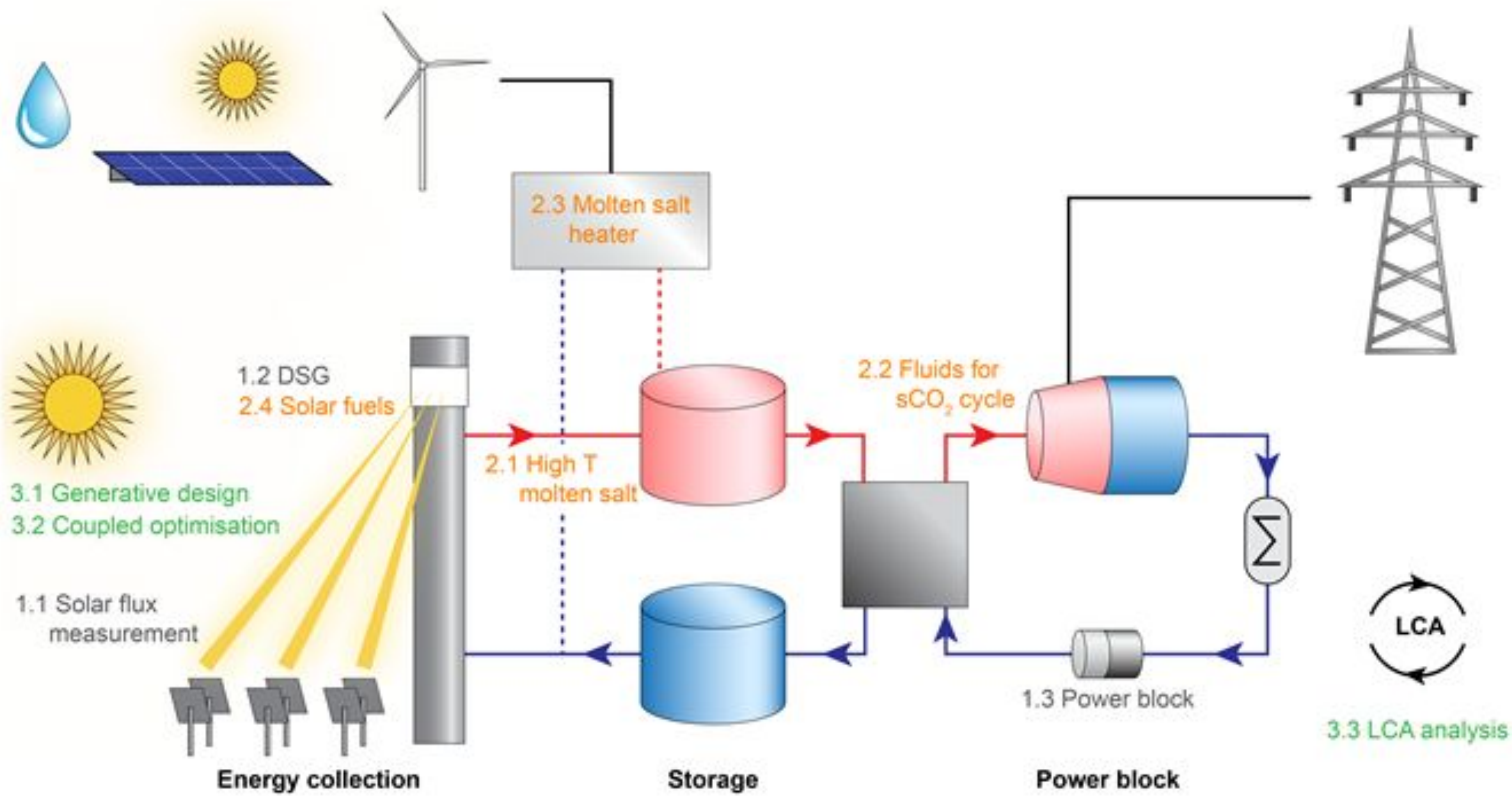
Funded by the European Union

# Towards, Competitive, Reliable, Safe and Sustainable Concentrated Solar Power (CSP) Plants

Midterm meeting REA, 18-19 April 2024

## Doctoral Candidate 8 – Jorge Moreno
## Generative design of solar tower receivers



# Overview

1. DC and Supervisors Introduction
2. Generative design overview
3. Data generation
4. Receiver performance evaluation
5. Receiver geometry definition
6. Optical simulation
7. Optimization
8. Preliminary results
9. Next steps



Funded by the European Union

# 1. DC and Supervisors Introduction

## Doctoral Candidate: Jorge Moreno

2016-2020: Bachelor degree in Industrial Engineering

2020-2023: Master degree in Industrial Engineering
Master degree in Energy Engineering

uc3m | Universidad Carlos III de Madrid

UNIVERSITAT POLITÈCNICA DE CATALUNYA BARCELONATECH

## Supervisors:

### Wojciech Lipiński

Doctorate in Mechanical and Process Engineering, the research interest encompass optical, thermal and chemical aspects of solar energy technologies.

His research focuses on transport and reactive flow phenomena, contributing in the development of concentrated solar thermal energy for power generation, processing of fuels and materials and environmental separations.

### Kypros Milidonis

Doctorate in Aerospace Engineering, the research interest is energy conversion systems, extending over a wide range of subjects, from fundamental theoretical research to applied industrial applications.

Experienced in cutting-edge research projects with a solid background in experimental and computational fluid mechanics, thermodynamics, heat transfer

### Mihalis Nicolau

Doctorate in computing, the research interest is on developing machine learning algorithms for a wide range of applications, such as computer vision and natural language processing.

Experience mainly in robust, efficient, generalizable and interpretable machine learning algorithms for climate monitoring and earth observation, health and science.



