies are limited to evaluate the performance of said systems taking into account specific moments of the day or a few days along the year, leaving unexplored time periods. Therefore, the present investigation evaluates a continuous performance of a solar concentrator by using the ray tracing method considering one-hour intervals along a year. As a case of study, a central receiver system is evaluated.

2. Method

The ray tracing evaluation method is depicted in Fig. 1. In the first stage, the concentration system is defined, including the solar tracking strategy, the heliostats CAD models and their relative position to each other. Then, a MATLAB code is developed including the equations to find the altitude and azimuth solar angles (α, γ) and the heliostats' position to the Sun and receiver. This information is then translated to TracePro through the DDE protocol in order to establish both, the radiation source and the heliostats' position to begin the simulation process. The obtained results for each cycle are then stored on MATLAB, including the amount and distribution of the concentrated energy on the receiver.

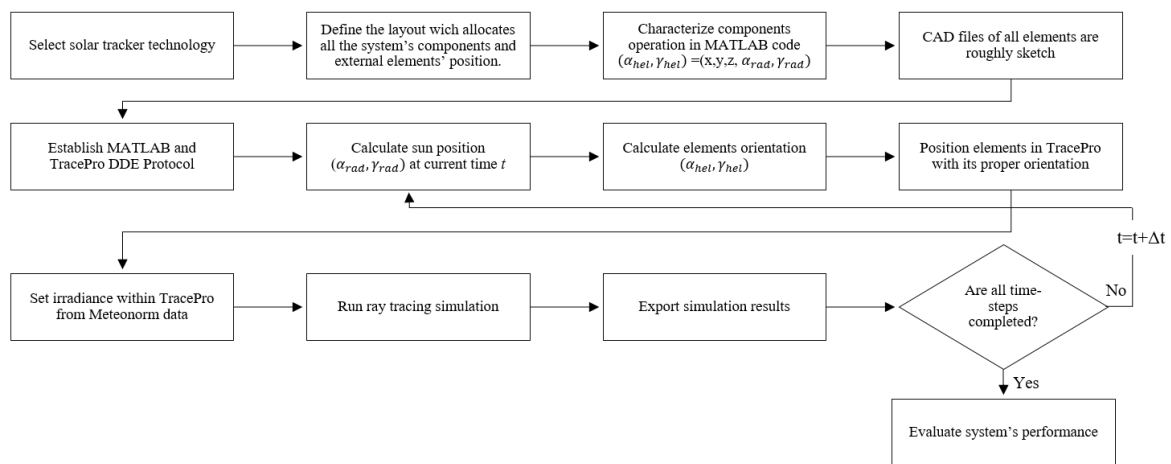


Fig. 1: Proposed ray tracing method

3.1 Solar tracking strategy

For each heliostat, a two-axis tracking strategy is defined in order to reflect the incoming radiation from the source to the center of the receiver as shown in Fig. 2. The purpose of the tracking method is to find the altitude and azimuth angles ($\alpha_{hel}, \gamma_{hel}$), as shown in a general way in Fig. 2(a), for each heliostat according to its relative position to the source and receiver. The difference of the unit vectors representing the position of the receiver and each heliostat (\vec{t}, \vec{h}) results on the reflected vector \vec{R} of the incoming sunrays. With this vector and the vector representing the incident sunrays \vec{S} , a normal vector \vec{N} at the surface of the heliostat is obtained, which is used to calculate the reflection angle to the target.

3.2 Apparent solar movement

Another input on the strategy is the solar position at any given time in order to obtain the incident ray vector \vec{S} previously mentioned. The solar altitude and azimuth angles (α, γ) are calculated according to the latitude of interest, the day of the year and the hour. These angles are calculated from the equations developed by Duffie et al. (1980).

