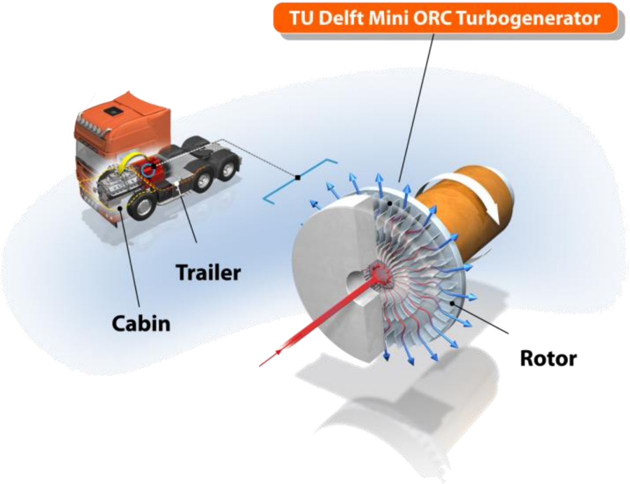
Design, Modelling, and Control of a Waste Heat Recovery Unit for Heavy-Duty Truck Engines

S. Trabucchi, C. De Servi, F. Casella, P. Colonna

4th International Seminar on Organic Rankine Cycle Power Systems

WELCOME BACK HOME!

Milan, 13th-15th September 2017



Contents

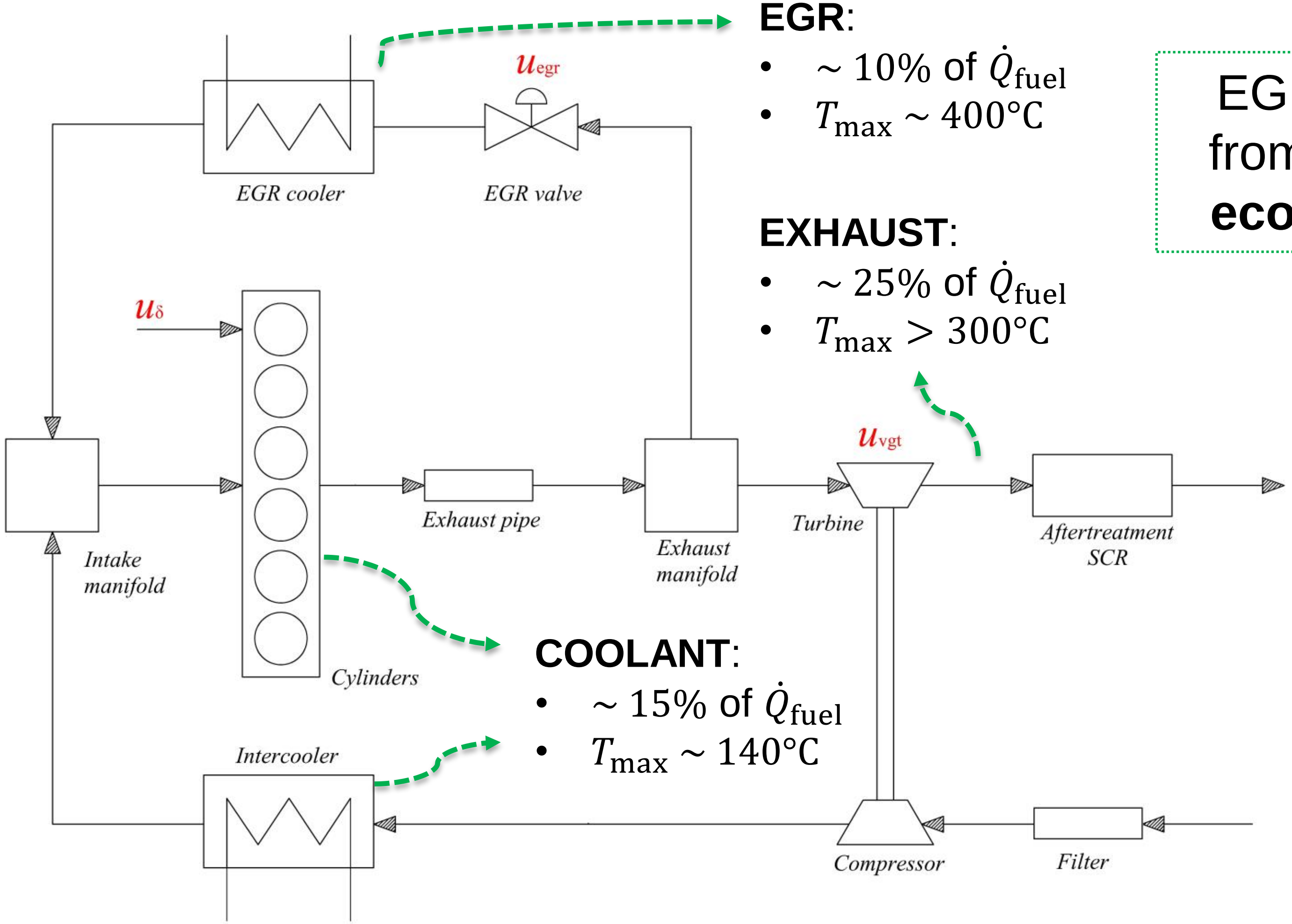
- Thermal sources for Waste Heat Recovery (WHR)
- ORC configuration and optimization
- Control system design and simulation
- Conclusions

