A systematic methodology for the techno-economic optimization of Organic Rankine Cycles

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INTRODUCTION

When designing ORCs, it is important to optimize:

- Fluid selection
- Cycle configuration
- Heat Exchanger Network (HEN)
- Cycle variables (*p*, *T*, $\dot{m}$)

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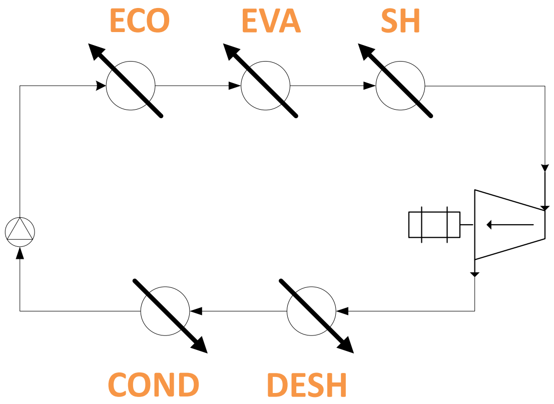
IN THIS WORK

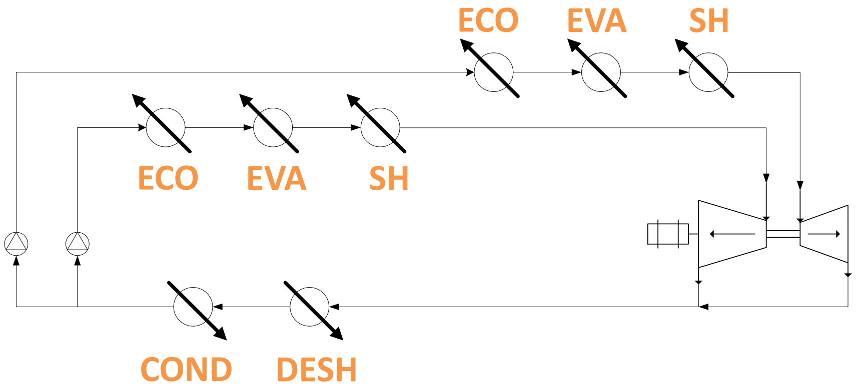
INTRODUCTION

Some different cycle configurations

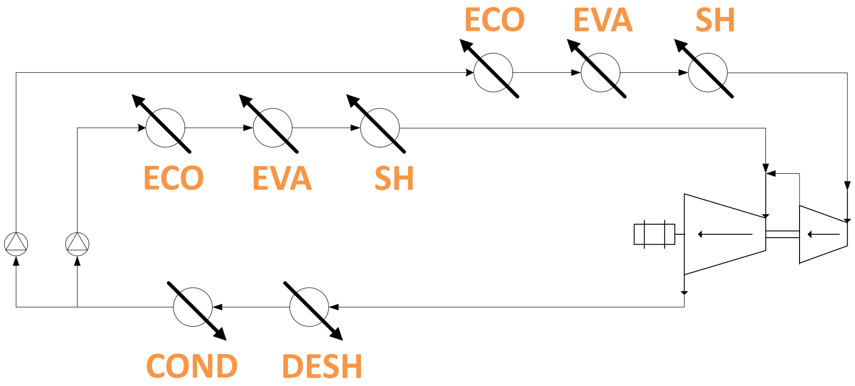
1-pressure level



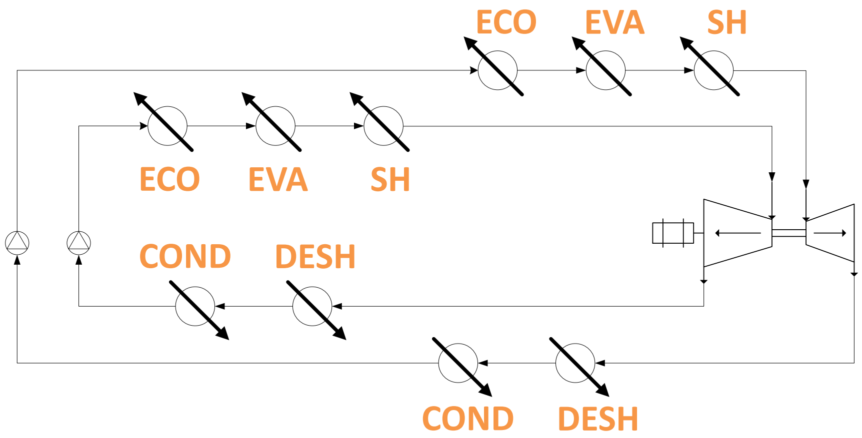
2-pressure level, turbines in parallel



2-pressure level, turbines in series



2-pressure level, tandem configuration



INTRODUCTION

Several possible Heat Exchanger layouts:

one pressure level, two heat sources

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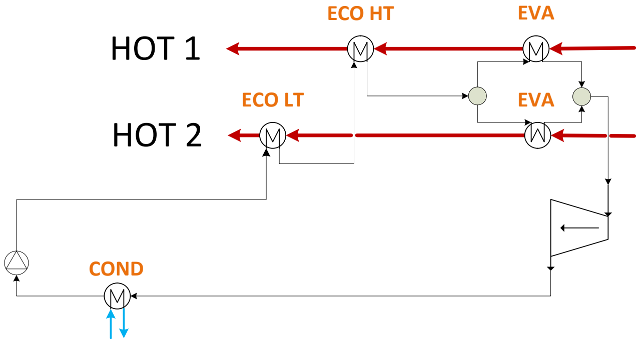
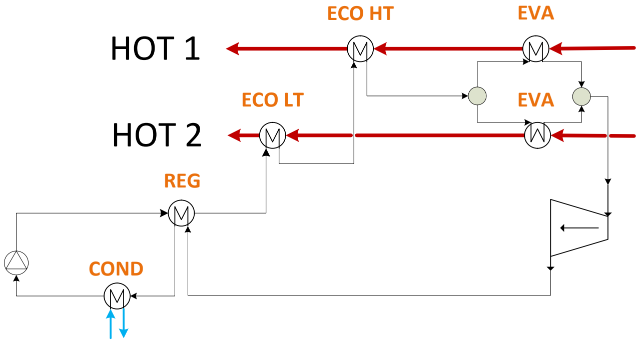
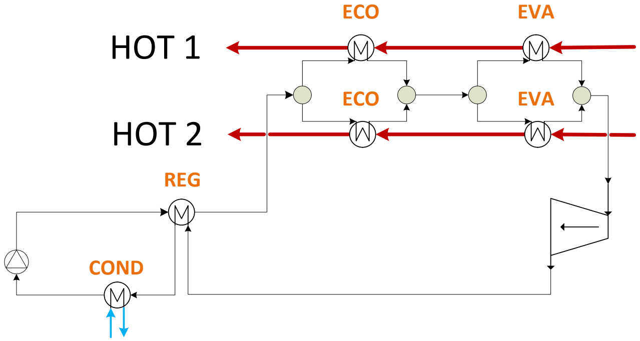
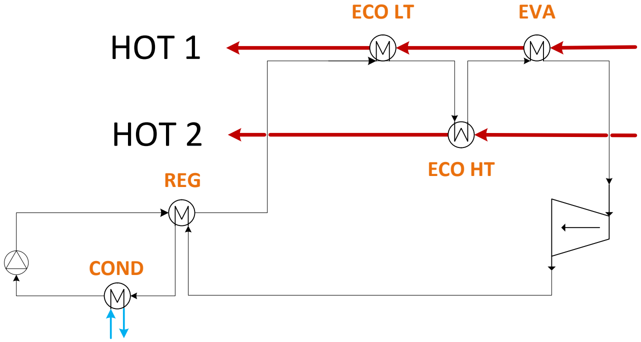
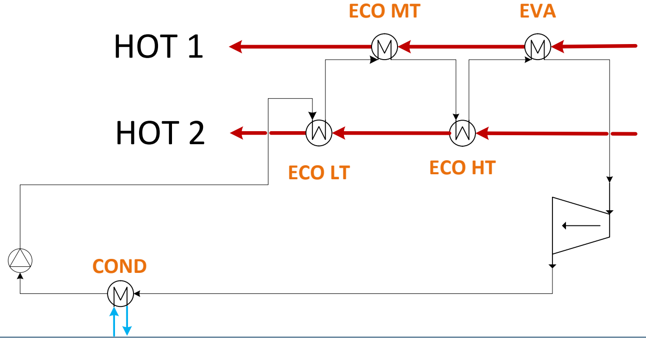
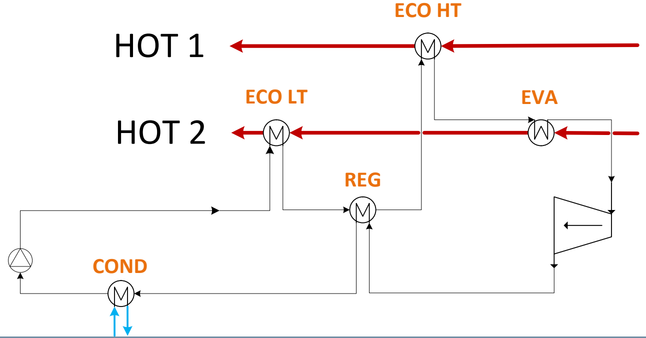












INTRODUCTION

Available ORC optimization approaches:

1. Optimization of cycle variables (p, T) with fixed cycle configuration

- Martelli et al., 2015
- Wang et al., 2012

2. Optimization of cycle variables (p, T) with fixed ORC scheme and simplified heat integration (Pinch Analysis)

- Toffolo et al., 2014
- Yu et al., 2017
- Scaccabarozzi et al., 2017

Limitations:

- Several possible ORC schemes (single vs. multiple levels, with/without regenerator, with turbines in series/parallel/tandem)
- Several possible arrangements of the heat exchangers
- ORC configuration and Heat Exchangers layout should be optimized simultaneously, specially for applications with two or more heat sources

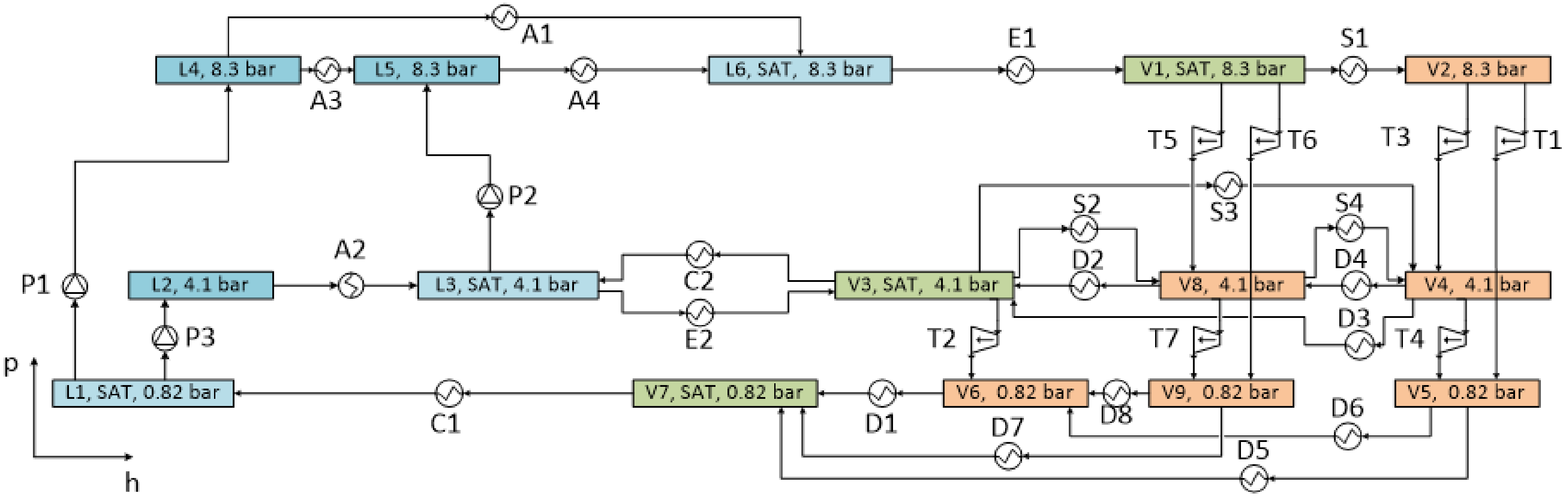
PROBLEM STATEMENT

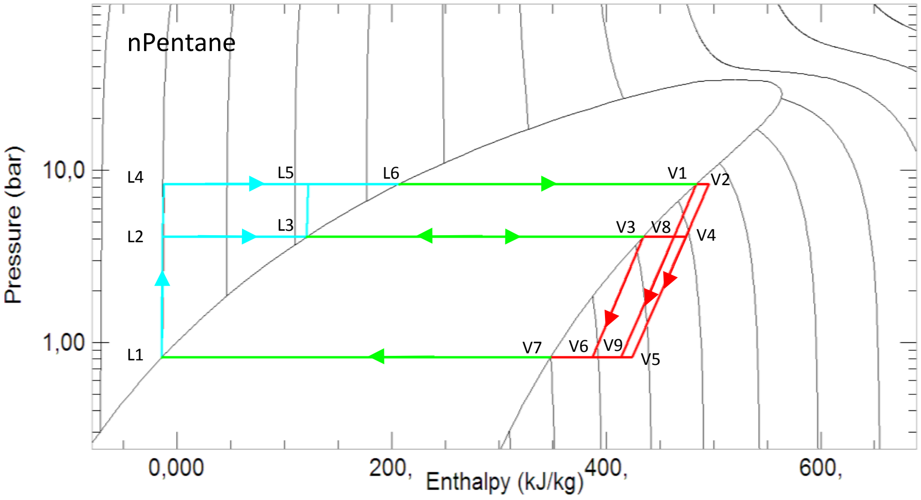
Given the available heat sources (fuel, hot gases, hot oil, etc.) and heat sinks (cooling water, air, etc.), determine:

- the optimal arrangement/optimal **layout of the Rankine cycle** (i.e., power cycle or heat pump, heat recovery or CHP, with single or double pressure levels, etc.)
- the optimal layout of the **heat exchanger network**
- the cost and optimal area of HXs, mass flow rates, pressures and temperatures of the streams

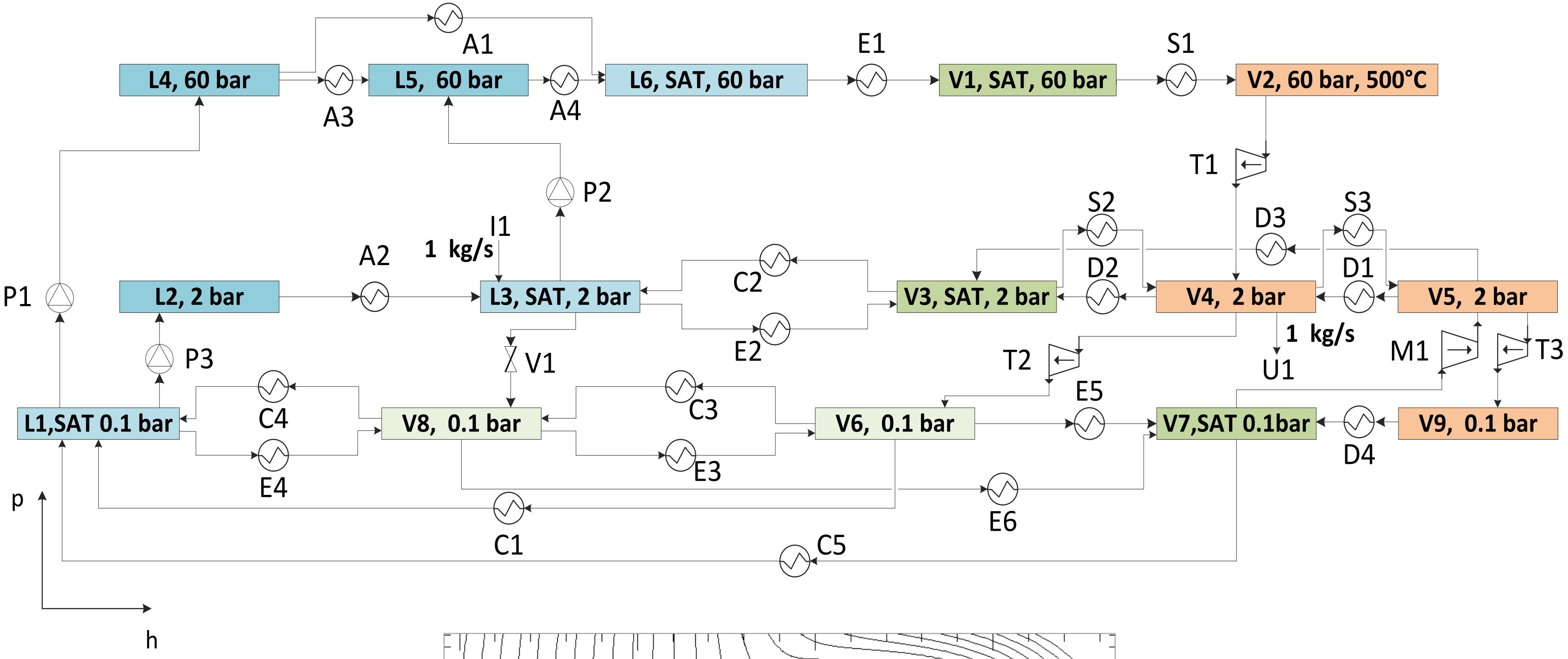
which maximize the **trade-off** between efficiency and capital costs

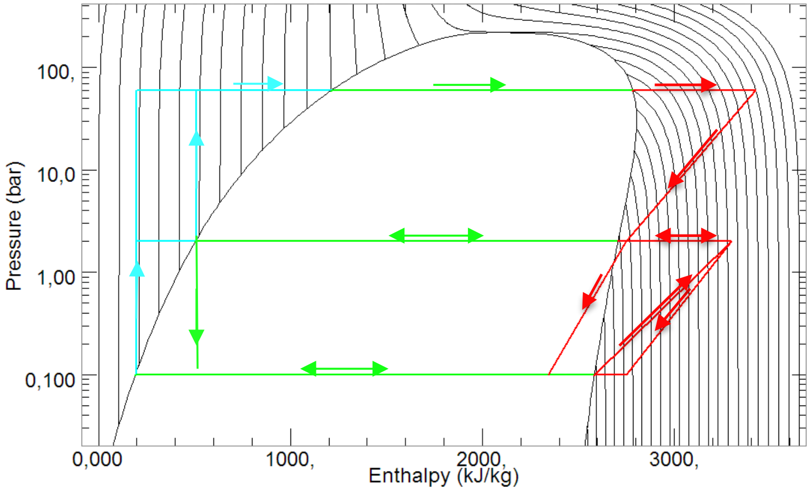
METHOD: the “p-h” superstructure for dry expansion fluids





