solar: **A solar thermal power plant simulator for blackbox optimization benchmarking**

Sébastien Le Digabel

GERAD
GROUP FOR RESEARCH IN
DECISION ANALYSIS

POLYTECHNIQUE
MONTRÉAL

TECHNOLOGICAL
UNIVERSITY

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Presentation outline

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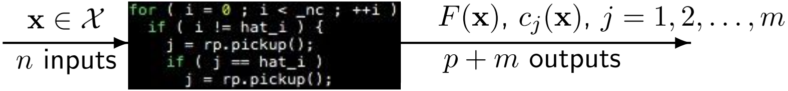
Contributors

- This work is based on the MSc thesis of Mathieu Lemyre Garneau [Lemyre Garneau, 2015]
- The other contributors are
  - Charles Audet
  - Miguel Diago
  - Aimen Gheribi
  - Viviane Rochon Montplaisir
  - Bastien Talgorn
  - Christophe Tribes
- MLG, MD, and AG, combine several expertises in concentrated solar power (CSP)

Context: Blackbox Optimization (BBO)

$$\min_{\mathbf{x}\in\mathcal{X}} \quad F(\mathbf{x}) \text{ s.t. } \mathbf{x} \in \Omega = \{\mathbf{x} \in \mathcal{X} : c_j(\mathbf{x}) \leq 0, j = 1, 2, \ldots, m\}$$

$\mathcal{X}$ is a n-dimensional space, F can have $p = 1$ or $p = 2$ components, and the evaluations of F and the c_j's are provided by a blackbox:


$\mathbf{x} \in \mathcal{X}$
n inputs
$F(\mathbf{x})$, $c_j(\mathbf{x})$, $j = 1, 2, \ldots, m$
$p + m$ outputs

```
for ( i = 0 ; i < _nc ; ++i )
  if ( i != hat_i ) {
    j = rp.pickup();
    if ( j == hat_i )
      j = rp.pickup();
```

- Each call to the blackbox may be expensive
- The evaluation can fail
- Sometimes $F(\mathbf{x}) \neq F(\mathbf{x})$
- Derivatives are not available and cannot be approximated

Issues with BBO benchmarking

- Benchmarking must consider lots of problems, which is problematic in BBO
- Testing on true applications is hard because
  - Evaluations are expensive
  - Codes are confidential
  - Codes depend on in-house or expensive libraries
  - Codes are difficult to install
  - The original designers are no longer available
- This results in the use of collections of artificial problems that are based on inexpensive analytical functions
- These collections are necessary, given the lack of true applications, but they are not sufficient: This leads to biased hierarchies of solvers that are useless to practitioners

Objectives of this work

Provide a realistic application for “true” BBO benchmarking, that

- includes numerical simulations
- is easy to install (stand-alone, standard code)
- is multiplatform
- allows to reproduce results
- includes many options that allow to
  - test different aspects of BBO such as
    - expensive evaluations
    - discrete/categorical variables
    - constraints handling
    - noise in the blackbox outputs
    - static surrogates
    - multiobjective optimization
  - define a collection of problems to draw profiles

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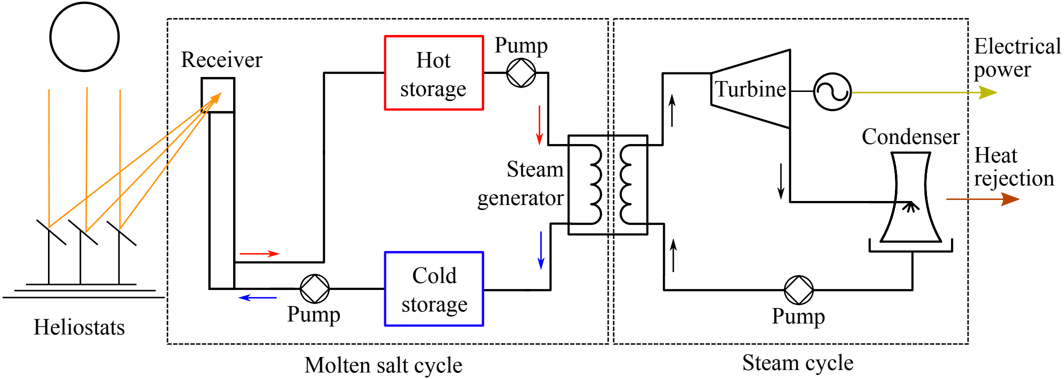
CSP tower plant with molten salt thermal energy storage