Motivations

1. Actual potential for the WHR unit?
2. Cycle configuration: best trade-off between simplicity and efficiency?
3. Control issues related to the chosen configuration?

WHR unit design

Truck engine waste energy



EGR:

- $\sim 10\%$ of $\dot{Q}_{\mathrm{fuel}}$
- $T_{\mathrm{max}} \sim 400°\mathrm{C}$

EXHAUST:

- $\sim 25\%$ of $\dot{Q}_{\mathrm{fuel}}$
- $T_{\mathrm{max}} > 300°\mathrm{C}$

COOLANT:

- $\sim 15\%$ of $\dot{Q}_{\mathrm{fuel}}$
- $T_{\mathrm{max}} \sim 140°\mathrm{C}$

EGR and EXH interesting from **thermodynamic** and **economical** point of view!

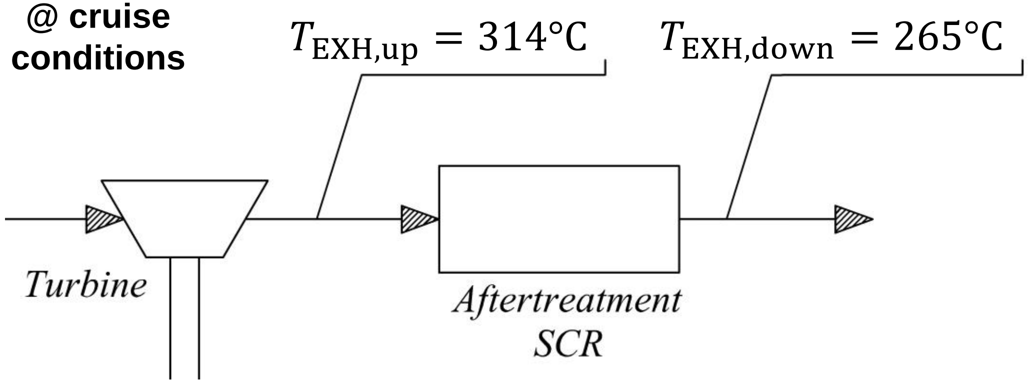
Diesel engine model tuned on experimental data from modern ICE:

- $\eta_{\mathrm{DE}} \cong 42\%$
- $\dot{W}_{\mathrm{net}} = 101.5\ \mathrm{kW}$
- $v_{\mathrm{cruise}} = 85\ \mathrm{km\ h^{-1}}$

WHR unit constraints

ORC can not affect η_{DE},
fully add-on system:

@ cruise conditions



- full cooling of EGR stream
  → maximize cylinders charge

- exhaust heat recovery upstream or downstream of the ATU
  → SCR minimum operating temperature is $200°\text{C}$

