IGBT Cold Plate Multi-parametric Optimization and Co-simulation

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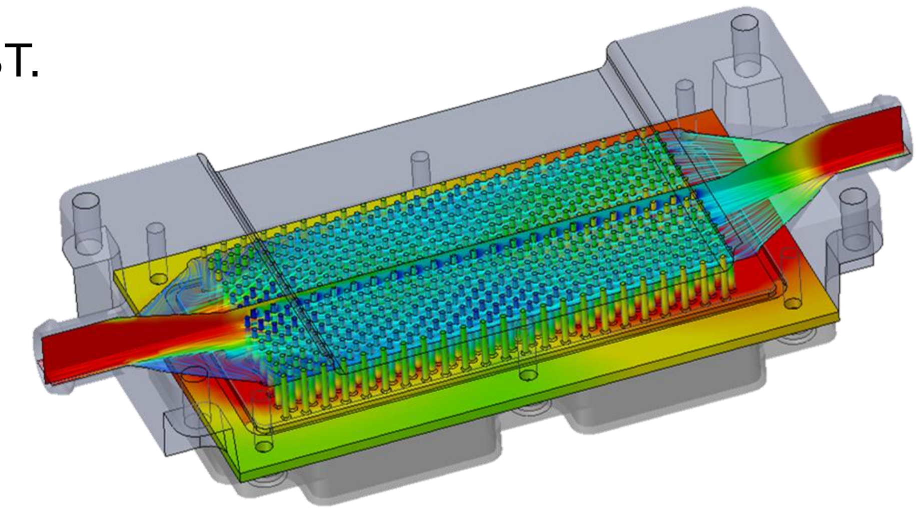
High-power electronics heat exchanger design

Use case demonstrates an IGBT cold plate geometry optimization

IGBT – insulated-gate bipolar transistor, a high-power small-size electronic component.

Applications: electric cars, trains, refrigerators, VFD etc.

Effective cooling is important for normal duty, safety and lifetime of IGBT.



Consider a water-cooled heat exchanger attached to electronic module.

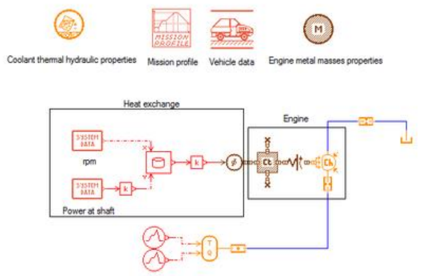
External dimensions of the plate are fixed.

Goal is to find an efficient heat exchanger design with respect to:

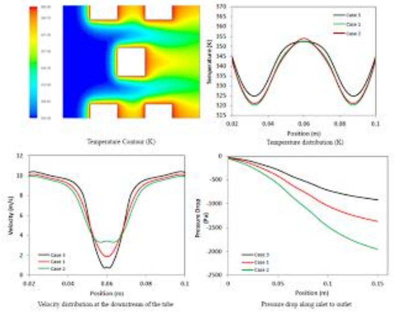
- Maximum temperature – to prevent electronics damage and extend lifetime.
- Flow drag force – for less fan power and battery charge saving.
- Temperature variation – to provide equal lifetime i.e. service interval.

Motivation of the study: design stages

Design and optimization stages



Accuracy ↑
Cost ↑



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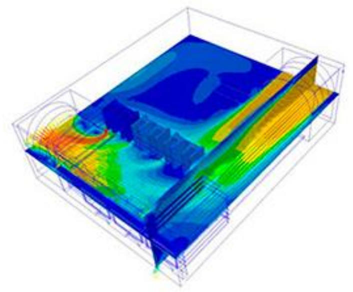


System level :

- Fast models
- All components
- Global optimization

✓ Overall performance
✓ Components balance
✓ Regimes fixing

1D and 2D models:

- Increasing accuracy
- Some physics not considered
- Global to local optimization

✓ Developing the component
✓ Limited interaction with system
✓ Performance and reliability

Detailed 3D models:

- Heavy simulations
- Tiny effects study
- Local optimization

✓ Search for top efficiency
✓ External conditions fixed
✓ Final tuning

Combine for fast and accurate design and optimization?

Simulation and optimization tools features

Problems to be handled:

- Easy setup
- Mesh size vs. small geometry features size (channels etc.).
- Automated and robust meshing for wide range of geometries.
- Reduced simulation time with suitable accuracy.
- Effective optimization algorithms (simulations are still heavy!).

Possible solution – CAD-embedded tools (NX CAE, Creo Simulate, FloEFD etc.)

- Closely integrated with geometry → stable meshing
- 3D simulation
- Accuracy can be a stopper
- Built-in optimization tools have limited efficiency

Simulation tool can be coupled with external optimizer for better efficiency.

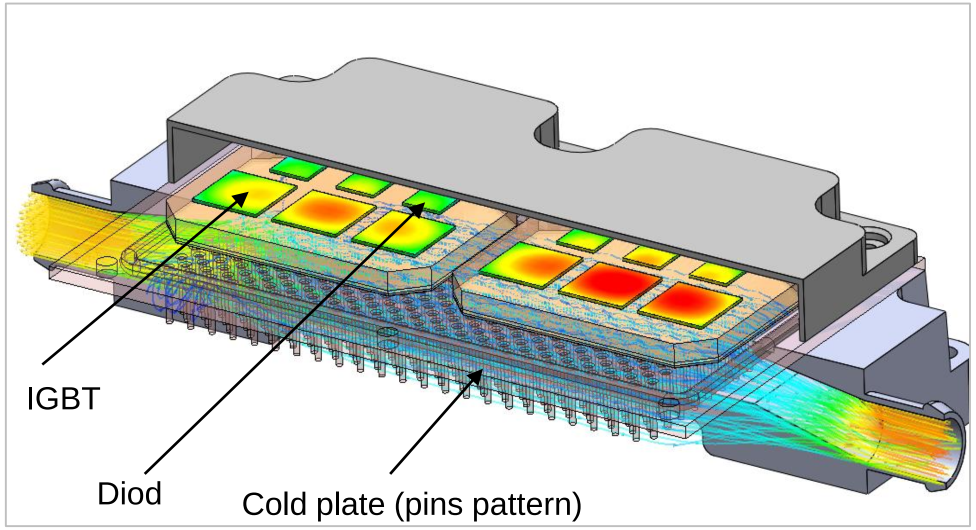
Integration and optimization setup should be smooth and easy.