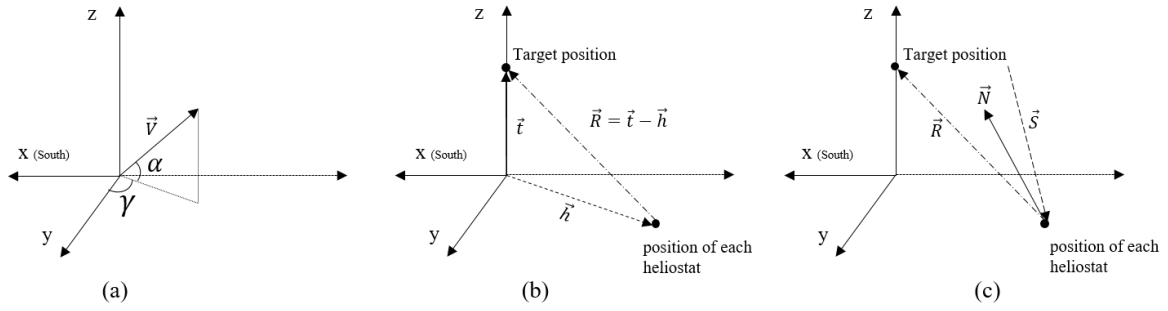


Fig. 1: Solar tracking strategy

3.3 Performance evaluation

The overall performance of a central tower concentrator is affected by cosine losses, reflectance, shadows, blockage and spillage. These factors reduces the amount of concentrated energy on the receiver compared to the incoming energy from the source. The different types of losses are described below.

Cosine losses. They are caused by the position of the heliostats to the Sun and receiver. This loss is proportional to the cosine of the angle θ between the normal vector of the reflecting surface \vec{N} and the vector of the incoming sunrays \vec{S} . The cosine loss η_{cos} can be found from eq. 1, that represents the effective area fraction of the i^{th} heliostat . Since every heliostat is in a different position to the target, the cosine loss on every surface varies. The total effective area of the heliostats field is given by eq. 2, where A_h corresponds to the heliostat area, in this case $1m^2$ and h is the total number of heliostats.

$$\eta_{cos} = \cos\theta = \vec{S} * \vec{N} \quad (\text{eq. 1})$$

$$A_{eff} = \sum_{i=1}^h A_h * \eta_{cos_i} \quad (\text{eq. 2})$$

Reflectance. These losses are caused since the reflecting surface absorbs a percentage of the incoming radiation. For each heliostat, a reflectance of $\eta_{ref} = 0.85$ is considered.

Shadows. The proximity of the heliostats causes the interference of the incoming radiation that strikes on them, thus producing a shadow on the reflective area. The shadow loss η_{sh} is determined from eq. 3, where HF is the amount of solar radiation that strikes on each heliostat and DNI is the direct solar radiation.

$$\eta_{sh} = \frac{\sum_{i=1}^h HF_i}{DNI * A_{eff}} \quad (\text{eq. 3})$$

Blockage. Blockage losses refer to the obstruction of the reflected radiation due to heliostats proximity. The blockage loss η_{block} can be obtained from eq. 4, where BF is the amount of energy that hits the back surface of each heliostat.

$$\eta_{block} = 1 - \frac{BF}{(\sum_{i=1}^h HF_i) * \eta_{cos} * \eta_{sh} * \eta_{ref}} \quad (\text{eq. 4})$$

Spillage. It is caused by the difference between the receiver and the heliostats' area. Since the position of the latter varies along the day for solar tracking, the projected heliostat area on the receiver varies. In general terms, spillage loss means the rate of reflected radiation and unblocked which cannot reach the receiver surface. Therefore, the amount of energy loss is the difference between the available energy, the energy that reaches the TF receiver and the blocked energy. Spillage η_{spi} can be found form eq. 5 as follows

$$\eta_{spi} = 1 - \frac{\left[\left(\sum_{i=1}^h HF_i \right) * \eta_{cos} * \eta_{sh} * \eta_{ref} \right] - BF - TF}{\left(\sum_{i=1}^h HF_i \right) * \eta_{cos} * \eta_{sh} * \eta_{ref} * \eta_{block}} \quad (\text{eq. 5})$$

By calculating the loss factors described above, the solar concentrator's efficiency η may be obtained from eq. 6.

$$\eta = \frac{TF}{DNI * h * A_h} = \eta_{cos} * \eta_{sh} * \eta_{ref} * \eta_{block} * \eta_{spi} \quad (\text{eq. 6})$$

During the application of the present method, is possible obtain the energy fraction lost by shadows or blockage, without do an analisis of area projection of neighbors heliostats. This is the most commonly used technique in different studies for the evaluation of heliostats fields such as FIELD (Collado and Guallar, 2012), DELSOL (Kistler, 1986) and MIRVAL (Learly and Hankins, 1979). However, the computational time for calculations increases with a greater amount of heliostats on the array. This limits the efficiency analysis of the system to a specific moment of the day or year, thus obtaining limited results.

