New methods and results in the optimisation of solar power tower plants

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Contents

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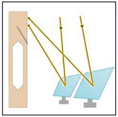
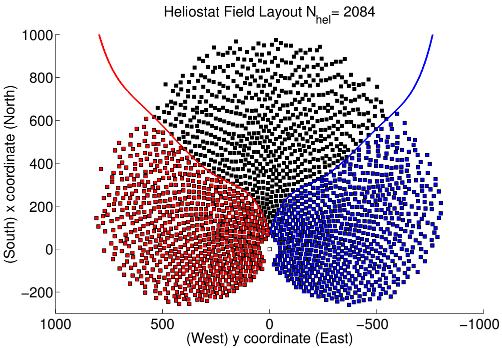
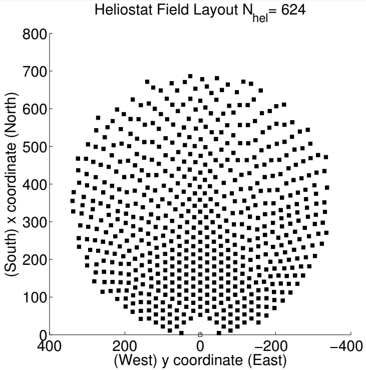
- Solar Power Plants
  - Solar Thermal
    - Non-Concentrating
      - Solar Chimney
    - Concentrating
      - Linear
        - Linear Fresnel
        - Parabolic Through
      - Point
        - Parabolic Dish
        - Heliostat
  - Photovoltaic
    - PV cell



- **Heliostat location**





Test Case

Planta Solar 10 (PS10), Sanlúcar la Mayor (Spain)

Energy 137 (2017) 285–291

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Optimisation of aiming strategies in Solar Power Tower plants

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ABSTRACT

The distribution of temperature on a Solar Power Tower (SPT) plant receiver directly affects the lifespan of the structure and energy generated by the plant. Temperature peaks and uneven distributions can be caused by the aiming strategy enforced on the heliostat field.

A non-optimised aiming strategy can lead to suboptimal energy generation and, more importantly, to risk of permanent damage to receiver components from thermal overloading due to sharp flux gradients.

In order to reduce damage to receivers and optimise the energy generation, an aiming strategy is developed which homogenises the flux distribution on a flat plate receiver in a SPT plant.

Results of a near real-time optimised aiming strategy are presented, demonstrating applicability to SPT plants of any size and shape, whilst also considering inclement weather conditions.

Ashley, Thomas; Carrizosa, Emilio; Fernández-Cara, Enrique; Optimisation of aiming strategies in Solar Power Tower plants. Energy, 137C, pp. 285-291 (2017). Q1 IF: 5.537

Literature review

- Besarati et al. Optimal heliostat aiming strategy for uniform distribution of heat flux on the receiver of a solar power tower plant. Energy Conversion and Management 84 (2014) 234–243.
- Kun wang et al. Multi-objective optimization of the aiming strategy for the solar power tower with a cavity receiver by using the non-dominated sorting genetic algorithm. Applied Energy 205 (2017) 399–416.

Spillage efficiency

Proportion of reflected energy captured by receiver, from heliostat located at x, y

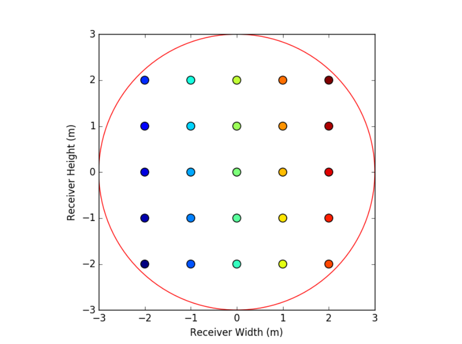
$$f_{sp}(x,y,\Theta) = f_1(x,y,\Theta)\int_0^{2\pi}\int_0^{r} exp\Big(\frac{-\tilde{f}_2(\rho,\phi,x,y)}{2f_3^2(x,y,\Theta)}\Big)\rho\, d\rho\, d\phi$$

where r is the radius of the circular receiver and

$$\tilde{f}_2(\rho,\phi,x,y) \equiv f_2(\rho\cos\phi,\rho\sin\phi,x,y).$$

Maximise energy

Binary integer linear programming used to maximise the energy reaching the receiver, with multiple aiming points considered



