4th International Seminar on ORC POWER SYSTEMS

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Dynamic modeling and optimization of an ORC unit equipped with plate heat exchangers and turbomachines

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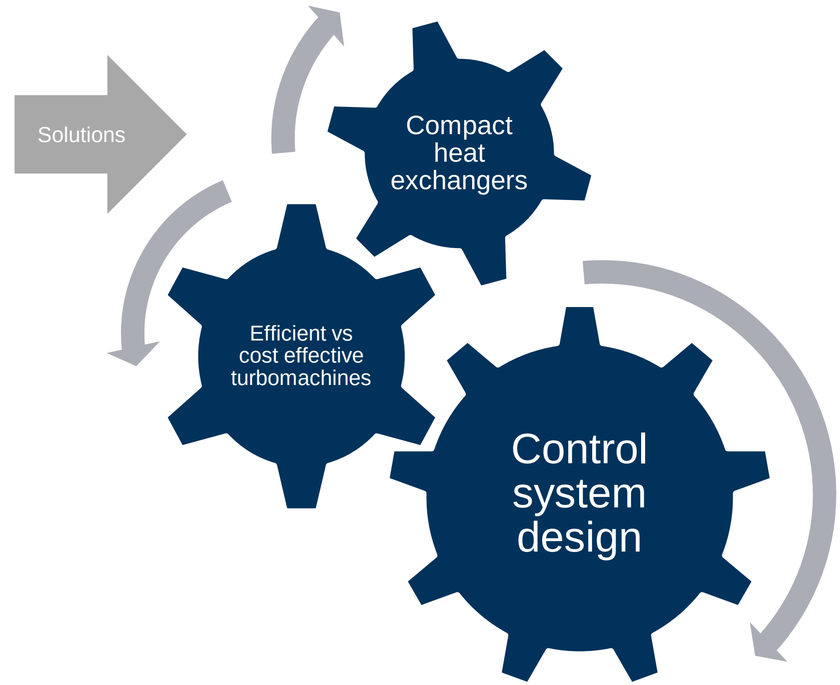
Market

- Large potential for small-scale ORC systems
- Distributed applications
- Waste Heat Recovery (WHR)
- Solar power
- Geothermal applications

Techno-economical barriers

- Low overall system efficiency
- Low reliability when the hot source has a highly variable thermal load
- Lack of availability of specialized technicians in distributed applications
- High capital cost per kW_{el} installed



Goals

- ❑ Introducing a novel modelling approach oriented to the control system design
- ❑ Studying the system dynamics

Outline

- Modelling approach
- Model description for each system device
- Steady state optimization
- Transient analysis
- Control system design and analysis
- Future steps

Modelling approach

Device models

- Experimental data or more complex models
- Off-design working points or performance maps are calculated

Overall system model

- The data obtained are given to the software GT-SUITE™ which is used to developed the model of the overall system
- Thermodynamic properties calculated with RefProp

Control system

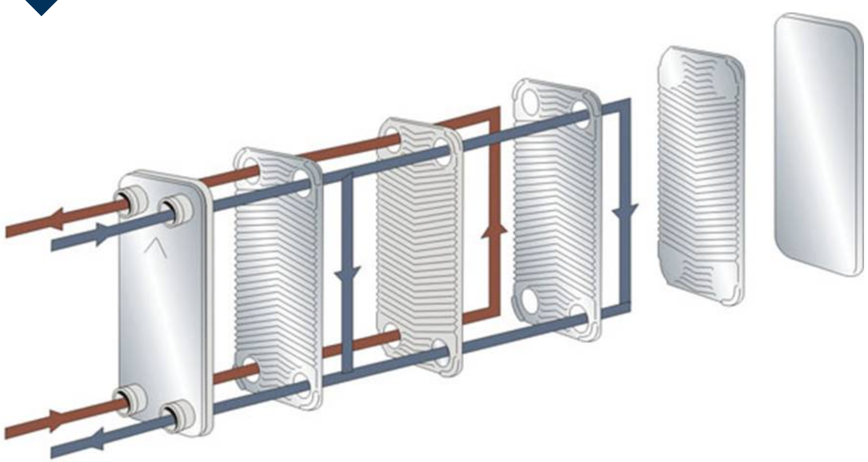
- A PI controller is designed and tested to maintain the system on the design working point when disturbances due to heat load of the hot source are introduced

Evaporator and condenser modelling

SWEP model
- Several working points
- Off-design outputs

GT-SUITE model
- Geometrical data
- Heat exchanger material
- Off-design points

Map
- Best fitting coefficient of Nusselt-Reynolds based correlations



Refrigerant mass flow rate

Refrigerant inlet temperatures

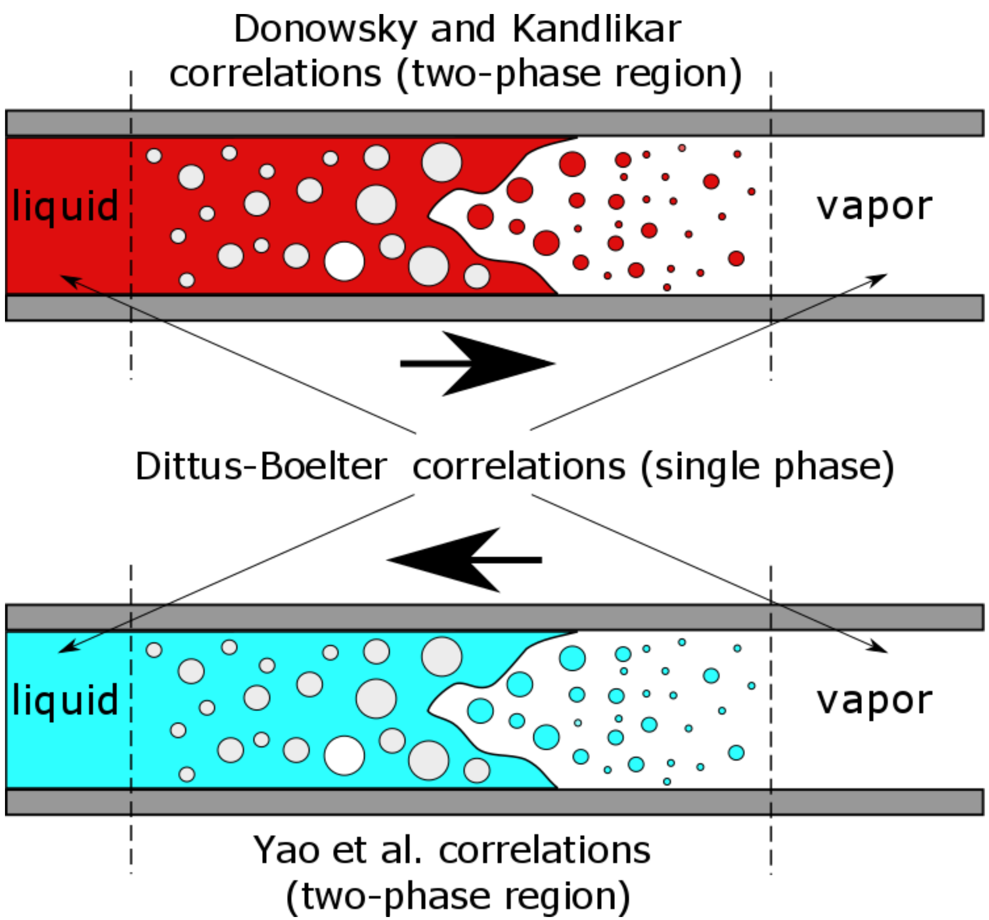
Inlet and outlet temperatures of the hot and the cold source