- A large number of mirrors (heliostats) reflects solar radiation on a receiver at the top of a tower
- The heat collected from the concentrated solar flux is removed from the receiver by a stream of molten salt
- Hot molten salt is then used to feed thermal power to a conventional power block
- The photo shows the Thémis CSP power plant [Drouot and Hillairet, 1984], the first built with this design

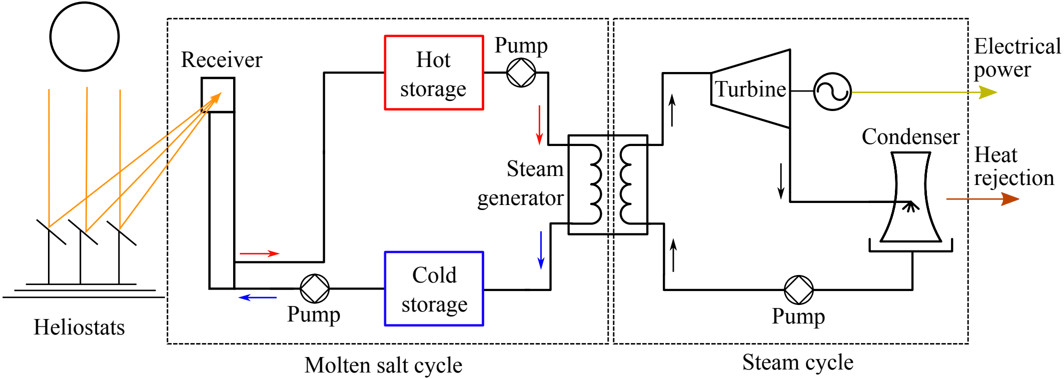
System dynamics

- Thermal power is extracted by raising the temperature of molten salt pumped through the receiver