Cold plate simulation model overview

Model in FloEFD Standalone v.16

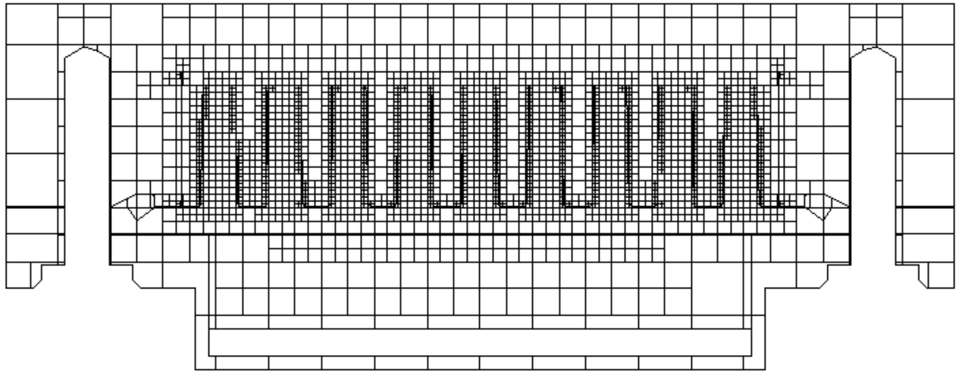
Features:

- Steady water flow
- Heat transfer from sources
- Flow rate and temperature as boundaries
- Parametric pins pattern geometry



Automatic mesh settings:

- ~1.5 million cells total
- ~0.5 million cells in solid
- ~1.5 hour calculation time (on desktop PC)



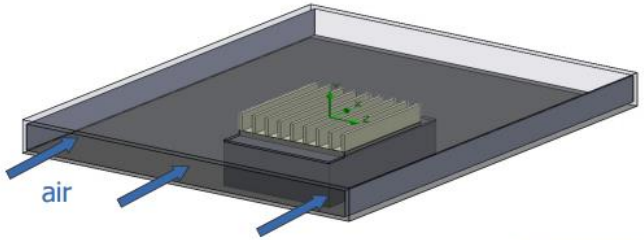
Model provided by Mike Gruetzmacher and colleagues from Mentor Graphics.

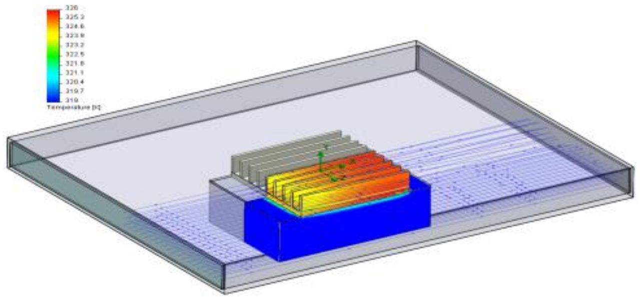
FloEFD benefits for DSE*

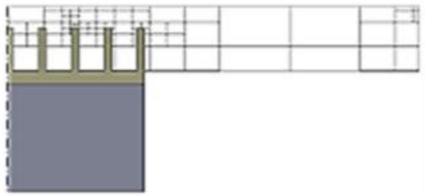
***Design Space Exploration** is a way to *systematically and automatically* explore very large numbers of design alternatives to find *optimal* performance parameters.

FloEFD faces most of the requirements for “fast” 3D in CFD and thermal problems:

- Coupled thermal-fluid solver
- Association with CAD. No “named selection” needed
- Automated and robust meshing
- Typically less detailed mesh required**
- Powerful API
- Automated BRP including particle tracking







Flow velocity	0.9 m/s		1.3 m/s		1.6 m/s		1.9 m/s	
$R_{t\ exp}$, K/W	3.72		3.20		2.91		2.69	
Cells number	3,900	180,000	3,900	180,000	3,900	180,000	3,900	180,000
$R_{t\ calc}$, K/W	3.714	3.77	3.213	3.22	2.969	2.93	2.78	2.70
δ_r, %	**0.2**	**1.3**	**0.4**	**0.6**	**2.0**	**0.7**	**3.3**	**0.3**

** Due to embedded engineering models. For example, “thin channel”- model useful for problems of heat exchanger design. Please, refer to presentation by Mentor Graphics.

Simulation and geometry parameters

Parameters:

Boundary

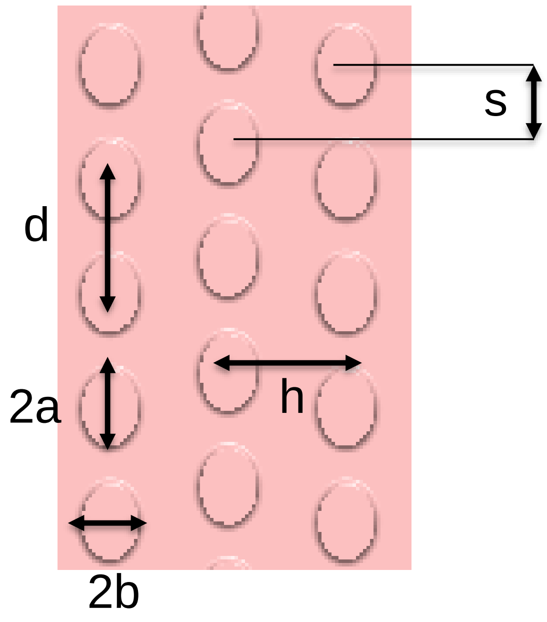
- Inlet flow rate
- Inlet flow temperature