→ Plate Heat exchanger model

OUTPUTS
- Quality of the refrigerant
- Pressure losses in the heat exchangers
- condensing or evaporating temperatures
- the cold and hot source mass flow rates

Evaporator and Condenser heat transfer correlations

- 1-D discretization
- Different heat transfer correlations depending on the heat exchanger and the working fluid phase
- Vapor formation and two-phase region extension predicted following the Rayleigh-Plesset equation
- Heat exchanger inertia is taken in account by specifying the geometrical data and the material of the device.



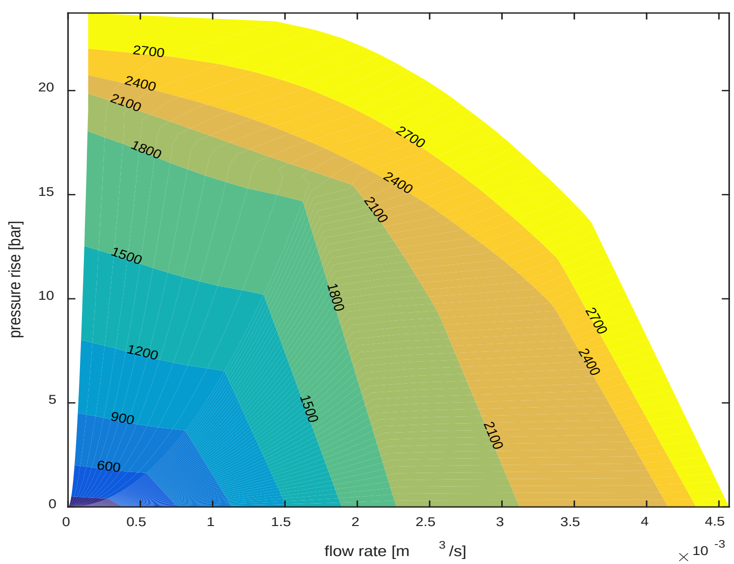
Pump modelling

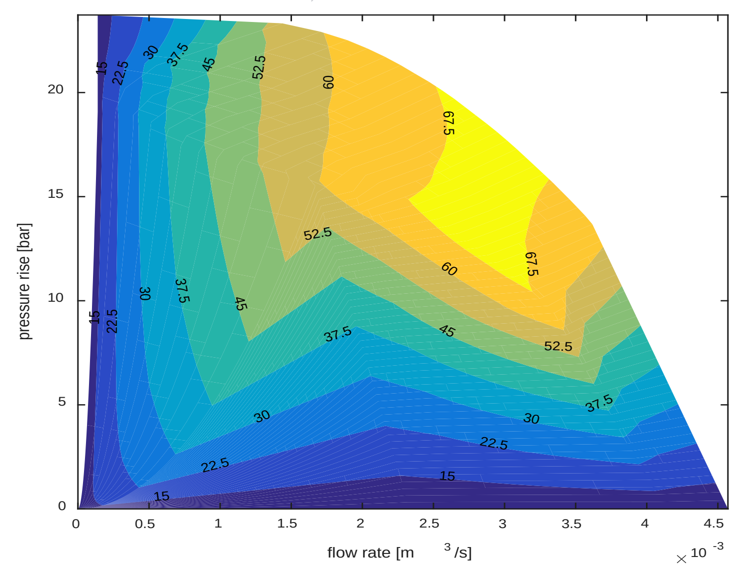
Input data
- Revolution speed
- Pressure rise
- Power consumption

Process data
- Interpolation of the curves in a range between 1800 and 3000 rpm
- Extrapolation of the curves for lower velocities

Process data
- Calculation of isentropic efficiencies for each point of the performance map

Performance Maps
- plot the performance and the isentropic efficiency maps of the centrifugal pump

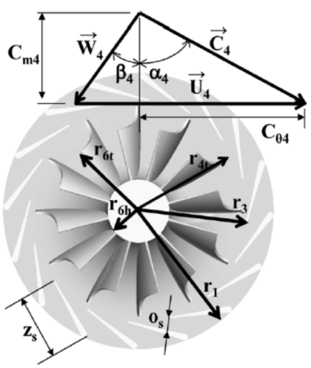




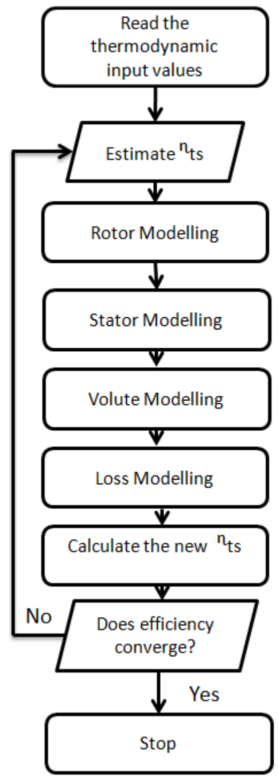
Radial Expander Design Methodology

Radial Turbine Design

RTD

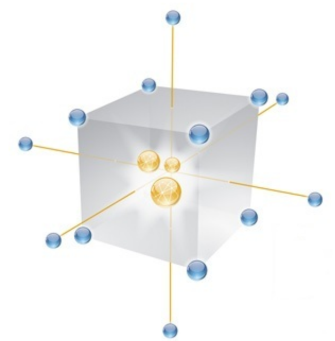


- Rotor
- Stator
- Volute
- Losses



Radial Turbine Optimisation

RTO



Advanced numerical methods for optimization:

- Objective function
- DoE

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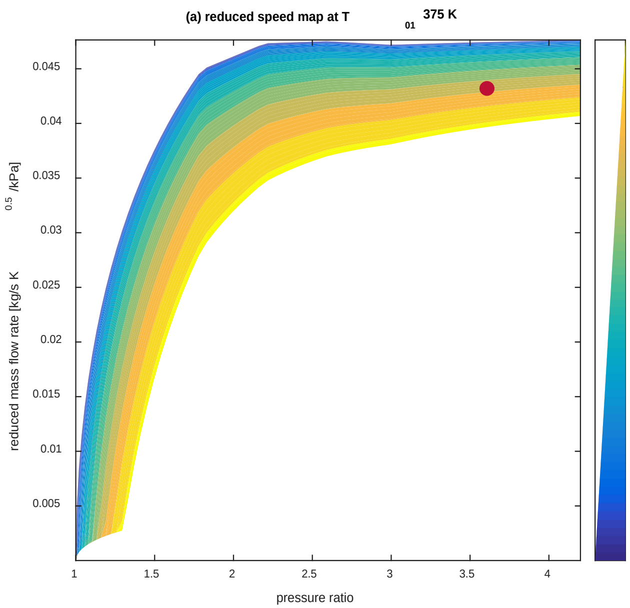
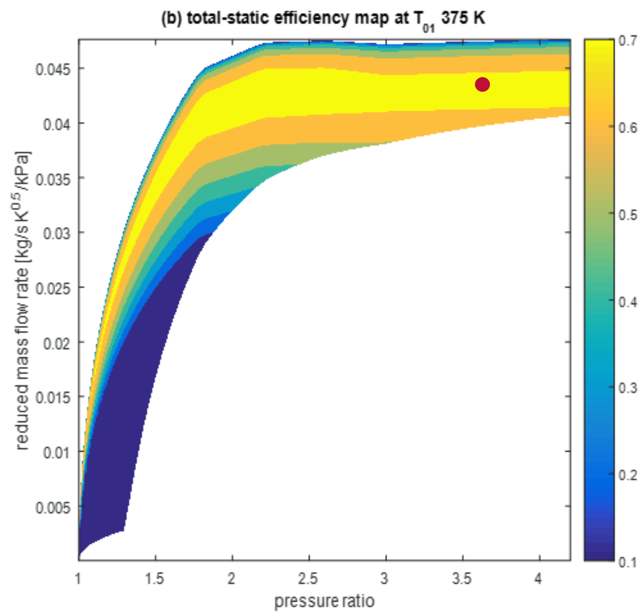
Off-Design Turbine Performance

- The optimum geometry was imported in Rital to generate an off-design turbine map
- NASA loss model was utilized being calibrated on the design point from RTD
- Turbine map was generated by running Rital at various PR and rotational speeds
- The final map was integrated in GT-Power





Receiver and piping modelling

- Straight pipes modelled as 1-D ducts with a circular cross section

- Bends are modelled as localized pressure drops

- Pipes and the receiver are considered adiabatic

- The receiver has been modelled as a capacity and sized as 25% of the overall system capacity

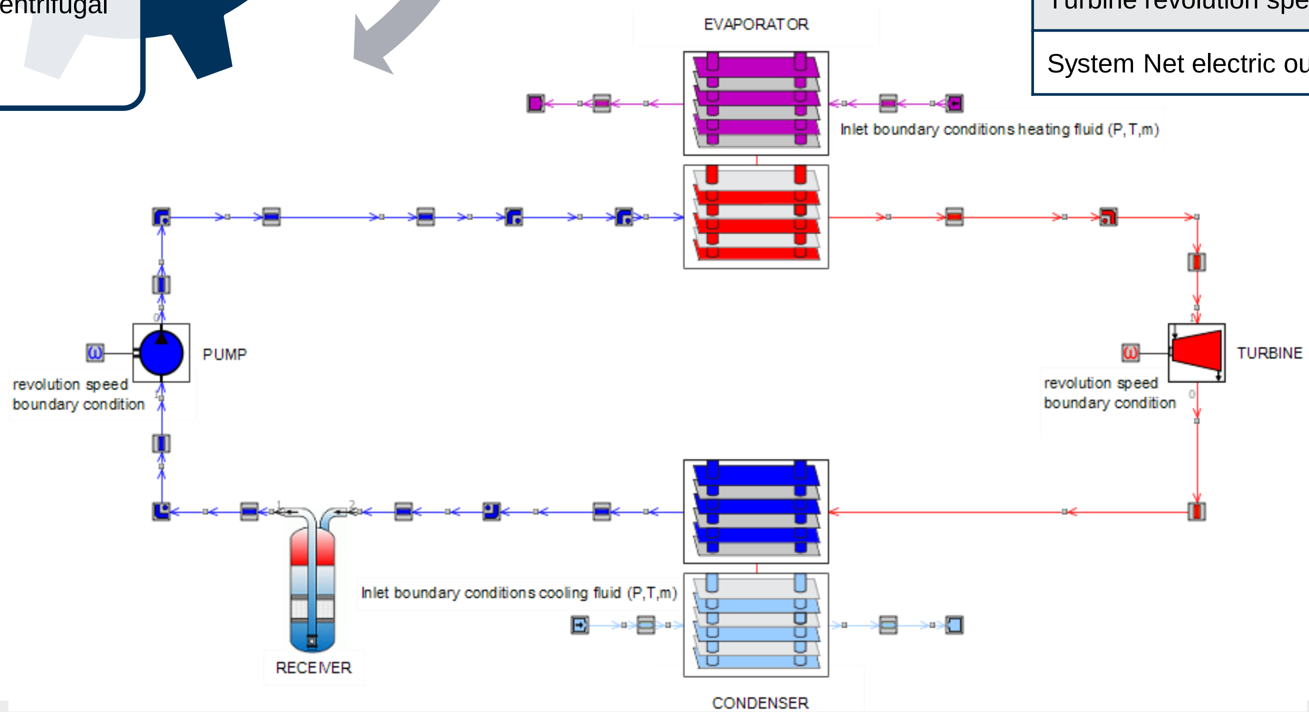
System description

Stationary 40 kW_{el} ORC system for WHR applications

- Plate heat exchangers
- Radial turbine
- Multi-stage Centrifugal pump
- R245 fa

System design point

Hot source mass flow rate	10 kg/s
Hot source inlet temperature	110 °C
Cold source mass flow rate	14.3 kg/s
Cold source inlet temperature	35 °C
Cycle pressure ratio	2.6
Pump revolution speed	2000 RPM
Turbine revolution speed	20000 RPM
System Net electric output	40 kW_{el}