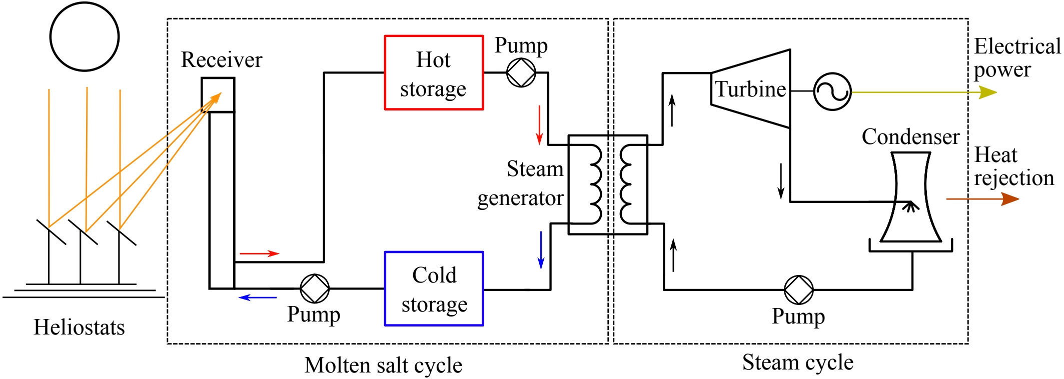
System dynamics

- The hot molten salt is directed to a hot storage tank



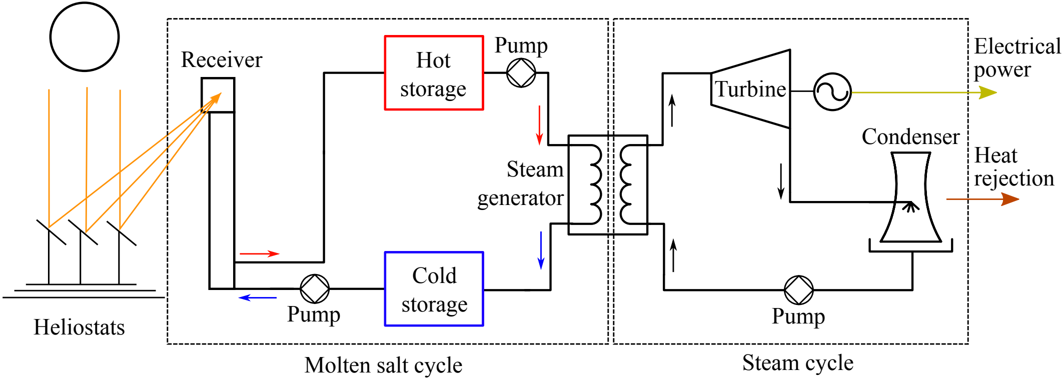
System dynamics

- Hot molten salt is pumped though the steam generator



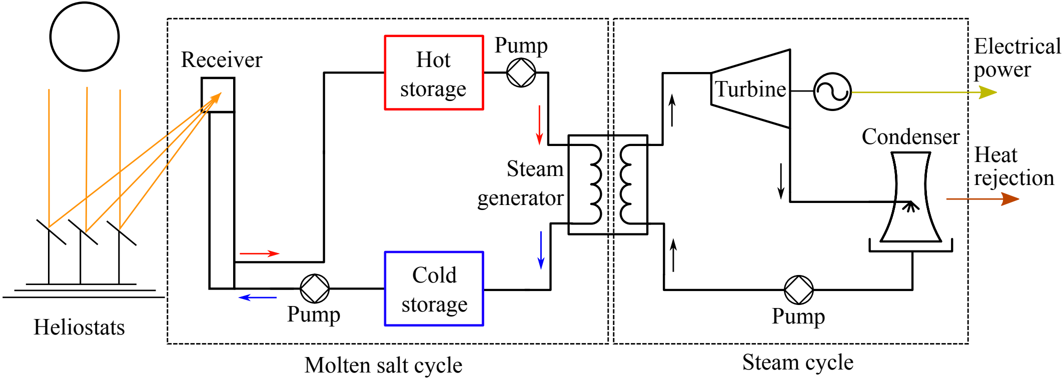
System dynamics

- Heat is transferred to a current of water on the other side of the steam generator which is transformed to superheated steam