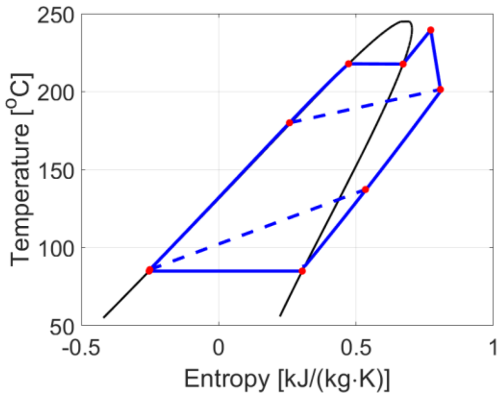
- radiator cooling capacity not fully exploited in cruise conditions
  → cooling water minimum temperature down to $70°\text{C}$
  → ORC condenser in series to engine radiator

Cycle design & optimization

- exhaust (EXH) and
  EGR evaporators in parallel
- single pressure level
- working fluid: MM (simple siloxane)
  → high molecular complexity,
  $h_{\text{blade}} \uparrow$ and $\omega \downarrow$
  → stable up to $300°\text{C}$
- compact end efficient
  two stages axial turbine
- $T_{\text{cond}} = 85°\text{C}$, fixed

Innovative integrated design method:
simultaneous optimization of cycle parameters and turbine geometry

$\eta_{\text{is,turb}}$ not set a priori



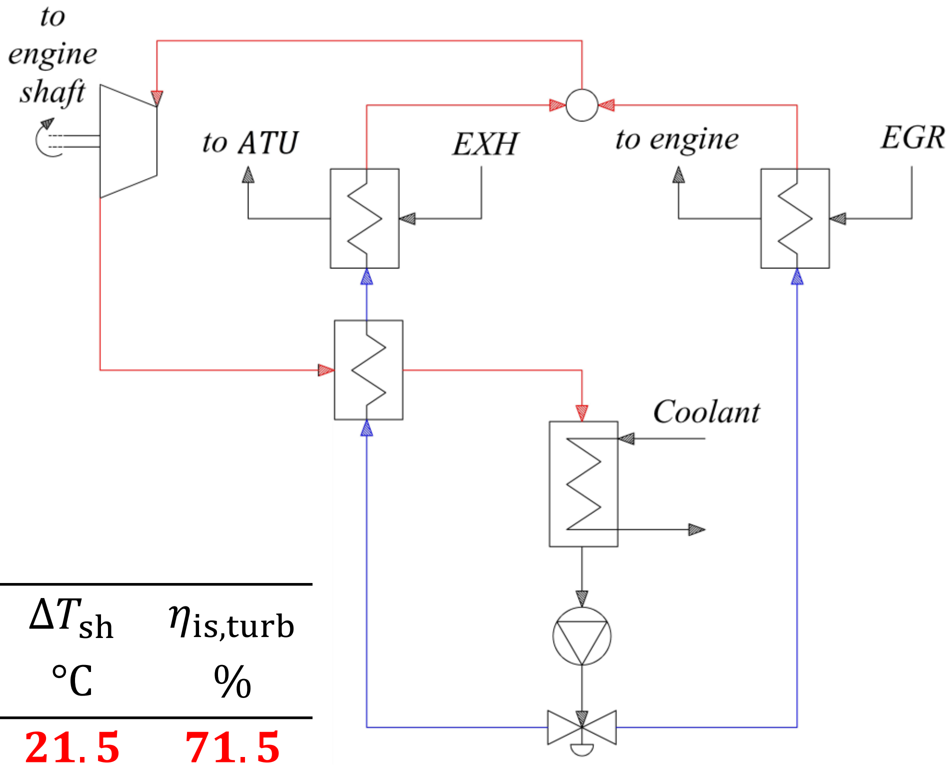
+

*image taken from www.braytonenergy.net

Best cycle configuration

Model assumptions and boundary conditions

$\dot{m}_{\mathrm{EXH}}$	0.131	kg/s
$\dot{m}_{\mathrm{EGR}}$	0.066	kg/s
T_{EGR}	400	°C
$T_{\mathrm{EXH,up}}$	314	°C
$T_{\mathrm{EXH,down}}$	265	°C
$\eta_{\mathrm{is,pump}}$	65	%
$\Delta P/P$	0.01	–



