Combined On-Design and Off-Design Modeling of Aerospace-grade Thermal Systems in Modelica

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Background: Hydrogen Power

- Reduce global warming ⟹ Sustainable aviation
- Solution: Liquid hydrogen (LH_2) + fuel cell
  - Higher efficiency than combustion architectures
  - No NO_x production
  - Silent operation

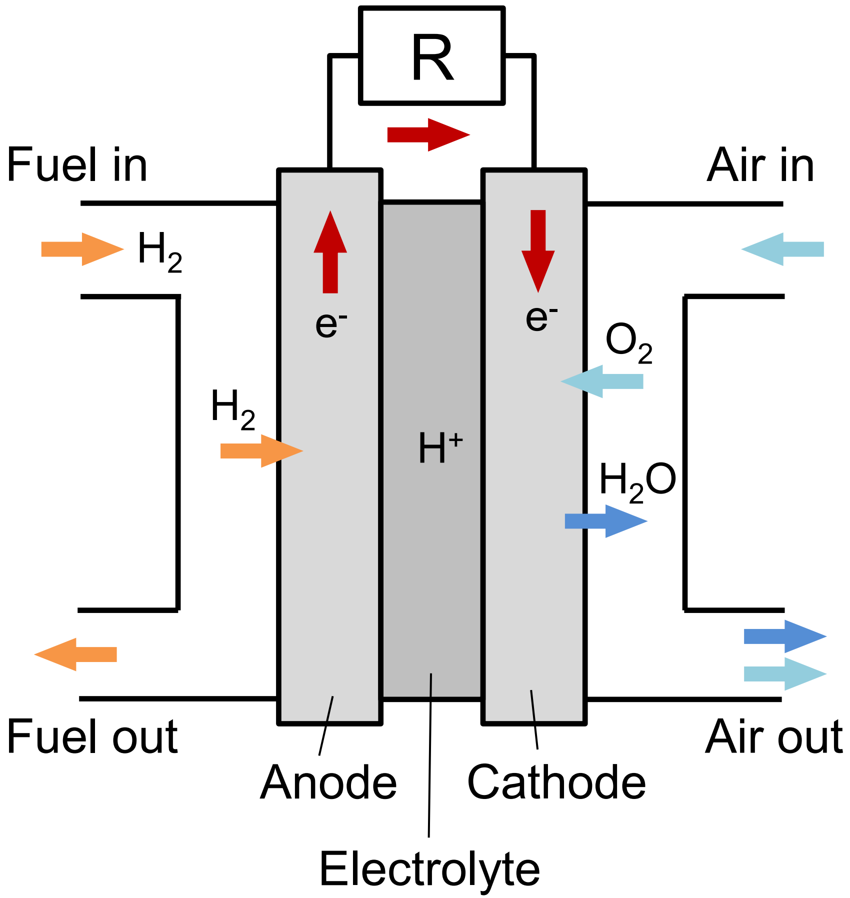
Courtesy of Airbus

Background: Fuel Cell

- Fuel cell operation:
  $2H_2 + O_2 \longrightarrow 2H_2O$
- Oxygen from ambient air

Condition (total*)	Ambient (7.6 km)	Fuel cell
Pressure [barA]	0.447	2
Temperature [°C]	-22.8	90

- Need for air conditioning!

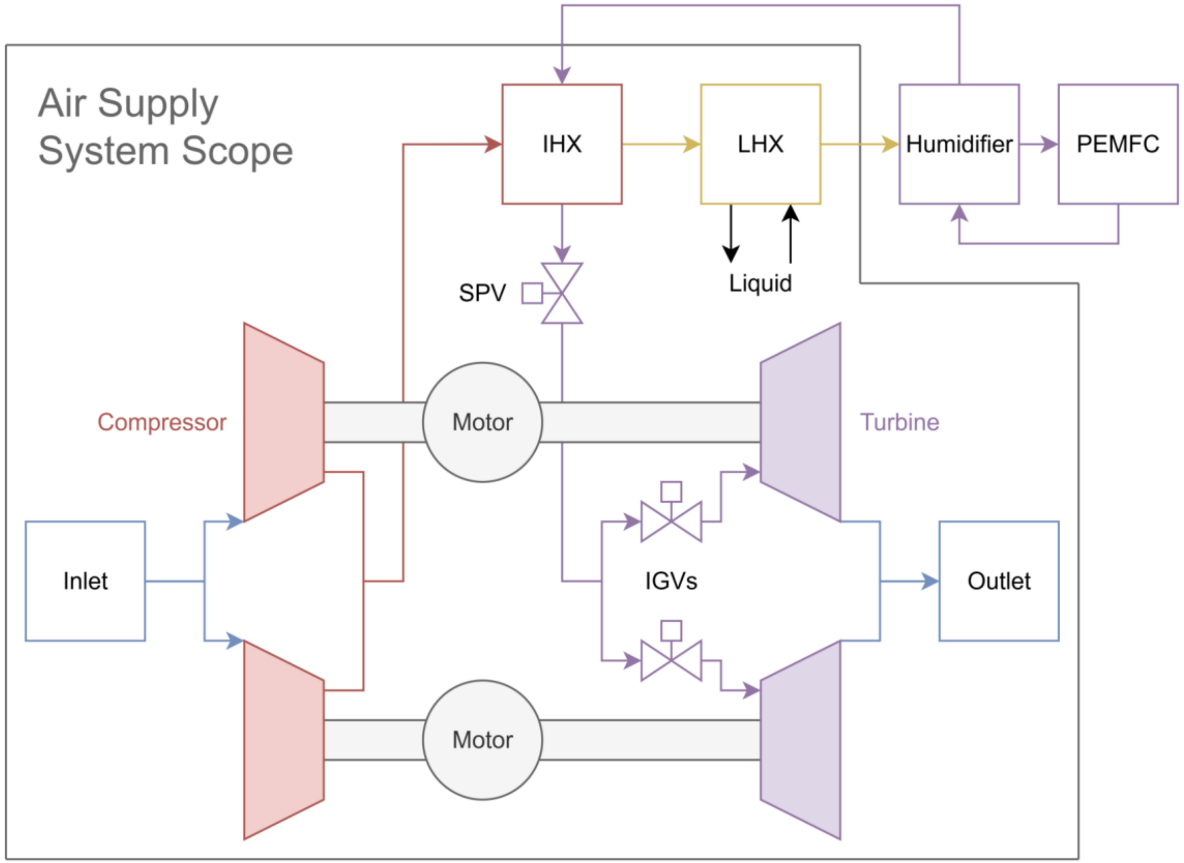


*For a flight speed of M=0.5

Background: Air Supply System

How to model this system?

- 3 analysis types:
  - On-design → Used for sizing
  - Off-design - - - ?
  - Dynamic - - - ?
- Requires integrated design optimization

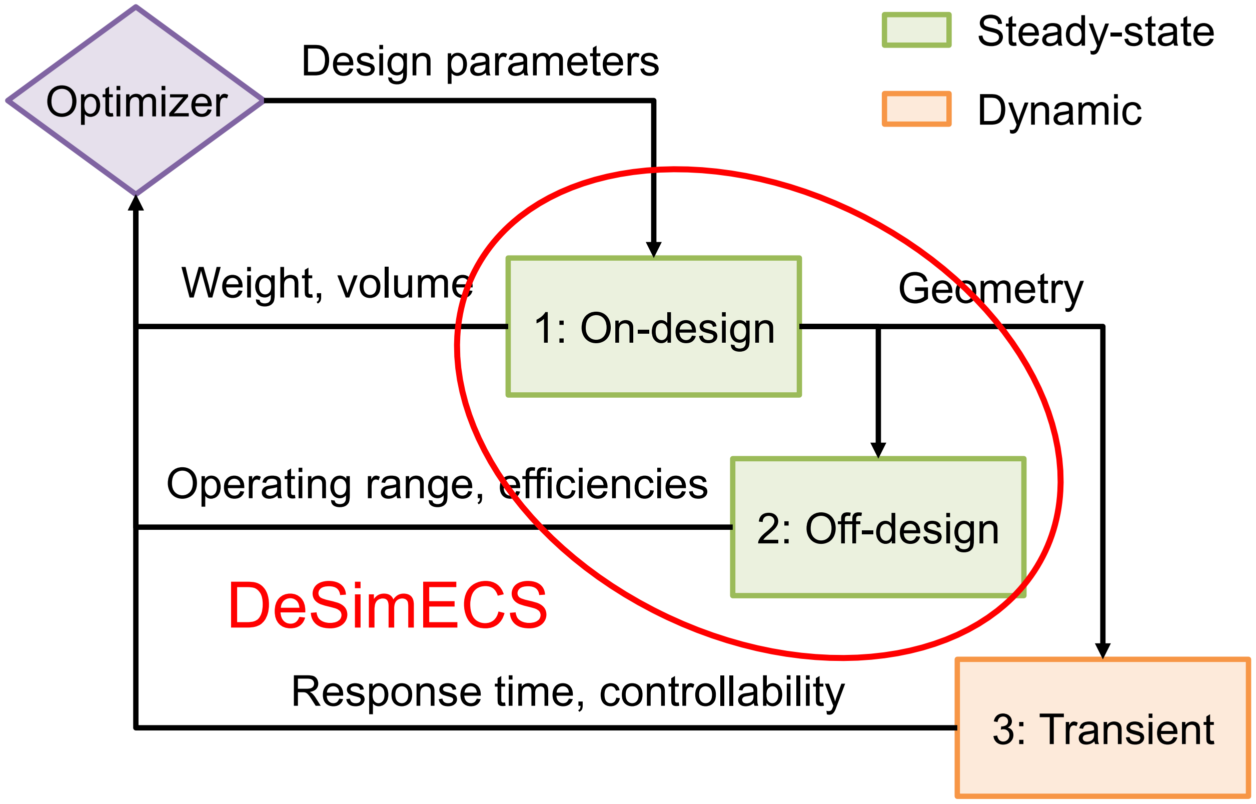


Research Question

"How can the air supply system of a fuel cell be optimized for on-design, off-design, and dynamic requirements in an integrated way?"