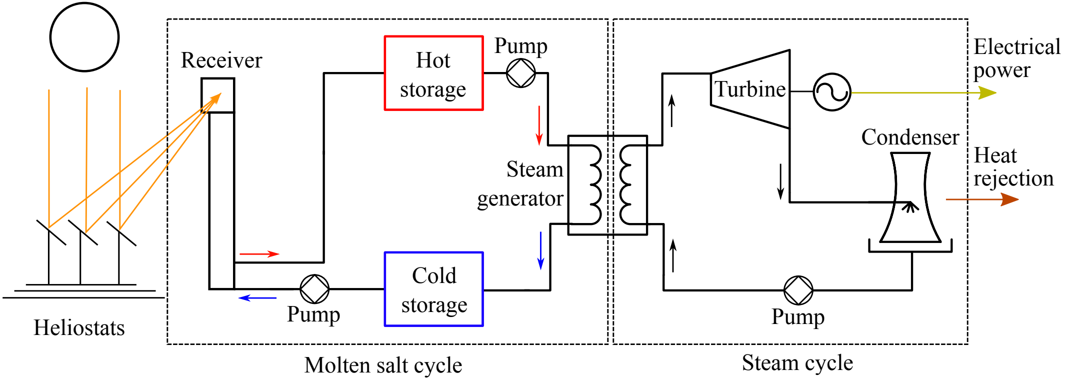
System dynamics

- Cold molten salt is recovered in the cold storage tank



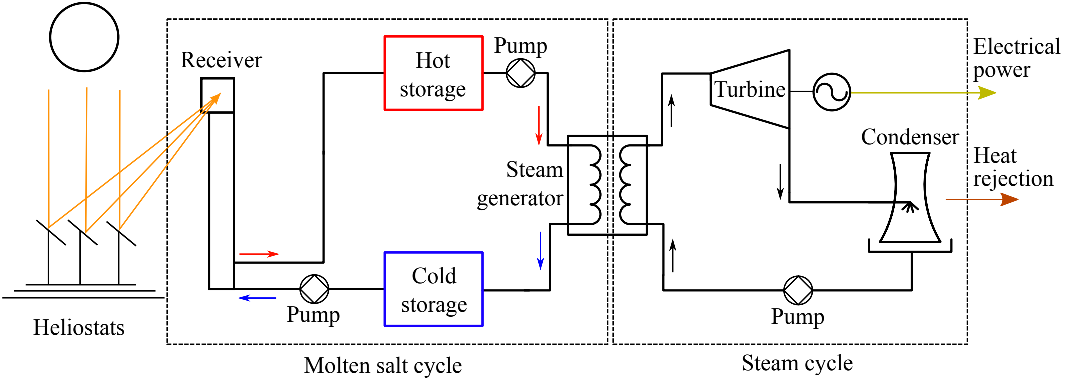
System dynamics

- Superheated high-pressure steam drives a turbine coupled to an electrical generator
- Low-pressure steam is condensed and pumped back as liquid water



System dynamics

- Losses due to non-idealities are accounted for in all components except the steam generator

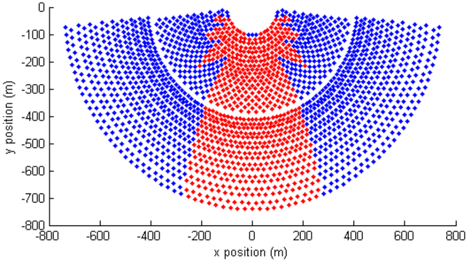


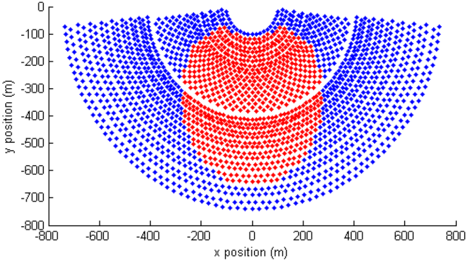
Heliostats field (1/2)

- The heliostats are laid on a radially staggered grid that prevents blocking losses between them
- The grid is calculated as a function of individual heliostat dimensions and tower height
- Once the grid layout is determined, each position is rated according to the average optical efficiency
- Shadowing effects are considered when calculating the overall performance
- The actual heliostats field is generated by occupying the first grid positions with the highest average optical efficiency for the given receiver aperture and tower height

Heliostats field (2/2)

- The images below show how the arrangement of 700 heliostats on the same spatial grid of 1960 points varies with the receiver aperture width (3 meters vs 15 meters)
- As the aperture narrows, the algorithm selects heliostats closer to the North-South axis to minimize spillage
- For wider apertures, the selection is dictated by cosine efficiency and atmospheric attenuation





Main components of the simulator

- Sun radiation model
- Thermal storage model
- Parasitic loads model
- Pumping models
- Shell-and-tubes models with stress models of the tubes in both the receiver and steam generator
- Energy losses model (reflective, emissive, convective, conductive)
- Powerblock model with only one parameter (=optimization categorical variable): the choice of the type of turbine
- Demand model
- Investment cost model

All models have been validated during MLG's masters thesis, using simulations, scenarios, and comparisons with literature results

Main numerical methods in the simulator

- Monte Carlo simulation to evaluate the field efficiency
- Newton's method to find roots in thermal equations
- Kernel smoothing to interpolate various discrete data
- Iterative methods to solve Heat Transfer Fluid equations

The solar code is

- a command-line application
- the "natural heir" of our STYRENE simulator [Audet et al., 2008]
- publicly available at https://github.com/bbopt/solar under the GNU Lesser General Public License
- a relatively simple code in standard C++ ($\simeq$13k lines of codes)
- stand-alone: no external library to install
- multi-platform: C++ compilator is the only requirement

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Ten instances

Instance	# of variables			# of obj.	# of constraints			# of stoch. outputs	Static
	cont.	discr. (cat.)	n	p	simu.	a priori (lin.)	m	(obj. or constr.)	surrogate
solar1	8	1 (0)	9	1	2	3 (2)	5	1	no
solar2	12	2 (0)	14	1[1]	9	4 (2)	13	3	yes
solar3	17	3 (1)	20	1	8	5 (3)	13	5	yes
solar4	22	7 (1)	29	1	9	7 (5)	16	6	yes
solar5	14	6 (1)	20	1	8	4 (3)	12	0	no
solar6	5	0 (0)	5	1	6	0 (0)	6	0	no
solar7	6	1 (0)	7	1	4	2 (1)	6	3	yes
solar8	11	2 (0)	13	2	4	5 (3)	9	3	yes
solar9	22	7 (1)	29	2	10	7 (5)	17	6	yes
solar10[2]	5	0 (0)	5	1	0	0 (0)	0	0	no