Funded by the European Union

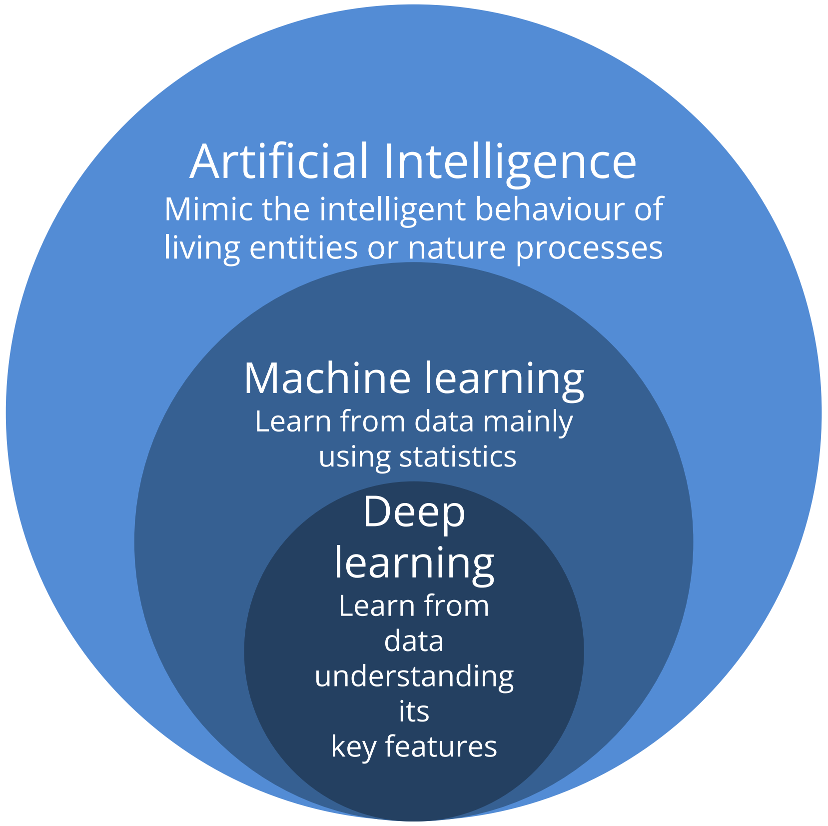
# 2. Generative design overview

## Classical design

Designer **experience** guides the optimization process, where a **low amount** of designs are evaluated

## Generative design

Iterative process where **computer algorithms** explore a **vast range** of possible designs to find the optimal designs based on specific parameters and constraints.




### Generative design in Solar Tower Receivers Literature review

- Metaheuristic Algorithms: optimize a very few and specific parameters or perform single-objective optimization.
- Artificial Neural Networks: replace simulations tools for very specific task decreasing computational cost and time. Usually trained with data extracted from simulations.

The most important factor nowadays is the **DATA**

### Research approach

1$^{st}$ Goal:

- Generate and collect data to be later used to for different machine learning techniques.
- Evaluate global systems (not task specific) automatically.
- While collecting the data, perform system optimizations.

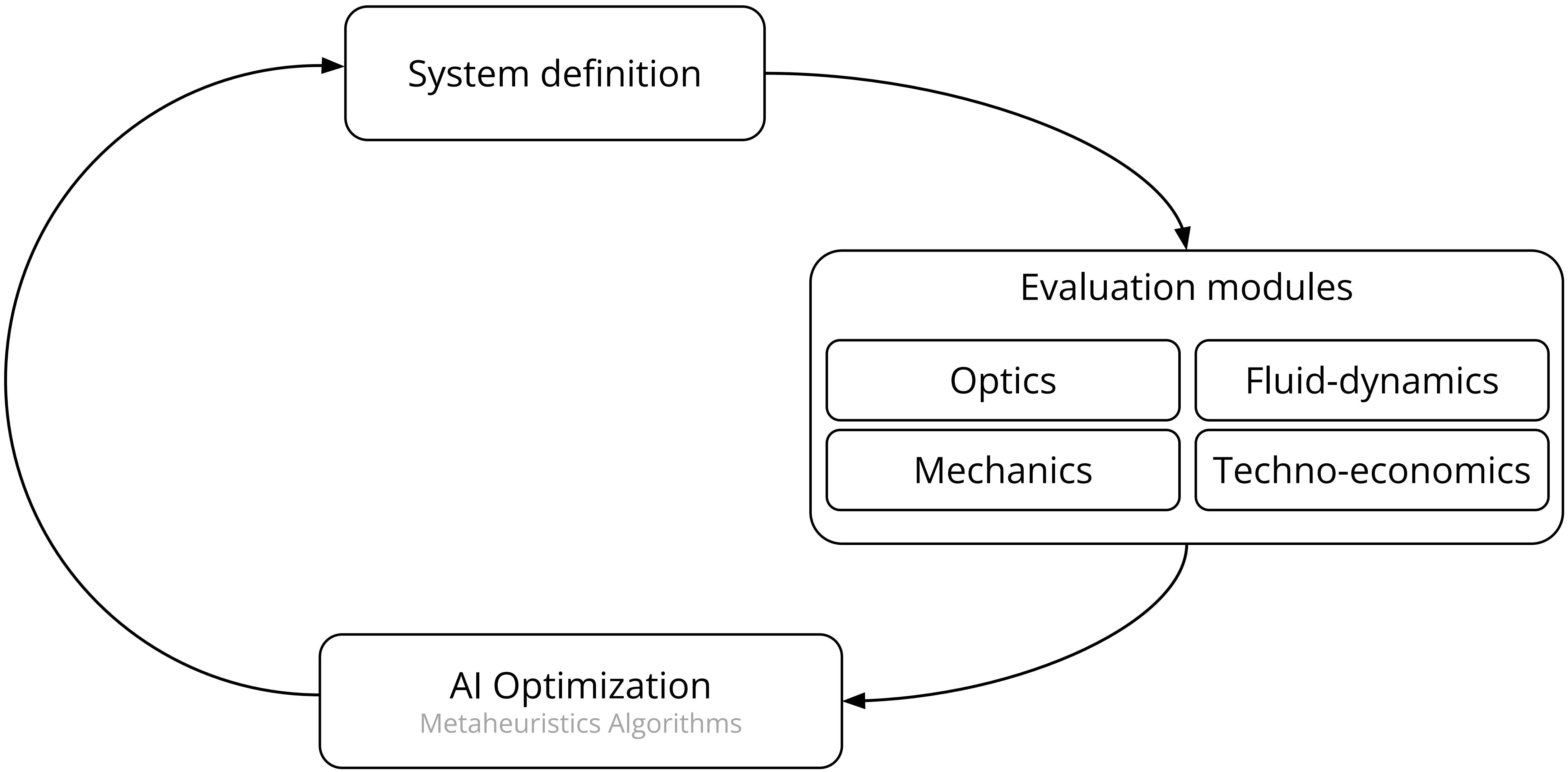
2$^{nd}$ Goal: (once the data is available)

- Employ machine and deep learning techniques: dimensionality reduction (PCA), ANNs to optimize new or existing power plants.