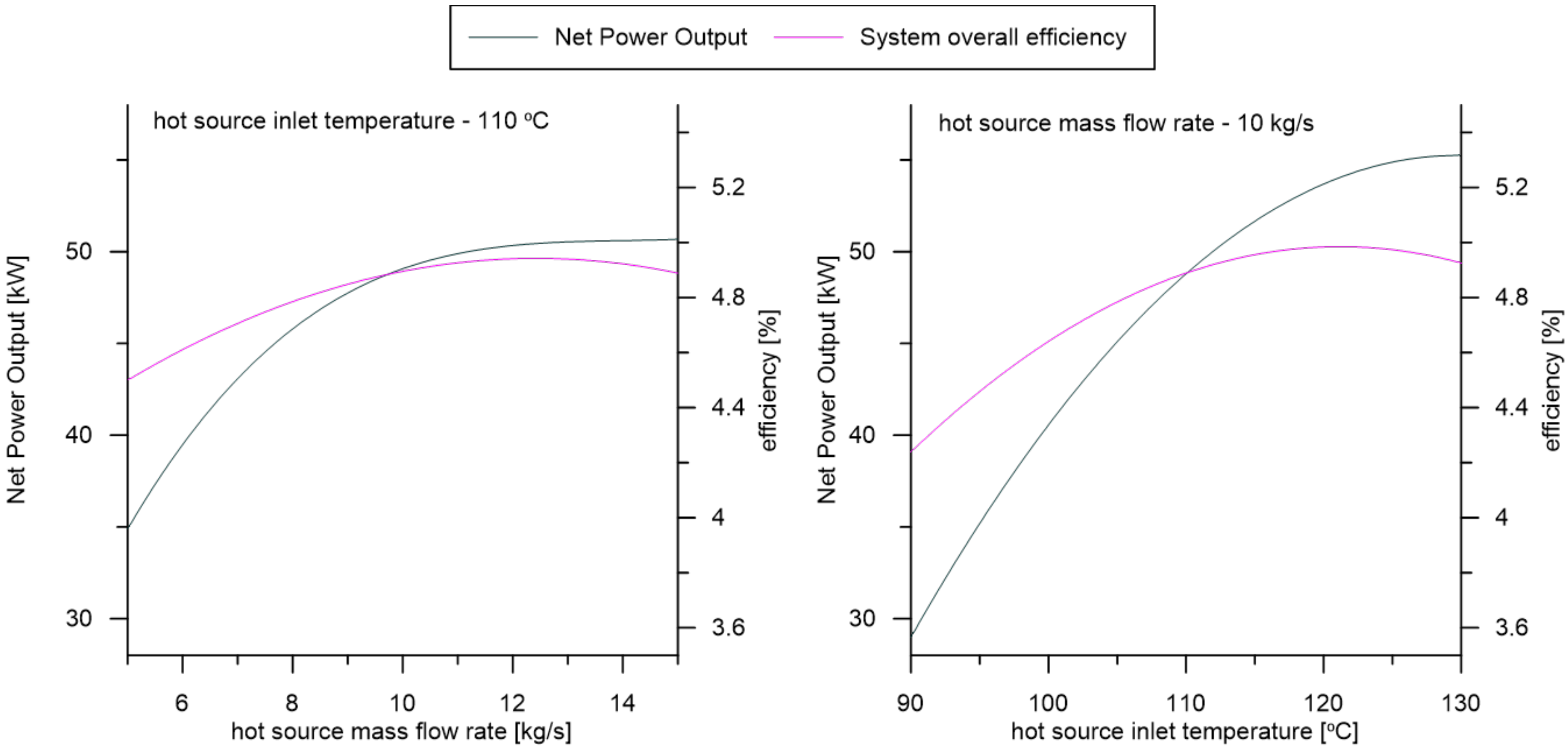
Analysis outline

- Steady state analysis of the ORC system performance varying the hot source inlet conditions (mass flow and inlet temperature)
- Constrained optimization of the turbine and pump revolution speed
- Dynamic response of the system to different time-scale transient thermal input
- Control system analysis