Methodology: Optimization Structure

- Sequential approach
- Modularity ⇒ Modelica
- Separate libraries:
  - Library 1: Steady-state
    - On- & off-design combined!
  - Library 2: Dynamic

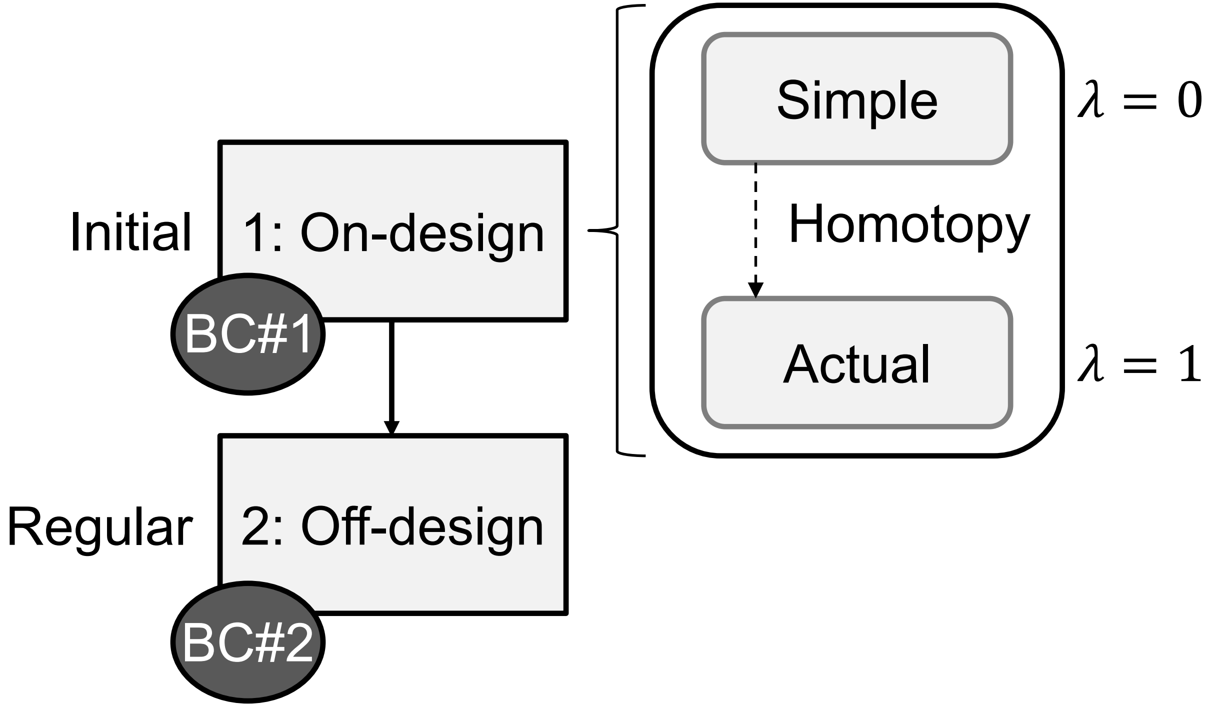


Methodology: DeSimECS

Design & Simulation of Energy Conversion Systems

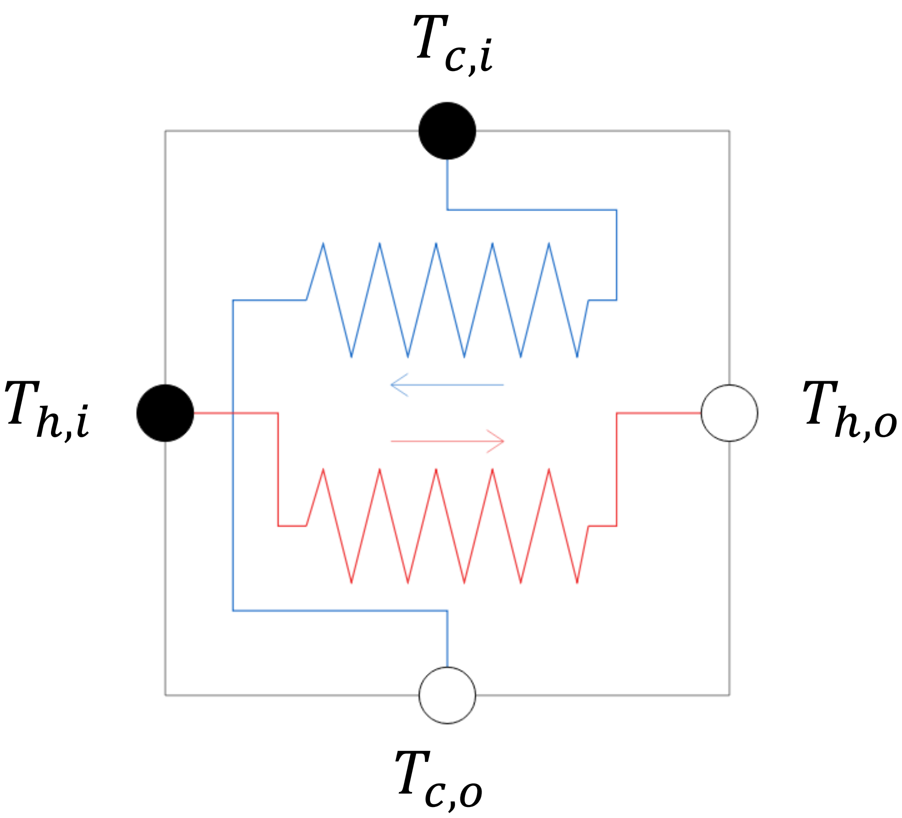
- Modelica implementation:

1. Initial: on-design problem
   - Design/boundary conditions #1
   - Fixed=false parameters
   - Homotopy for improved convergence
2. Regular: off-design problem.
   - Off-design/boundary conditions #2
   - On-design solution as initial guess
   - Quasi-steady-state trajectory



Methodology: DeSimECS

Example: Simple heat exchanger (e-NTU)



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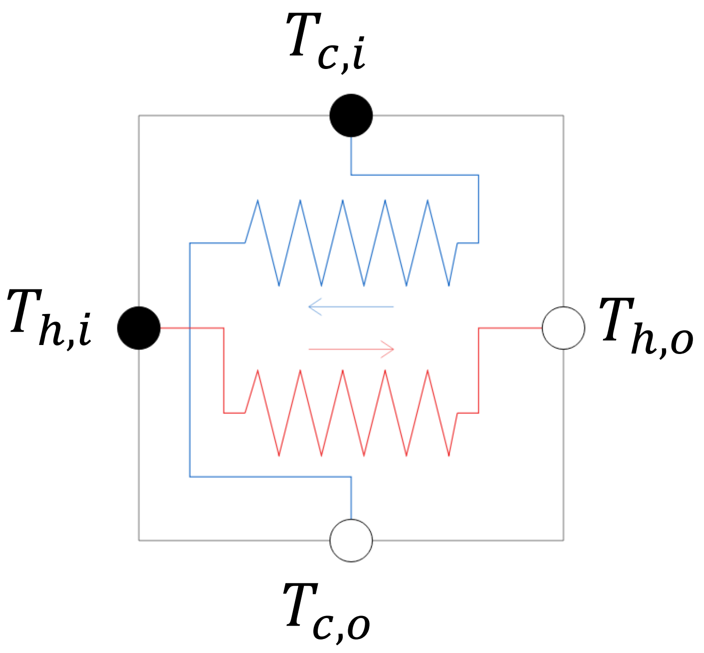
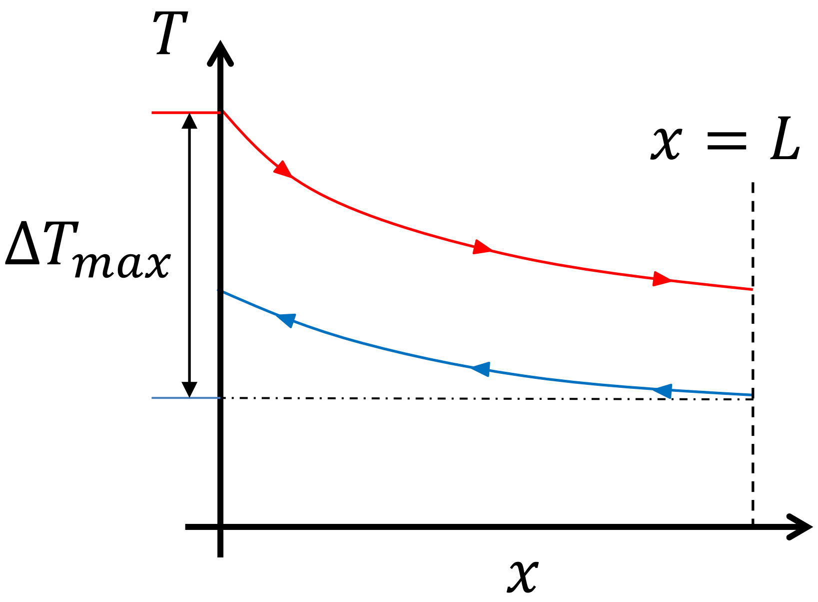




$$T_{max} = T_{h,i} - T_{c,i}$$

$$\dot{Q}_{max} \propto \Delta T_{max}$$

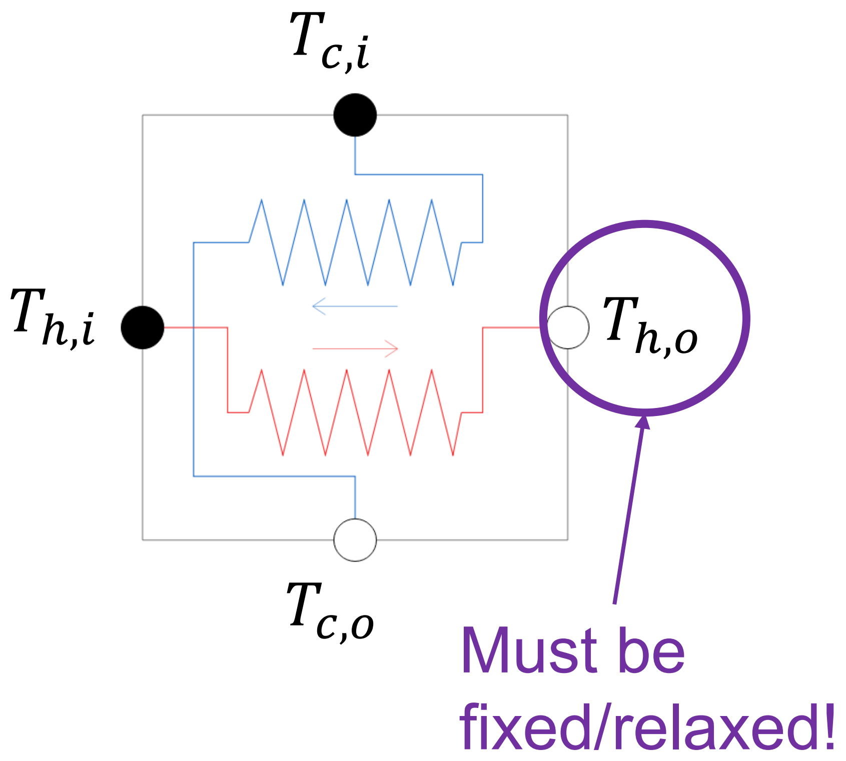
$$\dot{Q} = \varepsilon \dot{Q}_{max}$$
$$\varepsilon = f(L, \dots)$$

$$\dot{Q} \propto \Delta T_h$$
$$\dot{Q} \propto \Delta T_c$$

Methodology: DeSimECS

Example: Simple heat exchanger (e-NTU)