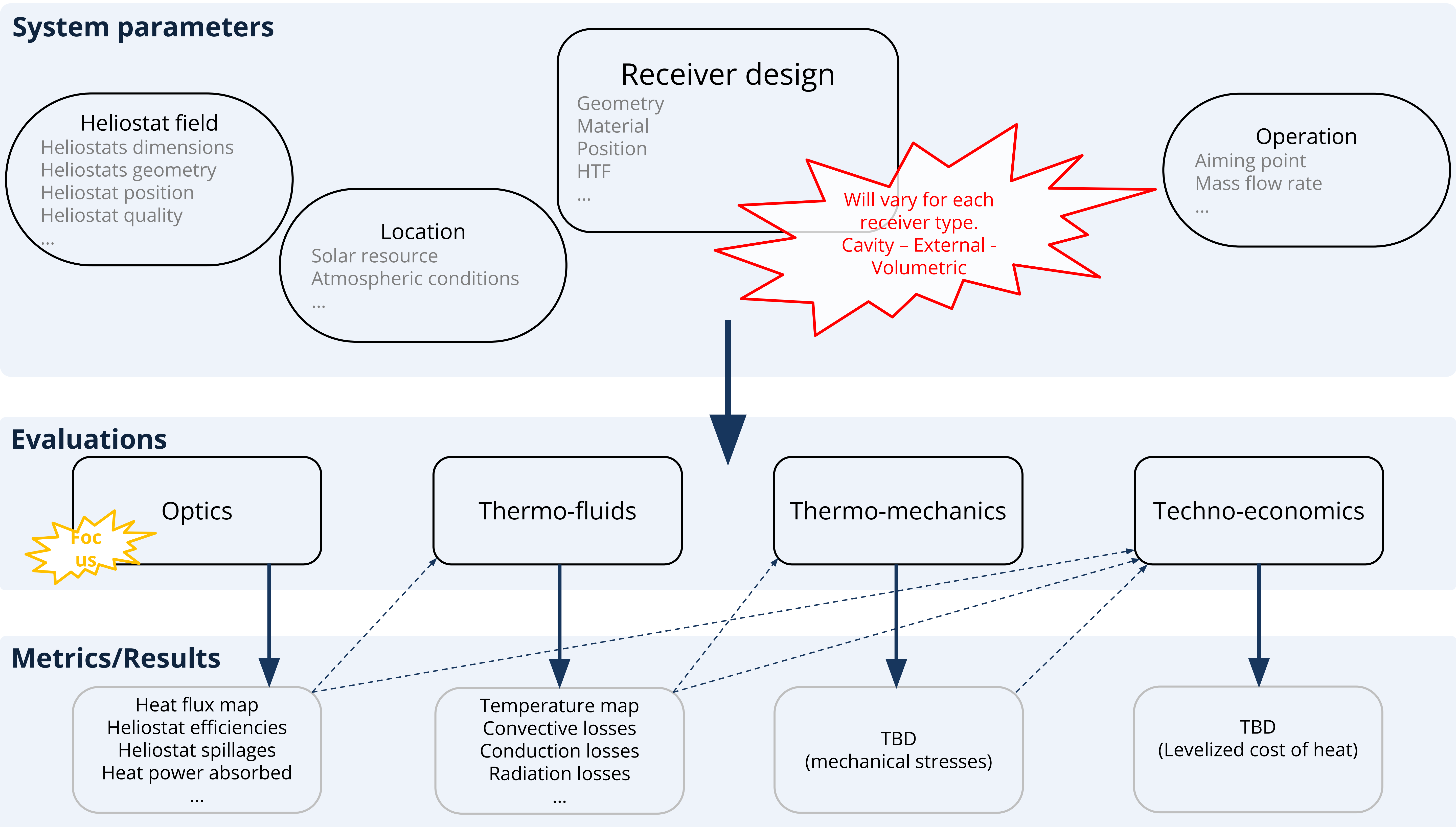


Funded by the European Union

# 3. Data generation



# 4. Receiver performance evaluation





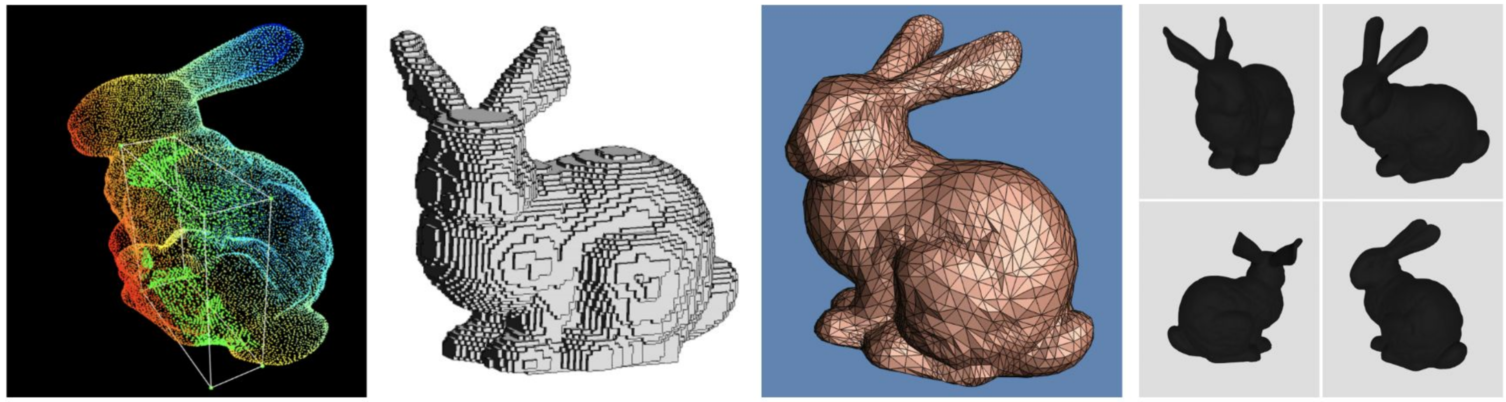

Funded by the European Union

# 5. Receiver geometry definition

Any 3D geometry can be mathematically described using the implicit function F(x,y,z) = 0

Complex and detailed geometries → Complicated mathematical representation (~7k parameters)

Common geometry representations that are easily processed computationally:



Point cloud | Voxels | Polygon meshes | Multi-view

Adapted from: Superquadrics Revisited: Learning 3D Shape Parsing beyond Cuboids

- Discrete (approximate)
- Resolution depends on the amount of pixels, voxels, polygons, views, etc.