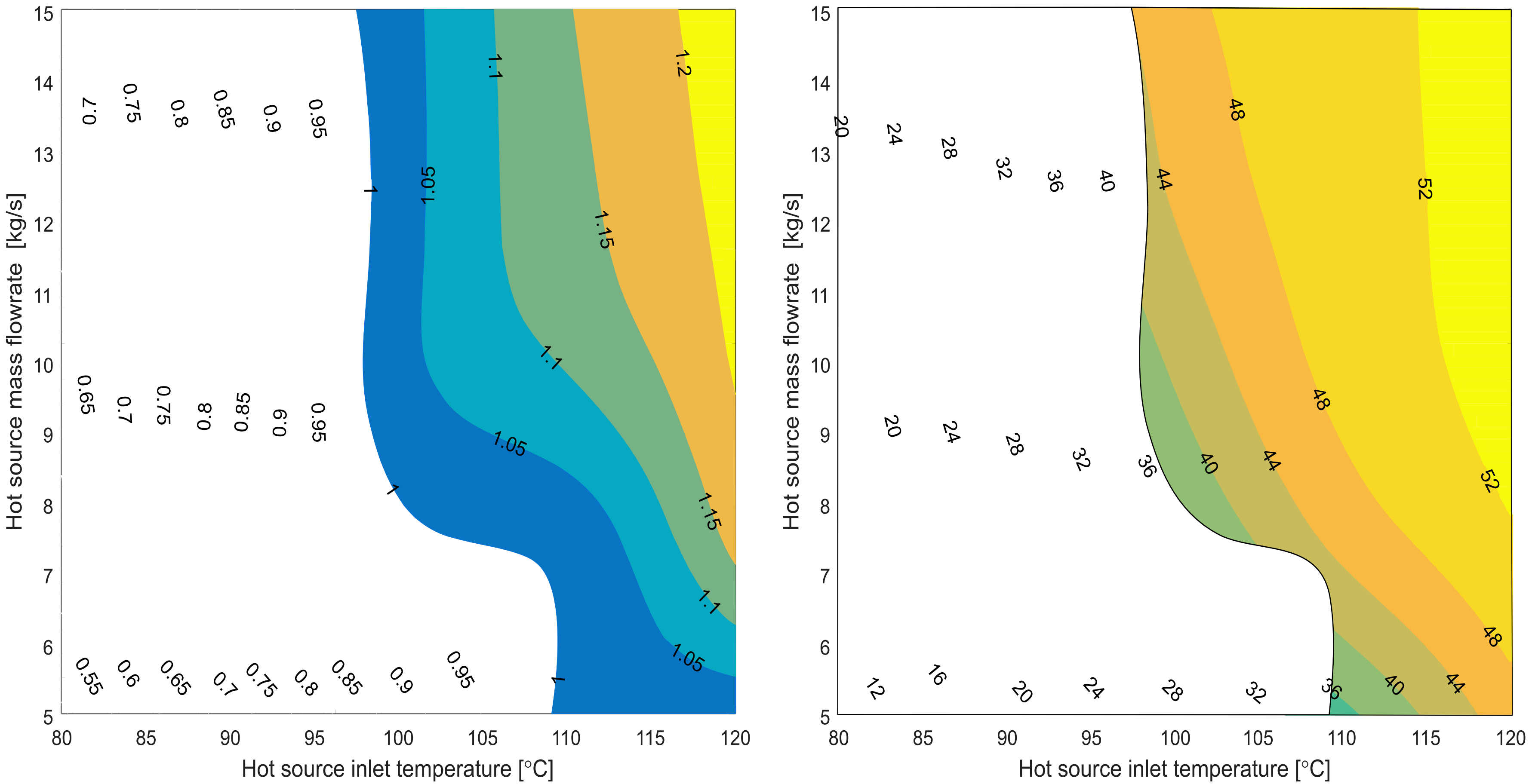
Simulation data

Solving method	Implicit-trapezoidal (2^{nd} order accuracy)
Simulation time step	0.001 s
Optimization algorithm	Nelder and Mead SIMPLEX
Kind of optimization	Constrained