Maximise energy

Binary integer linear programming used to maximise the energy reaching the receiver, with multiple aiming points considered

$$\textbf{Maximise} \sum_{\substack{h\in H \\ a\in A}} R_{ha} z_{ha}$$

Subject to:

$$\sum_{a} z_{ha} \le 1 \quad \forall h \in H,$$

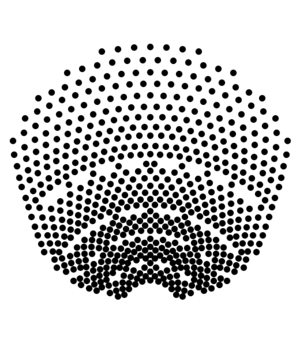
$$C_{*} \le \sum_{\substack{h\in H \\ a\in A}} r^{i}_{ha} z_{ha} \le C^{*} \qquad \forall i \in A,$$

$$\sum_{\substack{h\in H \\ a\in A}} r^{i}_{ha} z_{ha} \le \tau + \sum_{\substack{h\in H \\ a\in A}} r^{j}_{ha} z_{ha} \qquad \forall i, j \in A \ with \ i \neq j$$

$$z_{ha} \in \{0, 1\} \quad \forall h \in H, \ \forall a \in A$$

SPT plant details

- Name: *PS10, Sanlúcar la Mayor*
- Heliostats: 624
- Number of aiming points: 25



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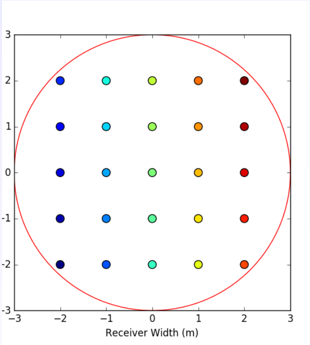

SPT plant details

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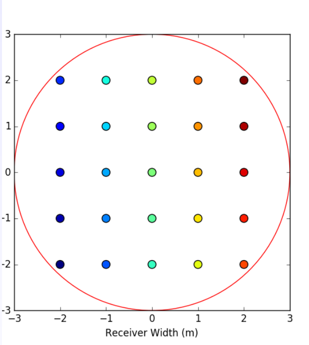
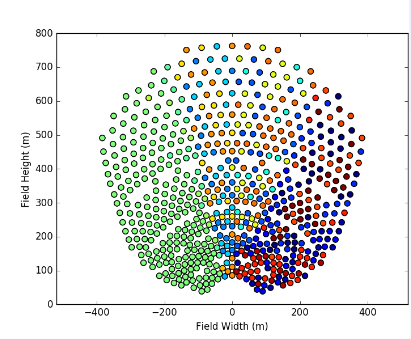
Computational aspects

- Python
- Gurobi
- 30s time limit



Morning: Sun in the East

- Cosine efficiency high in West
- Spillage efficiency low in East



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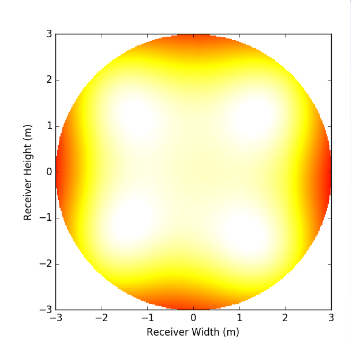
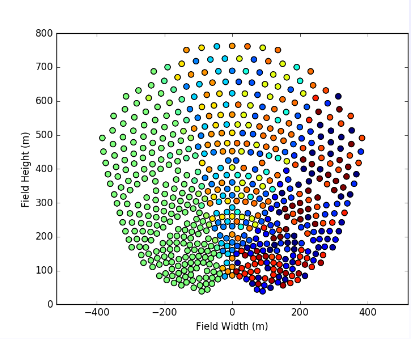
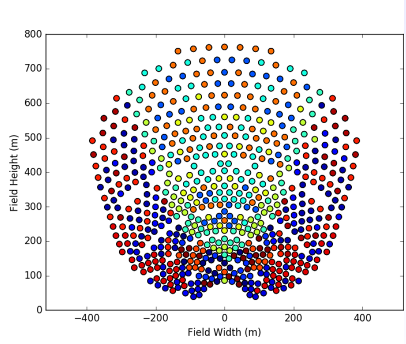




