Hybridization of Aim Point Optimization Methods for Solar Tower Power Plants

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1. INTRODUCTION

In solar tower power plants a large number of heliostats concentrate the solar irradiation onto a receiver, which is mounted on the top of a tower. The two-axis tracking systems allow an individual alignment for each heliostat in order to reflect the irradiation to a so called aim point. The aim point is located on the receiver surface or an off receiver point, e.g. as a safety position. The aiming strategy defines the aim point of each heliostat for a specific operating point over the day. The concentrated solar power is absorbed by the receiver and a heat transfer medium is used to pipe the heat to the connected process, e.g. a Rankine power cycle. Different receivers are currently employed or are under development using air, water/steam, molten salt, particles or liquid metals as heat transfer medium.

1.1 Aiming Strategy

A good aiming strategy is of great importance for an efficient operation of solar power towers. Most of the radiation will most likely hit the receiver if all heliostats aim to its centre. Unfortunately, this aiming strategy cannot be applied as temperature and/or stress limits of the receiver, which can be expressed in a limit for the flux density, will be exceeded. Therefore, the aim points of the heliostats have to be distributed over the receiver surface in order to lower the peak flux densities. But this will presumably reduce the amount of radiation hitting the receiver. The aiming strategy can be characterized as a constraint optimization problem, in which the optical or thermal performance is optimized with respect to all limits for the receiver.

2. OPTIMIZATION

2.1 Optimization Problem

The flux distribution for each heliostat and each aim point is calculated with a Monte Carlo ray tracing approach. For this calculation model a discrete optimization approach is appropriate. Allowing only a finite number of aim points defines the optimization as a discrete problem with combinatorial characteristics. As described by Belhomme et al. (2014) the size of the solution space S and therefore the number of possible heliostat aim-point combinations is equal to the number of fixed aim points n_Z to the power of the number of heliostats n_H, as in (1). In solar tower power plants n_H is typically larger than 5000.

$$\left|S\right| = {n_Z}^{n_H} \quad (1)$$

This combinatorial optimization problem belongs to the NP-complete class. A trivial solution method, the complete enumeration of the solution space, is obviously unrealistic for typical heliostat field sizes. Heuristic methods are needed. Belhomme et al. (2014) therefore adapted the ant colony optimization metaheuristic (ACO) for the specific optimization problem.

2.2 ACO

The ACO method is a probabilistic technique that benefits from the principles of swarm intelligence and imitates the behaviour of ant colonies during foraging. The aiming optimization is transferred to a suitable problem for the ACO by defining the aim point configuration as the trail of an ant. The entire trail is divided in edges, which represents the aim point assignment for a specific heliostat. One trail represents one possible heliostat aim point assignment for the entire concentrator field. A suboptimal trail at the beginning is improved according heuristic information. The heuristic information, namely intercept factor and receiver performance, are calculated with a Monte-Carlo-Raytracer (Belhomme et al. (2009)) and a Finite-Element-Method, respectively. The raytracer calculates the flux density distribution on the receiver surface and the FEM model determines the receiver performance, the model is described by Flesch et al. (2017). The FEM model is a black box for the optimization procedure and determines the so called global quality value. If receiver constraints like flux density limits are exceeded the quality value is penalized by the FEM model. The result serves the ACO to update the attractiveness of the edges, which affect the choice of a new trail in the following optimization step.

The optimization procedure was tested on a realistic power plant scenario by Maldonado et al. (2017). The results show, that in heavily constrained cases the performance of the ACO drops. This is because of the drawback that in case of a limit exceedance the entire path is penalized even if only one heliostat/edge is responsible. To overcome this drawback a second optimization algorithm called local search (LS) was implemented. In this study several optimization parameters were examined using the scenario of Maldonado et al. (2017) in order to find fast convergence behaviour.

2.4 LS

The LS starts from a solution and moves towards an improvement, equally to the ACO. In contrast to the ACO, it only manipulates the aim point configuration in a local region; this means that the calculation of the local quality at a single edge is restricted to a so called neighbourhood. For a single LS run all heliostats' assignments are examined one by one in a certain sequence. In each examination step the assignment for a single heliostat can change by shifting to one of the neighbouring aim points. The overall receiver performance is calculated after each shift until an improved solution is found in the neighbourhood. Otherwise the initial solution is maintained. Compared to the ACO a local change of a single heliostat aim point assignment is evaluated and local exceedances of allowable flux can be prevented without affecting the entire aim point configuration.

3. EVALUATION OF BOTH METHODS

For the comparison of the different optimization methods the thermal output of the receiver during the optimization is plotted in dependence of the evaluations of the thermal model. One exemplary plot is shown in figure 1. The black curve represents the ACO. The remaining plots represent LS optimization runs with different parameter.

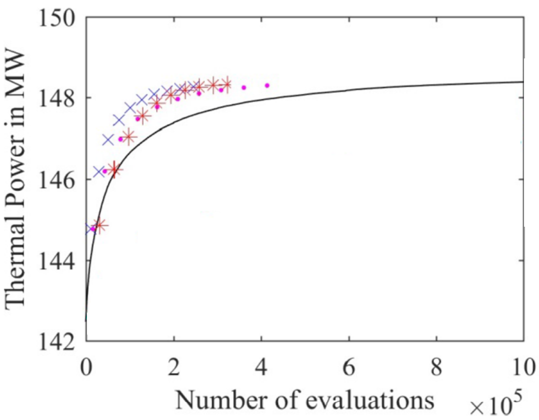

Fig. 1. Results of the optimization for an exemplary time point with high flux density constraints.

The curve with the blue crosses is parameterized with a small neighbourhood, whereas the curve with the red stars represents an enlarged neighbourhood. The purple dotted curve represents a case with the larger neighbourhood, but in comparison to the other cases the entire neighbourhood is examined in each evaluation. Figure 1 shows that the LS can outperform the ACO in the first $4 \cdot 10^5$ evaluation steps. The progresses for the LS are steeper at the very beginning and stagnate strongly afterwards. The black curve stagnates less and can outperform the LS after $6 \cdot 10^5$ evaluation steps.

5. HYBRIDIZATION

The evaluation of optimization processes for different time and operating points strongly suggests to combine the methods. Furthermore, the number of evaluations for a single method is too large for many cases. The computational time for an online optimization where boundary conditions, e.g. solar irradiation, can change quickly must be minimized.

Hybridization should be done automatically with a dynamic adjustment of the optimization parameters. The mathematical model of the receiver and the heliostat field should supply output quantities that decide on the optimization parameters and when to switch optimization strategy.

The LS performs well if the case is highly constrained and the initial solution is within the analysed neighbourhood. On the other hand it can get stuck in a local optimum or even cannot find a valid solution. The ACO in contrast performs fairly well for most cases and better than the LS if the initial solution is far away from the global optimum and not heavily constrained.

One hybridization approach is to start always with the ACO and to find a valid solution after very few runs. Afterwards switch to the LS to benefit from a possible steeper climb. The approach monitors a possible stagnation of the LS to decide if the ACO should continue proceeding. At the end of the optimization process the ACO should bring us close to the global optimum and the LS as a hill climber can do the rest.

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