- On-design:
  - Given $T_{h,i}$, $T_{h,o}$, $T_{c,i}$, $(T_{c,o})$
  - Find L
- Off-design:
  - Given L, $T_{h,i}$, $T_{c,i}$
  - Find $T_{h,o}$, $T_{c,o}$



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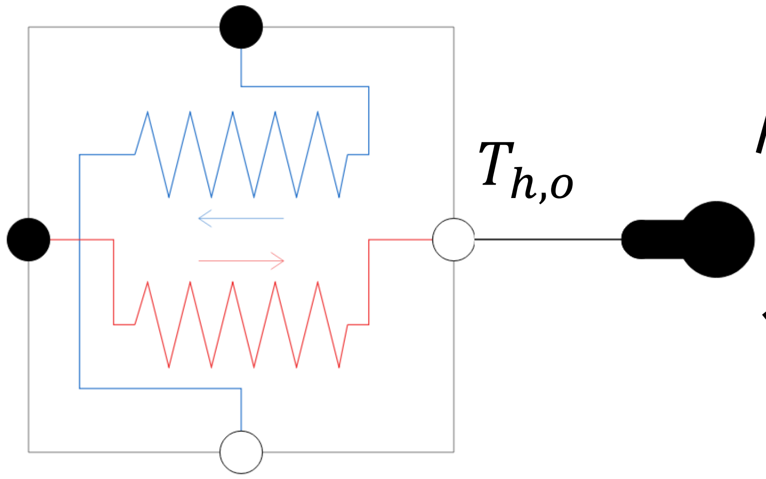
Methodology: DeSimECS

Example: Simple heat exchanger

- Use Boolean parameters to enable/disable boundary conditions
- Works really well with OM!



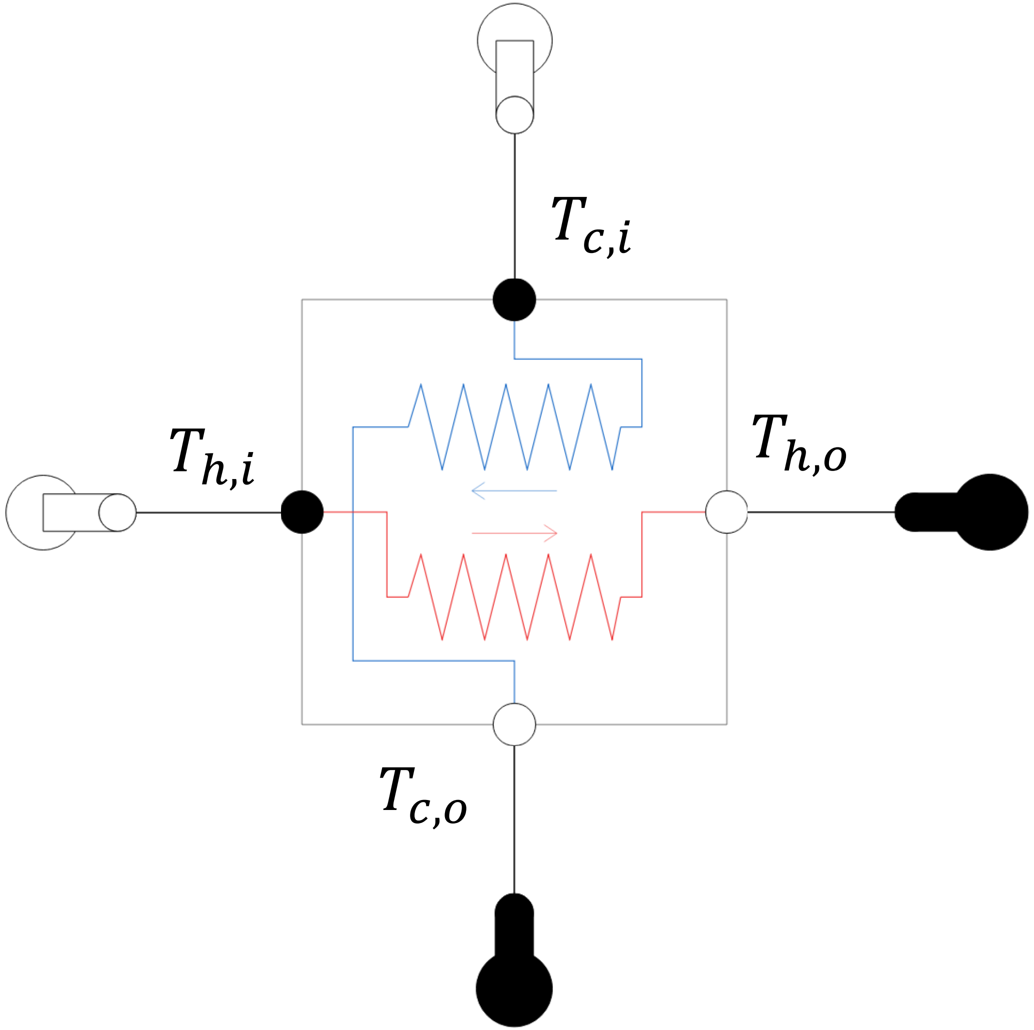

```
block BoundaryConditionSelector
  parameter Boolean initial_constraint;
  parameter Boolean regular_constraint;
  parameter Real ondesign_val;
  input Real offdesign_val;
  output Real value;
  Real v_dummy;
  parameter Real p_dummy(fixed=false);
equation
  value = if initial() then
            (if initial_constraint then
              ondesign_val else p_dummy)
          else
            (if regular_constraint then
              offdesign_val else v_dummy);
  if regular_constraint then
    v_dummy = 0;
  end if;
initial equation
  if initial_constraint then
    p_dummy = 0;
  end if;
  if not regular_constraint then
    v_dummy = 1;
  end if;
end BoundaryConditionSelector;
```

Methodology: DeSimECS

Example: Simple heat exchanger

- Use Boolean parameters to enable/disable boundary conditions
- Works really well with OM!
- Full flexibility for setting up any set of boundary conditions

Easy for this small example…



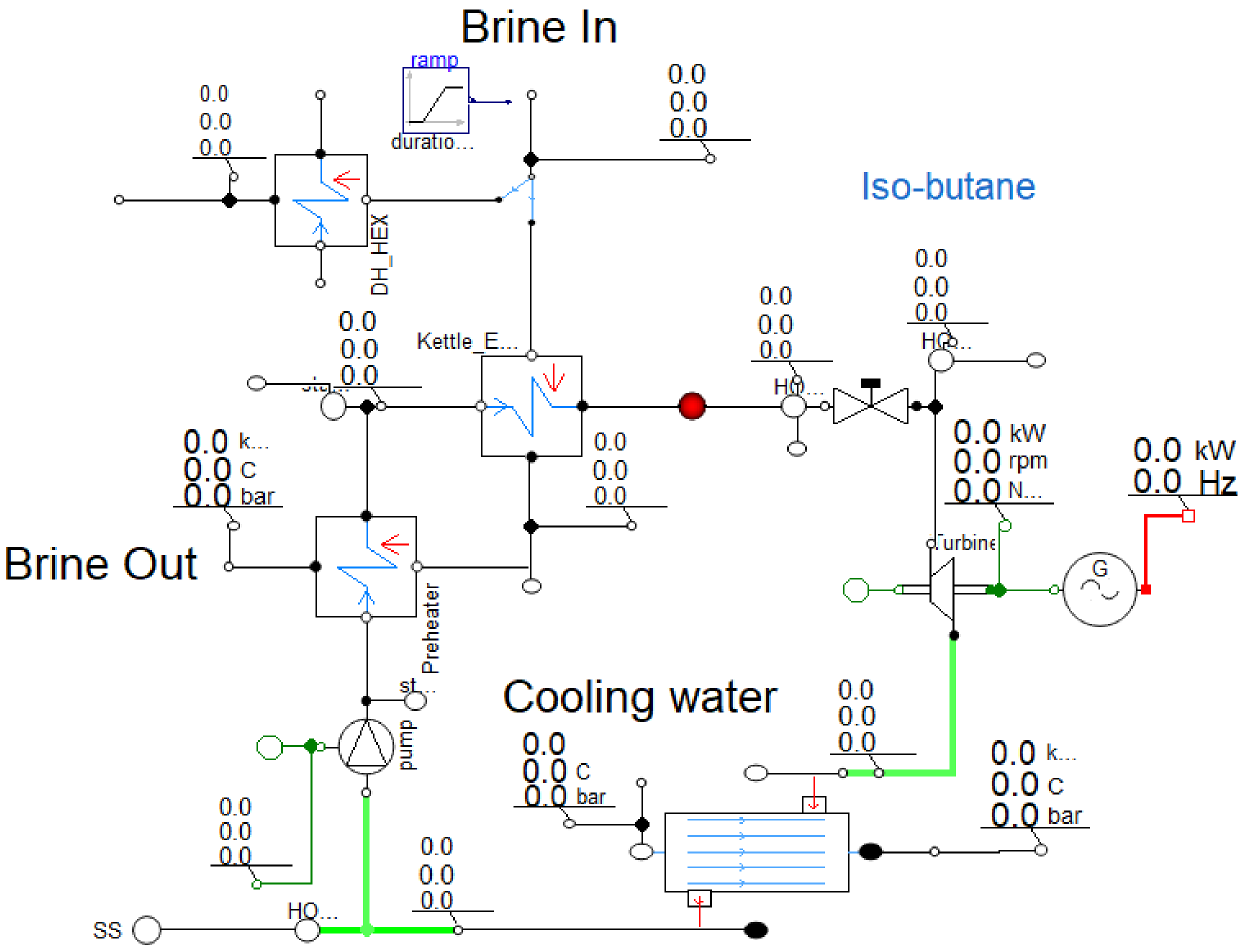
Methodology: DeSimECS

But for large systems…

- How to keep track of where constraining conditions are imposed?