Noon: Sun overhead

- Similar efficiencies
- Energy contribution important



Noon: Sun overhead

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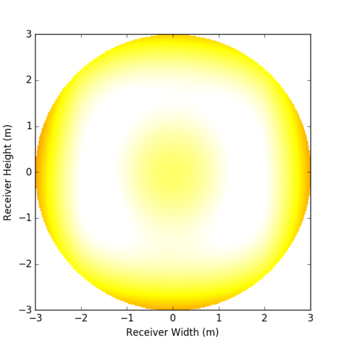
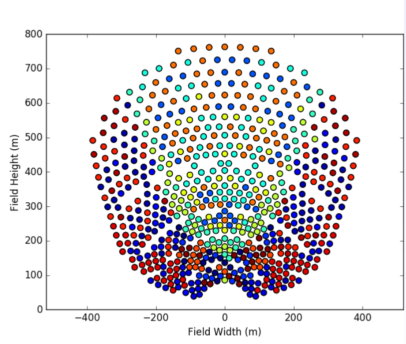
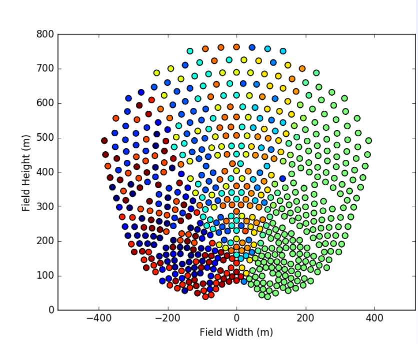




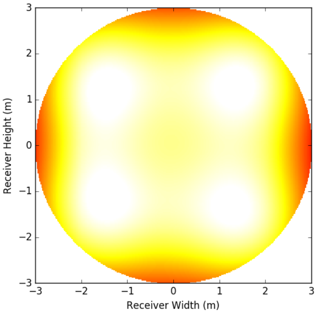
Afternoon: Sun in the West

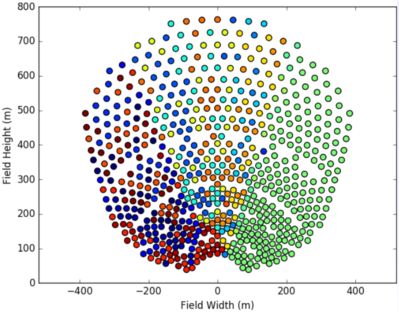
- Cosine efficiency high in West
- Spillage efficiency low in East



Afternoon: Sun in the West

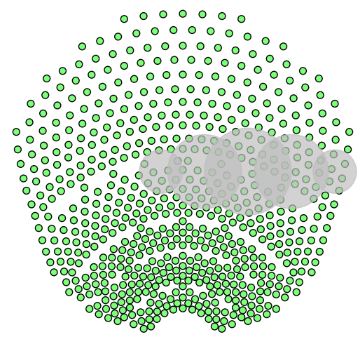
- Cosine efficiency high in West
- Spillage efficiency low in East





Cloud cover

Efficiency loss due to cloud cover investigated utilising stochastic linear programming techniques



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Continuous optimisation techniques for optimal aiming strategies in solar power tower plants

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Keywords:
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Aiming strategy
Operations research

ABSTRACT

Optimising the aiming strategy is crucial for Solar Power Tower plants, in order to maximise the energy generated, whilst also preventing catastrophic damage to receiver components. In this work, a bi-objective optimisation model is developed to find optimal aiming strategies for a Solar Power Tower plant. The primary objective to maximise the radiation captured by the receiver is offset by a secondary objective to minimise the deviation from a desired target distribution, which is designed by solar plant operators to improve plant efficiency. A numerical method is proposed to solve the optimisation problem, and an illustrative example is presented to show functionality of the model and the numerical method. Conclusions are drawn on the model presented, extensions are considered and current work is discussed.

Ashley, Thomas; Carrizosa, Emilio; Fernández-Cara, Enrique. Continuous optimisation techniques for optimal aiming strategies in solar power tower plants. Solar Energy Volume 190, 15 September 2019, Pages 525-530. Q1 IF: 4.674

Instead of fixing aiming point coordinates:

Continuous aiming point

Radiation reaching point (u, v) on receiver Ω from heliostat $h \in H$ aiming at $p_h \in \Omega$ given by $F_{u,v}(h, p_h)$

where,
Ω a non-empty bounded open convex set $\Omega \subset \mathbb{R}^2$.

Total radiation reflected by heliostat h aiming at p_h given by

$$f(h, p_h) = \int F_{u,v}(h, p_h) d\Omega.$$

Objective function

A weighted penalised objective function is considered

$$\text{Max} \quad A \sum_{h \in H} f(h, p_h) - (1-A) \int \left[\sum_{h \in H} F_{u,v}(h, p_h) - E^{tar}_{u,v} \right]^2 d\Omega$$

$$p_h \in \Omega$$

For numerical purposes, the objective function must be approximated as

$$g(\mathbf{P}) \colon A \sum_{h \in H} f_{sp}(h, p_h) - (1-A) \frac{|\Omega|}{I} \sum_{i=1}^{I} \left[\sum_{h \in H} F_{u_i, v_i}(h, p_h) - E^{tar}_{u_i, v_i} \right]^2$$

