

Parallelizing the heliostat field layout evaluation

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Abstract

In this paper, a parallelization approach of heliostat field optical efficiency computation is proposed and analyzed thinking of a background optimization process. In Solar Central Receiver Systems (SCRS), the heliostat field is generally the most important subsystem in terms of initial investment and energy losses. Therefore, its design needs to be carefully optimized when deploying this kind of power facilities. Optimization can be focused on multiple criteria that can lead to different and complex optimization problems in this general context. This fact may make a good and exhaustive optimization process infeasible, specially depending on the available resources. Fortunately, some of them can benefit from parallelization, even though this idea is not usually pointed out, and then allow better (or even just possible) search space explorations in reasonable time. In this work, the objective function selected is the yearly irradiance weighted efficiency of heliostat field layouts as a proof of concept. Then, it is analyzed to take advantage from its parallel nature. Afterwards, the original sequential version is compared to the parallel one in terms of performance when analyzing particular field configurations. Finally, conclusions are drawn from the obtained results and future work is proposed.

Key words: heliostat field layout, parallelization, optimization

1 Introduction

Solar Central Receiver Systems (SCRS) are one of the most promising flagships of renewable energies. This sort of systems basically consist of a radiation receiver placed over a tower and a broad set of high-reflectance mirrors, known as 'heliostats', that track the Sun

apparent movement to concentrate solar radiation on the receiver. It reaches very high temperatures that can be applied in classic power steam cycles and in scientific studies (additional information can be found in [CAM12, RED13] and in chapter 10 of [STI01]).

The set of heliostats forms what is known as 'heliostat field', it represents approximately the 50% of total initial investment and can generate up to 40% of energetic loss [JON07] in the power station cycle. Therefore, it needs to be carefully designed by solving complex optimization problems in which heliostats are distributed trying to fulfill, as best as possible, a set of criteria. Optical efficiency [NOO12] and investment cost (both combined in [ZHA07]) are some examples. However, functions derived from these requirements tend to be very CPU time and memory demanding, specially when considering many heliostats.

In this context, apart from applying simplifications at the problem domain level (surface discretization [NOO12, ZHA07, STI01], avoiding calculations in particular stages [BES14, NOO12], etc.), parallelization techniques can also reduce the computational effort. This interesting approach can lead to general better solving capabilities in optimization processes independently of the optimizer.

In the next section a possible objective function is defined for testing purposes. Then, a parallel implementation is proposed to take advantage of its implicit parallelism in section 3. After that, both the sequential version and the parallel one are compared when evaluating heliostat fields of different sizes 4. Finally, conclusions are commented on and future work is proposed in section 5.

2 Studied function

The selected function is the yearly irradiance weighted efficiency described in [NOO12] with some changes. This adaptable and high-level definition function represents the heliostat field capabilities to concentrate solar radiation over the receiver (optical properties) along the year also taking into account incident solar radiation (irradiance) as a weighting factor. It can be formulated as described below, where $I_b(t)$ is the beam irradiance and η is the field optical efficiency for instant t [NOO12]:

$$\eta_{year,I} = \frac{\sum_{day=1}^{365} \int_{sunrise}^{sunset} I_b(t)\eta(t)dt}{\sum_{day=1}^{365} \int_{sunrise}^{sunset} I_b(t)dt} \quad (1)$$

Field efficiency, well detailed in chapter 10 of [STI01], depends on optical properties of heliostat field layout at a particular instant t (as denoted in Eq.(1)). This factor η can be expressed in terms of a set of sub-factors that model different sources of energy loss in real

heliostat fields. For our purpose, field efficiency shown in Eq.(1) is defined as in [NOO12]

$$\eta = \eta_{cos} \cdot \eta_{sb} \cdot \eta_{itc} \cdot \eta_{aa} \cdot \eta_{ref} \quad (2)$$

where η_{cos} , η_{sb} , η_{itc} , η_{aa} and η_{ref} are the cosine, shadowing and blocking, interception, atmospheric attenuation and reflectivity field efficiency respectively. These concepts, well described in chapter 10 of [STI01] and in [NOO12], are also briefly presented below for the implemented model:

1. η_{cos} : Profitable reflective area of heliostats is reduced by the cosine of the angle formed by the incident solar beam with the heliostat normal direction. It is calculated as detailed in chapter 10 of [STI01].
2. η_{sb} : Heliostats can shadow each other and block their redirected radiation to the receiver. It is calculated as proposed in [NOO12].
3. η_{itc} : Radiation is intended to fall on the receiver but targeting may be not as perfect as expected because of different reasons. It is estimated mainly depending on general heliostat and receiver dimensions as done in [GOM11].
4. η_{aa} : Atmosphere attenuates reflected radiation over the receiver from heliostats along its trajectory. It is estimated by using the same model applied in [NOO12].
5. η_{ref} : Reflective surfaces may not grant a lossless reflection phenomenon by their construction and/or state. It is considered as a heliostat dependent constant.