Power

- IGBT heat rate
- Diode heat rate

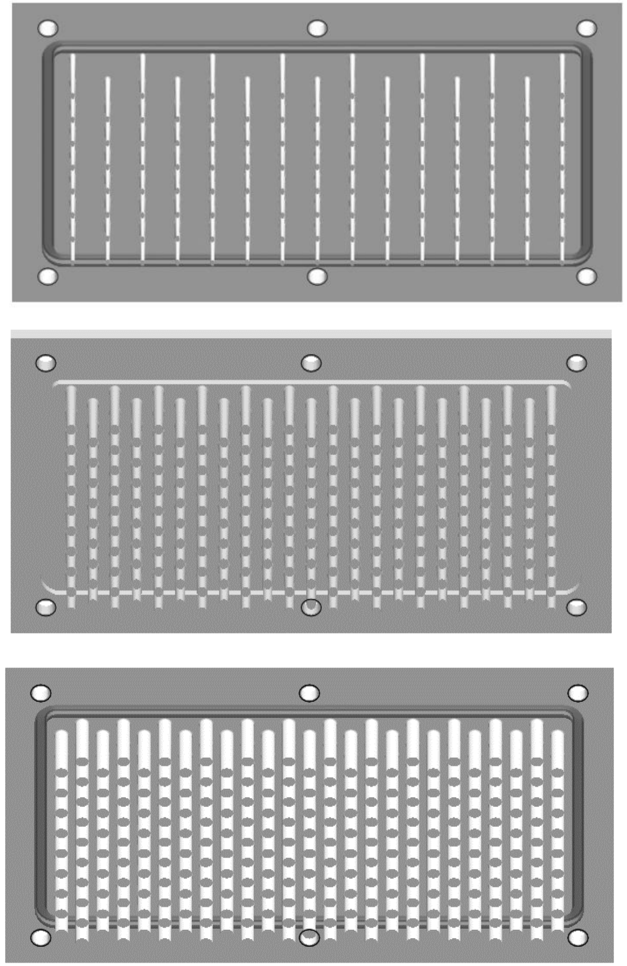
Geometry

- Pins cross section width **a**
- Pins cross section height **b**
- Pins cone angle **c**
- Pins distance in a row **d**
- Shift between rows **s**
- Distance between rows **h**



Obvious constraints:

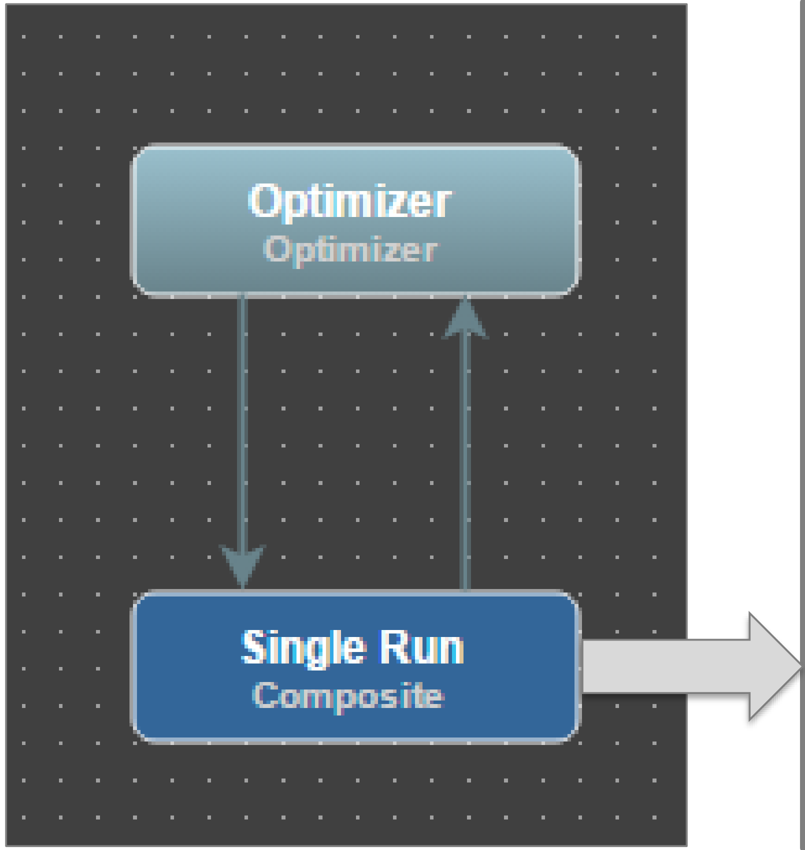
- $2a < d$
- $2b < h$
- $s < d/2$
- $c < \mathrm{arctg}(\min[a,b]/H)$