Objective function

A weighted penalised objective function is considered

$$\text{Max} \quad A \sum_{h \in H} f(h, p_h) - (1 - A) \int \left[\sum_{h \in H} F_{u,v}(h, p_h) - E^{tar}_{u,v} \right]^2 d\Omega$$

$$p_h \in \Omega$$

For numerical purposes, the objective function must be approximated as

$$g(\mathbf{P}) : A \sum_{h \in H} f_{sp}(h, p_h) - (1 - A) \frac{|\Omega|}{I} \sum_{i=1}^{I} \left[\sum_{h \in H} F_{u_i,v_i}(h, p_h) - E^{tar}_{u_i,v_i} \right]^2$$

Gradient ascent

First-order iterative optimisation algorithm iterates $\mathbf{P}_k$ towards a (local) optimum

$$\tilde{\mathbf{P}}_{k+1} = \mathbf{P}_k + \gamma_{k,h} \nabla g(\mathbf{P}_k)$$

Projection

Objective function constrained by $p_h \in \Omega$ requires projection function P to return the solution to Ω

$$\mathbf{P}_{k+1} = P(\tilde{\mathbf{P}}_{k+1})$$

where, for each $\mathbf{P}$, $P(\mathbf{P})$ denotes the component-wise projection of $\mathbf{P}$ onto Ω.

Step size

Adaptive step size using modified *Armijo's Rule*, with scaling parameter ϵ

$$\gamma_{k,h} = \gamma_{k-1,h} \cdot \epsilon$$

Step size convergence

Iterative line search used until maximum found

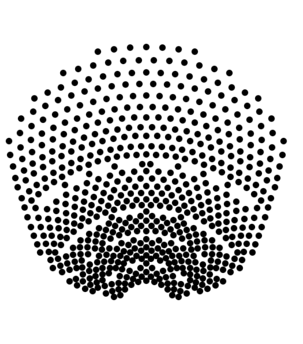
$$g(\mathbf{P}_k) > g(\mathbf{P}_{k-1})$$

SPT plant details

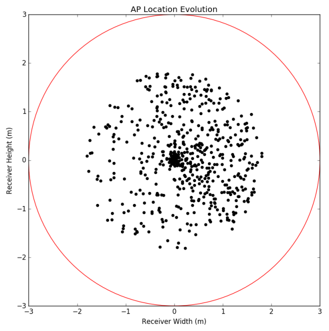
- Name: *PS10, Sanlúcar la Mayor*
- Heliostats: 624
- I = 900
- A: 100 values $\in [0, 1]$
- Target Distribution: homogeneous

Computation

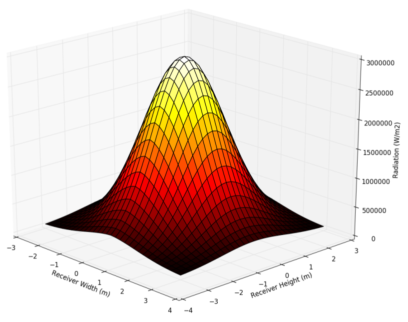
- Python
- Bespoke solver
- $< 10s$ per run



Single timepoint with $A = 0{,}9$

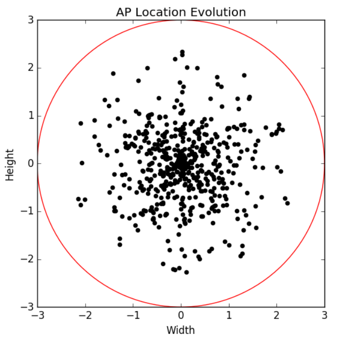


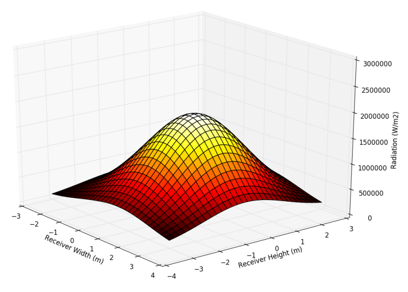
Aiming strategy



Radiation distribution

Single timepoint with $A = 0{,}3$





Aiming strategy

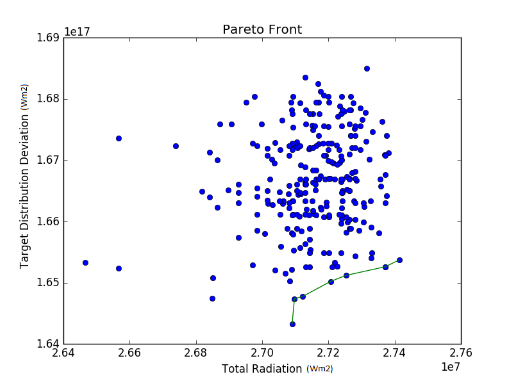
Radiation distribution

Pareto Front

- 100 values of A
- Minimising target distribution deviation
- Maximising total energy