3. Results

The proposed method was applied to an array of five heliostats in order to calculate their efficiency taking into account the loss factors. For simulation purposes, radiation data from 1998 to 2016 (omitting leap years) in one hour periods from 07:00 to 21:00 h were used. The data was obtained from Meteonorm, an online database platform that offers accurate irradiation data from any place of the Earth. In this case, irradiation data from Monterrey, Mexico (25°N, 100°W) was used. The simulations were executed only when the radiation value was greater than zero and the solar altitude angle greater than 15°, this latter considered as the minimum elevation angle for the operation of this type of systems (Collado and Guallar, 2012; Li et al., 2017).

As a preliminary validation, the method was applied to a single 1m²-heliostat. The target was placed 10m-height from the ground, tilted 40° to the vertical and 8.9m from the heliostat's center over the horizontal. The simulation was executed for a single year, in this case 2015. The annual solar radiation is shown in Fig. 3. This data is used to calculate the useful fraction of the heliostat reflective area by using the ray tracing method here proposed. The results obtained from the simulation can be seen in Fig. 4. On the one hand, since there is only one reflective surface, blockage losses are neglected. Therefore, the useful fraction is close to 1 most of the year. On the other hand, at the beginning and end of the period, this value decreases around noon since the target shades a percentage of the incoming radiation due to its position between the Sun and the heliostat. A comparison of HF values on winter (from day 3 to 19 of the year) and summer (from day 150 to 165 of the year) are show on Fig. 5(a) and 6, respectively. These plots present HF values calculated theoretically and obtained from Ray-Tracing, in winter, due to solar altitude is lower than summer, the target causes shadow over the heliostat, as shown in a detailed plot in Fig. 5(b).

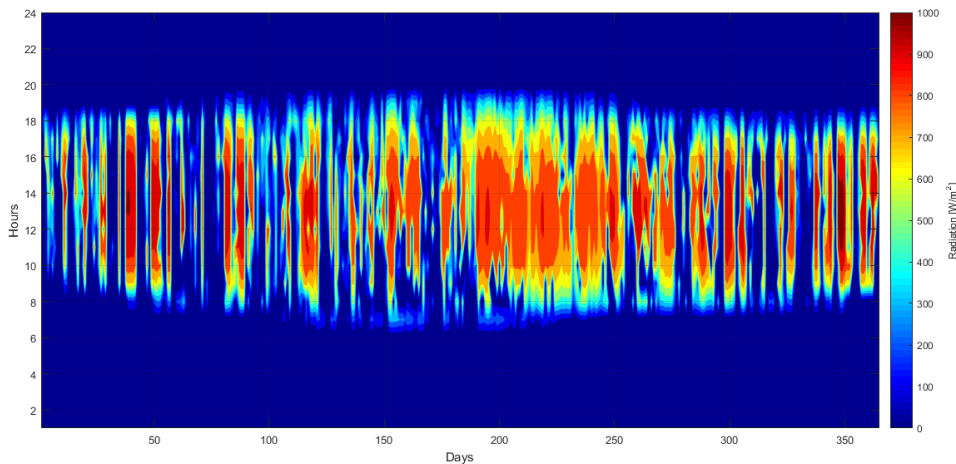


Fig. 3: Annual solar radiation (2015)