Solution:

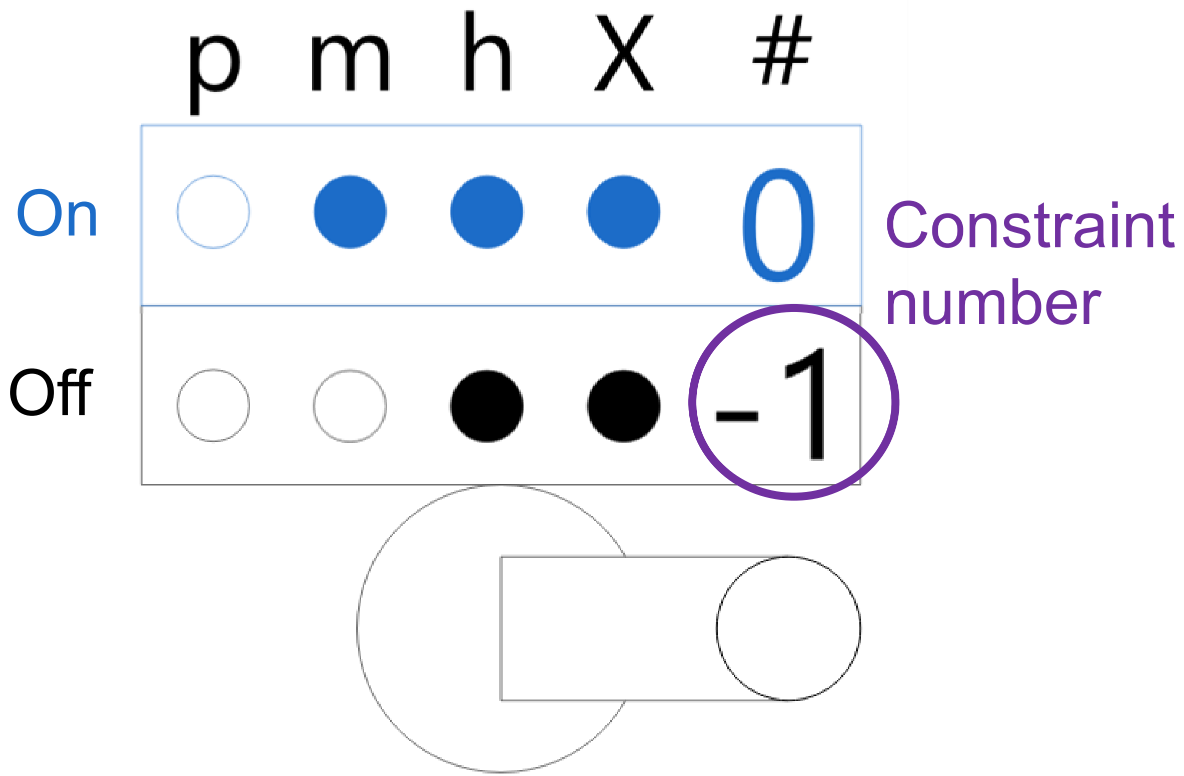
Visualize degrees of freedom in diagram view!



Methodology: DeSimECS

Key idea: “Neutral” constraint configuration

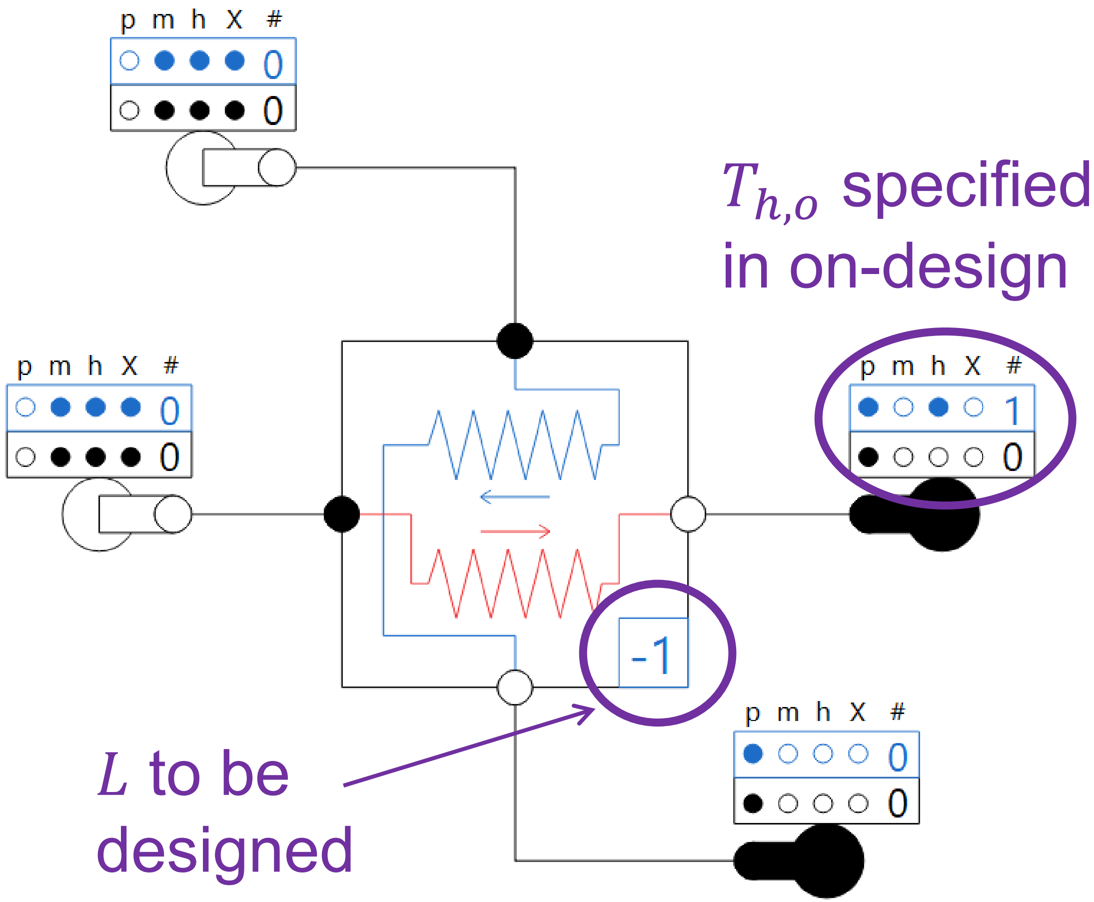
- Components show deviation from neutral within their icon
- Different configuration between on- & off-design



Methodology: DeSimECS

Key idea: "Neutral" constraint configuration

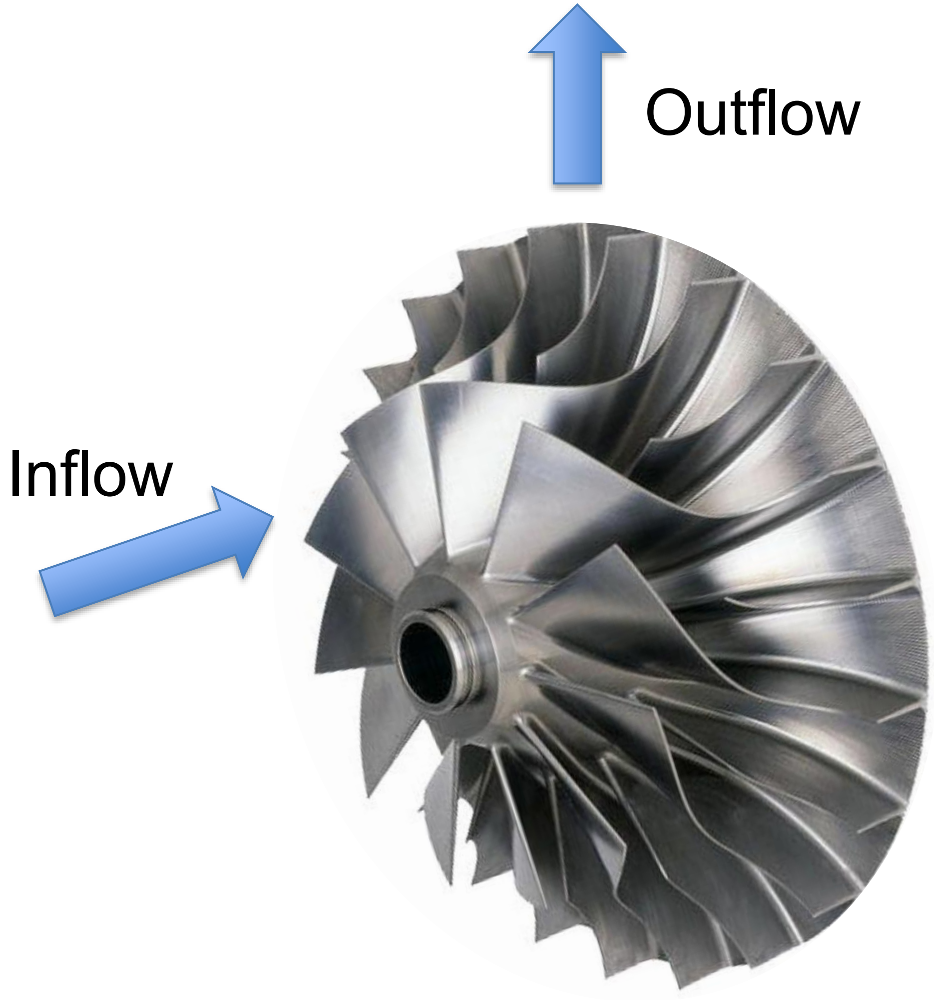
- Components show deviation from neutral within their icon
- Different configuration between on- & off-design
- Summation must equal zero to ensure balance



First Results: Developed Models

Simple heat exchanger

Centrifugal compressor:



source: cnctvar

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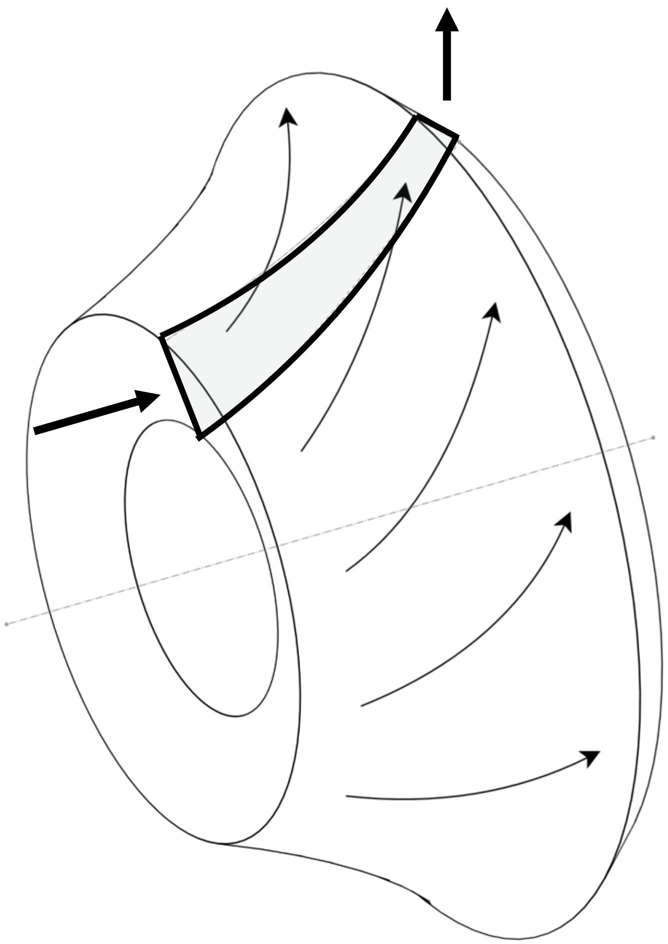