It is also important to note that Eq. (2) can be extended to any number of working heliostats by averaging their particular factors. Instantaneous radiation estimation for Eq. (1) is calculated over the 'air mass' concept by applying the [LAU70] model and timing between sunrise and sunset is done by a constant factor. Finally, Sun positioning and general coordinate systems are the same as in [STI01].

3 Parallelization approach

Function (1), taken as a proof of concept, can be applied to evaluate different heliostat field layouts in an optimization context as done in [NOO12]. However, its computation is expensive in terms of CPU, specially η_{sb} when there are numerous heliostats to be considered. Fortunately, it is intrinsically parallel, and this fact can be profited to speedup the process.

Heliostats can be divided in blocks and assigned to particular execution units that will compute the value of their specific region concurrently at every studied instant t . Each of

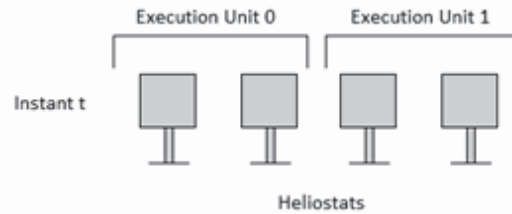


Figure 1: Scheme of the parallelization by heliostats approach.

these sub-values would be finally reduced to the global performance of the field at t . Furthermore, taking into consideration that there is no need to modify common values shared by every block (only reading general variables such as Sun position is needed), there are not critical sections to secure while computing. This scheme, depicted in figure 1, is generally applicable to the general problem, with different objective functions and independently of the optimizer.

4 Experimentation and results

Described model has been implemented in C++. Two versions have been developed, a sequential one and a parallelized version of it that uses PThreads. Both of them have been compiled with the '-O2' optimization flag. Then, they have been used to analyze the optical performance of different heliostat distributions as expressed in Eq. (1). The number of heliostats ranges from 30 to 500 with 10x10 meters of reflective area and the receiver is on a tower of 100 meters of height. The number of deployed threads for every problem instance ranges from 2 to 12 and all the experiments have been launched in a cluster 'BullX' with 18 nodes Intel Xeon E5 2650 of 16 cores and 64 GB of shared RAM.

In figure 2 the average speedup obtained, after 5 experiments, is presented for every case. There is no doubt about the result of parallelism: the same process is completed up to 10 times faster for the bigger cases and is significantly accelerated in most of them (apart from the smallest problem with only 30 heliostats, what is not a realistic field either). It must also be noted that the behavior shown seems to be quite scalable.

5 Conclusions and future work

In this work, a possible objective function for heliostat field optimization has been presented and proposed to be parallelized. Then, both the sequential and the parallel versions have been compared when computing the optical performance of different fields. Results

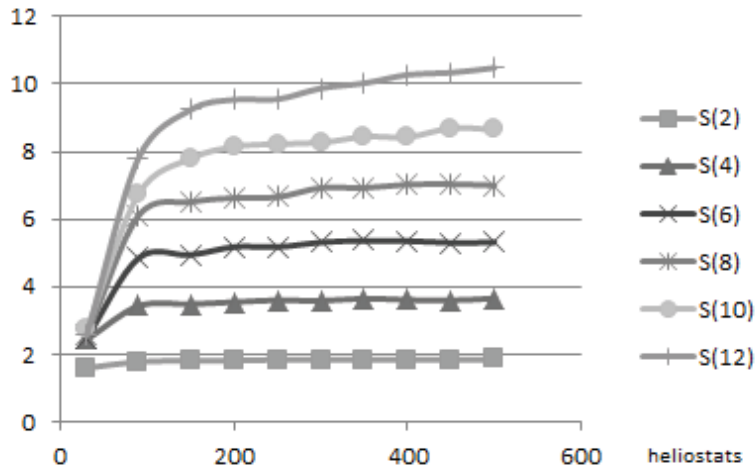


Figure 2: Average speedup of the parallel version.

show that the process is significantly accelerated when working with numerous heliostats. Therefore, any optimization process built over this function could perform more evaluations per unit of time making then possible to do better search space explorations and reducing the necessity to do problem level simplifications. Furthermore, it is important to note that applying parallelism to this problem could not be optional when working with thousands of heliostats (an active trend) or when memory needed by models was not possible to achieve out of distributed environments.

There are numerous points to work on from exposed herein. First, it would be interesting to analyze the real impact of parallelizing on different optimization procedures. Second, other parallelization strategies could be proposed and analyzed. Third, load balancing is a complex issue for this problem that should be studied in depth. Finally, commented ideas could be exported and tested over different models and situations. This could be specially interesting when parallelization made possible solving instances that could not be afforded by traditional means.

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