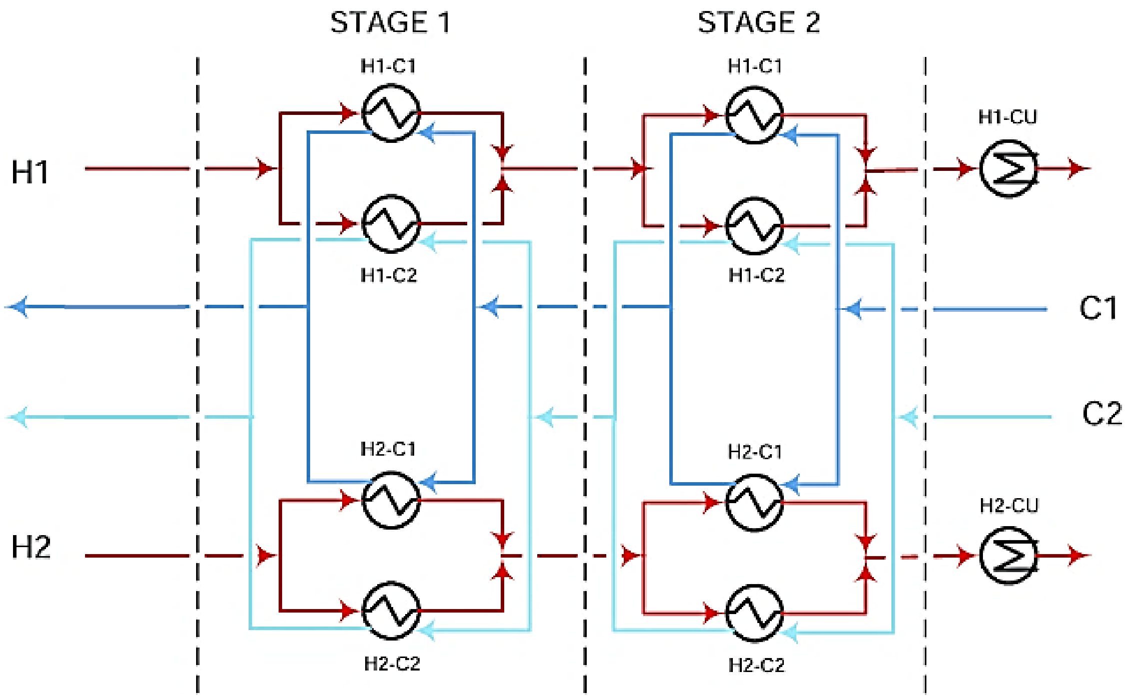
METHOD: the “p-h” superstructure for wet espansion fluids





Heat integration and heat exchanger network design

«SYNHEAT» model
(Yee & Grossmann 1990)
Mathematical model for Heat Exchanger Networks, recovering heat between hot and cold streams



Source: Escobar et al. *Applied Thermal Engineering* 63(1):177–191, 2014

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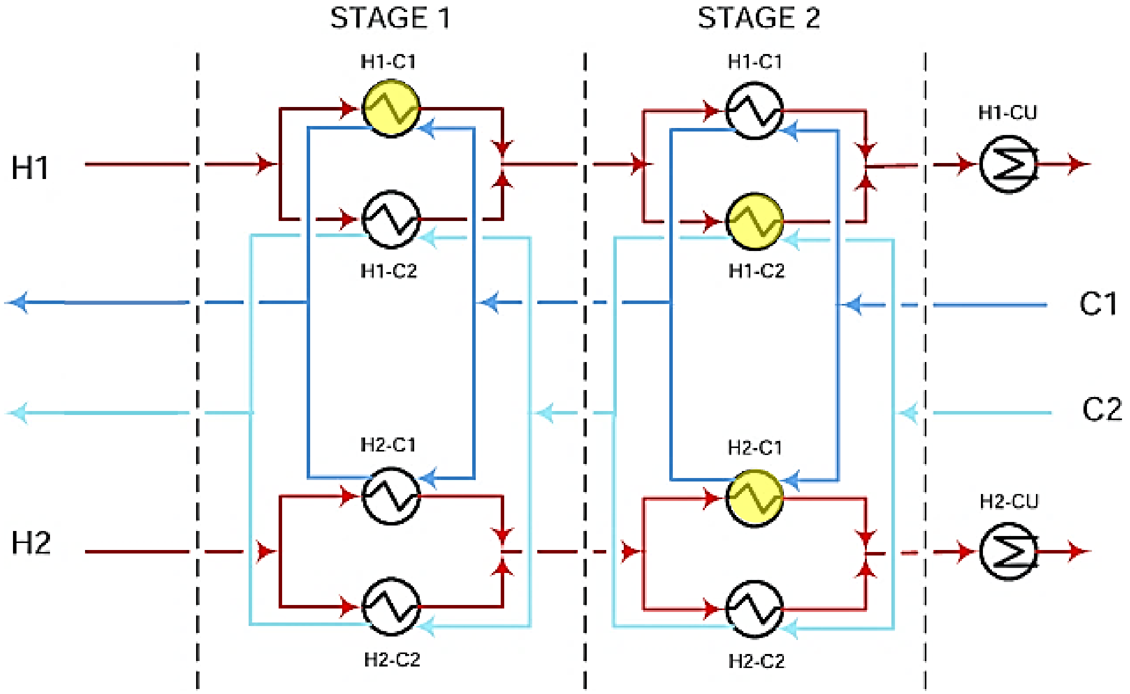

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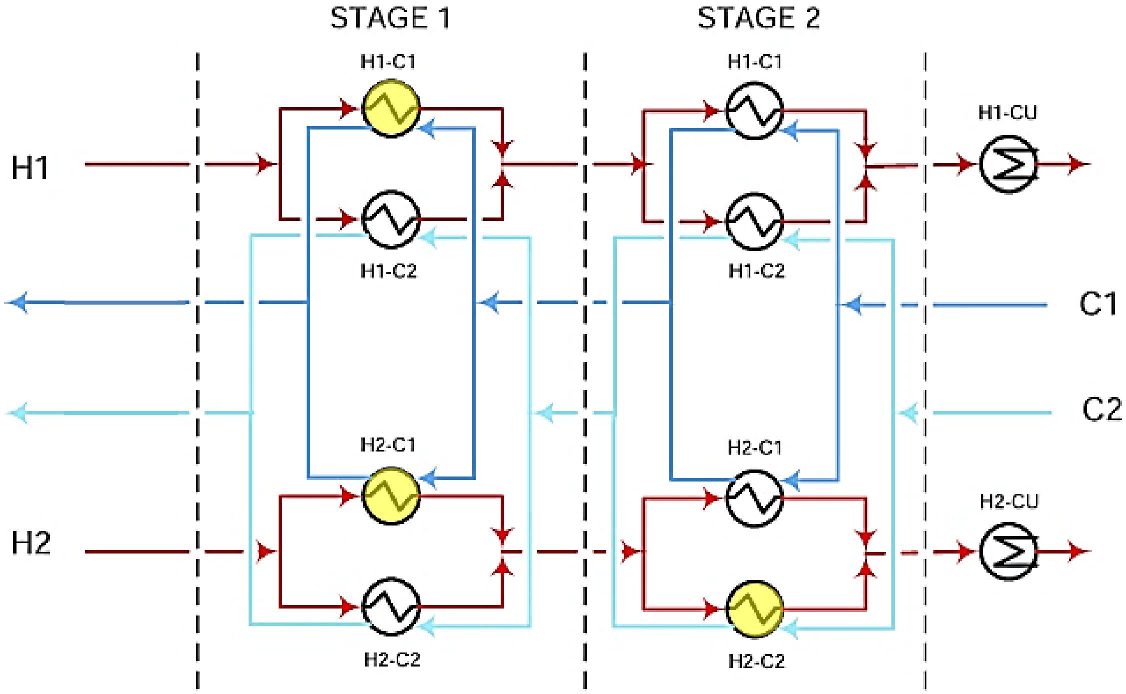

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METHOD

Main features:

- Extension of SYNHEAT superstructure

- Complex multiple level **heat recovery Rankine cycle superstructure**

- Selection of Rankine cycle components and HEN is modelled with binary variables; mass flow rates of cycle streams are optimized

- Design constraints and technical limitations (forced matches, forbidden matches, no stream splitting)

- Investment costs of the equipment units are accurately modeled

Cost models for Heat Exchangers

Bare module cost of the heat exchanger between hot stream *i* and cold stream *j:*

$$C_{HX} = F_M \cdot F_P \cdot c_{ref} \cdot \left(\frac{A_{ij}}{A_{ref}}\right)^f$$

where: A_{ij} heat exchanger area, F_M material factor, F_P pressure factor, c_{ref} specific area cost at the reference area A_{ref}, f scale-law exponent.