## Research approach for solar tower cavity (and external) receivers

1. No use of implicit function.
2. Generation of point cloud and triangular mesh.
3. Parametrization based on definition of sections, and interpolation:

    - Multiple control sections are defined.
    - Each control section is defined by two or more parameters.
    - Geometry spatial resolution is user-defined by two parameters.
    - Three geometry definition approaches are currently defined (low, medium and high complexity).
    - Geometry definitions employed in optics simulations for cavity and external receivers.



Funded by the European Union

# 5. Receiver geometry definition

## Axis-symmetric receivers

Low complexity geometry
Easy to define and optimize

Parameters:

- Axial (z-axis) control points coordinates: 1D array

| | | | | | |
|---|---|---|---|---|---|
| -5.0 | -4.0 | -3.0 | -2.0 | -1.0 | -0.0 |

- Radial (x-axis) control points coordinates: 1D array

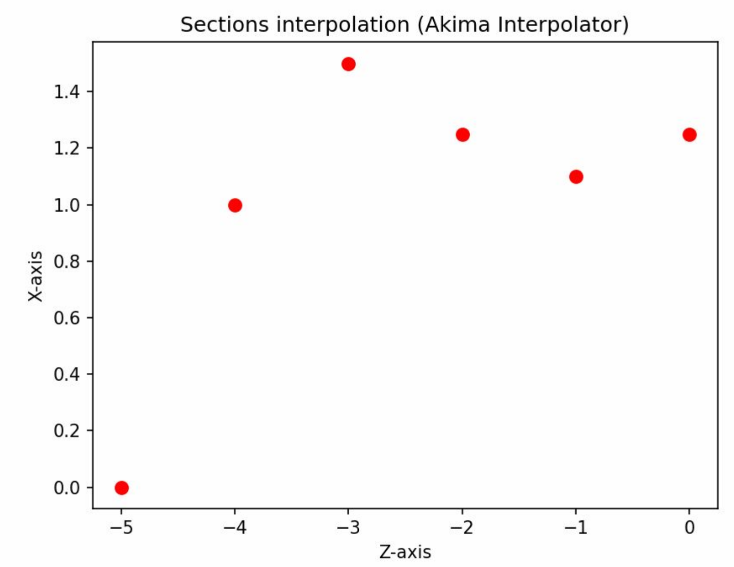
| | | | | | |
|---|---|---|---|---|---|
| 0.0 | 1.0 | 1.5 | 1.25 | 1.1 | 1.25 |