[1] analytic objective

[2] available in the next release

Objectives

- solar1 Max. total solar energy concentrated on the receiver aperture through one day (stochastic)
- solar2 Min. total heliostats field surface to run a pre-determined powerplant (analytic): $x_3^2(x_9^2 - x_8^2)x_7\frac{\pi}{180}$
- solar3 Min. total investment cost
- solar4 Min. cost of powerplant to respect a given demand with a limited size of field
- solar5 Max. compliance to a demand profile
- solar6 Min. cost of storage
- solar7 Max. receiver efficiency (energy transferred to the molten salt) (stochastic)
- solar8 Max. heliostat field performance (absorbed energy) and min. cost of field, tower and receiver
- solar9 Max. power and min. losses (stochastic)
- solar10 Min. cost of storage

Types of variables

$$\min_{\mathbf{x}\in\mathcal{X}} \quad F(\mathbf{x}) \text{ s.t. } \mathbf{x} \in \Omega = \{\mathbf{x} \in \mathcal{X} : c_j(\mathbf{x}) \leq 0, j = 1, 2, \ldots, m\}$$

- The n variables are described by the set $\mathcal{X}$. They can be continuous or discrete.
- The solar6 and solar10 instances have no discrete variables. In these cases $\mathcal{X} \subset \mathbb{R}^5$
- One of the discrete variable (the type of turbine) is categorical. solar considers it as an integer in $\{1, 2, \ldots, 8\}$
- $\mathcal{X}$ also includes bounds on most of the variables

The following slides list all 29 possible variables. Each instance considers a subset of these variables. solar4 and solar9 consider all $n = 29$ variables

All variables: Heliostats field

#	Symbol	Quantity	Unit	Type	Lower bound	Upper bound
1	L_{hs}	Heliostats length	m	cont.	1	40
2	W_{hs}	Heliostats width	m	cont.	1	40
3	H_{twr}	Tower height	m	cont	20	250
4	H_r	Receiver aperture height	m	cont.	1	30
5	W_r	Receiver aperture width	m	cont.	1	30
6	N_{hs}	Number of heliostats to fit		discr.	1	$+\infty$
7	θ_{hs}	Field angular width	deg	cont.	1	89
8	R_{hs}^{min}	Min. distance from tower	$\times H_{twr}$	cont.	0	20
9	R_{hs}^{max}	Max. distance from tower	$\times H_{twr}$	cont.	1	20

All variables: Heat transfer loop

#	Symbol	Quantity	Unit	Type	Lower bound	Upper bound
10	T_r^{out}	Receiver outlet temp.	K	cont.	793	995
11	H_{hot}	Hot storage height	m	cont.	1 or 2	30 or 50
12	d_{hot}	Hot storage diameter	m	cont.	1 or 2	30
13	t_{hot}	Hot storage insulation thickness	m	cont.	0.01	2 or 5
14	t_{cold}	Cold storage insulation thickness	m	cont.	0.01	2 or 5
15	T_{cold}^{min}	Min. cold storage temp.	K	cont.	495	650
16	$N_{r,tb}$	Receiver number of tubes		discr.	1	$+\infty$
17	t_r	Receiver insulation thickness	m	cont.	0.01 or 0.1	2 or 5
18	d_r	Receiver tubes inner diameter	m	cont.	0.005	0.1
19	D_r	Receiver tubes outer diameter	m	cont.	0.005 or 0.0055 or 0.006	0.1

All variables: Steam generator and powerblock

#	Symbol	Quantity	Unit	Type	Lower bound	Upper bound
20	S_t	Tubes spacing	m	cont.	0.006 or 0.007	0.2
21	L_{sg}	Tubes length	m	cont.	0.5	10
22	d_{sg}	Tubes inner diameter	m	cont.	0.005	0.1
23	D_{sg}	Tubes outer diameter	m	cont.	0.006	0.1
24	$H_{sg,baf}$	Baffles cut		cont.	0.15	0.4
25	$N_{sg,baf}$	Number of baffles		discr.	2	$+\infty$
26	$N_{sg,tb}$	Number of tubes		discr.	1	$+\infty$
27	$N_{sg,sh,p}$	Number of shell passes		discr.	1	10
28	$N_{sg,tb,p}$	Number of tube passes		discr.	1	9
29	ST	Type of turbine		cat.	1	8