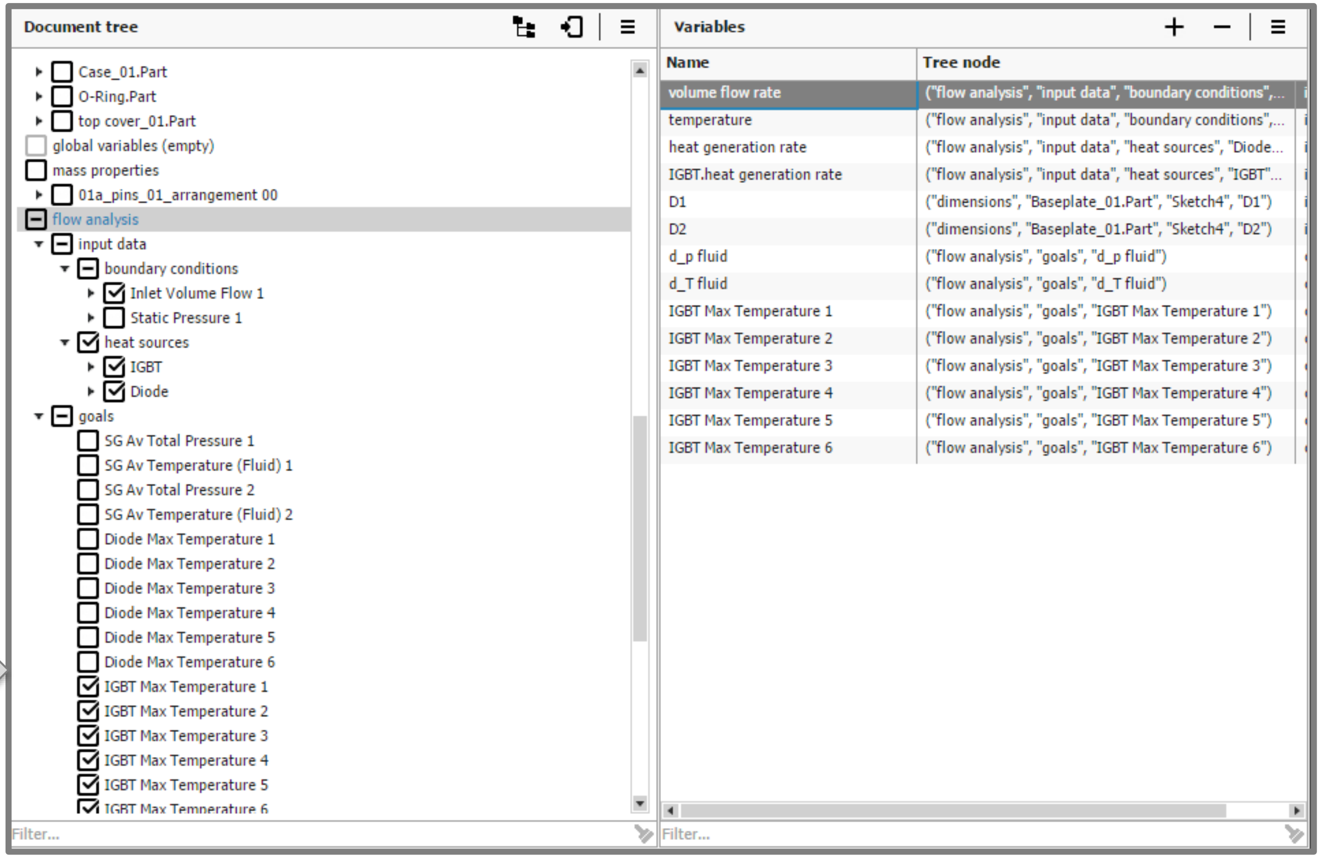


Optimization workflow

pSeven provides full direct integration with FloEFD through API (SW, Creo, NX)

Simple optimization cycle example:





Optimization problem

Parameters and bounds:

Parameter	Description	Lower bound	Upper bound
a	Pin cross section width, mm	0.5	1.6
b	Pin cross section height, mm	0.5	1.6
c	Pin cone angle, deg.	0	2
d	Pins distance in a row, mm	3.5	7
h	Distance between rows, mm	3.5	7
s	Shift between rows, mm	0	3.5

Goals:

Function	Description	Goal
Max T	Maximum temperature at IGBT, C	min
Drag	Fan power characteristics, Pa m3/s	min

Constraints:

Function	Description	Limit
Max dT	Max temperature variation, relative to mean	<0.1

Flow rate = 2 liters/min

Flow temperature = 22^0 C

Diode heat rate = 140 W

IGBT heat rate = 360 W

Two-criterion optimization problem
with time-consuming calculation of responses.

Surrogate-Based Optimization algorithm

pSeven tool is used for automation and optimization.

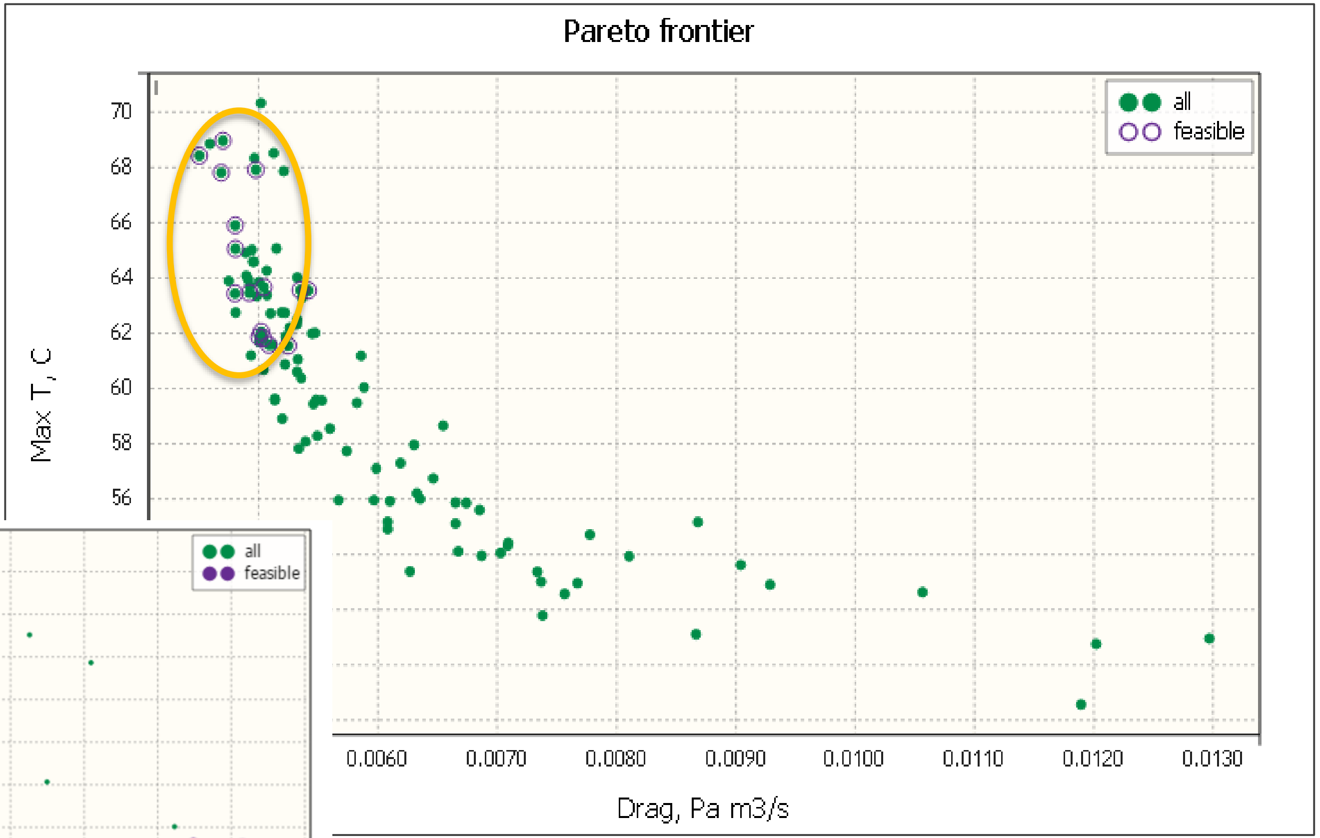
SBO in pSeven allows to set the budget.
Total number of simulations: **120**