Computation

- Multi modal
  - 30 runs
- < 10 iterations



Dynamic Continuous Optimisation Applied to Renewable Energy

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April 26, 2019

Abstract

Dynamic optimisation provides complex challenges for optimal solution, but greatly increases applicability when considering time dependent situations. In this work, a constrained dynamic optimisation problem is analysed and subsequently applied to the resolution of a real-world engineering problem concerning Solar Power Tower plants. We study the existence of solutions and deduce an appropriate optimality characterisation in this applied framework. Two iterative algorithms are

Ashley, Thomas; Carrizosa, Emilio; Fernández-Cara, Enrique. Dynamic Continuous Optimisation Applied to Renewable Energy. (Under Review)

$$J(\mathbf{p}) = \textbf{Maximise} \quad A\int_0^T \Big(\iint_R \sum_{h\in H} f(h,\mathbf{p},t)\,du\,dv\Big)dt -$$

$$(1-A)\int_0^T \iint_R \Big(\sum_{h\in H} F^{u,v}(h,\mathbf{p},t) - E_{tar}^{u,v,t}(t)\Big)^2 du\,dv\,dt$$

with $A \in [0,1]$.

Subject to:

$$\int_0^T (||\dot{p}_h(t)|| - V_p)_+^2\,dt \le \tau_1 \quad \forall h \in H$$

$$\int_0^T \iint_R \Big(\sum_{h\in H} \frac{\partial}{\partial t} F^{u,v}(h,\mathbf{p},t)\Big)^2 du\,dv\,dt \le \tau_2$$

$$p_h(t) \in \Omega \qquad \forall h \in H,\ t \in [0,T]$$

Maximise $J(\mathbf{p}) = \int_0^T G(t, \mathbf{p}(t))\, dt$

Subject to

$$\mathbf{p} \in \mathbf{P}_{ad}, \quad M(\mathbf{p}) \leq \sigma$$

Maximise $J_\mu(\mathbf{p}) := J(\mathbf{p}) - \frac{1}{2\mu}|(M(\mathbf{p}) - \sigma)_+|^2$

$$\nabla J_\mu(\mathbf{p}_N) = \nabla J(\mathbf{p}_N) - \frac{1}{\mu}(M(\mathbf{p}_N) - \sigma)_+ \cdot \nabla M(\mathbf{p}_N)$$

$$\text{Maximise } J(\mathbf{p}) = \int_0^T G(t, \mathbf{p}(t))\, dt$$

Subject to

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$$\nabla J_\mu(\mathbf{p}_N) = \nabla J(\mathbf{p}_N) - \frac{1}{\mu} (M(\mathbf{p}_N) - \sigma)_+ \cdot \nabla M(\mathbf{p}_N)$$

$$\mathcal{L}_\mu(\mathbf{p};\lambda) := J(\mathbf{p}) - \sum_{i=1}^{2} \psi(M_i(\mathbf{p}) - \sigma_i, \lambda_i; \mu)$$

where,

$$\psi(z,\beta;\mu) := \begin{cases} z\cdot\beta + \frac{1}{2\mu}|z|^2 & \textbf{if} \quad z+\mu\beta \geq 0 \\ -\frac{\mu}{2}|\beta|^2 & \textbf{otherwise,} \end{cases}$$

$\mu > 0$.

$$\begin{cases} \textbf{Minimise} \quad \sup_{\mathbf{p}\in\mathbf{P}_0} \mathcal{L}_\mu(\mathbf{p};\lambda) \\ \textbf{Subject to:} \ \lambda \in \mathbf{E}, \ \ \lambda \geq 0. \end{cases}$$

$$\mathcal{L}_\mu(\mathbf{p};\lambda) := J(\mathbf{p}) - \sum_{i=1}^{2} \psi(M_i(\mathbf{p}) - \sigma_i, \lambda_i; \mu)$$

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Gradient Ascent

Aiming points p_N^{n+1} found by gradient ascent with projection $\mathcal{P}_{0,N}$

$$\mathbf{p}_N^{n+1} = \mathbf{p}_N^n + \gamma_h^k \nabla G_N(\mathbf{p}_N^n).$$

$$\mathbf{p}_N^{n+1} = \mathcal{P}_{0,N}(\tilde{\mathbf{p}}_N^{n+1}), \quad \tilde{\mathbf{p}}_N^{n+1} = \mathbf{p}_N^n + \Gamma^k \nabla J_\mu(\mathbf{p}_N^n)$$

where $\Gamma^k =$ **diag**$(\gamma_1^k, \ldots, \gamma_N^k)$.