Types of constraints

$$\min_{\mathbf{x}\in\mathcal{X}} \quad F(\mathbf{x}) \text{ s.t. } \mathbf{x} \in \Omega = \{\mathbf{x} \in \mathcal{X} : c_j(\mathbf{x}) \leq 0, j = 1, 2, \ldots, m\}$$

Following the taxonomy of constraints [Le Digabel and Wild, 2015]:

- $\mathcal{X}$ describes bounds on the variables and the discrete nature of some of the variables. These constraints are unrelaxable
- The m constraints in Ω may be of type a priori or simulation
- a priori constraints are also considered unrelaxable. In case of violation, the solar executable returns a flag to indicate a potential solver not to count the evaluation
- Most of the a priori constraints are linear
- simulation constraints are relaxable
- solar includes hidden constraints
- All constraints (except the hidden ones) are quantifiable

The following slide lists all 18 possible constraints. Each instance considers a subset of these constraints, for a maximum of $m = 17$ constraints in solar9

All possible constraints

- 7 a priori constraints:
  1. Tower is at least twice as high as heliostats (linear)
  2. Min. distance from tower $\leq$ Max. distance from tower (linear)
  3. Receiver inside diameter $\leq$ outside diameter (linear)
  4. Steam generator outer tubes diameter $\leq$ tubes spacing (linear)
  5. Steam generator inside diameter $\leq$ steam generator outside diameter (linear)
  6. Field surface area
  7. Number of tubes in receiver fit inside receiver
- 11 simulation constraints:
  1. Cost of plant $\leq$ budget
  2. Check that the heliostats can fit in the field
  3. Molten salt melting point $\leq$ hot storage lowest temperature
  4. Molten salt melting point $\leq$ steam generator outlet temperature
  5. Receiver outlet temperature $\geq$ steam turbine inlet temperature
  6. Compliance to demand (stochastic)
  7. Pressure in receiver tubes $\leq$ yield pressure (stochastic)
  8. Molten salt melting point $\leq$ cold storage lowest temperature (stoch.)
  9. Check if storage is back to initial conditions (stochastic)
  10. Parasitics do not exceed a % of energy production (stochastic)
  11. Minimal acceptable energy production (stochastic)

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Getting started with solar

- Get the code at https://github.com/bbopt/solar and compile

- Command-line program that takes as arguments
  - a problem id (or instance number) in $\{1, 2, \ldots, 10\}$
  - the name of a file containing the coefficients of a point $\mathbf{x}$

  and displays the values of $F(\mathbf{x})$ and the $c_j(\mathbf{x})$'s

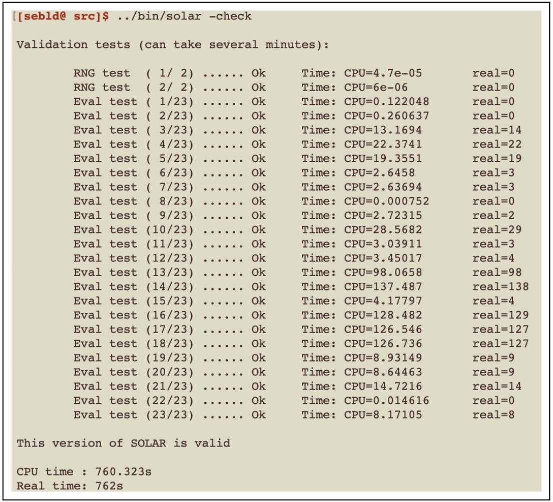
- Example: `> solar 6 x.txt` displays `f c1 c2 ... c6`

  (objective and six constraints)

- Simply executing `> solar` will guide the user and display the options, including a complete inline help with `> solar -help`