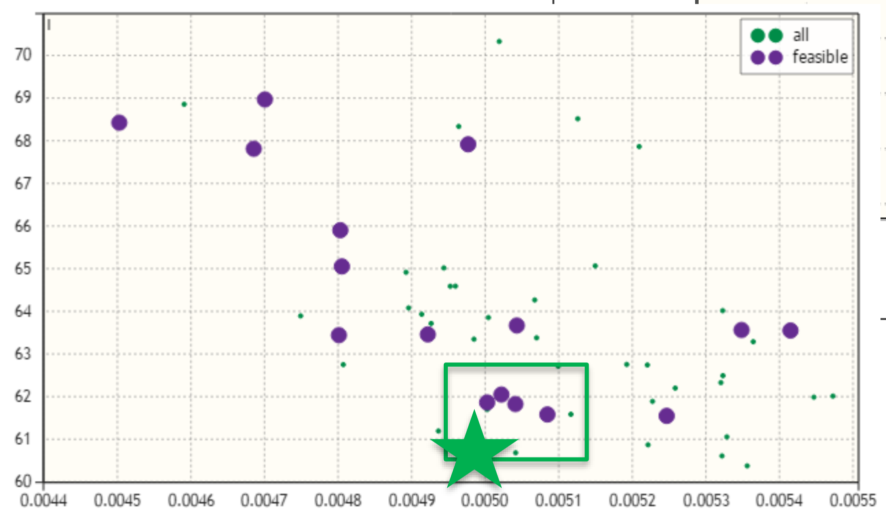
Optimization results: Pareto frontier

With only 120 simulations a Pareto frontier was discovered.

Temperature variation constraint is active and significantly narrows the allowed configurations region.

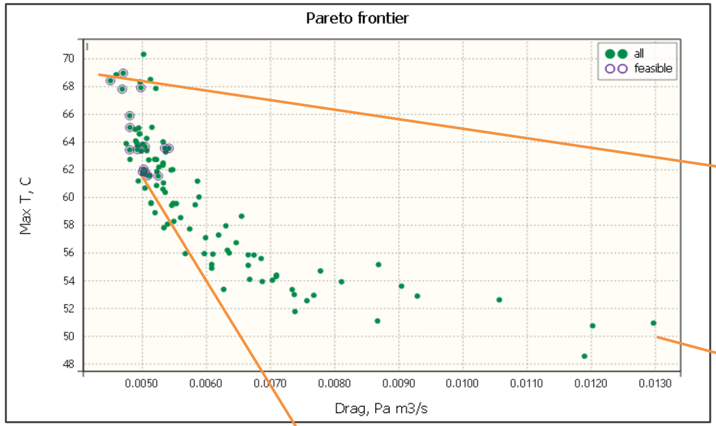
Since all feasible points have very similar drag value, a single optimal configuration can be located.



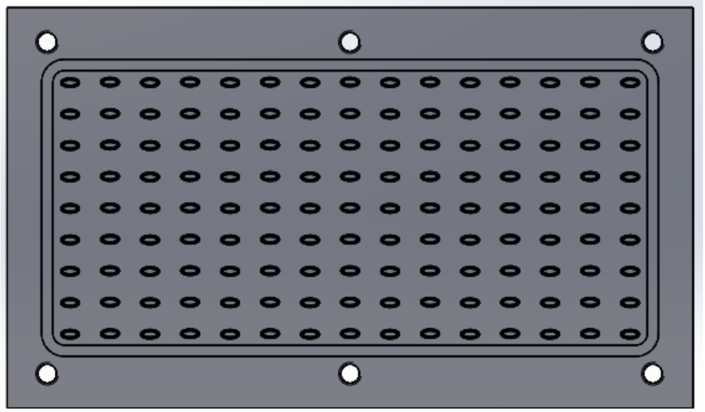


Optimization results: trade-off

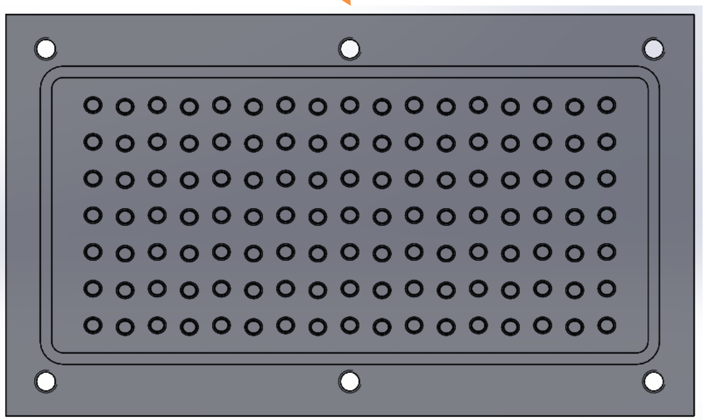
Pareto frontier allows to study possible ‘equivalent’ configurations.
In this case we can even locate a single optimal point with respect to constraint.