- ➢ Superstructure for Rankine cycles allows to reproduce a **wide range** of cycle configurations
- ➢ All heat integration options can be considered **systematically**
- ➢ **Best trade-off** between efficiency and capital costs

Mixed-Integer Non Linear Programming (MINLP) models

$$\min_{x,y} Z = c(x,y)$$

$$s.t. \quad h(x,y) = 0$$

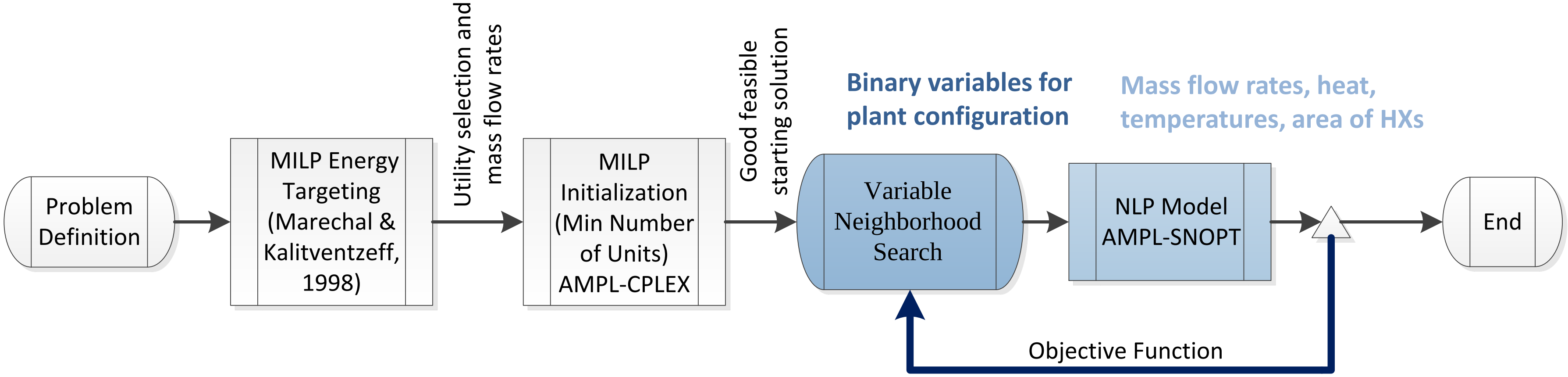
$$g(x,y) \leq 0$$

$$x \in X, y \in \{0,1\}^m$$

- $\boxed{x}$ is the vector of the **continuous variables** of the system (temperatures, pressures, mass flow rates, …); $\boxed{y}$ indicate the potential existence of components, such as heat exchangers (**binary variables**)
- The mass and energy balance equations $\boxed{h(x,y) = 0}$ are usually non-linear
- Inequalities $\boxed{g(x,y) \leq 0}$ indicate process specifications or bounds to the continuous variables

METHOD

Solution algorithm


Problem Definition

MILP Energy Targeting (Marechal & Kalitventzeff, 1998)

Utility selection and mass flow rates

MILP Initialization (Min Number of Units) AMPL-CPLEX

Good feasible starting solution

Binary variables for plant configuration

Variable Neighborhood Search

Mass flow rates, heat, temperatures, area of HXs

NLP Model AMPL-SNOPT

End

Objective Function

- Model written in AMPL
- Thermodinamic properties evaluated with Refprop V9.1

Martelli, E., Elsido, C., Mian, A. & Marechal, F. (2017). MINLP model and two-stage algorithm for the simultaneous synthesis of heat exchanger networks, utility systems and heat recovery cycles. *Computers and Chemical Engineering*

EXAMPLE 1

Data

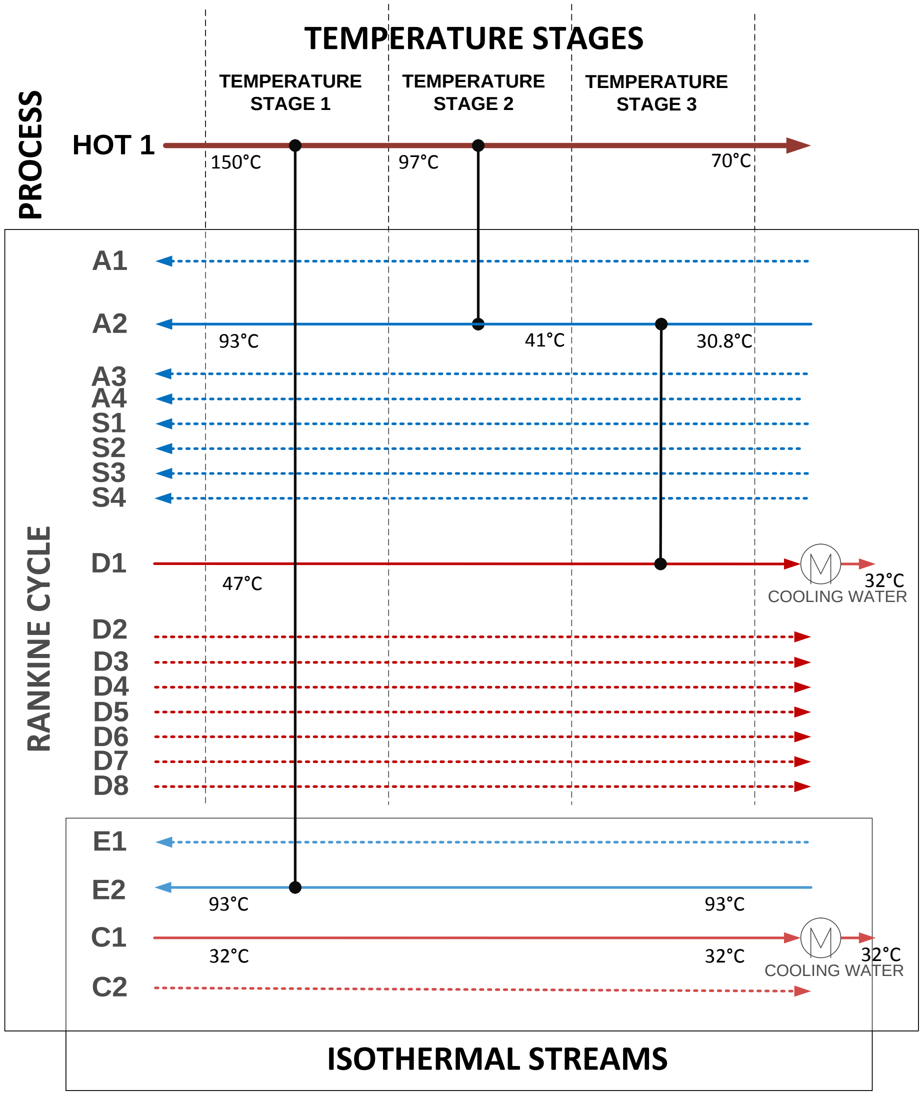
Process stream	$\dot{m}c_P$ [kW/K]	T_{IN} [° C]	T_{OUT} [° C]
HOT 1	125	150	70
CW	variable	15	20