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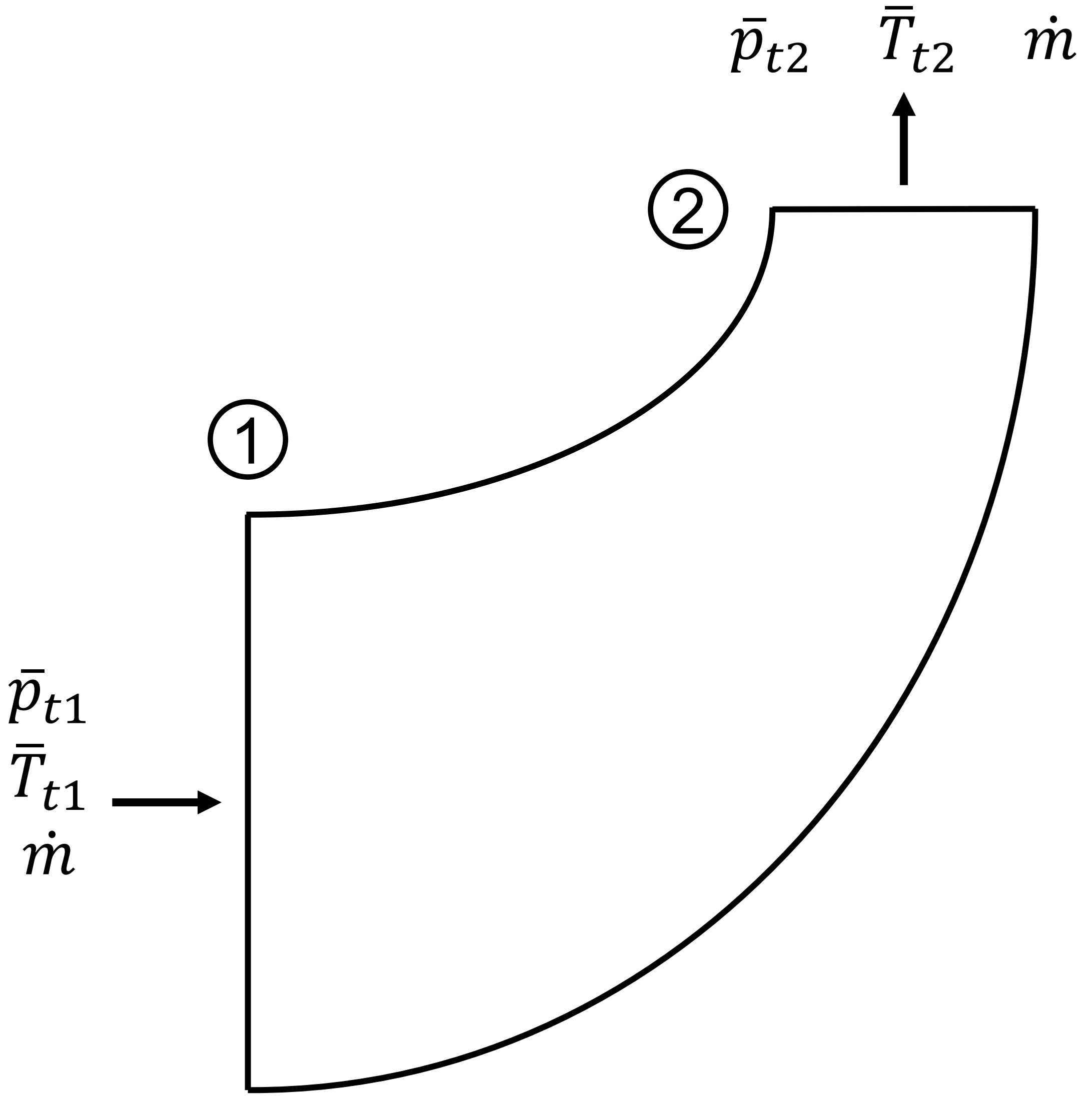
Centrifugal compressor:

- Meanline (0D)
  - Lumped values at boundaries



First Results: Developed Models

Simple heat exchanger

Centrifugal compressor:

- Meanline (0D)
  - Lumped values at boundaries
  - Various loss correlations

Fluid model (p,h)

Velocity triangles

$$\dot{m} = \rho_1 c_{1m} A_1$$

$$\dot{m} = \rho_2 c_{2m} A_2$$

$$h_{t2} - h_{t1} = \Omega \left(R_2 c_{\theta 2} - R_1 c_{\theta 1} \right)$$

$$h_{t2} = h_{t2,is} + \Delta h_{t,loss}$$

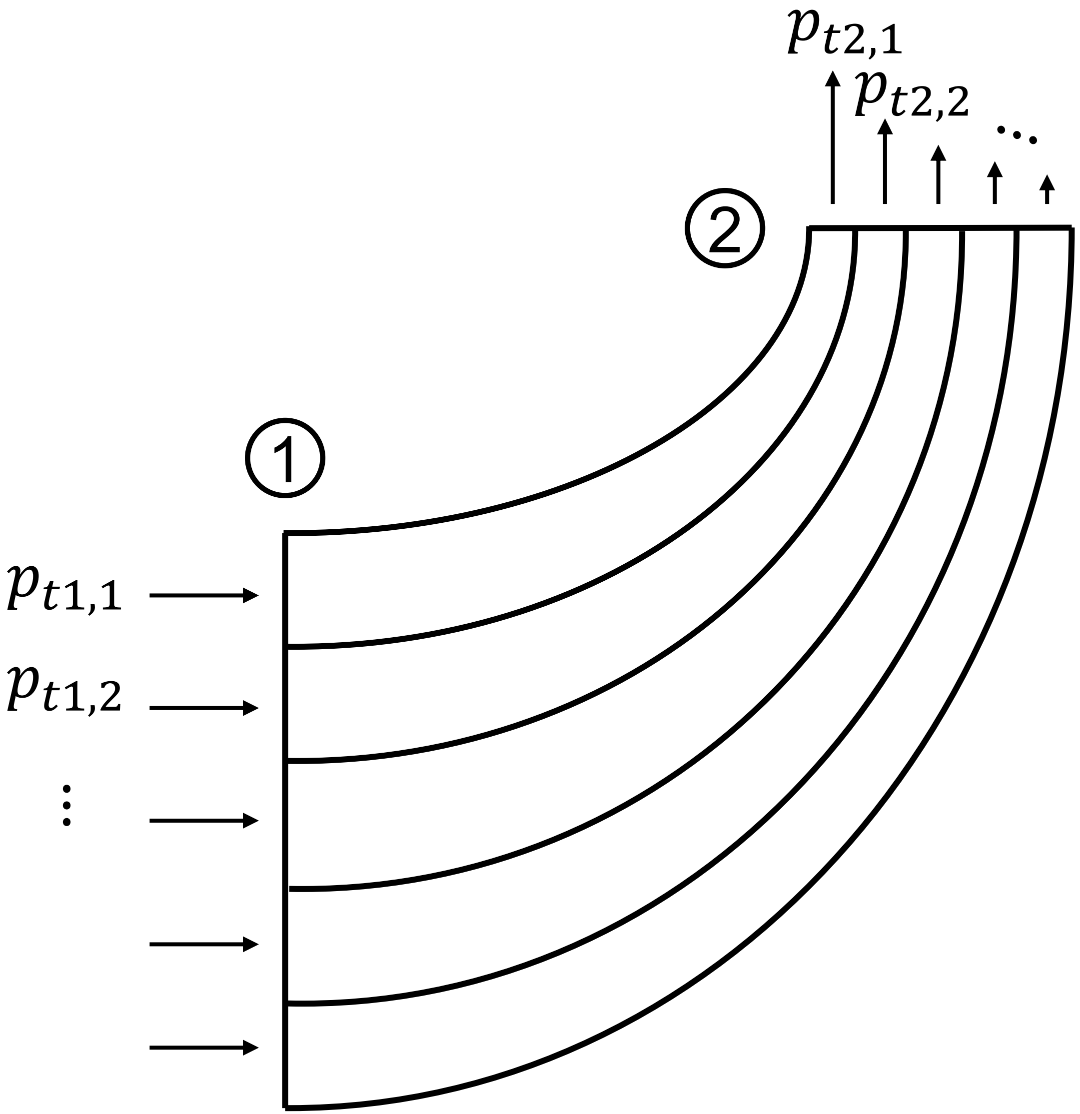
$$\Delta h_{t,loss} = \Delta h_{bl} + \Delta h_{sf} + \cdots$$

First Results: Developed Models

Simple heat exchanger

Centrifugal compressor:

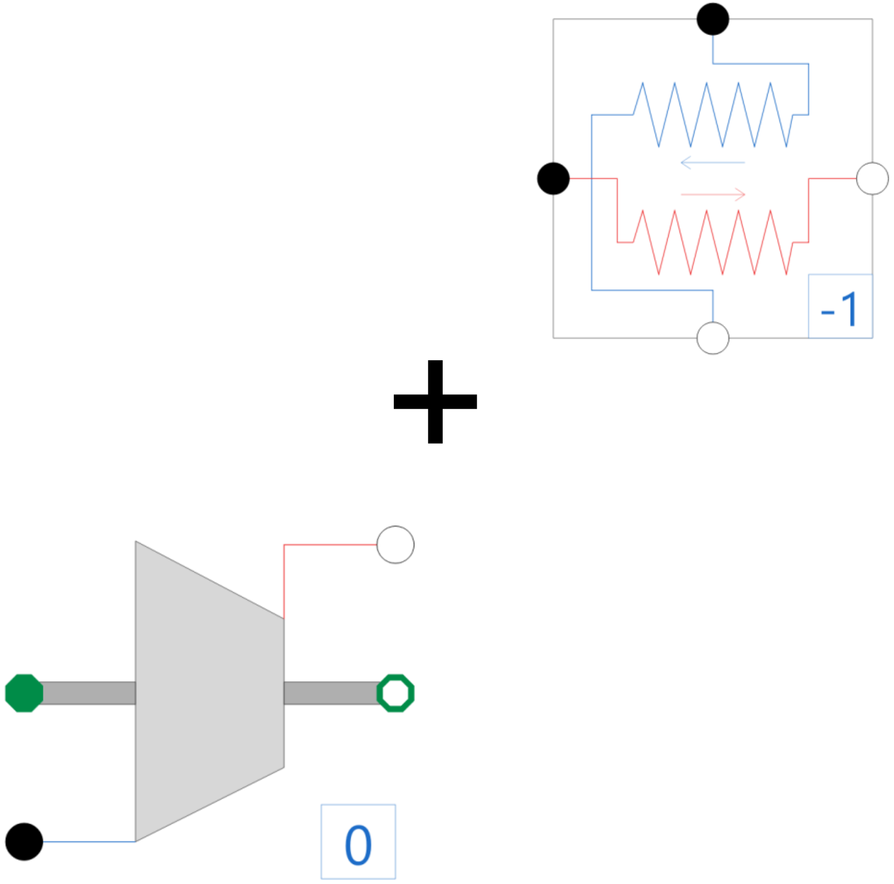
- Meanline (0D)
  - Lumped values at boundaries
  - Various loss correlations
- Multiple non-interacting stream tubes (1D)
  - Under construction...