Check the solar installation

```
> solar -check
```



```
[[sebld@ src]$ ../bin/solar -check

Validation tests (can take several minutes):

        RNG test  ( 1/ 2) ...... Ok     Time: CPU=4.7e-05       real=0
        RNG test  ( 2/ 2) ...... Ok     Time: CPU=6e-06         real=0
        Eval test ( 1/23) ...... Ok     Time: CPU=0.122048      real=0
        Eval test ( 2/23) ...... Ok     Time: CPU=0.260637      real=0
        Eval test ( 3/23) ...... Ok     Time: CPU=13.1694       real=14
        Eval test ( 4/23) ...... Ok     Time: CPU=22.3741       real=22
        Eval test ( 5/23) ...... Ok     Time: CPU=19.3551       real=19
        Eval test ( 6/23) ...... Ok     Time: CPU=2.6458        real=3
        Eval test ( 7/23) ...... Ok     Time: CPU=2.63694       real=3
        Eval test ( 8/23) ...... Ok     Time: CPU=0.000752      real=0
        Eval test ( 9/23) ...... Ok     Time: CPU=2.72315       real=2
        Eval test (10/23) ...... Ok     Time: CPU=28.5682       real=29
        Eval test (11/23) ...... Ok     Time: CPU=3.03911       real=3
        Eval test (12/23) ...... Ok     Time: CPU=3.45017       real=4
        Eval test (13/23) ...... Ok     Time: CPU=98.0658       real=98
        Eval test (14/23) ...... Ok     Time: CPU=137.487       real=138
        Eval test (15/23) ...... Ok     Time: CPU=4.17797       real=4
        Eval test (16/23) ...... Ok     Time: CPU=128.482       real=129
        Eval test (17/23) ...... Ok     Time: CPU=126.546       real=127
        Eval test (18/23) ...... Ok     Time: CPU=126.736       real=127
        Eval test (19/23) ...... Ok     Time: CPU=8.93149       real=9
        Eval test (20/23) ...... Ok     Time: CPU=8.64463       real=9
        Eval test (21/23) ...... Ok     Time: CPU=14.7216       real=14
        Eval test (22/23) ...... Ok     Time: CPU=0.014616      real=0
        Eval test (23/23) ...... Ok     Time: CPU=8.17105       real=8

This version of SOLAR is valid

CPU time : 760.323s
Real time: 762s
```

Typical execution times (for one replication)

	$\mathbf{x}_0$	$\mathbf{x}^\star$
solar1	0 sec	14 sec
solar2	15 sec	20 sec
solar3	3 sec	3 sec
solar4	3 sec	4 sec
solar5	2 min	2 min
solar6	4 sec	2 min
solar7	5 sec	5 sec
solar8	9 sec	
solar9	4 sec	

We observe an impact of the following factors on the execution time: violation of a priori constraints (instantaneous), violation of simulation constraints, number of heliostats

Stochasticity

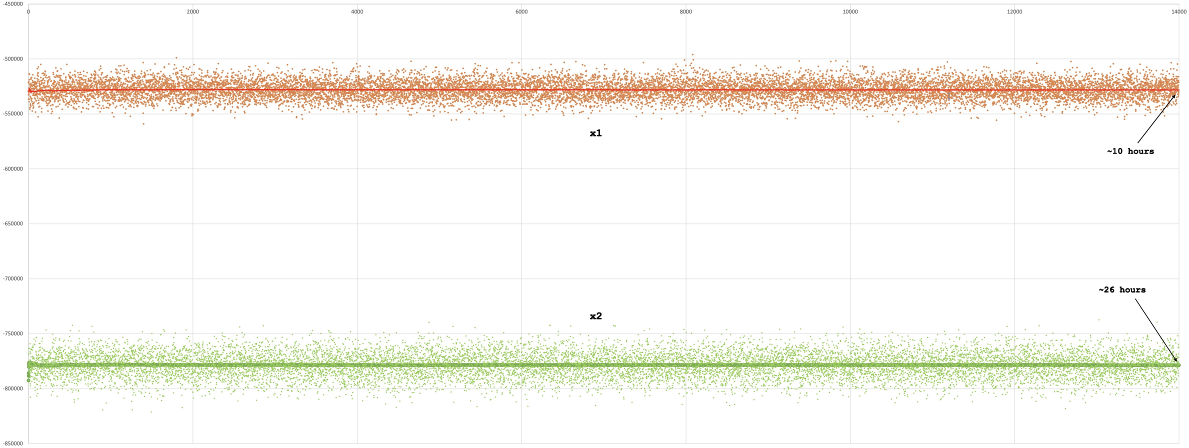
- Stochasticity is due to the Monte Carlo simulation for the heliostats field
- Random seed is set to the same value by default: This corresponds to a deterministic blackbox
- Use the option `-seed` to change the random seed
- The option `-seed=diff` makes the blackbox stochastic
- The option `-rep` executes several simulations and outputs average values
- A high number of replications will tend to decrease stochasticity but will lead to expensive evaluations (which is great in BBO benchmarking)