Results

	nPentane	nButane
Type of ORC	two-pressure level, turbines in series	one-pressure level
Selected components	A1, A2, E1, E2, D1, D2, C1, T5, T2, P1, P3	A2, E2, D1, C1, T2, P3
Mass flow rate HP	13.87 kg/s	-
Mass flow rate LP	9.10 kg/s	24.29 kg/s
Net power	1.33 MW	1.18 MW
Net electric efficiency	13.31%	11.75%
Number of heat exchangers	9	5
Regenerators	YES	YES
TAC (cycle + HEN)	**-0.321 M$/y**	**-0.331 M$/y**

EXAMPLE 1

Output



TEMPERATURE STAGES

TEMPERATURE STAGE 1

TEMPERATURE STAGE 2

TEMPERATURE STAGE 3

PROCESS

HOT 1

150°C

97°C

70°C

RANKINE CYCLE

A1

A2

93°C

41°C

30.8°C

A3

A4

S1

S2

S3

S4

D1

47°C

32°C

COOLING WATER

D2

D3

D4

D5

D6

D7

D8

E1

E2

93°C

93°C

C1

32°C

32°C

32°C

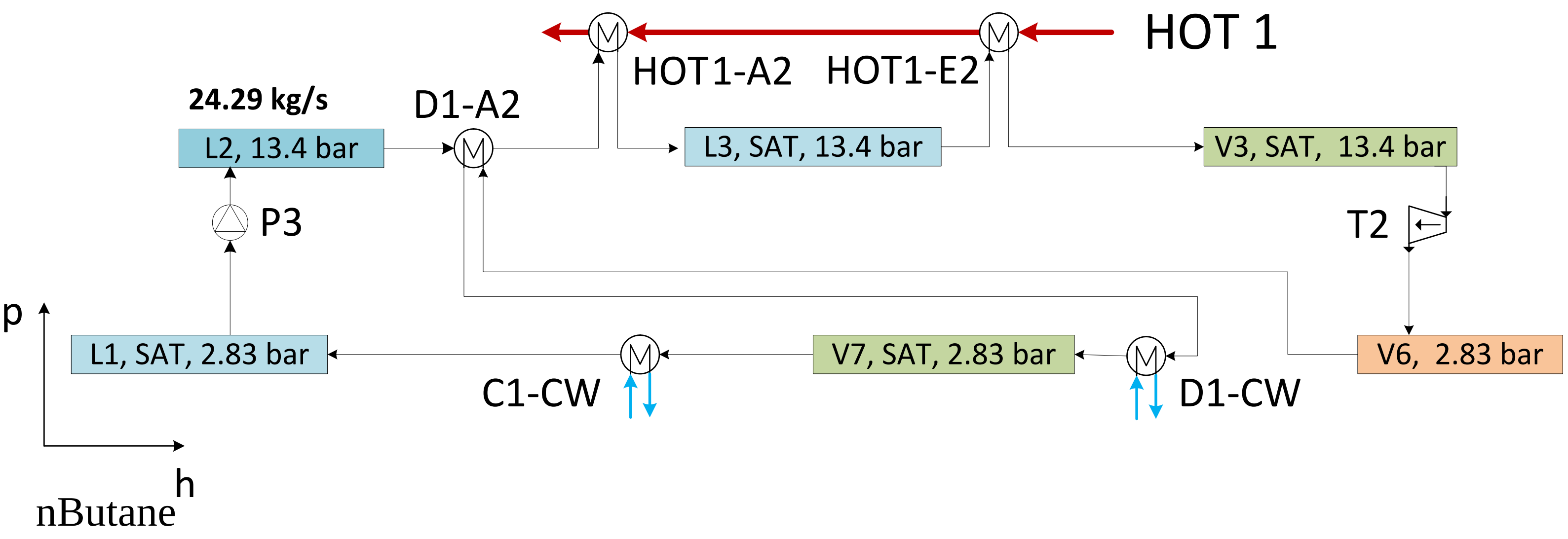