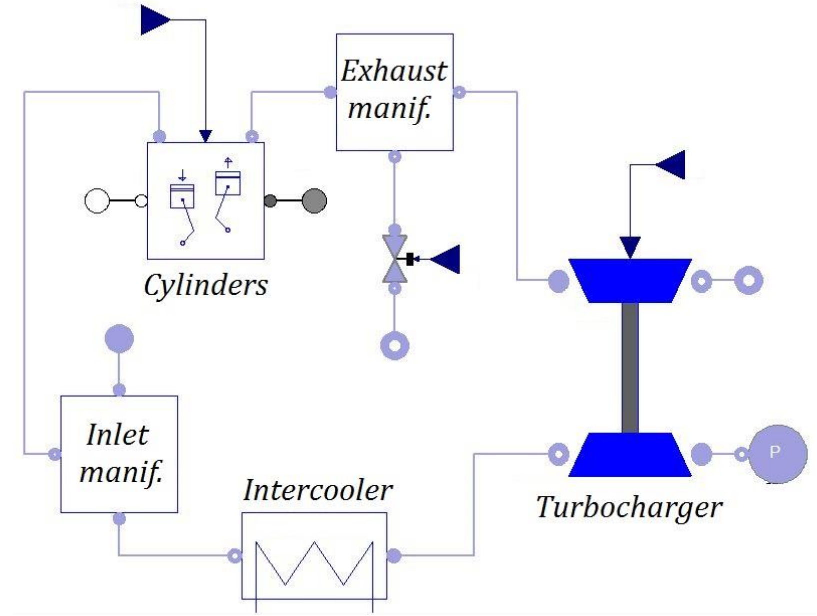
Optimization results

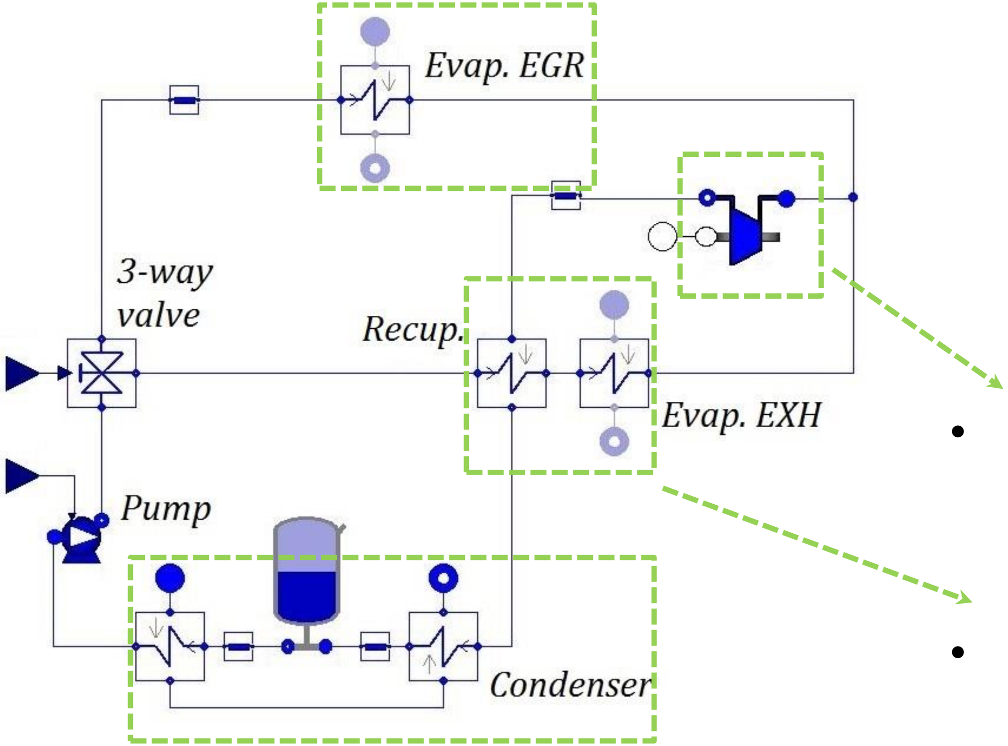
Source	$\dot{W}_{\mathrm{mec}}$ kW	$\dot{Q}_{\mathrm{EXH}}$ kW	$\dot{Q}_{\mathrm{EGR}}$ kW	p_{eva} bar	ΔT_{sh} °C	$\eta_{\mathrm{is,turb}}$ %
EGR + $\mathrm{EXH}_{\mathrm{up}}$	**4.8**	**15.6**	**20.7**	**12.6**	**21.5**	**71.5**
EGR + $\mathrm{EXH}_{\mathrm{down}}$	4.0	21.2	20.7	6.4	6.5	74.7
$\mathrm{EXH}_{\mathrm{down}}$	2.0	22.3	–	6.4	8.6	72.3