Illustration of replications for the objective of solar1

```
> solar 1 -rep=14000 x1.txt
```

and

```
> solar 1 -rep=14000 x2.txt
```



Multi-fidelity

- The option `-prec`[3] changes the fidelity of the simulator
- It has been tuned by changing the stopping criteria and precisions in the different numerical methods in the simulator
- Each different value of this option generates a static surrogate
- `-prec=1` corresponds to the “true” blackbox (called the truth)
- This option allows to consider multi-fidelity metamodels or variable precision static surrogates
- Note that using the `-rep` option also allows to consider such surrogates when the truth is considered to be obtained with high number of replications

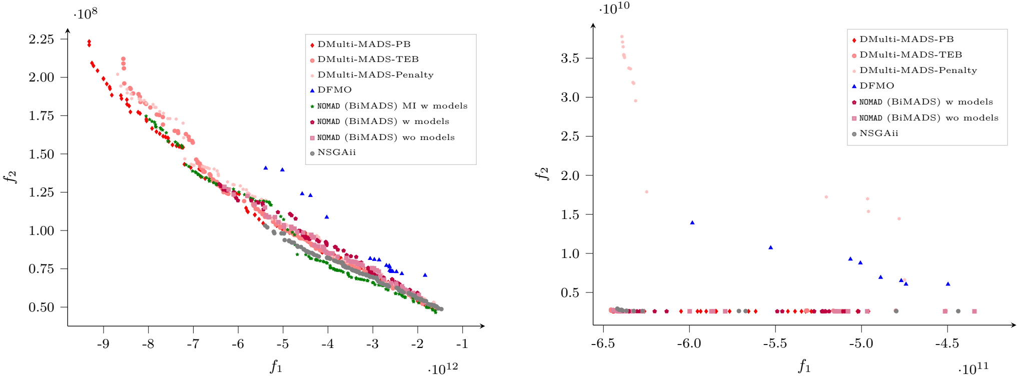
[3] the option will be renamed `-fid` in a future release

Illustration of the multi-fidelity in solar2 with its (infeasible) $\mathbf{x}_0$

prec.	time reduction	c_2	c_3	c_6	c_7	c_8	c_9	c_{10}	c_{13}
0.95	7 (14 sec.)	6	0	0	0.3	0	0	0	0
0.90	13	7	0	0	1	0	0	0	0
0.85	20	4	0	0	0.4	0	0	0	0
0.80	33	0.3	0	0	0.3	0	0	0	0
0.75	33	1	0	0	1	0	0	0	0
0.70	40	6	0	0	2	0	0.1	0	0
0.65	40	12	0	0	3	0	0.2	0	0
0.60	47	26	0	0	4	0	0.3	0	0
0.55	47	23	0	0	5	0	0.3	0	0
0.50	60	18	0	0	3	0	0.3	0	0
0.45	67	13	0	0	0.2	0	0.3	0	0
0.40	73	15	0	0	1	0	0.3	0	0
0.35	73	35	0	0	7	0	0.5	0	0
0.30	73	53	0	0	4	0	0.6	0	0
0.25	80	79	0	0	6	0	0.7	0	0
0.20	80	89	0	0	8	0	0.8	0	0
0.15	87	100	0	0	14	0	0.8	0	0
0.10	93	100	0	0	52	0	0.9	0	0
0.05	100 (0 sec.)	100	0	0	214	0.07	1	0	0

- Values correspond to relative errors with the truth (in %)
- Obj. and a priori constraints are not shown
- Some constraints can be evaluated at no cost
- Others (c_2 and c_7) need the default precision

Biobjective optimization



Pareto front approximations for solar8 (left) and solar9 (right) with different solvers with a budget of 5K evaluations. Taken from [Bigeon et al., 2022]

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