System performance

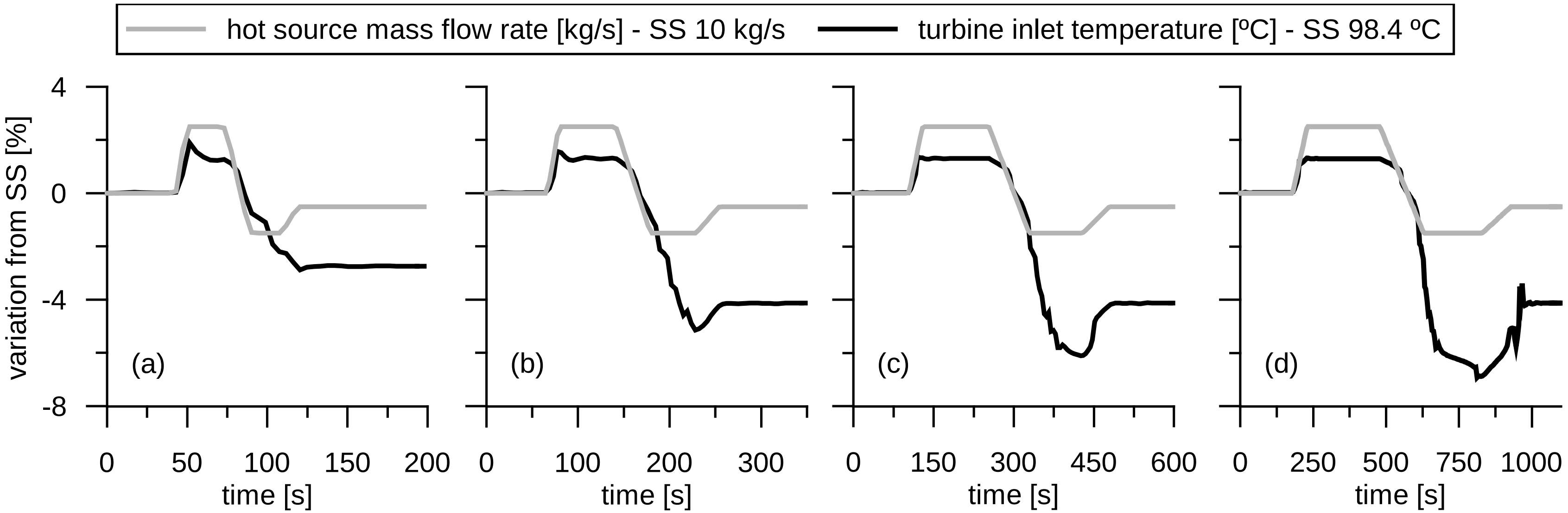


Optimized system performance map



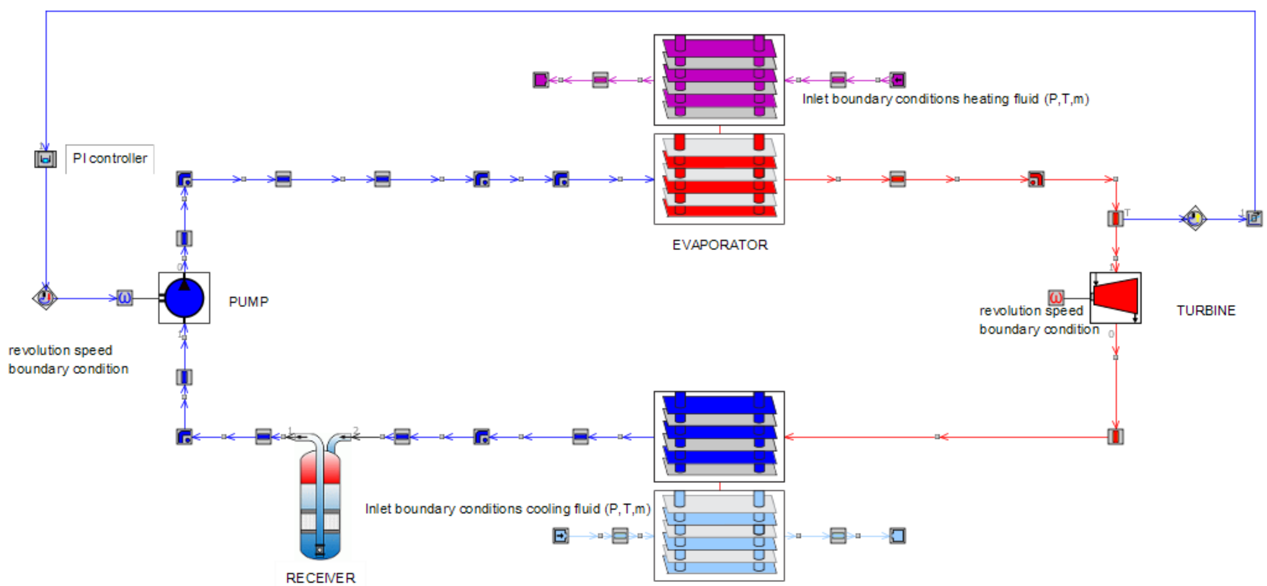
Transient analysis

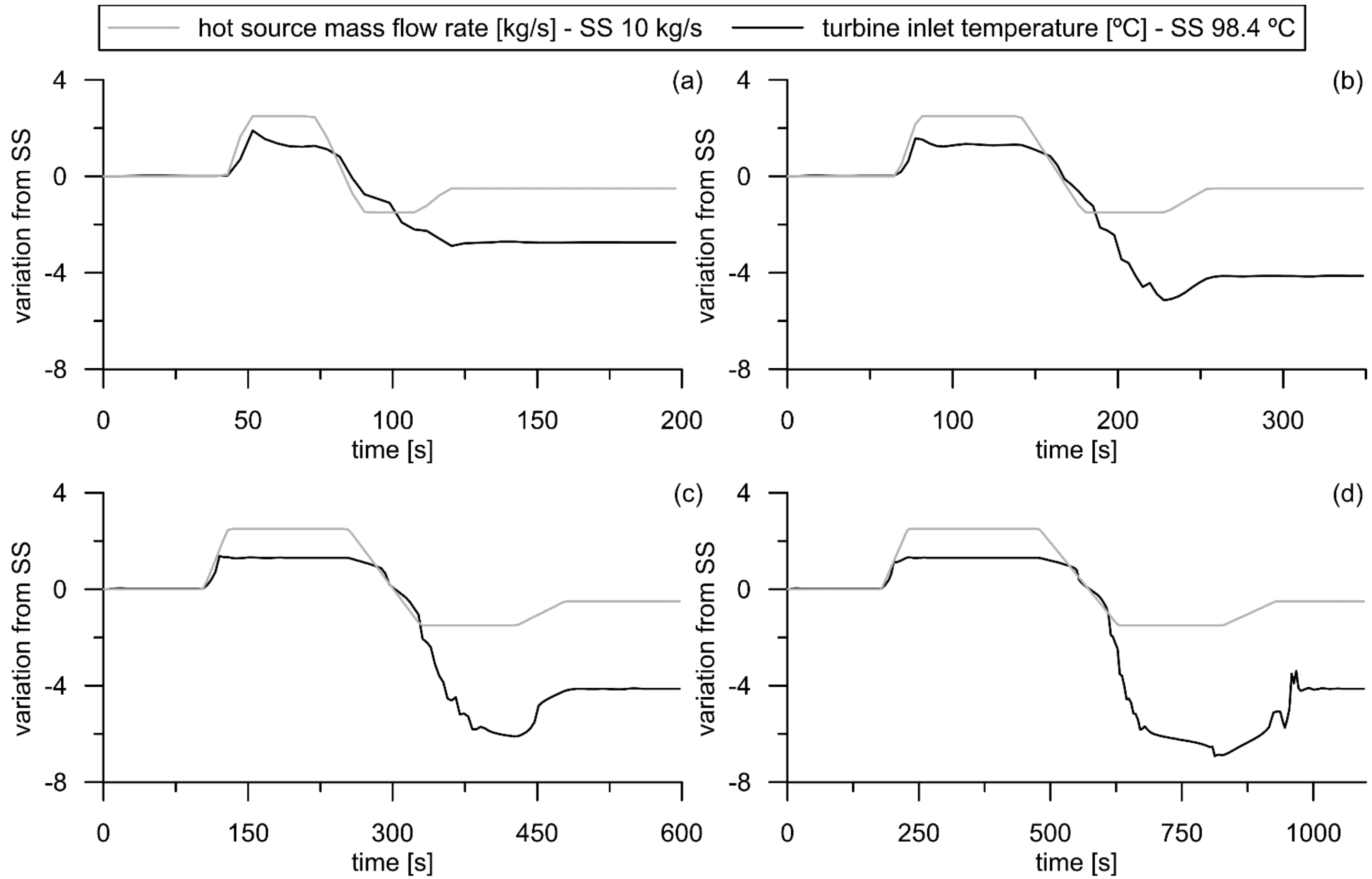
- A transient thermal input has been applied to identifying the dynamics of the system
- The different heat load profiles have been obtained by applying the same percentage variation of the hot source mass flow rate from its steady state value with different time scales
- The hot source mass flow rate at the system design point of the system has been assumed as the steady state value



Control system

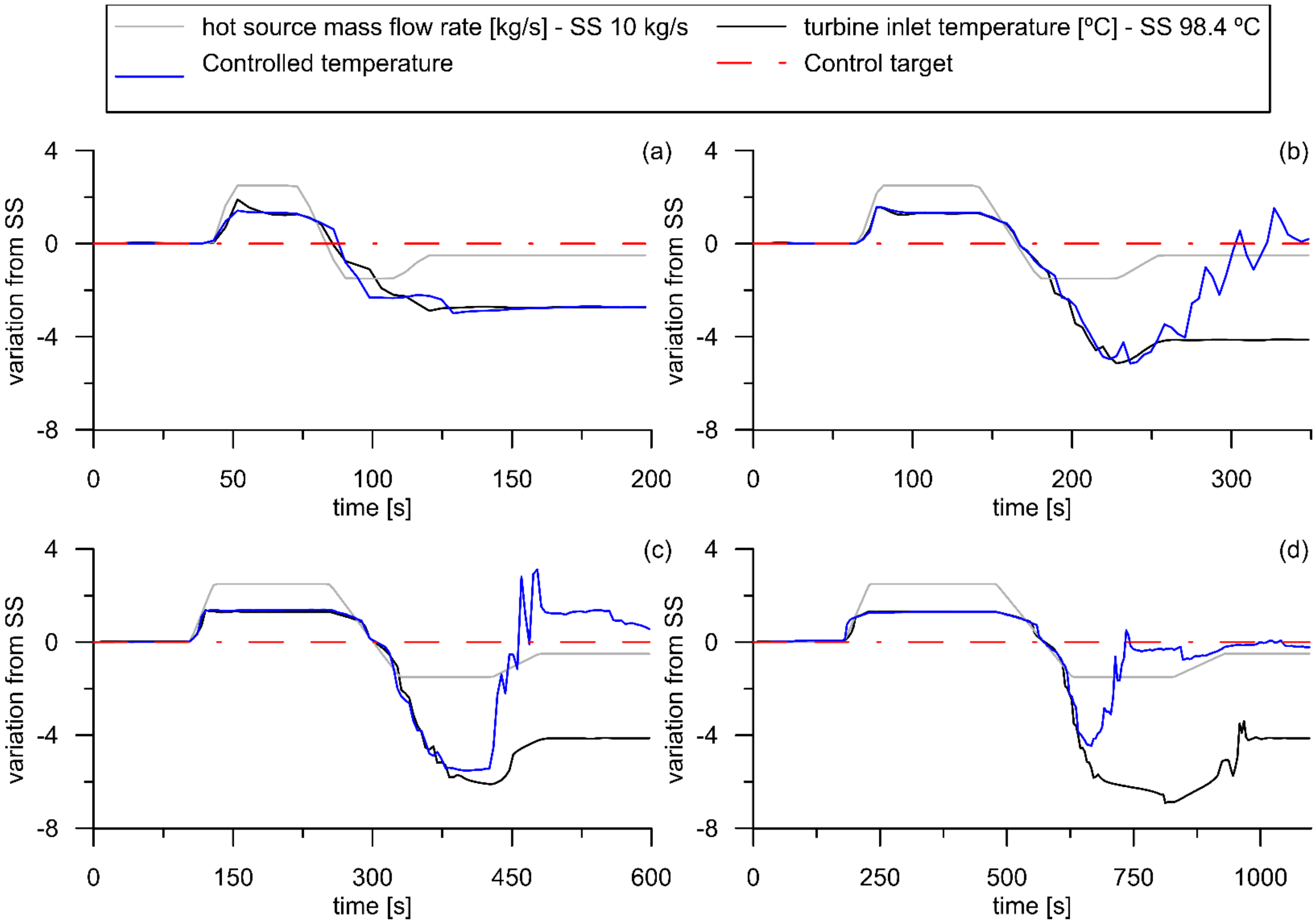
- The manipulated variable is the pump revolution speed
- A PI controller has been designed to control the turbine inlet temperature
- The control target is to maintain constant the temperature of the working fluid at the expander inlet despite the varying heat load of the hot source