Dynamic modelling & control

Dynamic model

Whole powertrain system modeled in *Modelica*





▶ = system inputs / control variables

● ◎ = gas connection between DE and WHR unit

- Turbomachinery:
  - off-design performance predicted as function of β and ω
- Plate Heat Exchangers (PHEs):
  - preliminary static design;
  - 1D finite volume model
  - simplified off-design correlations

Control objectives

Control objectives → > 5

1. $\max(\dot{W}_{\mathrm{ORC}})$
2. $\boldsymbol{T_{\mathrm{max,ORC}} < 300°\mathrm{C}}$
3. $\boldsymbol{T_{\mathrm{min,EXH}} > 200°\mathrm{C}}$
4. $\Delta T_{\mathrm{sh}} > 5°\mathrm{C}$
5. cavitation, limit on p_{max}

..but..

Control variables → 2

1. evaporators split
2. pump speed

→ **nr. objectives > nr. degree of freedom**

Set points optimization

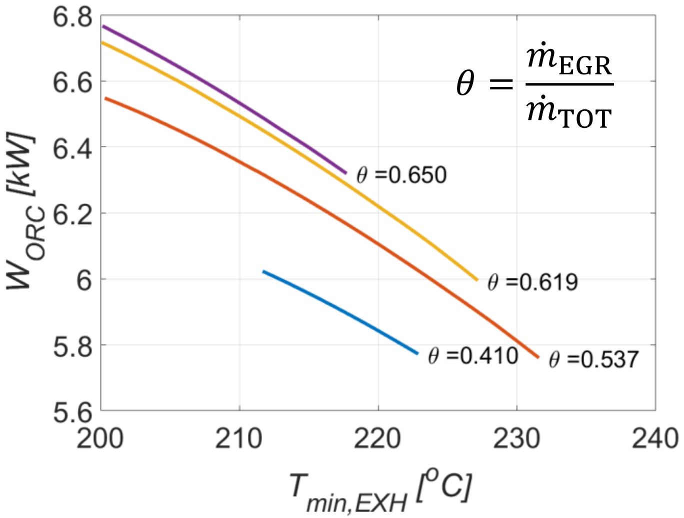
Primary requirements:

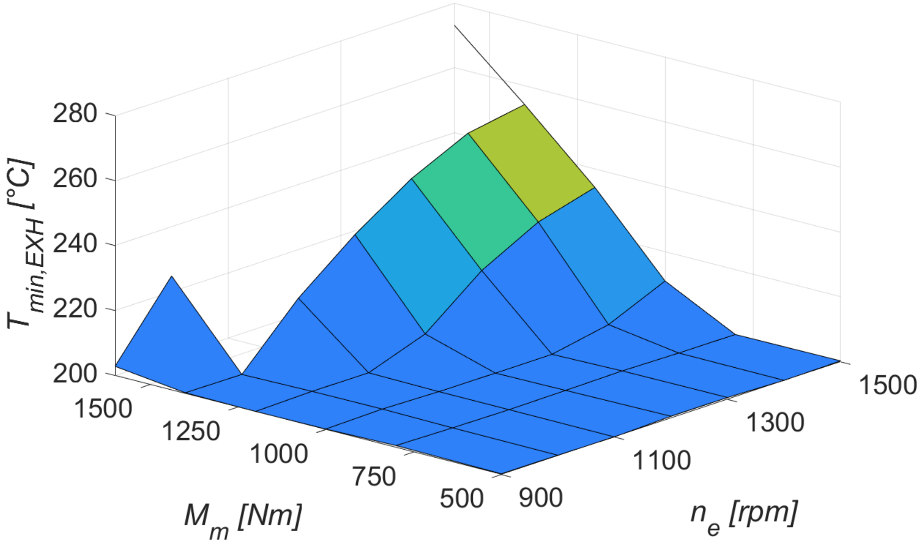
- SCR safe operation
- organic fluid stability

Controlled variables:

- $T_{\mathrm{min,EXH}}$
- ΔT_{sh}

Set-points constrained optimization

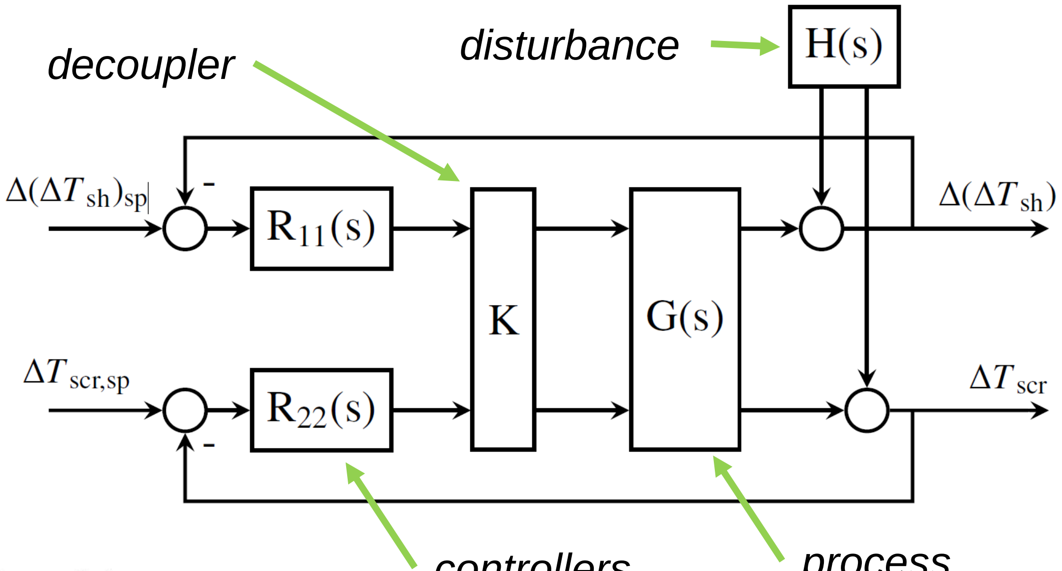




Control architecture

2 x 2 MIMO system → Relative Gain Array Λ matrix based on process transfer function matrix G(s), to quantify mutual interaction

$$G(s) = \begin{bmatrix} \dfrac{\Delta(\Delta T_{\mathrm{sh}})(s)}{\delta \dot{m}_{\mathrm{EGR}}(s)} & \dfrac{\Delta(\Delta T_{\mathrm{sh}})(s)}{\delta \dot{m}_{\mathrm{EXH}}(s)} \\ \dfrac{\Delta T_{\mathrm{scr}}(s)}{\delta \dot{m}_{\mathrm{EGR}}(s)} & \dfrac{\Delta T_{\mathrm{scr}}(s)}{\delta \dot{m}_{\mathrm{EXH}}(s)} \end{bmatrix} = \begin{bmatrix} G_{11}(s) & G_{12}(s) \\ G_{21}(s) & G_{22}(s) \end{bmatrix} \rightarrow \Lambda = \begin{bmatrix} \lambda_{11} & 1-\lambda_{11} \\ 1-\lambda_{11} & \lambda_{11} \end{bmatrix} \text{ with } \lambda_{11} = \frac{1}{1-\dfrac{g_{12}\, g_{21}}{g_{11}\, g_{22}}}$$