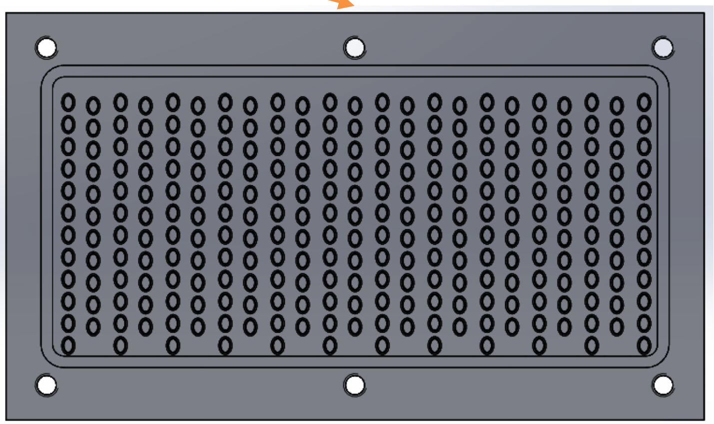
Minimal drag



‘Optimal’



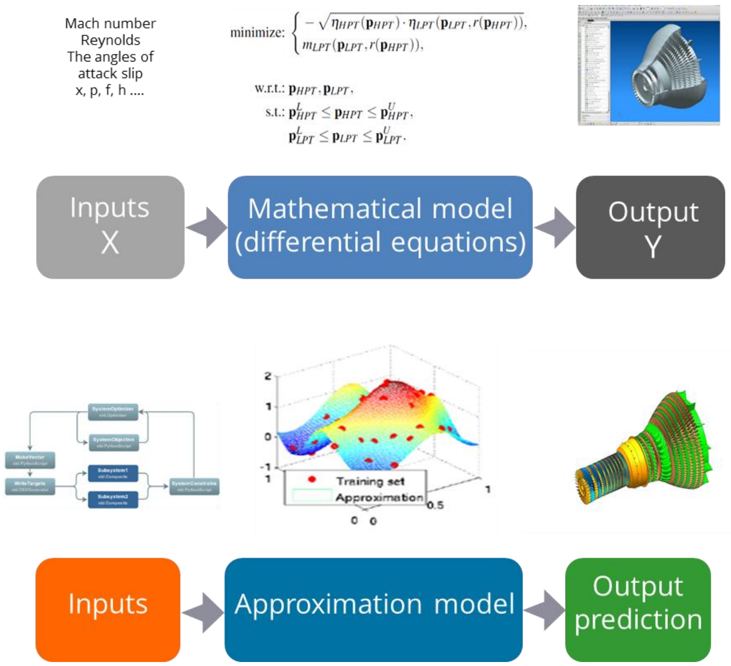
Maximal drag



What else? Approximation models

Approximation models are the **substitution** of existing data and simulation models.

- Predict response function values for new designs.
- Accelerate computation of complex simulation models.
- Use fast surrogate models in parametric and optimization studies.
- Capture essential knowledge from vast amounts of data.
- Export models to create standalone applications (exe) or use in co-simulation.



Once built, approximation models allow to study a variety optimization problems.

Export to FMI helps to use them in system level co-simulation simulations.

DoE parameters

Parameters and bounds:

Parameter	Description	Lower bound	Upper bound
a	Pin cross section width, mm	0.5	1.6
b	Pin cross section height, mm	0.5	1.6
c	Pin cone angle, deg.	0	2
d	Pins distance in a row, mm	3.5	7
h	Distance between rows, mm	3.5	7
s	Shift between rows, mm	0	3.5
flowrate	Inlet flow rate, l/min	0.5	5
flowtemp	Inlet flow temperature, C	22	60
diode power	Diod heat rate, W	100	200
IGBT power	IGBT heat rate, W	300	400

Responses:

Function	Description
Max T	Maximum temperature at IGBT, C
Max dT	Temperature variation, relative to mean
Drag	Fan power characteristics, Pa m3/s

DoE sample generated with OLHC technique.

150* points in the sample.

Simulation time: 1 week

Model built with GP (Gaussian processes) algorithm**:

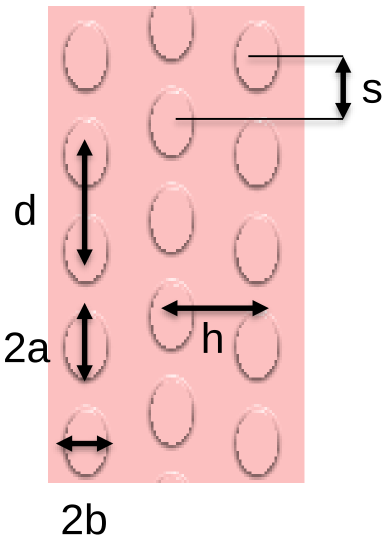
- Efficient for small samples
- Stable to noise
- Error estimation support

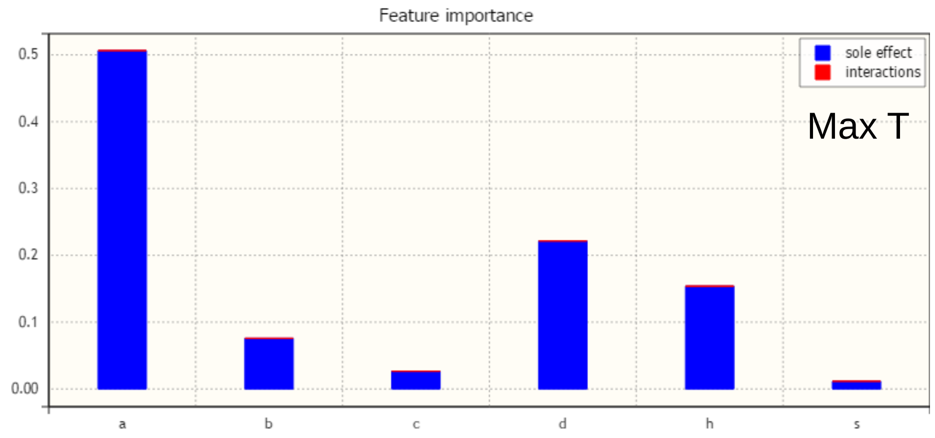
*For demonstration only.
Small sample size can lead to significant inaccuracy of the model.