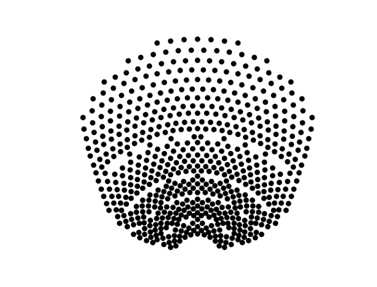
Adaptive step size with modified *Armijo's Rule*

$$\gamma_h^k = \gamma_h^{k-1} \cdot \epsilon, \quad \epsilon \in (0,1)$$

Aiming Strategy III - Illustrative Example

PS10 SPT plant

Variable	Value	Description
H	624	Heliostats
T	10	Time points
V_p	0.5	Velocity limit
E_{tar}	2.2e6	Flux gradient limi
ϵ	0.9	*Armijo's* constant
γ_0	0.1	Initial step size
μ	1e5	Penalty constant
A	0.7	Weighting parame
σ_1	0	Velocity constrain
σ_2	1e4	Flux gradient constraint



AS III - Illustrative Example

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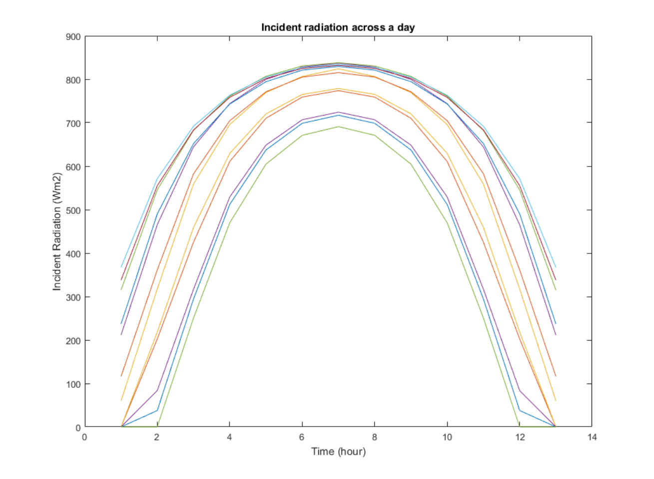
A	0.7	Weighting parameter
σ_1	0	Velocity constraint
σ_2	1e4	Flux gradient constraint

Computation

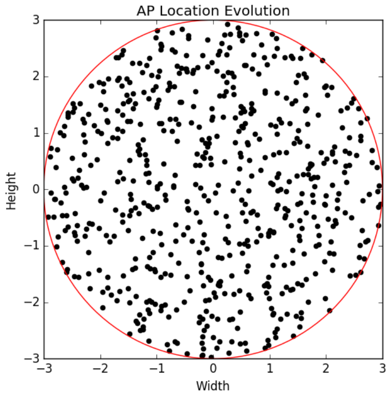
- Python
- Bespoke solver
- Solution in $< 2{,}5$min

Aiming Strategy III - Illustrative Example



Incident radiation

Aiming Strategy III - Illustrative Example



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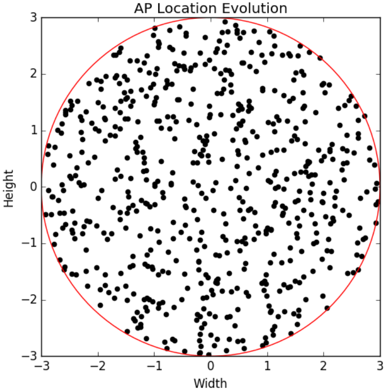
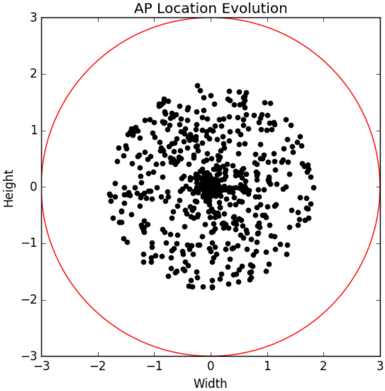
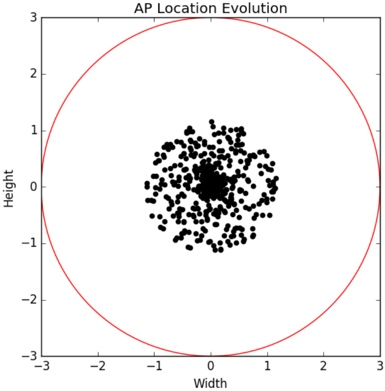
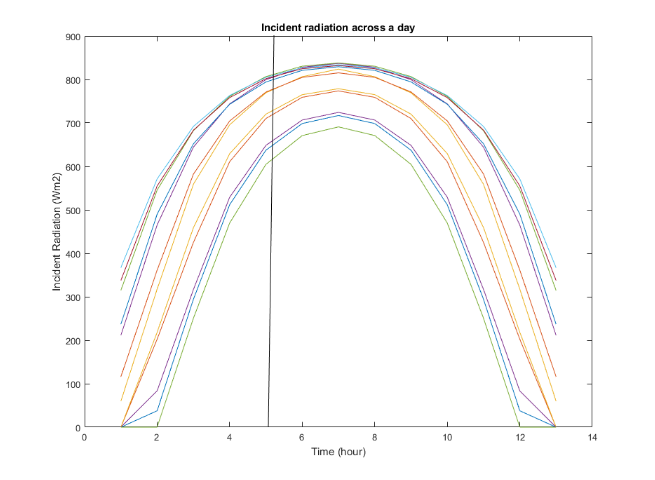