COOLING WATER

C2

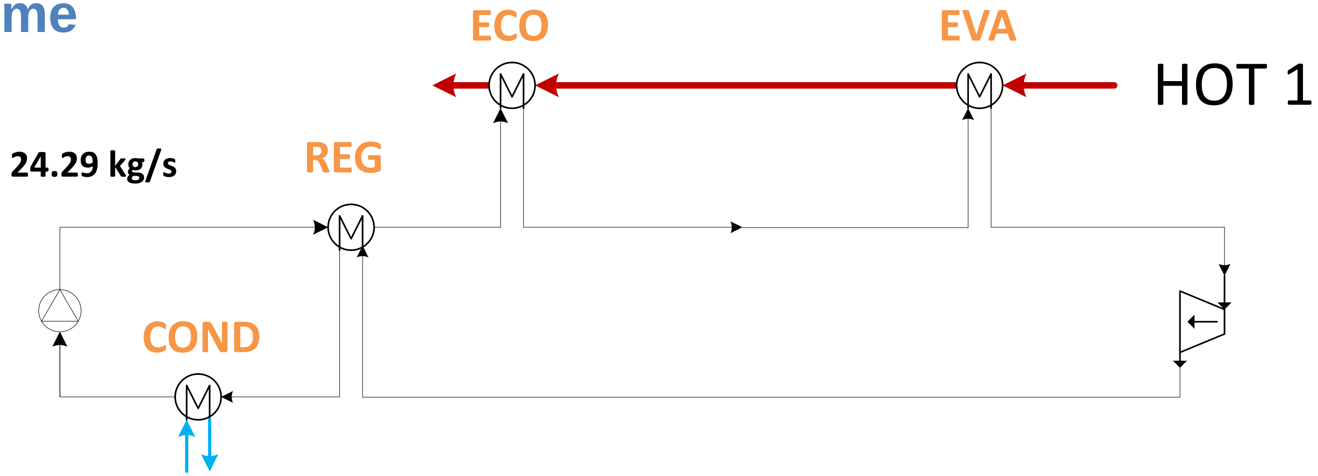
ISOTHERMAL STREAMS

EXAMPLE 1

Superstructure scheme



Plant scheme



EXAMPLE 2

Data

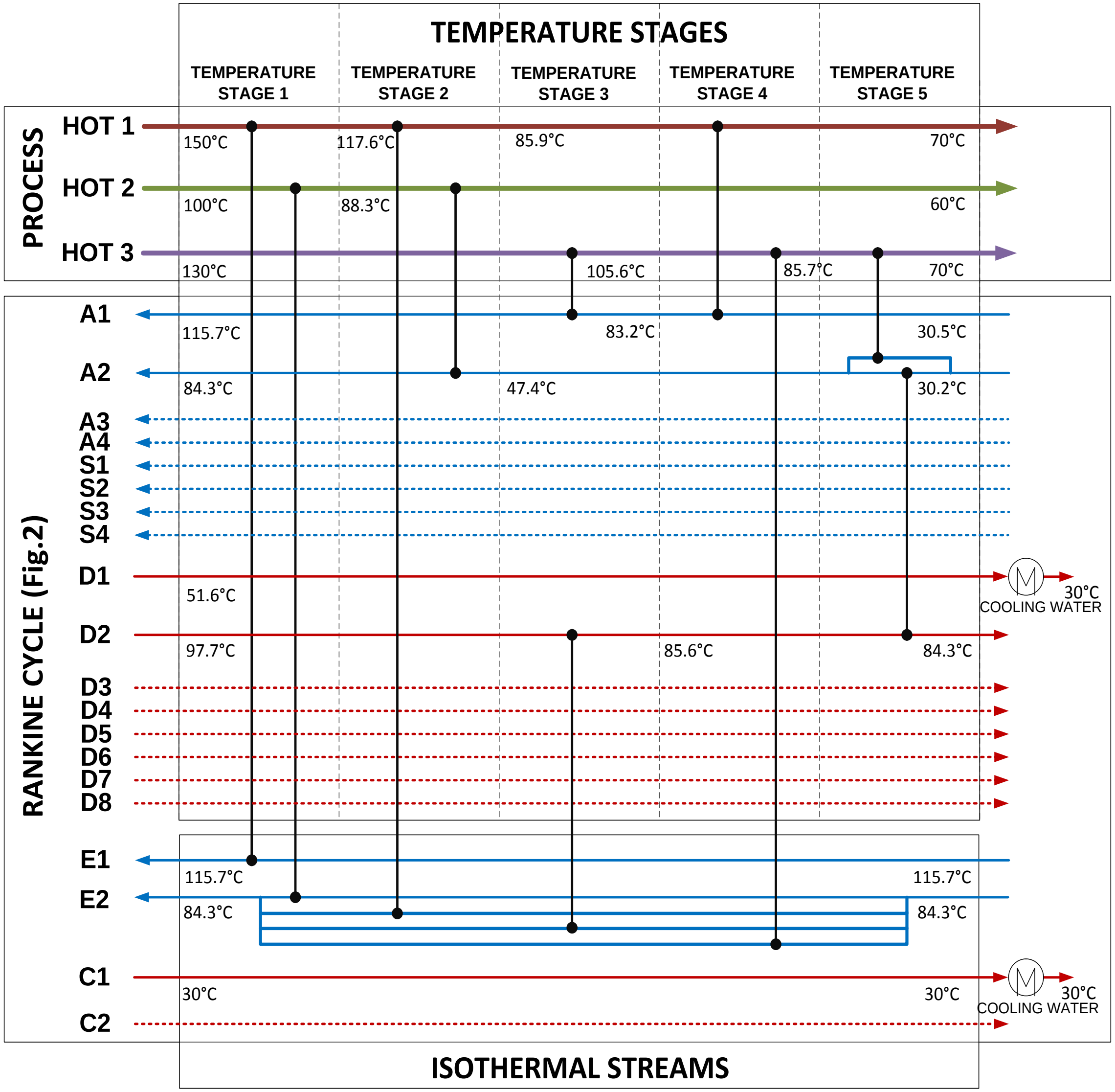
Process stream	$\dot{m}c_P$ [kW/K]	T_{IN} [°C]	T_{OUT} [°C]
HOT 1	125	150	70
HOT 2	62.5	100	60
HOT 3	50	130	70
CW	variable	15	20

Results

Working fluid	nPentane	isoPentane	nButane	R245fa
Mass flow rate HP	14.63 kg/s	15.59 kg/s	0 kg/s	0 kg/s
Mass flow rate LP	19.31 kg/s	20.35 kg/s	32.52 kg/s	57.91 kg/s
Net power	1.85 MW	1.85 MW	1.57 MW	1.50 MW
Net electric efficiency	11.93%	12.59%	11.02%	11.21%
Number of heat exchangers	12	13	9	8
Regenerator? (Yes/No)	Yes	Yes	No	No
TAC (ORC + HEN)	**-0.501 M$/y**	**-0.480 M$/y**	**-0.404 M$/y**	**-0.374 M$/y**