First Results: Proof of concept

Centrifugal compressor + heat exchanger

1. Determine heat exchanger length to reach desired outlet temperature
   - Compressor design given!
2. Perform off-design analysis to construct compressor speed line at design speed



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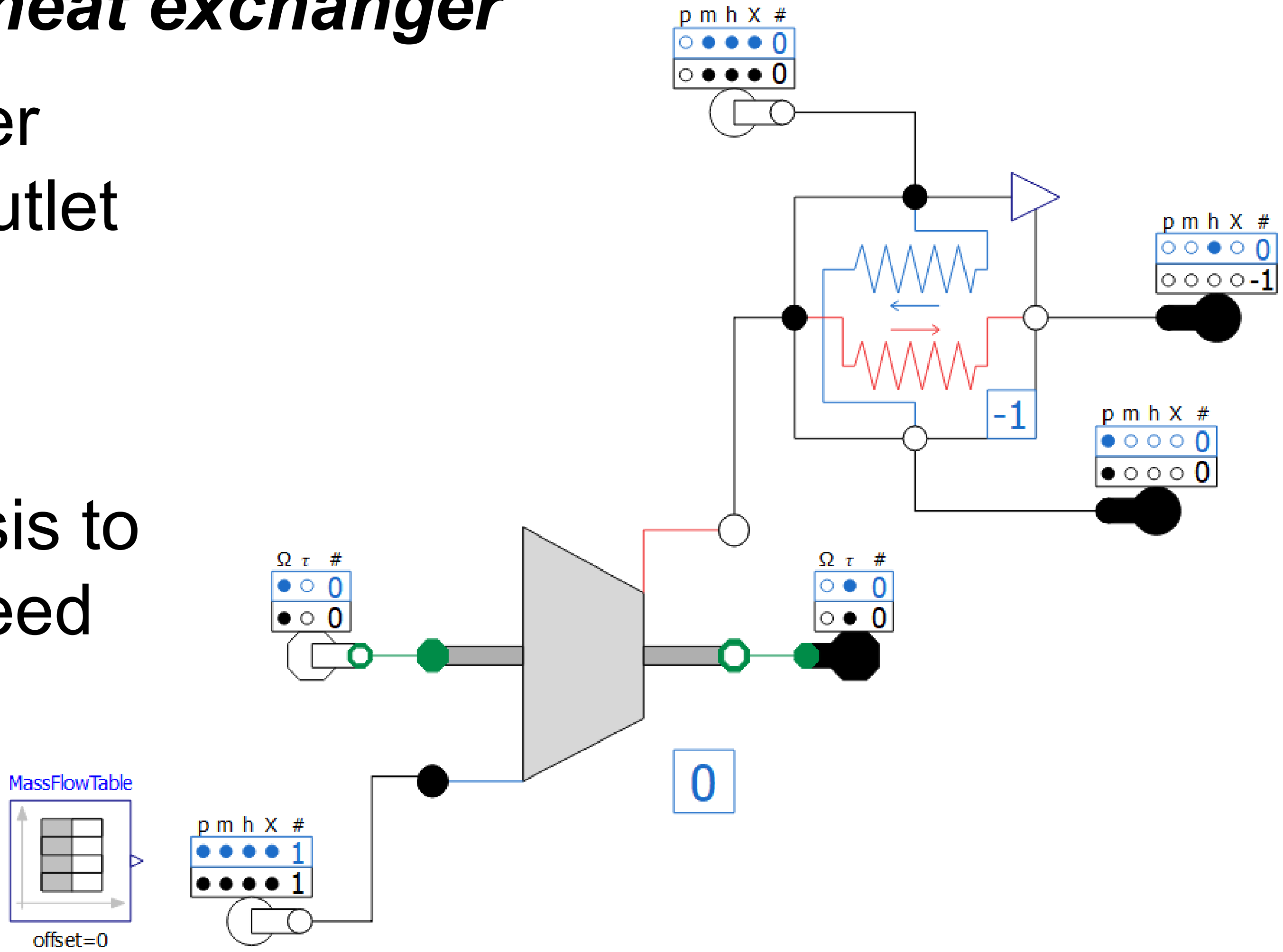
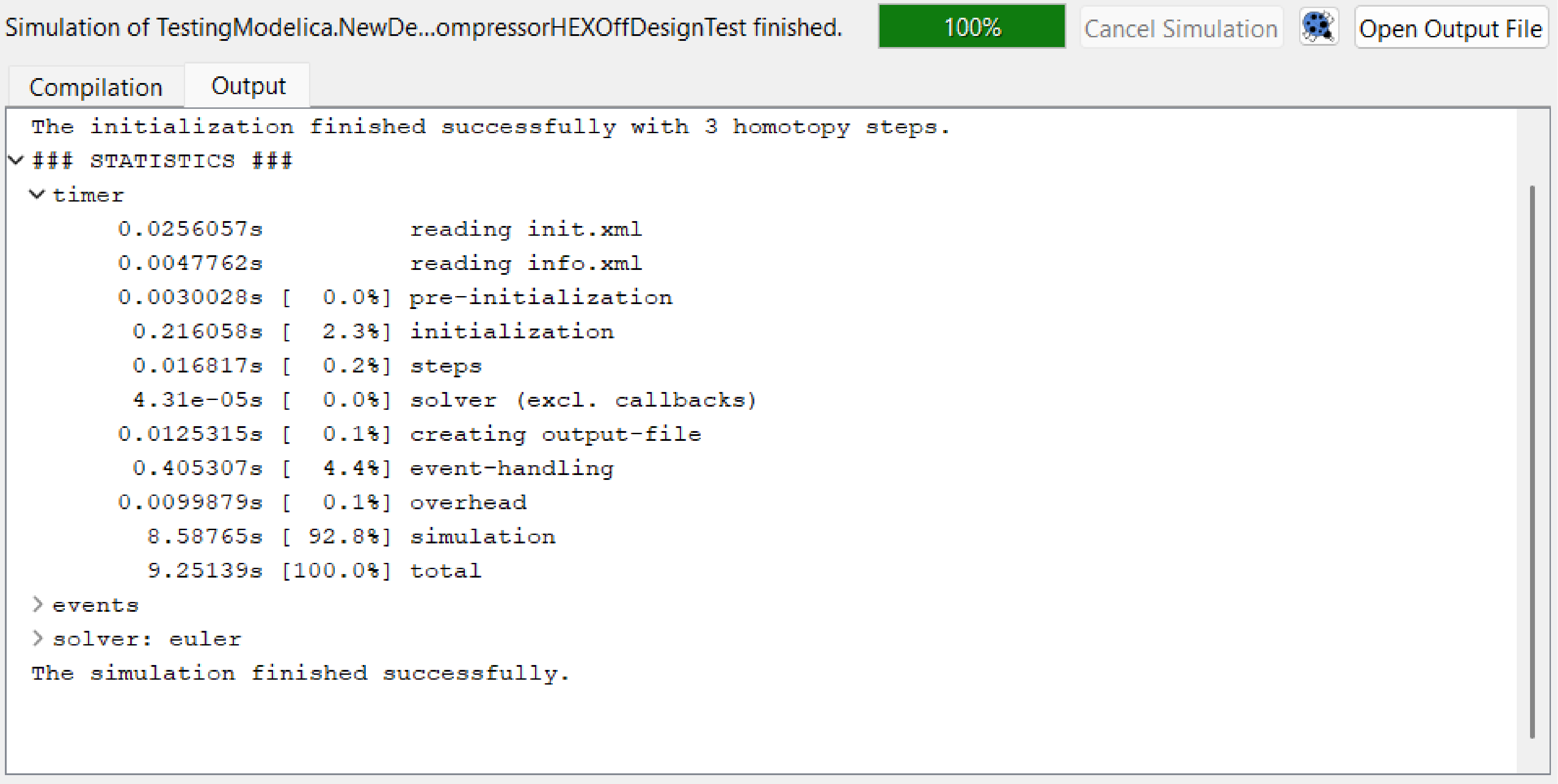


First Results: Proof of concept

Simulation converged!

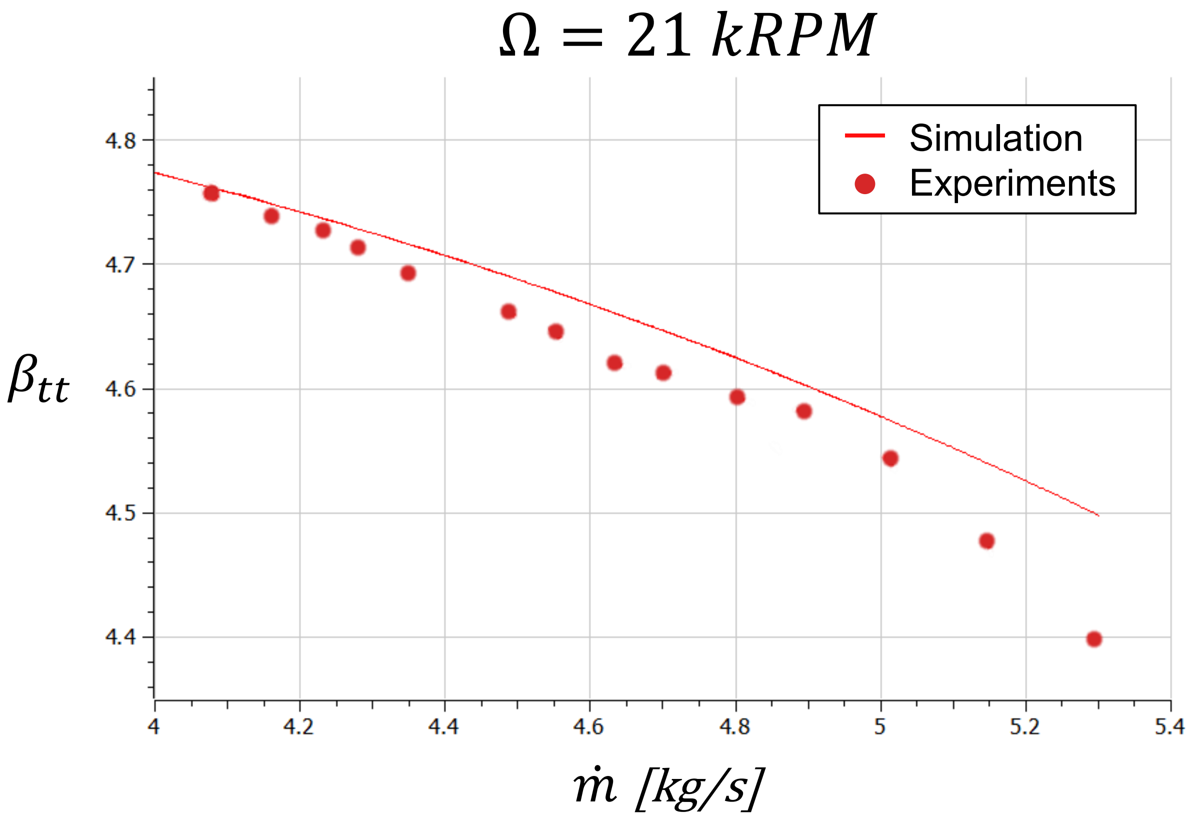


First Results: Proof of concept

Results

1. For given design & boundary conditions: ***L = 4.3m***
2. Reference data from NASA High Efficiency Centrifugal Compressor (HECC) [1]

- Loss correlation parameters must be chosen appropriately!