decoupler

disturbance

controllers

process

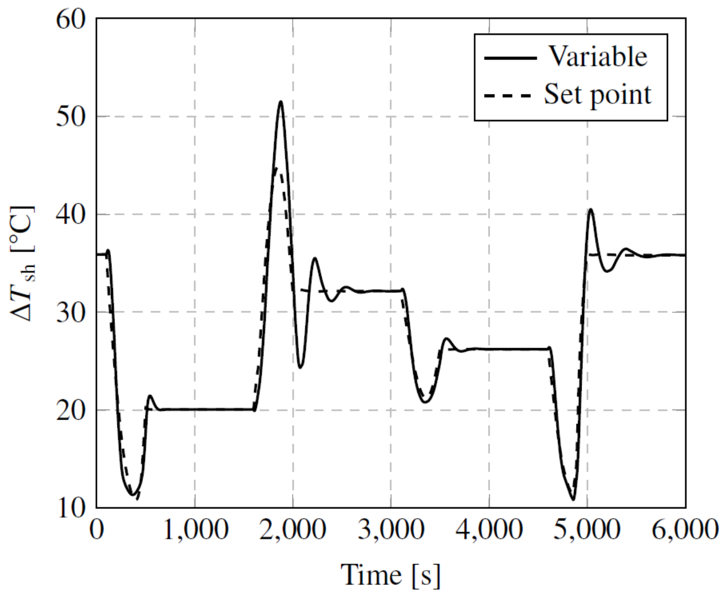
$$\bar{\lambda}_{11} = 2.5$$

statically decoupled centralized control architecture

Control limitations

Multivariable Right-Half-Plane transmission zeros analysis:
process is non-minimum phase → result of system design

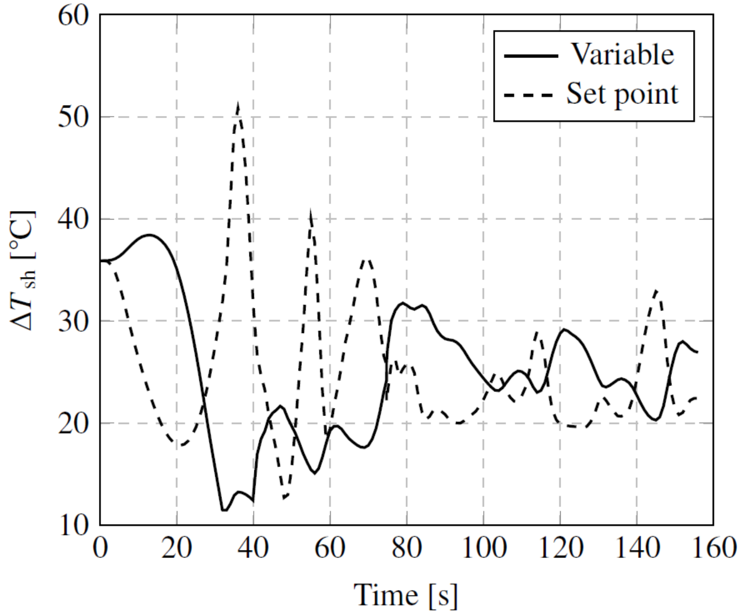
➡ limitation on bandwidth for stability reason, $\omega_{\mathrm{c,max}} = 0.01\ \mathrm{rad/s}$