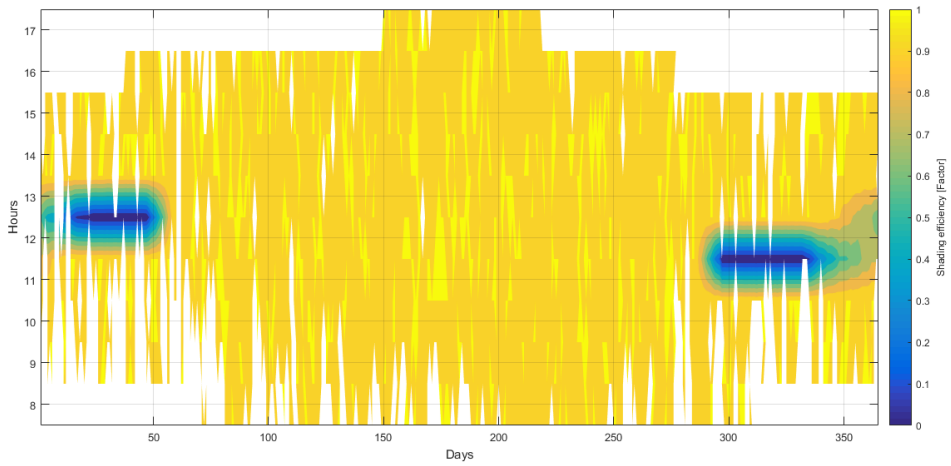
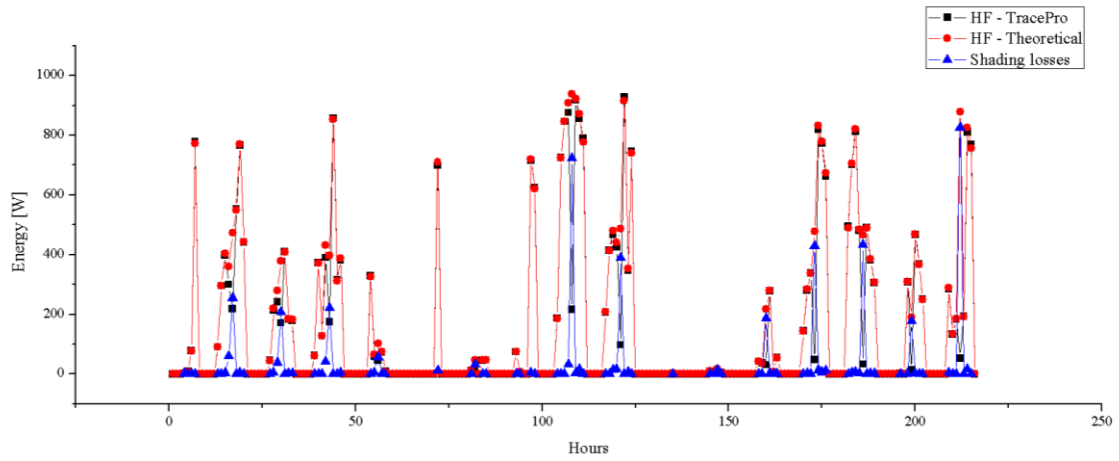
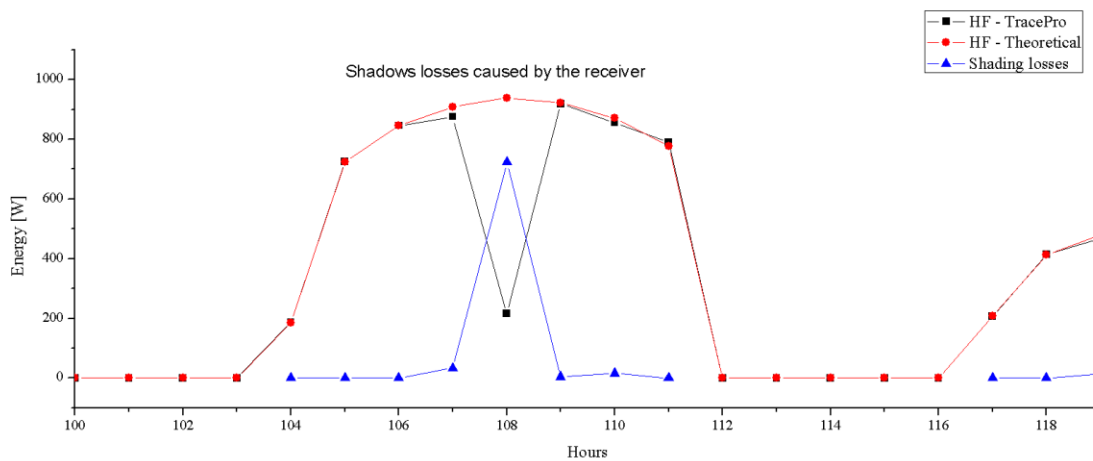