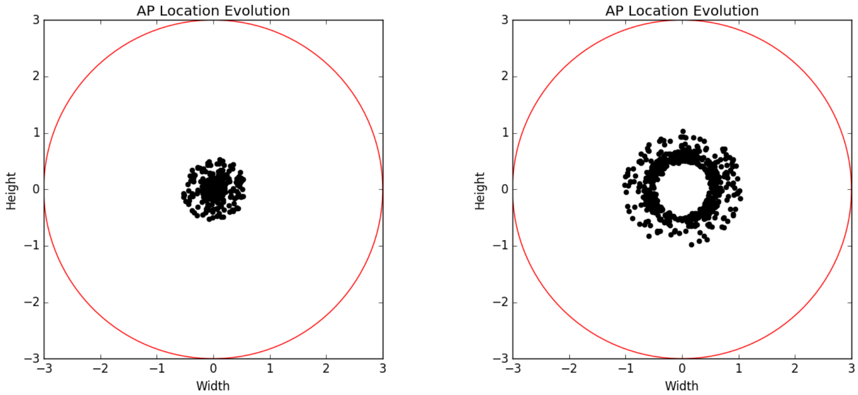
Aiming Strategy III - Illustrative Example

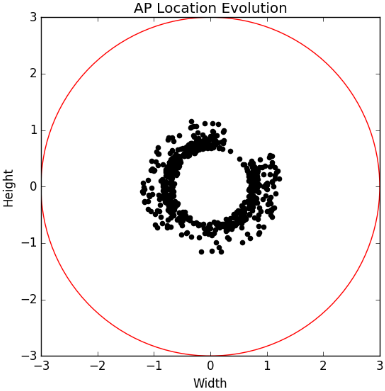





Incident radiation across a day
Incident Radiation (Wm2)
900
800
700
600
500
400
300
200
100
0
0
2
4
6
8
10
12
14
Time (hour)

Aiming Strategy III - Illustrative Example




AP Location Evolution
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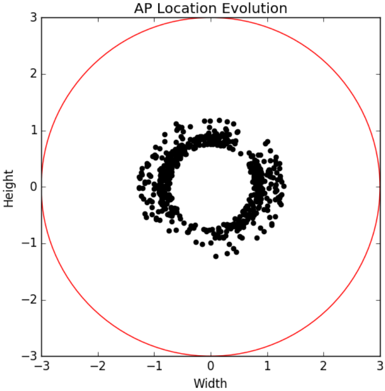
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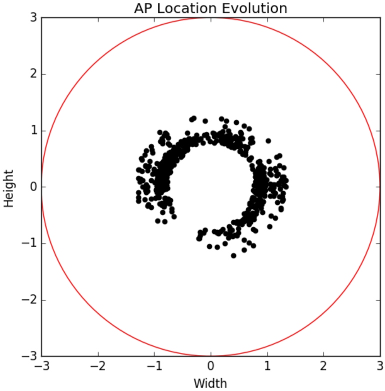