hot source mass flow rate [kg/s] - SS 10 kg/s
turbine inlet temperature [ºC] - SS 98.4 ºC
(a)
(b)
(c)
(d)
variation from SS
time [s]
4
0
-4
-8
0
50
100
150
200
300
450
600
250
500
750
1000

Controlled system simulations



Conclusions

- This work presented a modelling approach to analyse and design waste heat to power conversion units based on the ORC technology
- The approach is highly replicable, low time consuming, and then particularly suitable for overall system analysis
- The range of operation of the optimized system (from 34.5 kW up to 55.5 kW) has been calculated and can be useful to define proper control strategies to maximize the system power output in transient heat load conditions
- The control strategy adopted is able to reject the disturbances introduced by the varying heat load of the hot source

Future steps

- Short term
  - Experimental validation of the developed model
  - Application of the modelling approach to other novel heat to power conversion systems for WHR applications (sCO_2 power cycle)
  - Using the platform for the design of a novel control strategy
  - Journal paper
- Long term
  - Validation of the control strategy designed on the real system

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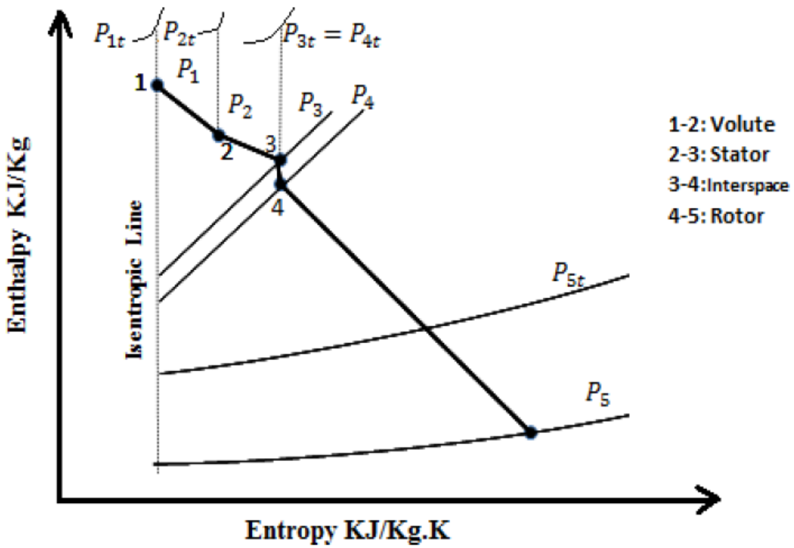
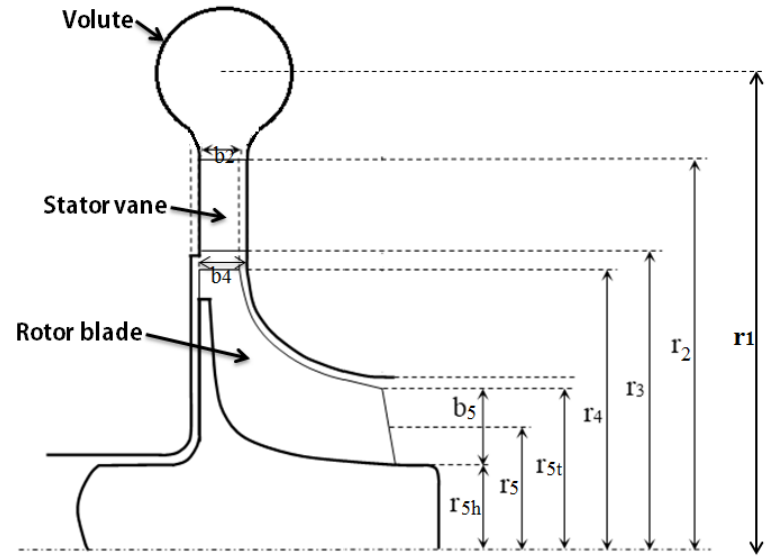
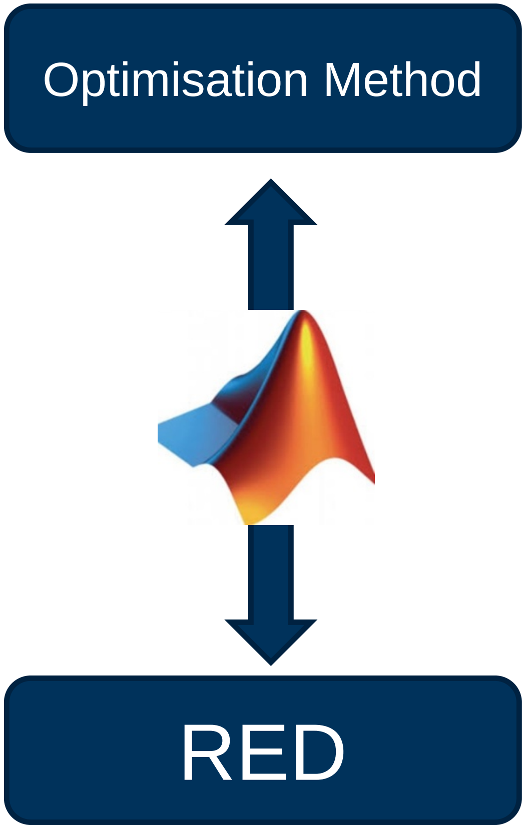
Radial Turbine Design (RTD)





- **<u>Input Data</u>:** Operating parameters and thermodynamic conditions
- **<u>Output Data</u>:** The result of Radial Turbine Design (RTD) is the calculation of <u>turbine geometry</u> (number of blades, blades angles and length) and <u>performance</u> features (η_{ts} , W).

