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

Cristina Elsido\textsuperscript{a}, Alberto Mian\textsuperscript{b}, Emanuele Martelli\textsuperscript{a,}\textsuperscript{*}

\textsuperscript{a} Department of Energy, Politecnico di Milano
\textsuperscript{b} IPESE Laboratory, Ecole Polytechnique Fédérale de Lausanne
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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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
Several possible Heat Exchanger layouts: one pressure level, two heat sources

HOT 1

HOT 2
Several possible Heat Exchanger layouts:

one pressure level, two heat sources
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 expansion 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

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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

\[
\min_{x,y} Z = c(x,y) \\
\text{s. t.} \quad h(x, y) = 0 \\
\quad g(x, y) \leq 0 \\
x \in X, y \in \{0,1\}^m
\]

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

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

### Example 1

#### Data

<table>
<thead>
<tr>
<th>Process stream</th>
<th>( \dot{m}_c p ) [kW/K]</th>
<th>( T_{\text{IN}} ) [°C]</th>
<th>( T_{\text{OUT}} ) [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>HOT 1</td>
<td>125</td>
<td>150</td>
<td>70</td>
</tr>
<tr>
<td>CW</td>
<td>variable</td>
<td>15</td>
<td>20</td>
</tr>
</tbody>
</table>

#### Results

<table>
<thead>
<tr>
<th></th>
<th>nPentane</th>
<th>nButane</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of ORC</td>
<td>two-pressure level, turbines in series</td>
<td>one-pressure level</td>
</tr>
<tr>
<td>Selected components</td>
<td>A1, A2, E1, E2, D1, D2, C1, T5, T2, P1, P3</td>
<td>A2, E2, D1, C1, T2, P3</td>
</tr>
<tr>
<td>Mass flow rate HP</td>
<td>13.87 kg/s</td>
<td>-</td>
</tr>
<tr>
<td>Mass flow rate LP</td>
<td>9.10 kg/s</td>
<td>24.29 kg/s</td>
</tr>
<tr>
<td>Net power</td>
<td>1.33 MW</td>
<td>1.18 MW</td>
</tr>
<tr>
<td>Net electric efficiency</td>
<td>13.31%</td>
<td>11.75%</td>
</tr>
<tr>
<td>Number of heat exchangers</td>
<td>9</td>
<td>5</td>
</tr>
<tr>
<td>Regenerators</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>TAC (cycle + HEN)</td>
<td>-0.321 M$/y</td>
<td>-0.331 M$/y</td>
</tr>
</tbody>
</table>
EXAMPLE 1

Output

TEMPERATURE STAGES

HOT 1

TEMPERATURE STAGE 1
150°C

TEMPERATURE STAGE 2
97°C

TEMPERATURE STAGE 3
70°C

TEMPERATURE STAGE 1

150°C

97°C

70°C

TEMPERATURE STAGE 2

TEMPERATURE STAGE 3

D1

47°C

D2

D3

D4

D5

D6

D7

D8

E1

E2

C1

C2

COOLING WATER

COOLING WATER

PROCESS

RANKINE CYCLE

ISOTHERMAL STREAMS
EXAMPLE 1

Superstructure scheme

Plant scheme

24.29 kg/s

REG

ECO

EVA

HOT 1

COND

nButane

24.29 kg/s

P3

L1, SAT, 2.83 bar

L2, 13.4 bar

L3, SAT, 13.4 bar

V3, SAT, 13.4 bar

V6, 2.83 bar

V7, SAT, 2.83 bar

T2

C1-CW

D1-CW
## Data

<table>
<thead>
<tr>
<th>Process stream</th>
<th>$\dot{m}_p$ [kW/K]</th>
<th>$T_{IN}$ [°C]</th>
<th>$T_{OUT}$ [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>HOT 1</td>
<td>125</td>
<td>150</td>
<td>70</td>
</tr>
<tr>
<td>HOT 2</td>
<td>62.5</td>
<td>100</td>
<td>60</td>
</tr>
<tr>
<td>HOT 3</td>
<td>50</td>
<td>130</td>
<td>70</td>
</tr>
<tr>
<td>CW</td>
<td>variable</td>
<td>15</td>
<td>20</td>
</tr>
</tbody>
</table>

## Results

<table>
<thead>
<tr>
<th>Working fluid</th>
<th>nPentane</th>
<th>isoPentane</th>
<th>nButane</th>
<th>R245fa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass flow rate HP</td>
<td>14.63 kg/s</td>
<td>15.59 kg/s</td>
<td>0 kg/s</td>
<td>0 kg/s</td>
</tr>
<tr>
<td>Mass flow rate LP</td>
<td>19.31 kg/s</td>
<td>20.35 kg/s</td>
<td>32.52 kg/s</td>
<td>57.91 kg/s</td>
</tr>
<tr>
<td>Net power</td>
<td>1.85 MW</td>
<td>1.85 MW</td>
<td>1.57 MW</td>
<td>1.50 MW</td>
</tr>
<tr>
<td>Net electric efficiency</td>
<td>11.93%</td>
<td>12.59%</td>
<td>11.02%</td>
<td>11.21%</td>
</tr>
<tr>
<td>Number of heat exchangers</td>
<td>12</td>
<td>13</td>
<td>9</td>
<td>8</td>
</tr>
<tr>
<td>Regenerator? (Yes/No)</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>TAC (ORC + HEN)</td>
<td><strong>-0.501 M$/y</strong></td>
<td><strong>-0.480 M$/y</strong></td>
<td><strong>-0.404 M$/y</strong></td>
<td><strong>-0.374 M$/y</strong></td>
</tr>
</tbody>
</table>
### Example 2

#### Temperature Stages

<table>
<thead>
<tr>
<th>Process</th>
<th>Temperature Stage 1</th>
<th>Temperature Stage 2</th>
<th>Temperature Stage 3</th>
<th>Temperature Stage 4</th>
<th>Temperature Stage 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>HOT 1</td>
<td>150°C</td>
<td>117.6°C</td>
<td>85.9°C</td>
<td>70°C</td>
<td></td>
</tr>
<tr>
<td>HOT 2</td>
<td>100°C</td>
<td>88.3°C</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HOT 3</td>
<td>130°C</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Isothermal Streams

- **A1**: 115.7°C → 83.2°C → 30.5°C
- **A2**: 84.3°C → 47.4°C → 30.2°C
- **A3**: 84.3°C → 84.3°C → 30°C
- **A4**: 84.3°C → 30°C → 30°C
- **S1**: 84.3°C → 84.3°C → 30°C
- **S2**: 84.3°C → 30°C → 30°C
- **S3**: 84.3°C → 30°C → 30°C
- **S4**: 84.3°C → 30°C → 30°C
- **D1**: 51.6°C → 30°C
- **D2**: 97.7°C → 85.6°C → 84.3°C
- **D3**: 97.7°C → 85.6°C → 84.3°C
- **D4**: 97.7°C → 85.6°C → 84.3°C
- **D5**: 97.7°C → 85.6°C → 84.3°C
- **D6**: 97.7°C → 85.6°C → 84.3°C
- **D7**: 97.7°C → 85.6°C → 84.3°C
- **D8**: 97.7°C → 85.6°C → 84.3°C
- **E1**: 115.7°C → 115.7°C
- **E2**: 84.3°C → 84.3°C
- **C1**: 30°C
- **C2**: 30°C
EXAMPLE 2

Superstructure scheme
Plant scheme

Two pressure levels with turbines in series and regenerator.

14.63 kg/s

19.31 kg/s
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)