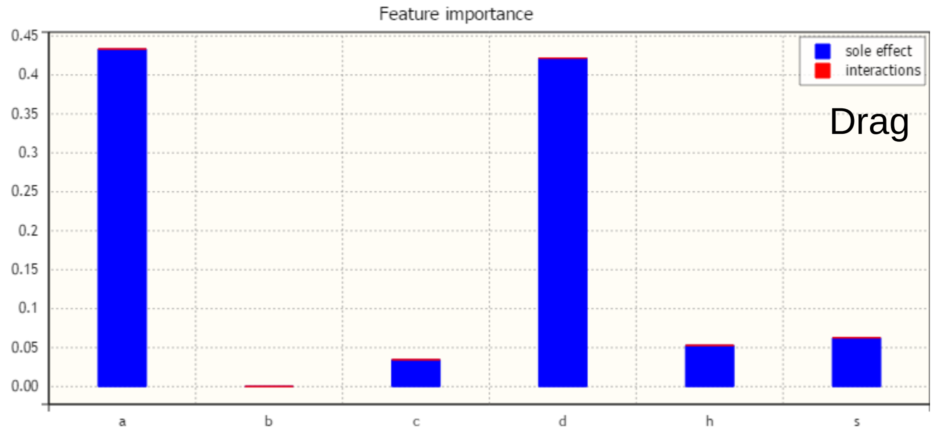
** Automated choice via SmartSelection technique.

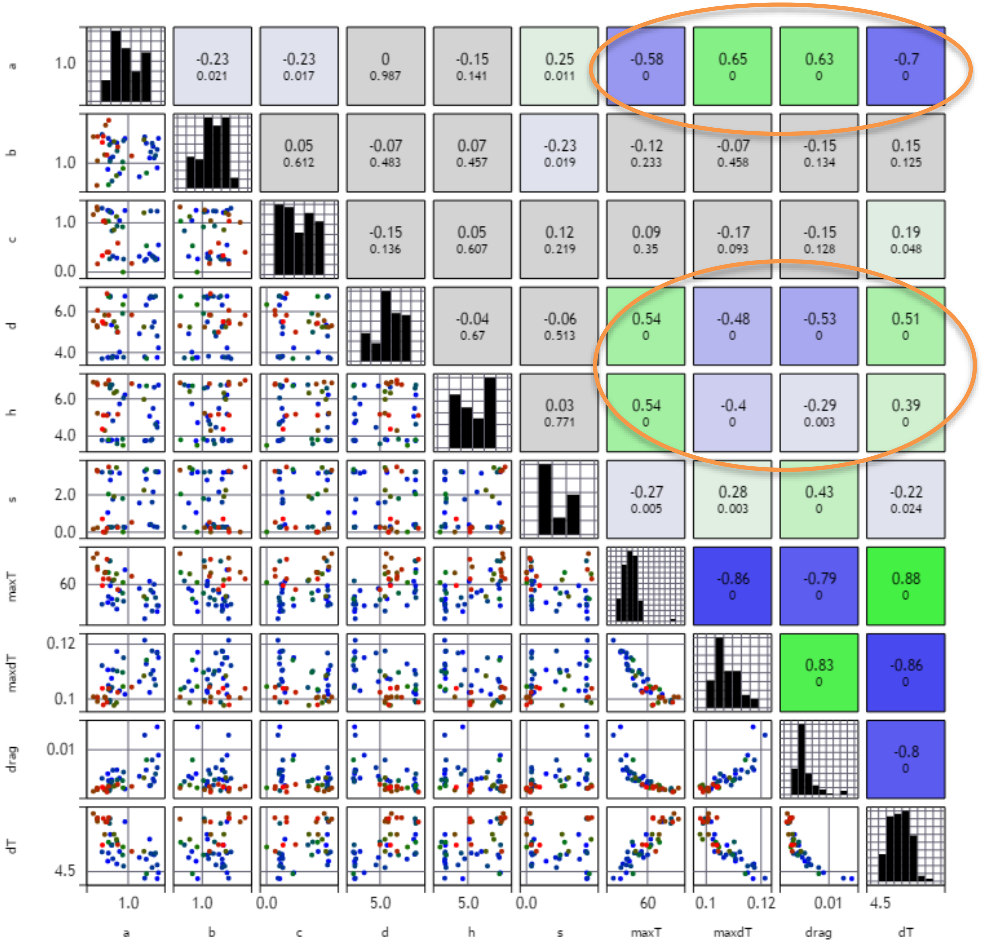
Feature ranking. Fixed flow

Additional correlation analysis of the sample allows to estimate the impact of parameters on model responses. Flow parameters are fixed (22^0 C, 2 liters/min).