Radial Turbine Optimisation (RTO)



Target: Maximisation of the objective function on the given range of the input parameters

Objective functions

- Isentropic efficiency (η_{eff})
- Expander power (W)
- Expander power density (W/d_{max})

Some of the most important optimization parameters:

- Loading coefficient (Ψ)
- Flow coefficient (Φ)
- Pressure ratio (π)
- Mass flow rate (m)
- Turbine rotational speed (N)
- Inlet pressure (P_{in})

❑ Finally the optimum geometry is calculated

Nelder and Mead SIMPLEX Optimization algorithm

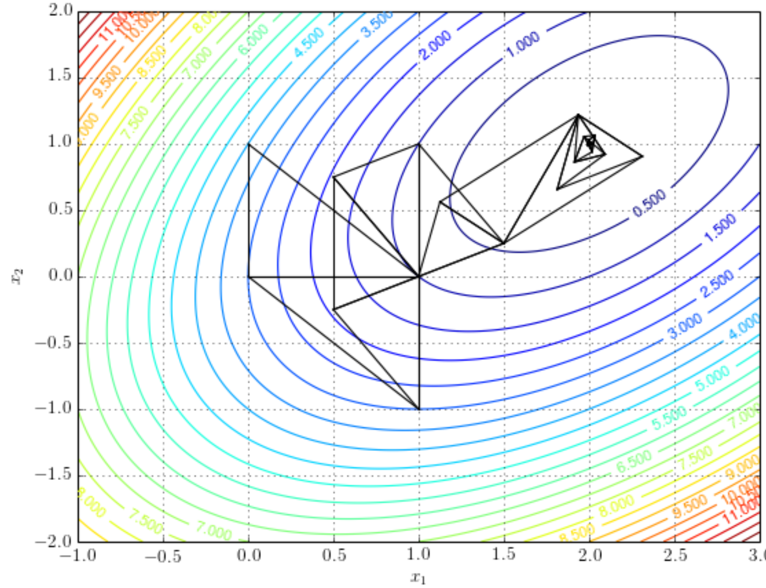
Start
- Generate a new simplex

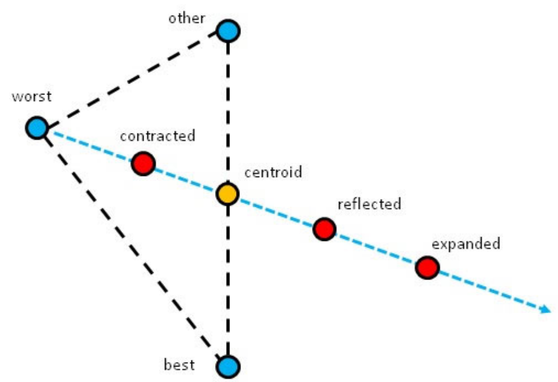
Alternative solutions
- Reflection
- Contraction
- Expansion

Sufficient progress?
- Yes, proceed with the algorithm
- No, Shrink the simplex and check if the minimum is attained

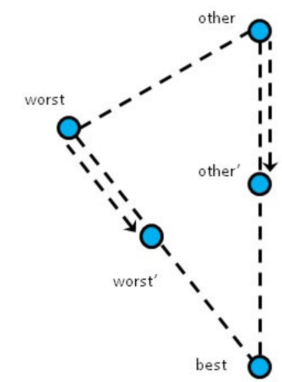
Substitution
- Substitute the worst point of the triangle with the best alternative solution found

Minimum attained?
- Yes, the algorithm stops
- No, a new simplex is generated

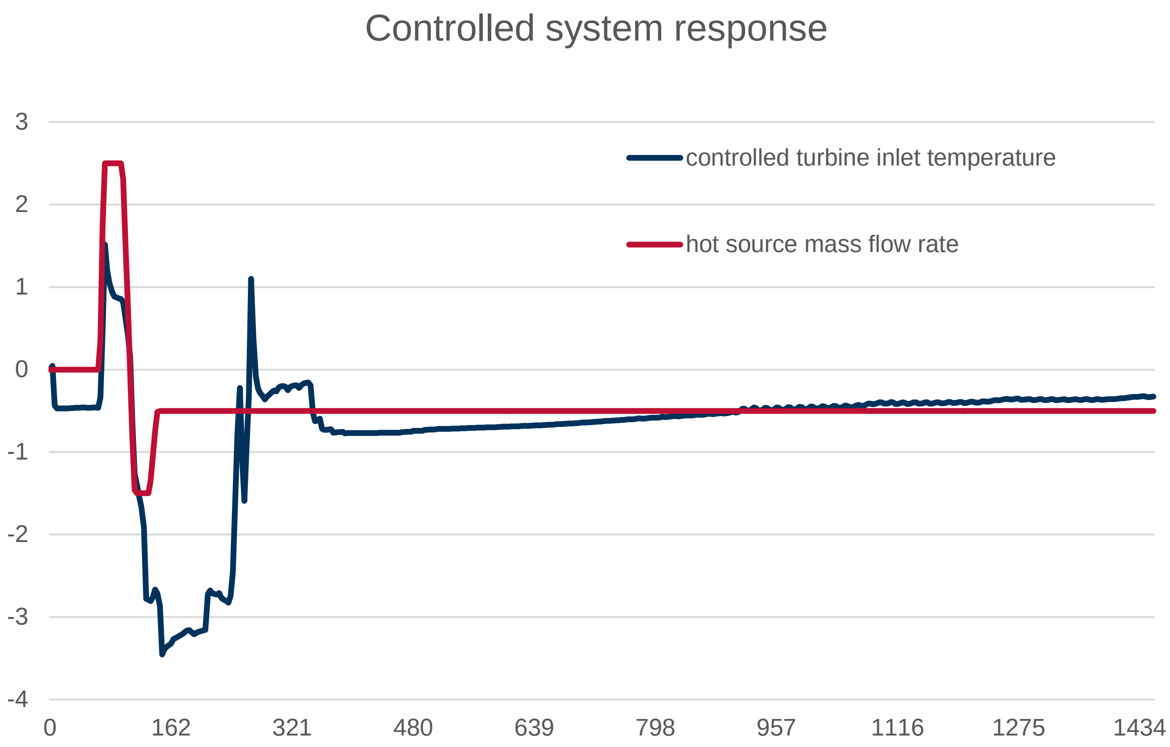




Three candidates to replace worst



Shrinking


Controlled system response
3
2
1
0
-1
-2
-3
-4
0
162
321
480
639
798
957
1116
1275
1434
controlled turbine inlet temperature
hot source mass flow rate