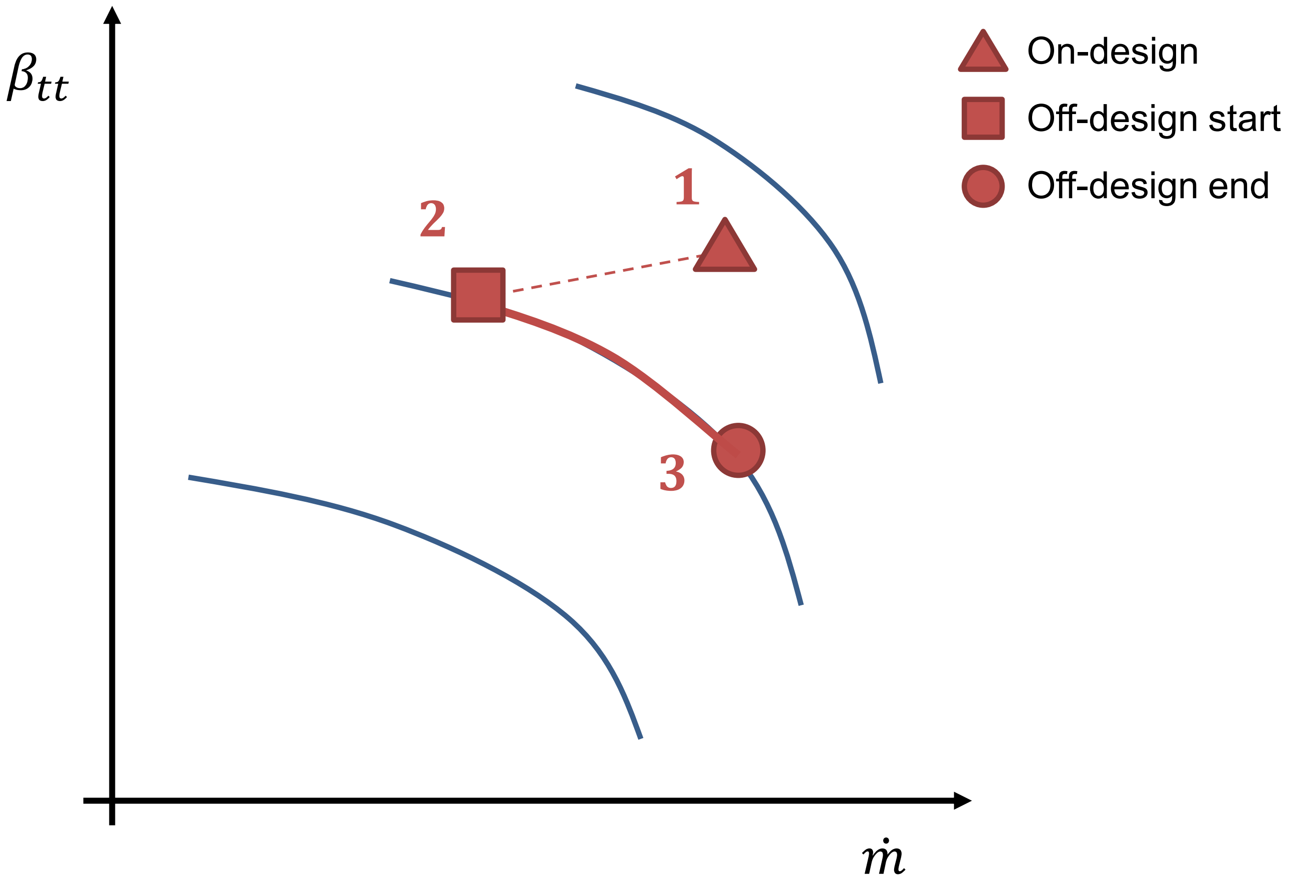


[1] NASA Technical Report ID: 20180001471

Limitations

Current "issues":

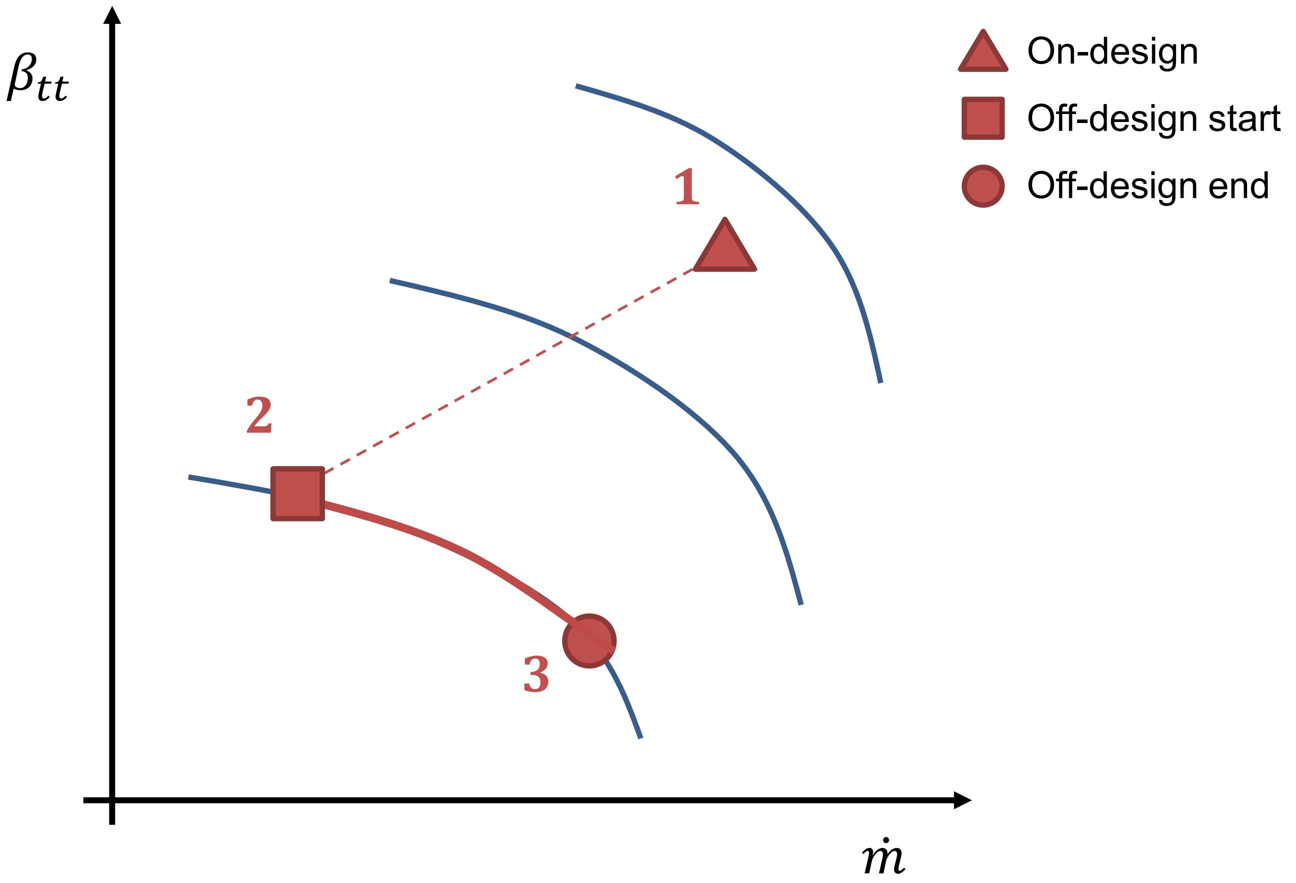
1. Jumping between on- & off-design



Limitations

Current "issues":

1. Jumping between on- & off-design
   - Extended homotopy



Limitations

Current "issues":

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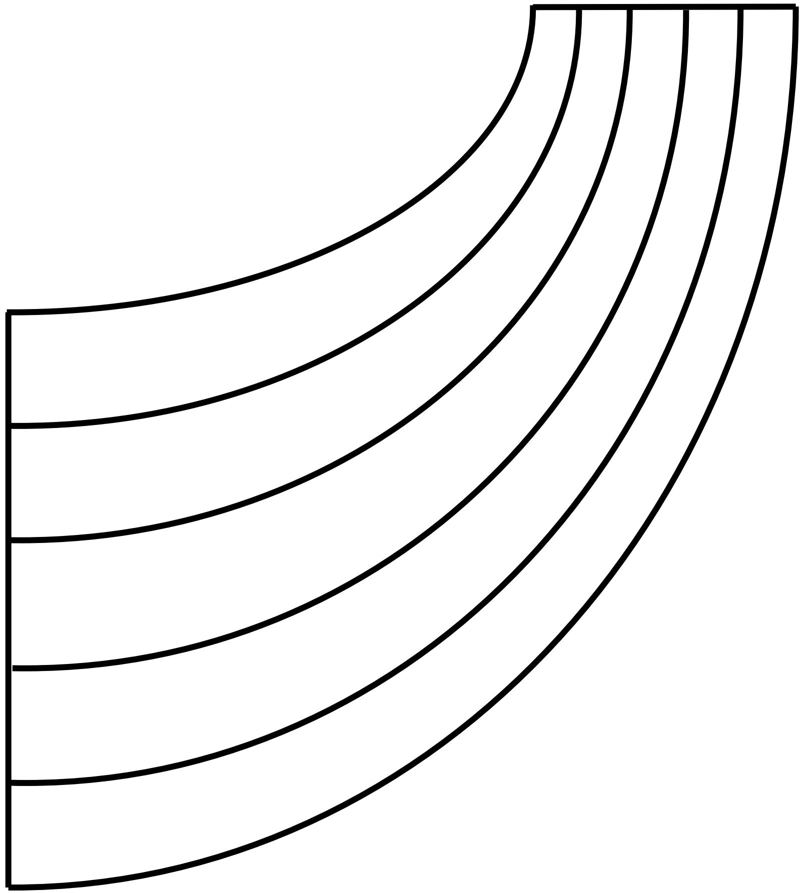
2. Incremental streamtube refining method not possible