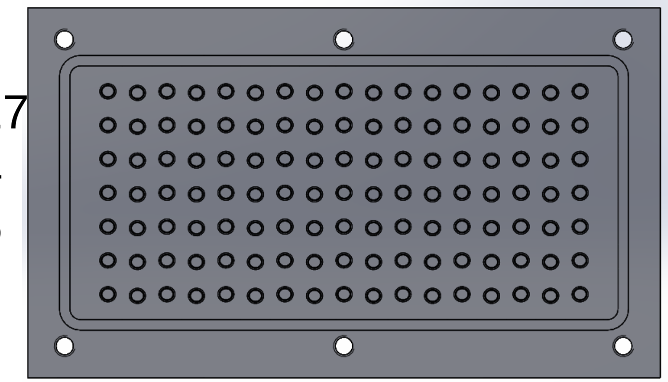


Optimization results: comparison

We can use approximation model to solve the same optimization problem and compare results.

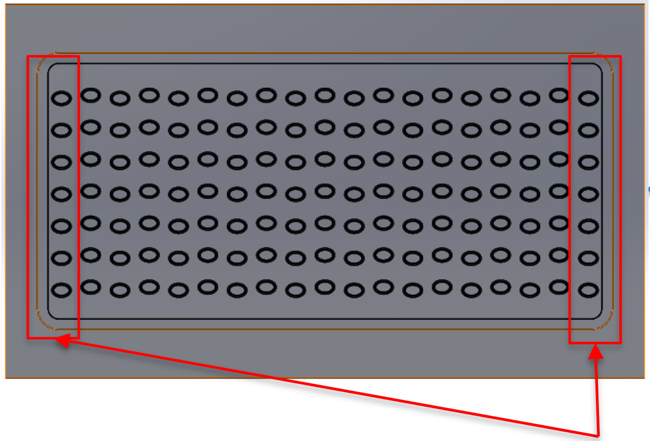
Direct result

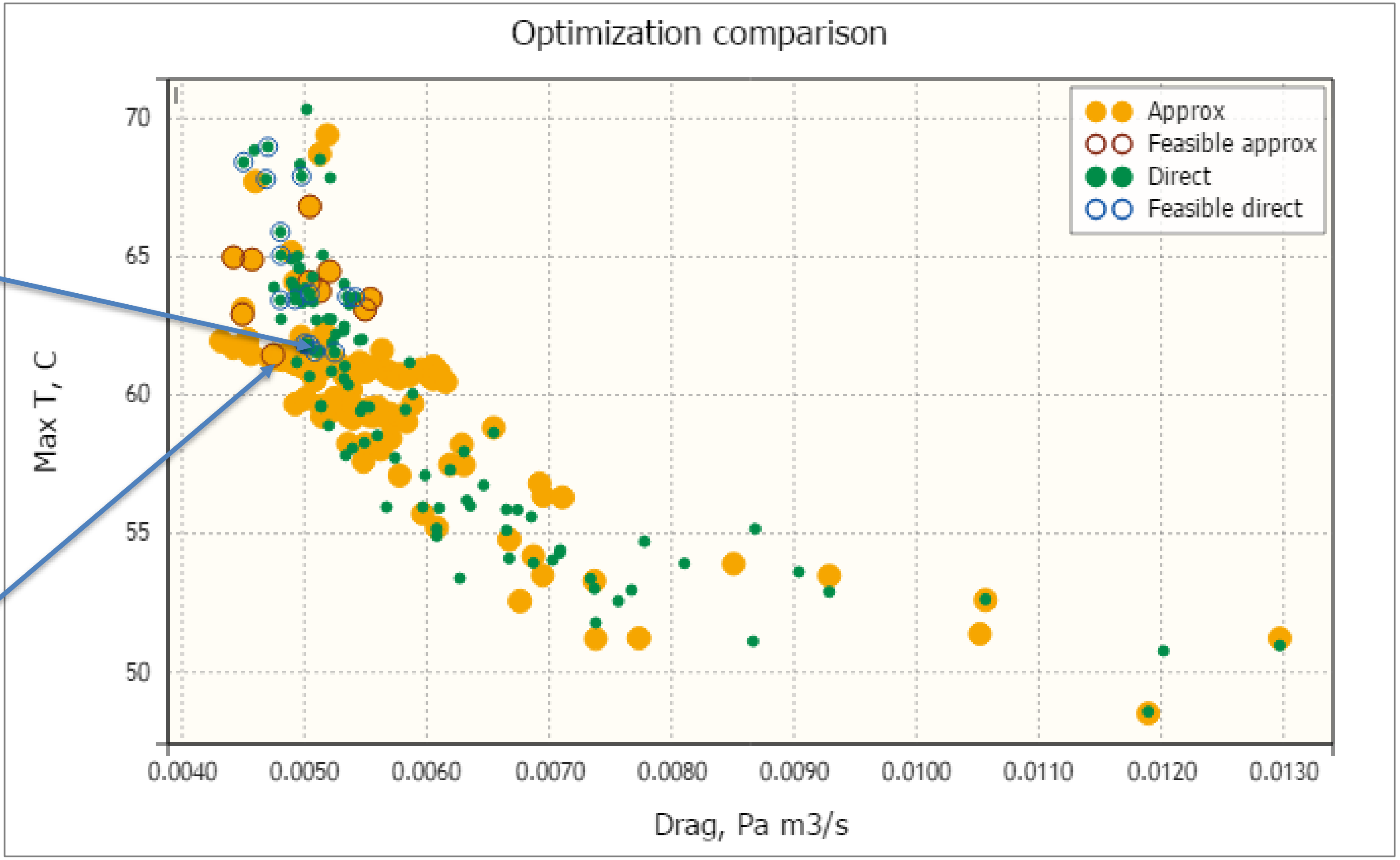
a = 1.17
d = 6.4
h = 5.6



Approx result

a = 1.1
d = 5.9
h = 5.3





Difference in parameters values leads to additional pin rows

Conclusion

- IBGT cold plate design optimization use case considered as an example of frontloading 3D CFD and optimization approach.

- Drag vs. cooling efficiency optimization problem solved with only 120 calculations. Pareto frontier and “optimal” configuration of 6 parameters discovered.

- Approximation model for cold plate performance for different geometries and inlet conditions built. Different optimization problems studied.

- Feature ranking analysis conducted to reveal most important parameters.

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