Fig. 4: Annual performance of a single heliostat (2015)



(a)



(b)

Fig. 5: Solar radiation hitting on a single heliostat in winter

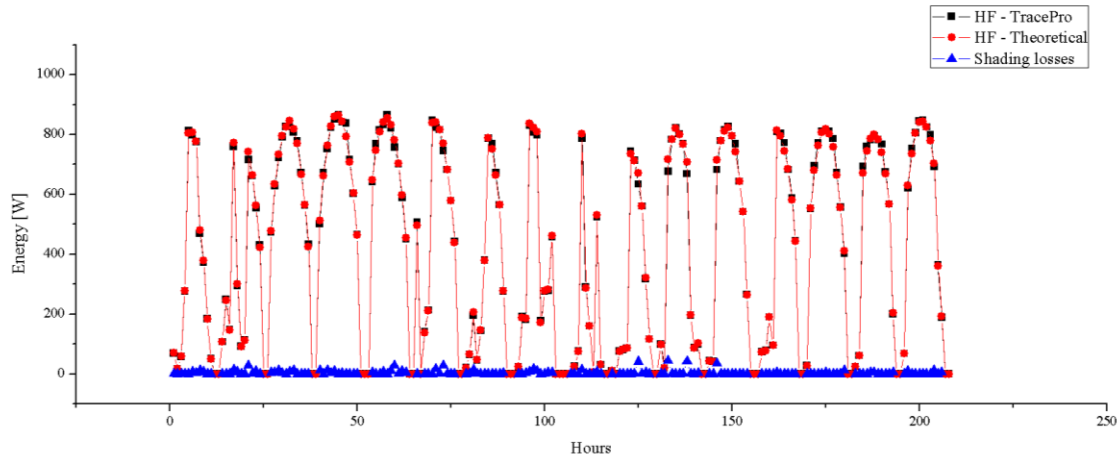


Fig. 6: Solar radiation hitting on a single heliostat in summer

After the simulation of the single heliostat along a year, a set of five heliostats was simulated in order to calculate their optical and geometrical losses. The system distribution is illustrated in Fig. 7. Each heliostat has an area of 1m^2 and its position has been established in such a way that there is a deliberate obstruction of radiation between them. Fig. 8 shows an instant of the Tracepro simulation (day 190, 13:00 h). Each heliostat position allows the reflection of the incoming radiation onto the center of the target.