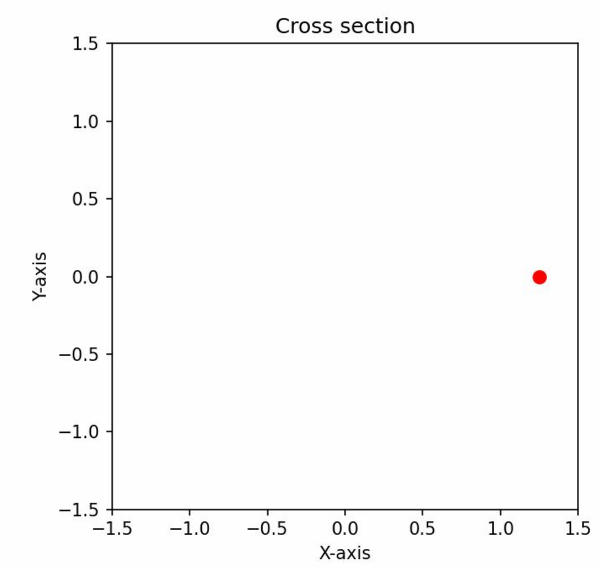
- Axial resolution: scalar

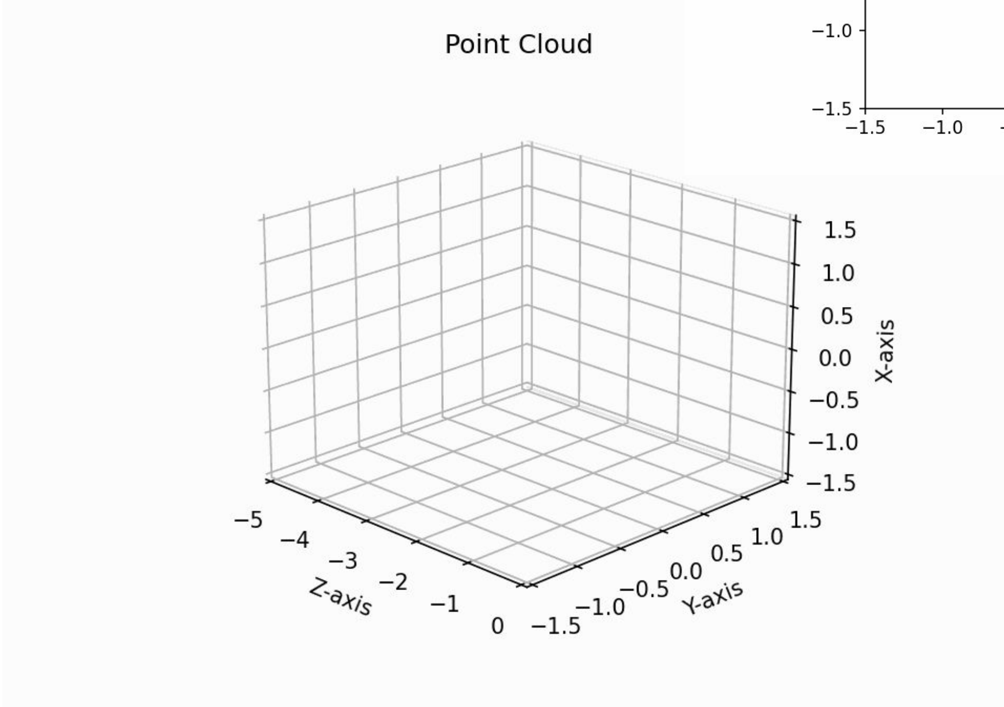
| |
|---|
| 40 |

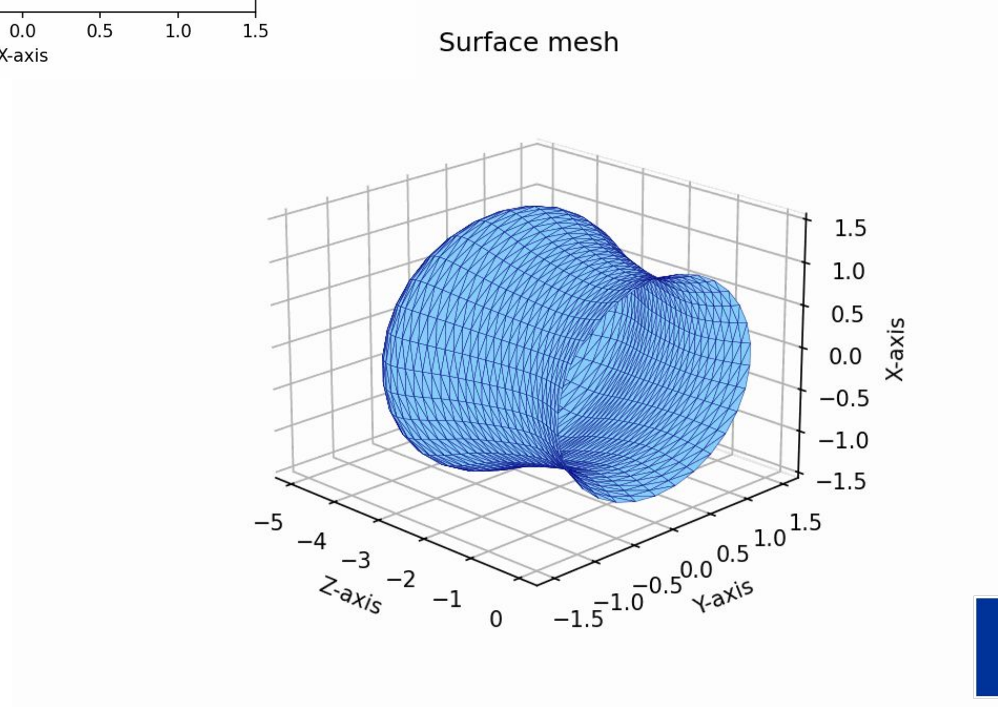
- Circumferential resolution: scalar

| |
|---|
| 30 |






Funded by the European Union

# 5. Receiver geometry definition

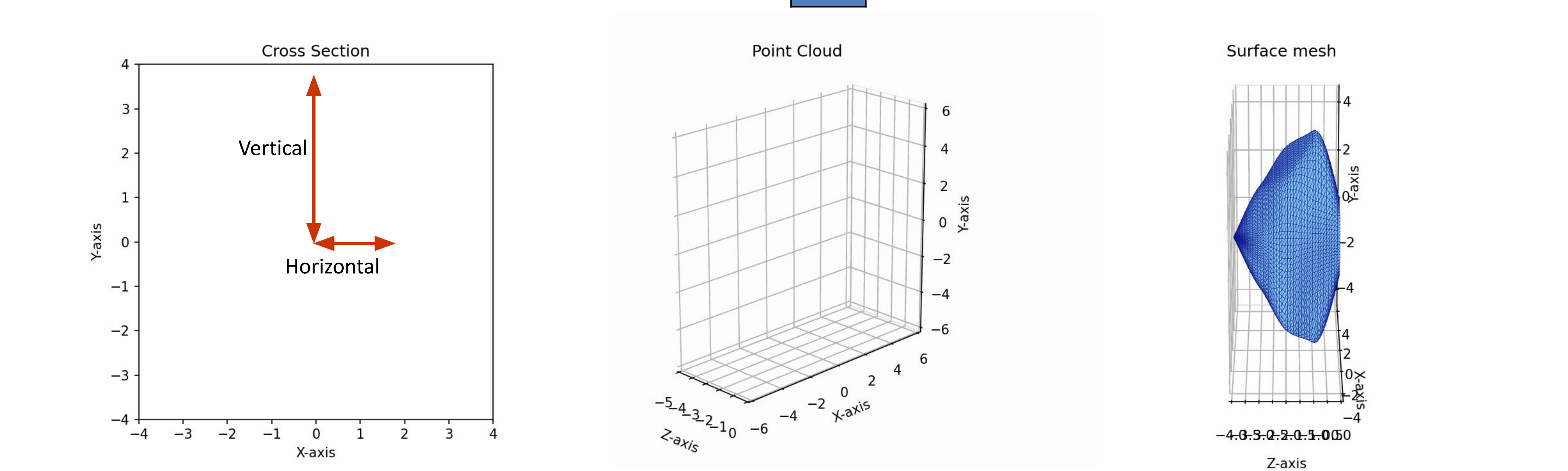
## Bi-plane symmetry receivers

Useful for polar fields which are usually symmetric, as well as the sun trajectory.
Axis-symmetric receivers can be defined in using this parametrizations (vertical=horizontal=radius)

Parameters:

- Axial (z-axis) control points coordinates: 1D array
- Vertical (y-axis) length: 1D array
- Horizontal (x-axis) length: 1D array
- Radius: 1D array
- Axial resolution: scalar
- Circumferential resolution: scalar

| | | | | | |
|---|---|---|---|---|---|
| Axial (z-axis) control points coordinates | -4.0 | -3.0 | -2.0 | -1.0 | -0.0 |
| Vertical (y-axis) length | 0.0 | 1.0 | 3.0 | 2.0 | 1.5 |
| Horizontal (x-axis) length | 0.0 | 1.0 | 3.0 | 2.0 | 1.5 |
| Radius | 0.0 | 1.0 | 1.25 | 1.5 | 1.5 |
| Axial resolution | 40 | | | | |
| Circumferential resolution | 80 | | | | |



# 5. Receiver geometry definition

## Complex receivers

Useful for multi-cavity receiver solar fields.