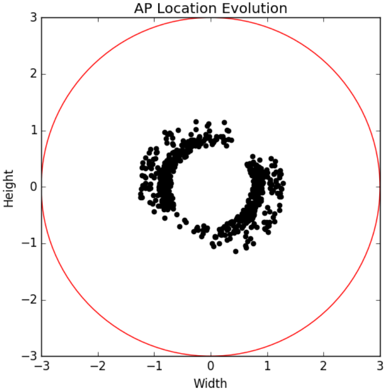

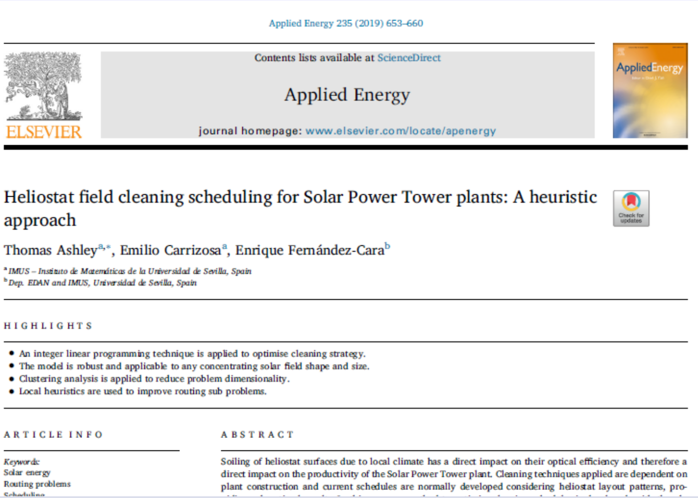
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Heliostat field cleaning scheduling for Solar Power Tower plants: A heuristic approach

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HIGHLIGHTS

- An integer linear programming technique is applied to optimise cleaning strategy.
- The model is robust and applicable to any concentrating solar field shape and size.
- Clustering analysis is applied to reduce problem dimensionality.
- Local heuristics are used to improve routing sub problems.

ARTICLE INFO

Keywords:
Solar energy
Routing problems
Scheduling

ABSTRACT

Soiling of heliostat surfaces due to local climate has a direct impact on their optical efficiency and therefore a direct impact on the productivity of the Solar Power Tower plant. Cleaning techniques applied are dependent on plant construction and current schedules are normally developed considering heliostat layout patterns, pro-

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Objective

Maximise received energy across a defined length of time by optimising the cleaning schedule

- Consider a 3 Stage optimisation process
  - Clustering optimisation
  - Schedule optimisation
  - Local search heuristics

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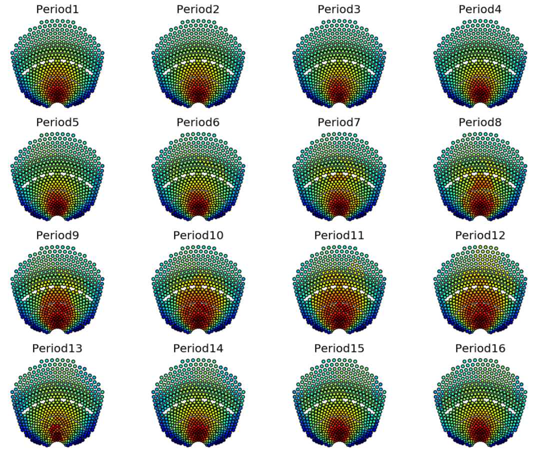
Schedule parameters

- Schedule length: 16 periods
- Number of groups: 52
- Groups per day: 4

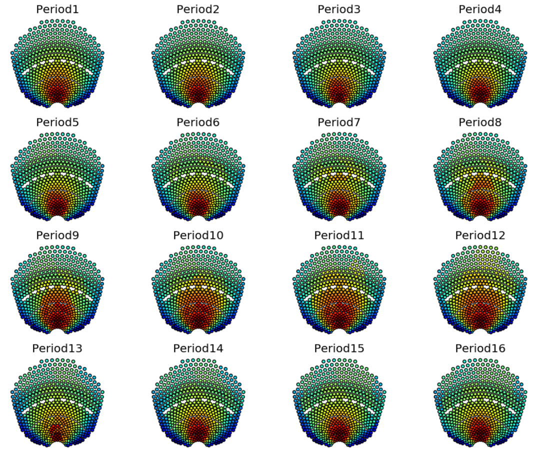
Cleaning Strategy - Schedule Example



Cleaning Strategy - Schedule Example

Computational aspects

- Python
- Gurobi Solver
- 10min time limit



Cleaning optimisation

- Multi-depots/vehicles
- Unmanned aerial vehicles (UAVs)
  - Large-dimensional optimisation problem
  - Vehicle routing problem with multiple trips VRPMT
  - Multiple moving depots (charging vehicles)

Energy Storage

- Market price
- Thermal losses

Integrated optimisation

- Thermal modelling
  - Numerical model of receiver components
- Coupled model
  - Integration into dynamic aiming strategy optimisation

New methods and results in the optimisation of solar power tower plants

Thomas Ian Ashley

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