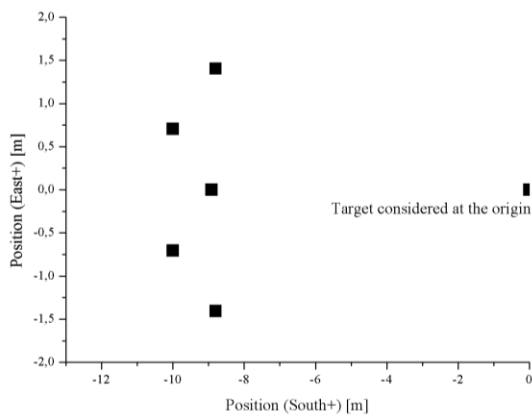


Fig. 7: Distribution of the heliostats array and target

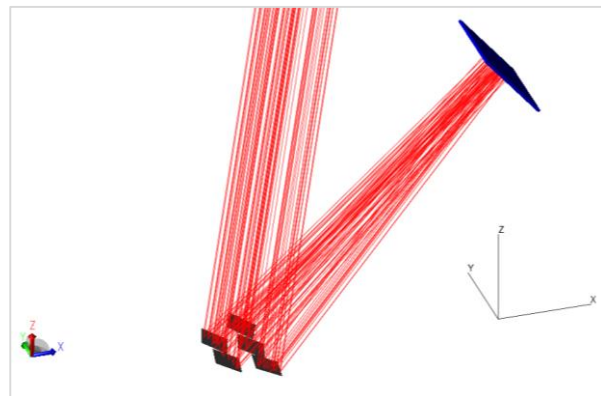


Fig. 8: Tracepro simulation of an instant

Fig. 9 shows the monthly average efficiency for each simulated year, neglecting leap-years. The efficiency of every heliostat is affected by the optical performance losses previously described. In this case, spillage losses were neglected and a reflective value of 0.85 remained constant. As it is observed, the most considerable loss is caused by the radiation blockage between heliostats. However, in real applications blockage is avoided by using algorithms that establish the optimal separation between contiguous heliostats. Similarly, the system's performance is affected by cosine losses, which represents one of the most significant loss of this type of solar concentrators. Finally, shadow losses due to interference between heliostats and/or the projection of the receiver on the reflecting surfaces is the factor that least affects the performance of the system. The concentrator performance was obtained from the simulation taking into account the previously described losses. It can be seen that the efficiency factor varies from 0.35 to 0.5 along the simulated period of time.

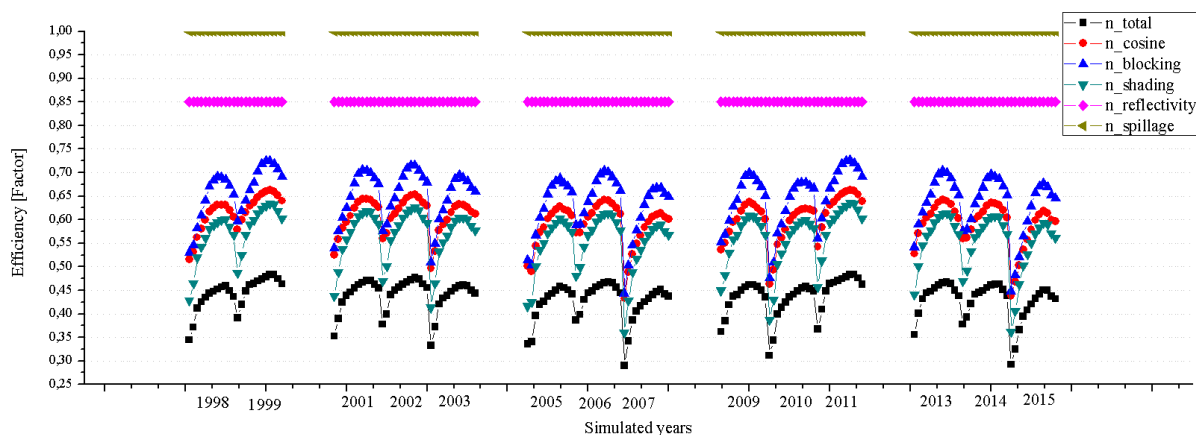


Fig. 9: Monthly average heliostats' performance from 1998 to 2015 (leap-years neglected)

4. Conclusions

In the present research, the performance of an array of heliostats was obtained through a ray tracing iterative method. The routine was successfully implemented by simulating a conventional heliostats array widely studied in the literature. The result of annual simulations in one hour intervals can be applied to different distributions of heliostats, a common study in this type of technology. In addition, the obstruction of radiation caused by nearby objects, either between heliostats themselves or other external objects, can be obtained.

Although the present method was evaluated in a simplified set of heliostats, the tool can be applied for the evaluation and optimization of other types of solar concentrators, especially those in which their annual performance has not been validated using experimental data. In addition, the method has the ability to include external elements such as trees, buildings or other objects that may be present in a real environment.

The obtained results through this method can be used in other softwares such as TRNSYS, regularly used to perform annual energy studies in short time intervals. In addition, the method allows the evaluation of solar concentration systems by using continuous data records in order to validate the annual results obtained from conventional simulations.

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