Parameters:

- Axial (z-axis) control points coordinates: 1D array

| | | | | |
|---|---|---|---|---|
| -4.0 | -3.0 | -2.0 | -1.0 | 0.0 |

- Polar magnitude control points magnitudes: 2D array

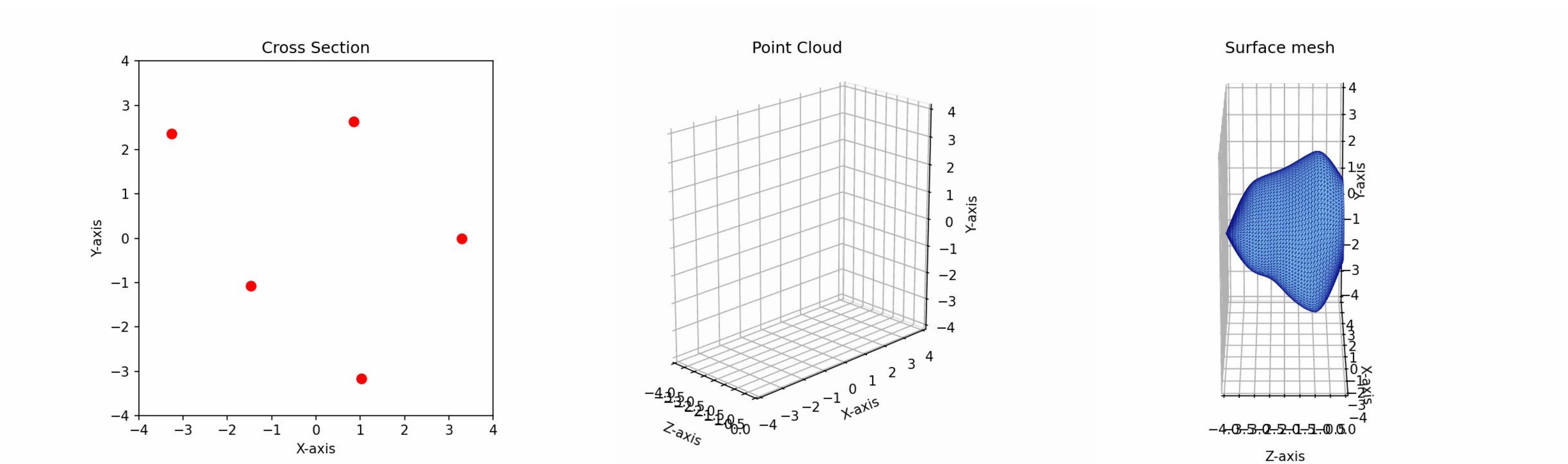
| | | | | |
|---|---|---|---|---|
| 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 1.3 | 1.8 | 1.1 | 1.5 | 1.1 |
| 2.8 | 2.2 | 2.5 | 1.3 | 2.6 |
| 3.5 | 2.8 | 4.1 | 1.9 | 3.5 |
| 1.3 | 1.8 | 1.1 | 0.9 | 1.1 |

- Axial resolution: scalar

| |
|---|
| 40 |

- Circumferential resolution: scalar

| |
|---|
| 80 |





Funded by the European Union

# 6. Optical simulation

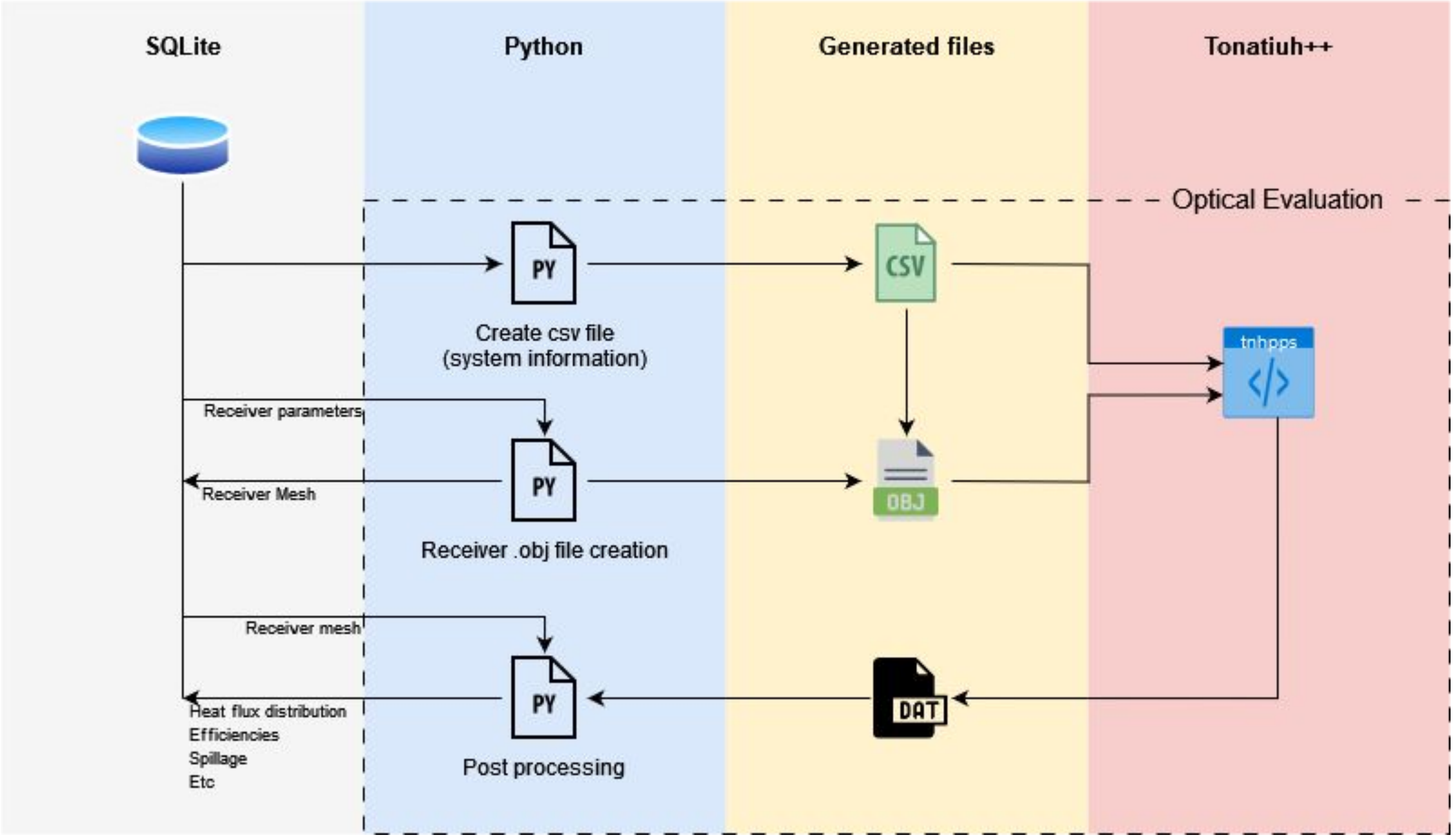
**Free and open source** software:

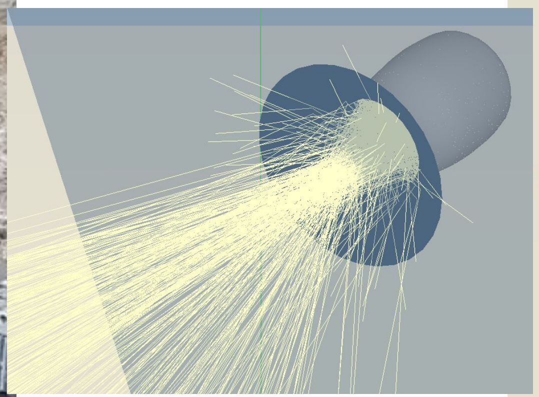
- Monte Carlo Raytracer to solve RTE

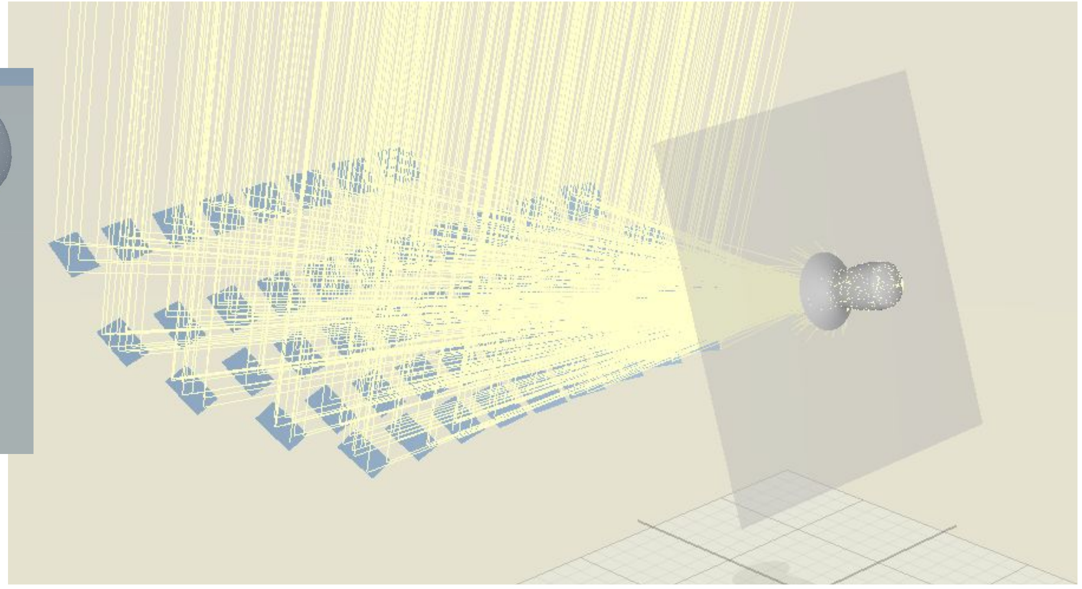
Source: Grigoriev, V., Blanco, M., & Milidonis, K. Tonatiuh++ Solar Raytracer

- Python to provide the input information to Toantiuh++ in the proper format, compute post-processing calculations

Source: Van Rossum, G., & Drake, F. L. (2009). Python 3.





Source: Kypros Milidonis



Funded by the European Union

# 7. Optimization

Optimization problem definition:

Objective functions: $\min \quad f_m \qquad m = 1, \dots, M$

Constrains:

Inequality constrains: $g_j(x) \leq 0 \qquad j = 1, \dots, J$

Equality constrains: $h_k(x) = 0 \qquad k = 1, \dots, K$

Variables bounds: $x_i^L \leq x_i \leq x_i^U \qquad i = 1, \dots, I$

The receiver design is composed of multiple variables, which must satisfy multiple objectives.

Multi-variable multi-objective optimization

pymoo
Multi-objective Optimization in Python

Source: J. Blank and K. Deb, "Pymoo: Multi-Objective Optimization in Python".

- Single (1) vs multi (2-3) vs many (>3) objectives optimization
- Implements different standards algorithms
- Many objectives algorithms are stable
- Possibility to create our own algorithm



Funded by the European Union

# 8. Preliminary results

Geometry optimization for axis-symmetric receivers based on PROTEAS heliostat field.