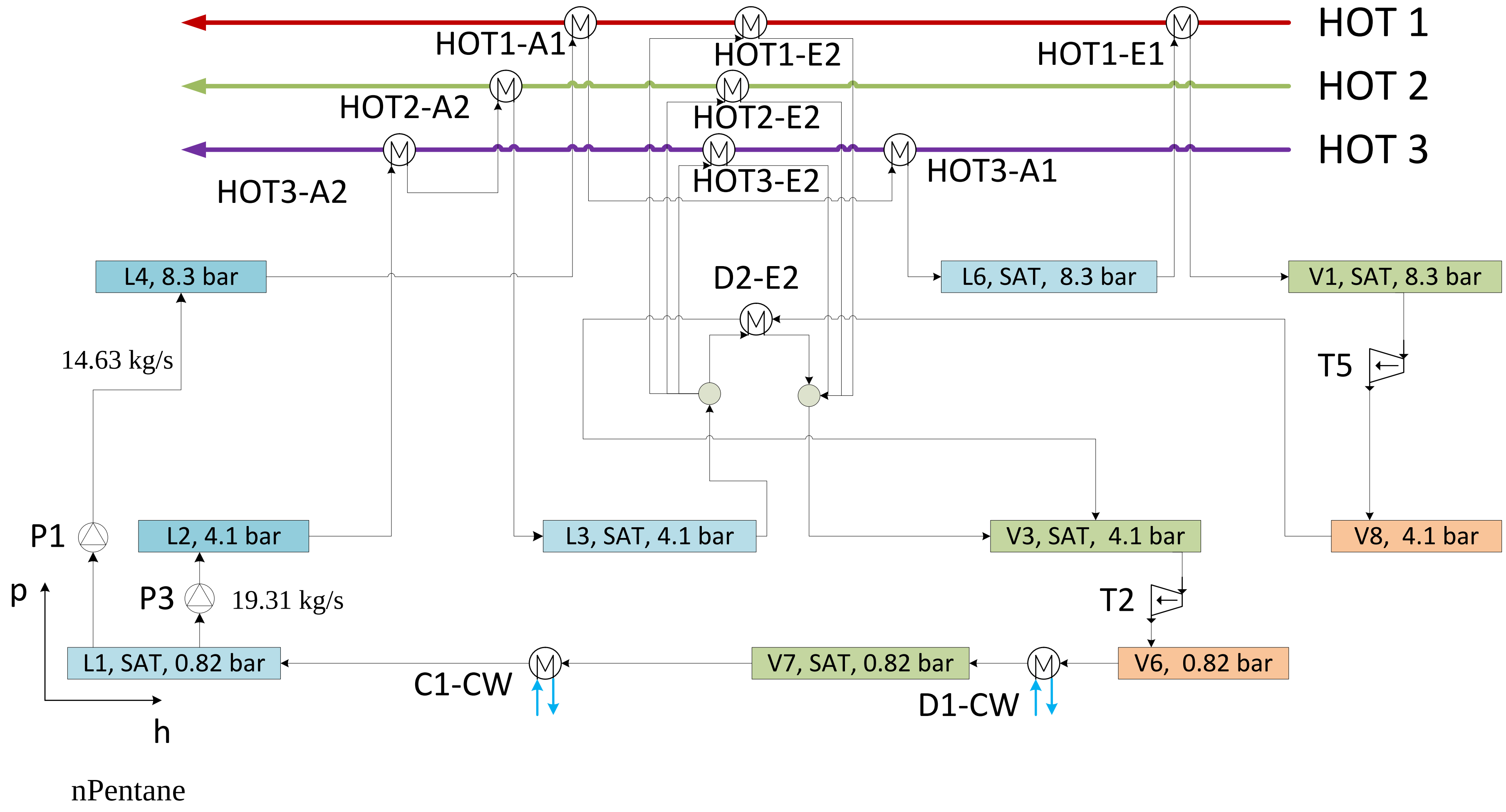
EXAMPLE 2

Output



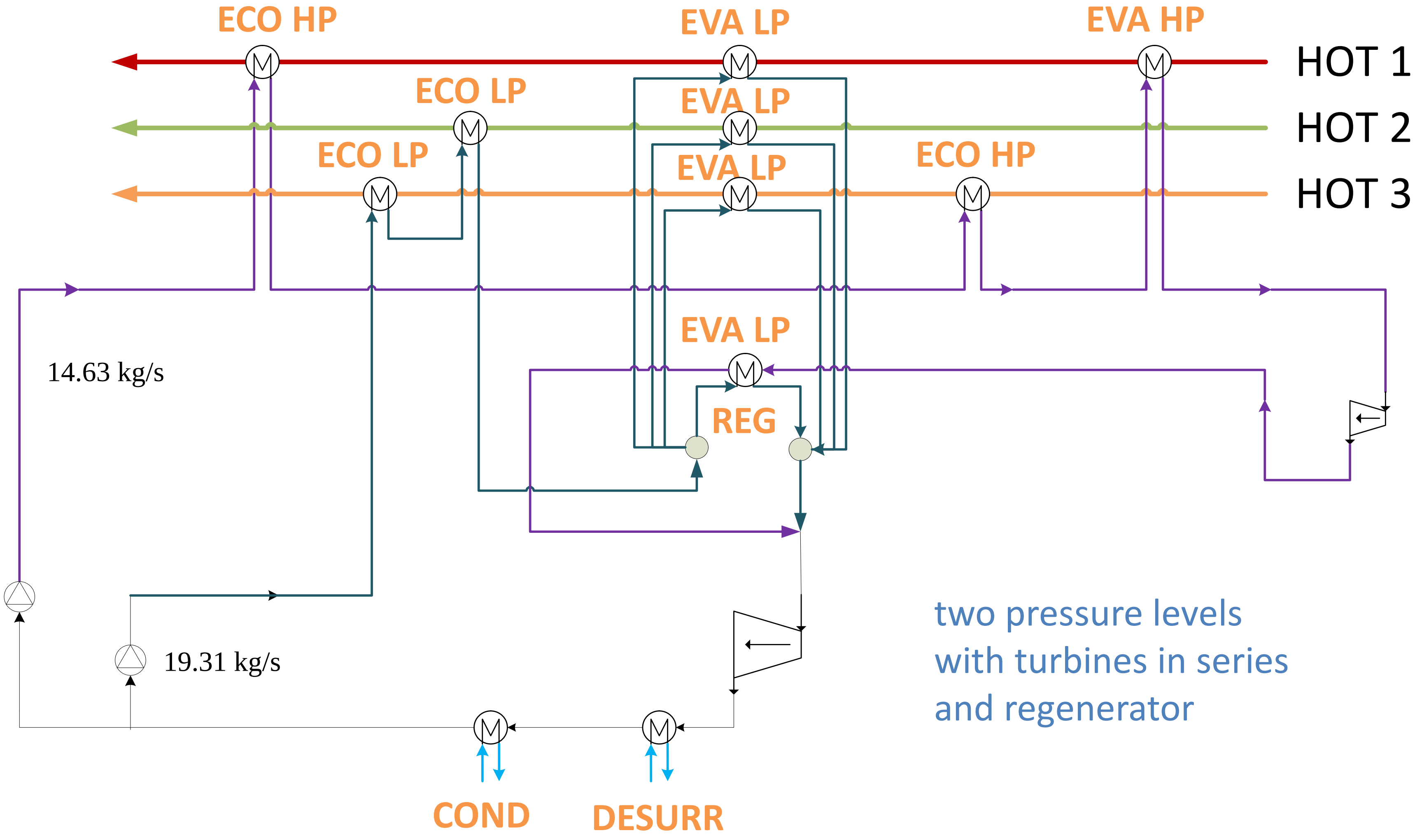
EXAMPLE 2

Superstructure scheme



EXAMPLE 2

Plant scheme



two pressure levels
with turbines in series
and regenerator

CONCLUSIONS

- The methodology allows to **systematically** optimize not only the cycle configuration but also the heat integration and HEN while considering the **trade-off** between efficiency and costs
- Compared to other cycle optimization methods, the proposed superstructure is more **general** as it can reproduce a wide variety of Rankine cycles
- The method can be applied to problems with **multiple heat sources/sinks** and it can handle both **power and inverse cycles**

Many thanks for your attention!
Any questions?

FUTURE ACTIVITIES

- Extension: different operating conditions and operational flexibility of cycles → multiperiod MINLP
- Improve *p* and *T* optimization (numerical issues due to integration between AMPL and Refprop)
- Other applications such as inverse Rankine cycles (for refrigeration or heat pumps)