TU Delft

Propulsion & Power

Limitations

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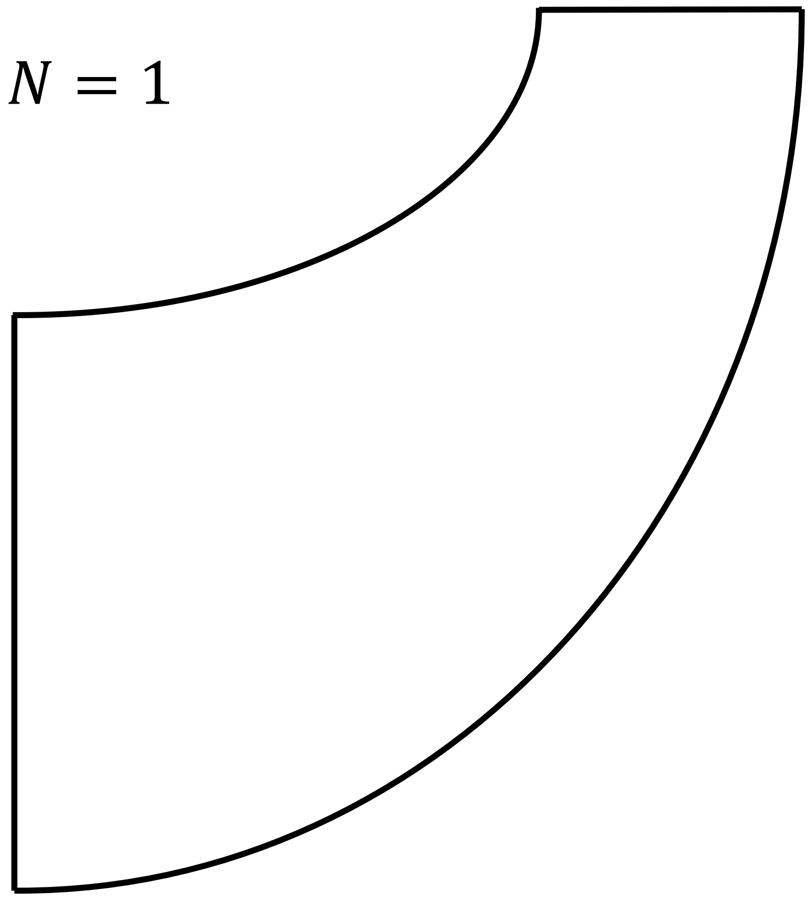

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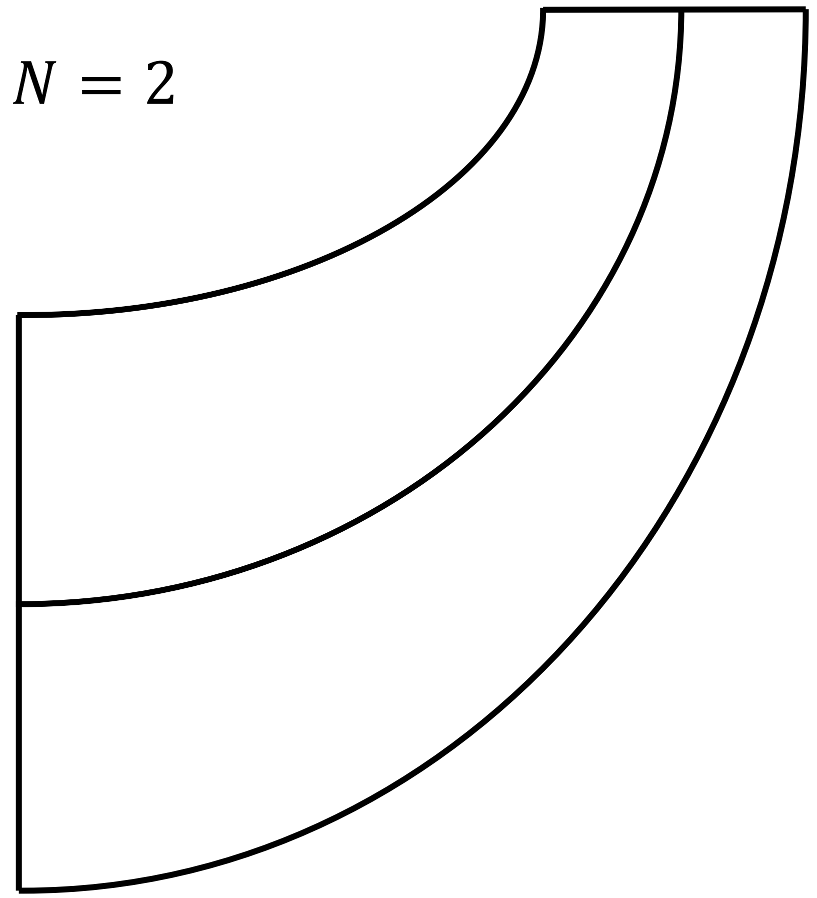

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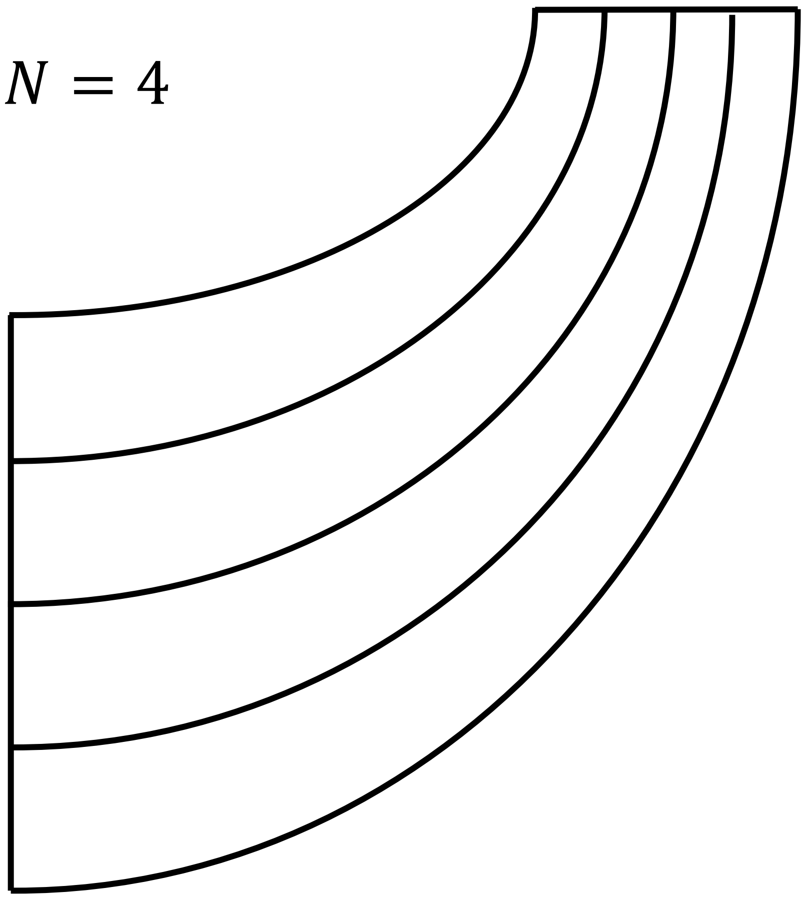
$N = 4$



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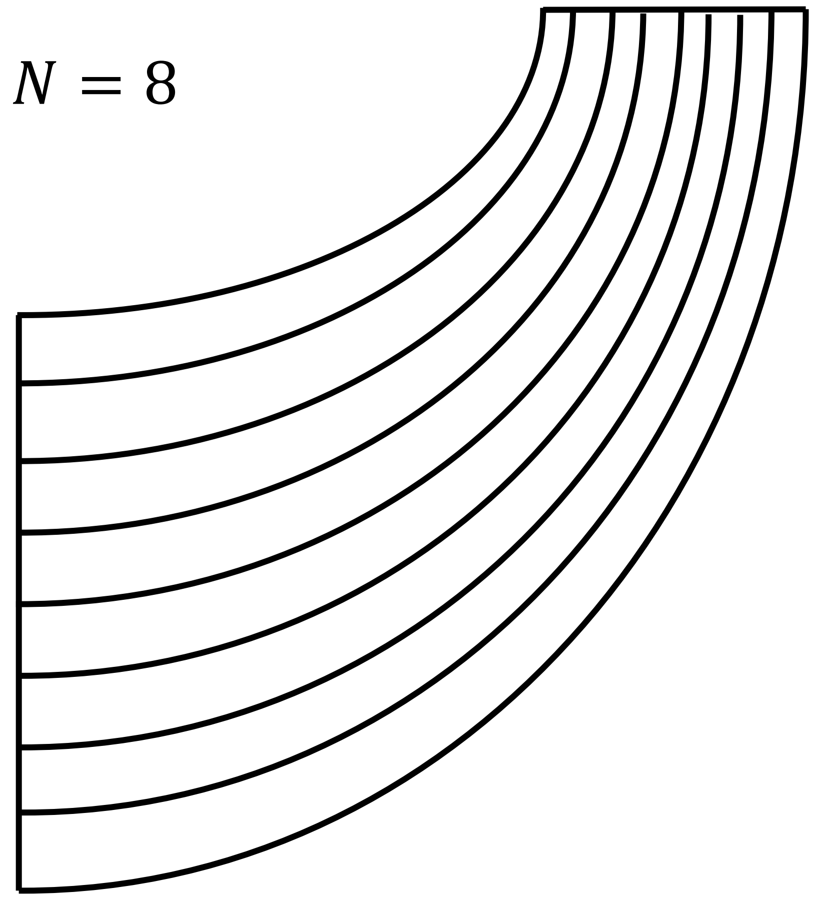

Conclusions

- ✓ DeSimECS ideal for combined on- & off-design modelling.
- ✓ Visual indication of degrees of freedom
- ✓ Strong foundation for integrated optimization

Future Work

- Additional component models:
  - Turbine
  - Detailed heat exchangers
  - Valves
- Initial optimization framework for steady-state
- Development of dynamic library

Thank you!