Objective functions:

$$\left.\begin{array}{ll} \max & \mathit{Power\ absorbed} \\ \min & \mathit{Peak\ heat\ flux} \end{array}\right\} \text{Heat flux uniform distribution}$$

$$\begin{array}{ll} \min & \mathit{Receiver\ Area} \end{array}$$

Constrains:

Inequality constrains: $$\mathit{Peak\ heat\ flux} < \max\ \mathit{allowable\ heat\ flux}$$

Variables bounds:

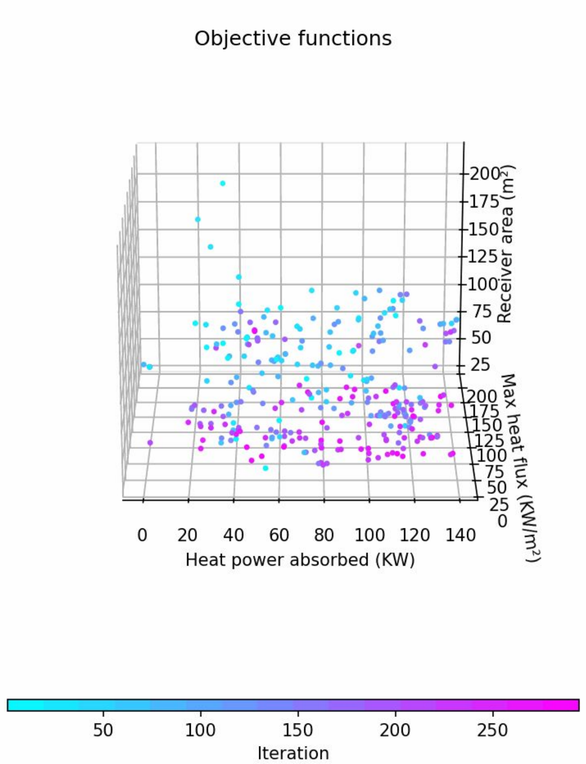
$$0.01 \leq x_1 \leq 4.00$$

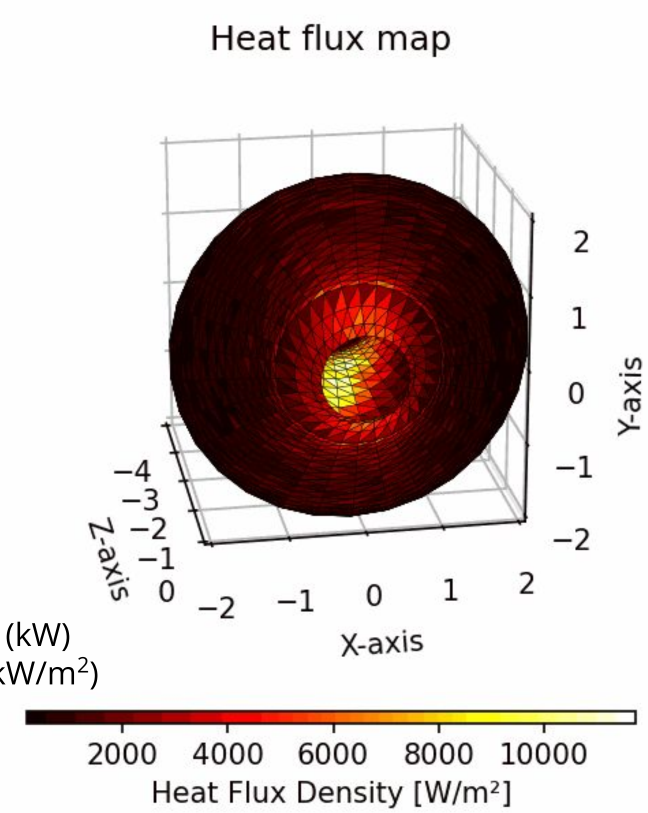
$$0.01 \leq x_2 \leq 4.00$$

$$0.01 \leq x_3 \leq 4.00$$

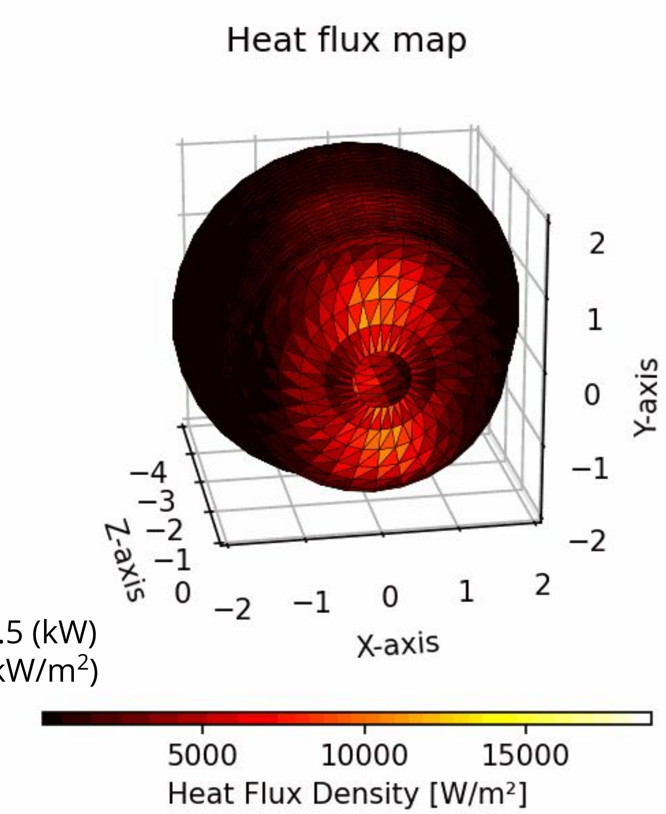
$$0.01 \leq x_4 \leq 4.00$$

- Low geometry resolution
  - Triangular mesh with 1500 faces
- Low number of rays
  - 1.5 million rays
- Time spent per receiver evaluation
  - ~ 2 min
- Variables to optimize
  - Radial control points of 4 sections.
- Algorithm NSGA-III




Power absorbed: 100 (kW)
Peak heat flux: 11.7 (kW/m$^2$)
Area: 49.9 (m$^2$)




Power absorbed: 130.5 (kW)
Peak heat flux: 18.8 (kW/m$^2$)
Area: 61 (m$^2$)




Funded by the European Union

# 9. Next steps

## Technical

1. Include axial control points in the optimization
2. Develop fluid-dynamics evaluation
3. Test different many-objectives optimization algorithms
4. Include more parameters/objective functions in the optimization

## Dissemination in relation to year 1

1. Complete review paper on “Generative design of solar tower receivers”.
2. Solar Paces publication



Funded by the European Union

# Last slide

# Thanks!

## Any questions?

j.moreno@cyi.ac.cy



HORIZON MSCA Doctoral Network
Project number 101072537

Funded by the European Union