"Ideal" driving cycle = slow ramps

→ good performance when system stressed at $\omega < \omega_{\mathrm{c,max}}$

“Real” drive cycle

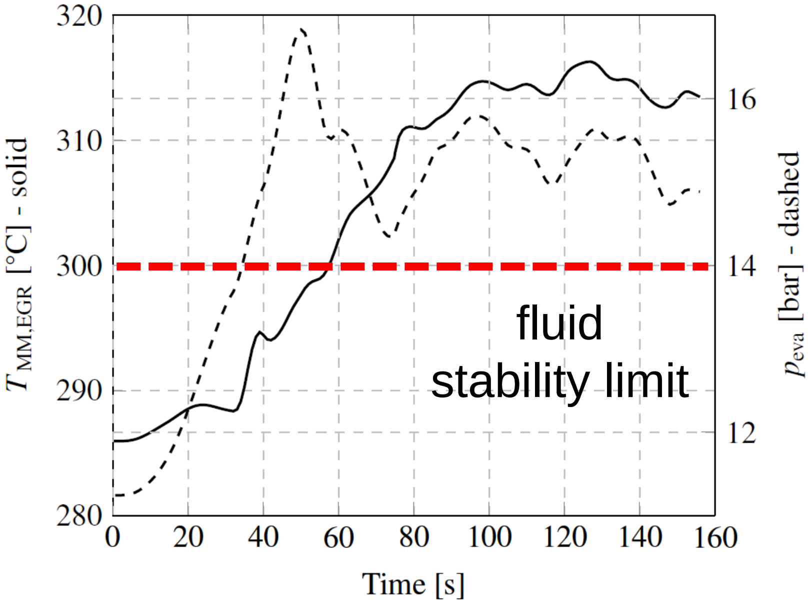


“Real” driving cycle = fast ramps

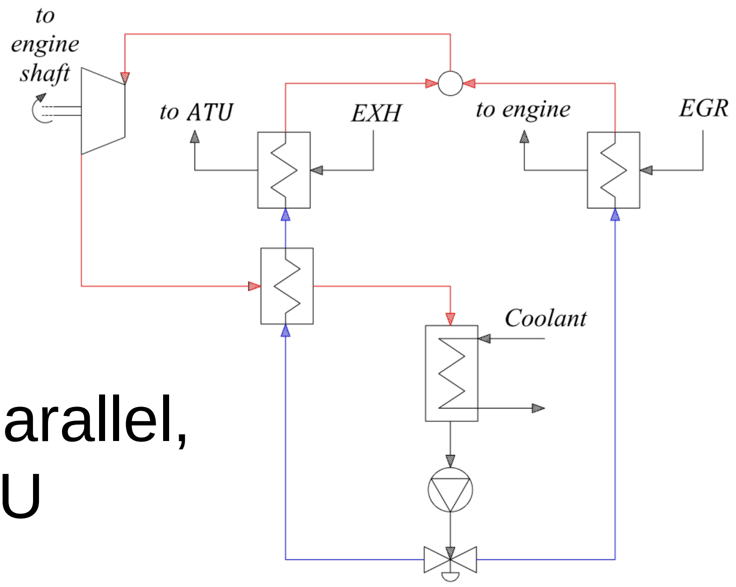
→ poor performance when system stressed at $\omega > \omega_{\mathrm{c,max}}$ (disturbance faster than process!)

$$T_{\mathrm{MM}} > 300°\mathrm{C} = T_{\mathrm{MM,max}}$$

→ primary control objective not satisfied



Conclusions

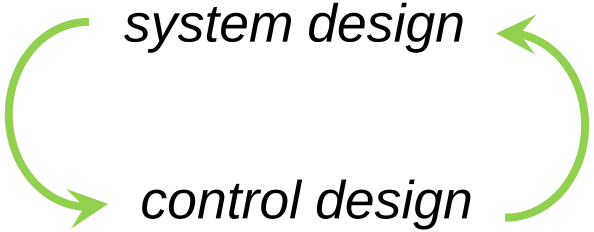


1. ORC power output at cruise speed is $4.8\ \mathrm{kW}$ → roughly 5% of fuel saving

2. Best configuration: two evaporators in parallel, exhaust gas cooling upstream of the ATU

3. Simple PI-based control system not safe

   - review of process design → change of system dynamics →
   - adoption of more sophisticated control system



system design

control design

Thank you for your attention!