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

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Abstract

This work presents a general and systematic methodology for the techno-economic optimization of Rankine cycles. The proposed superstructure for Rankine cycles allows to reproduce a wide range of cycle configurations, such as cycles with/without regenerator, cycles with single or multiple pressure levels, and cycles integrated with multiple heat sources. The model is integrated with a recently developed methodology capable of optimizing also the arrangement and sizing of the heat exchangers of the plant (heat exchanger network synthesis). This allows to perform a full techno-economic optimization of the entire system. The resulting problem is a challenging Mixed Integer Non Linear Problem (MINLP) which is solved with an ad hoc algorithm. The methodology is applied to two case studies for power cycles with single and multiple heat sources. This work can help engineers identify the right thermodynamic cycle to integrate with an industrial process and design techno-economically optimal Rankine cycles for waste heat recovery from single or multiple heat sources, by considering heat integration and cycle design optimization simultaneously.

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Keywords: Superstructure; optimization; heat integration; Heat Exchanger Networks

1. Introduction

The successful integration of technologies to recover useful energy from waste heat can offer great advantages in

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the fields of chemical, oil refining and energy industry in terms of reduction of costs, improvements in energy efficiency and reduction of greenhouse gas emissions. Organic and Steam Rankine Cycles (respectively denoted as ORC and SRC) can be customized to recover low/high temperature heat from different waste heat sources and generate useful power. Consequently, the optimization of Rankine cycles is a highly investigated research topic. Several design approaches have been proposed in the last years for the optimization of Rankine cycles [1]. The typical approach consists in fixing the plant configuration (i.e., cycle configuration and integration of the heat exchangers with the boiler/waste heat recuperator) and optimizing the cycle variables with the black-box strategy [2]: the cycle model is executed by the optimization algorithm as a "black-box" function. The optimization algorithm varies the design variables looking for the minimum of the selected objective function, and, for each sampled solution, an ad hoc routine (in Aspen Plus®, Fortran or Matlab®) solves the model to evaluate the cycle performance. For example, in Dai et al. [3] the cycle model is solved with an ad hoc iterative routine written by the authors in Fortran, while the optimization problem is tackled with a Genetic Algorithm. The optimization of the cycle variables is repeated for ten different working fluids. Wang et al. [4] propose a Matlab model of a low temperature waste heat recovery ORC which includes thermodynamic, heat transfer and economic relations. A set of thirteen working fluids is defined, and for each of them the main four design variables (pressures of evaporation and condensation pressures, and velocities of working fluid and cooling water in the heat exchangers) are optimized with a black-box approach: the cycle simulation code is executed as a black-box function by a Simulated Annealing algorithm. Pierobon et al. [5] propose a similar multi-objective optimization approach for the design of heat recovery ORCs for offshore platforms (where cycle weight and size matter). Other works using the black-box approach with fixed heat integration are those by Lecompte et al. [6], Maraver et al. [7], Walraven et al. [8], Martelli et al. [9].

To the best of our knowledge, Desai & Bandyopadhyay [10] are the first authors to consider process integration of ORCs for waste heat recovery. They assume ORC schemes with turbine bleeding and regeneration and place the ORC below the pinch point (i.e., the ORC can utilize the low-temperature heat below the process pinch point). The authors use pinch analysis to determine the operating conditions of the ORCs and then use heuristics to derive a feasible heat exchanger network. Based on this work, Chen et al. [11] optimize the ORC and the Heat Exchanger Network (HEN) in two steps: first they design a stand-alone HEN for minimum utility consumption, using the well-known SYNHEAT superstructure proposed by Yee and Grossmann [12]; then they integrate a simple single-level ORC below the process pinch point maximizing the work produced from waste heat. Chen et al. [13] consider the use of an intermediate heat transfer fluid or the direct integration of ORC and heat sources/sinks. They use a simplified method to solve the Mixed Integer NonLinear Programming (MINLP) problem, with the objective to maximize the net power output of the ORC. The economic feasibility of the solutions is considered only after the optimization.

Hipolito-Valencia et al. [14] propose a method that simultaneously optimizes HEN and ORC based on two simplifying assumptions: (i) use of fixed ORC schemes, and (ii) fixed heat integration options between ORC streams and heat sources/sinks. Yu et al. [15] address the problem of techno-economic ORC optimization from multiple waste heat stream recovery. For safety and controllability reasons, they only consider indirect integration with hot water as an intermediate heat transfer fluid between heat sources/sinks and ORC. The hot water is used as cold end utility in the HEN, to recover the low temperature waste heat. The well-known energy targeting model proposed by Duran & Grossmann [16] is used to address the heat integration, then a suboptimal HEN is derived heuristically. Toffolo et al. [17] optimize also the heat integration and assess different heat exchanger networks (HEN) of the ORC plant. They use the HEATSEP method [18], based on the Pinch Analysis approach [19], and the Sequential Quadratic Programming algorithm. Scaccabarozzi et al. [20] have recently proposed another methodology for the thermodynamic optimization of ORCs and preliminary screening of working fluids capable of accounting for the heat integration between ORC and multiple heat sources. The methodology employs the energy targeting technique by [21] and an evolutionary algorithm [2]. The output is the maximum achievable efficiency of the ORC by recovering heat from all the available heat sources. However, the HEN arrangement is not determined because such mathematical problem is extremely challenging [22].

In this work, we propose a superstructure based approach for the techno-economic optimization of ORCs and SRCs. 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 and it optimizes also the heat exchanger network of the plant, integrating the heat sources/sinks with the Rankine cycle. In addition, the method can be applied to problems with multiple heat sources/sinks and it can handle both power and inverse cycles.

2. General p-h superstructure for Rankine cycles

The problem of designing the optimal Rankine cycle for a chemical/energy process can be stated as follows: "Given the set of hot and cold streams of the process (i.e., heat sources/sinks), the process needs of hot water/liquid and steam/vapor (to be extracted), the technical limitations (e.g., forbidden/forced matches, no stream splitting, etc.) and economic data (e.g., price of fuels, price of electricity, cost models of process units, etc.), determine the optimal configuration of the Rankine Cycle (i.e., power cycle or heat pump, heat recovery or CHP, with single or double pressure levels, etc.), the optimal working fluid selection, mass flow rates and the optimal HEN."

A schematic representation of the Rankine cycle superstructure proposed to tackle such design problem is represented in Fig. 1 for wet-expansion fluids and Fig. 2 for dry-expansion fluids. The values of pressures and temperatures in Fig. 1 and Fig. 2 are just exemplary to illustrate the features of the superstructure.

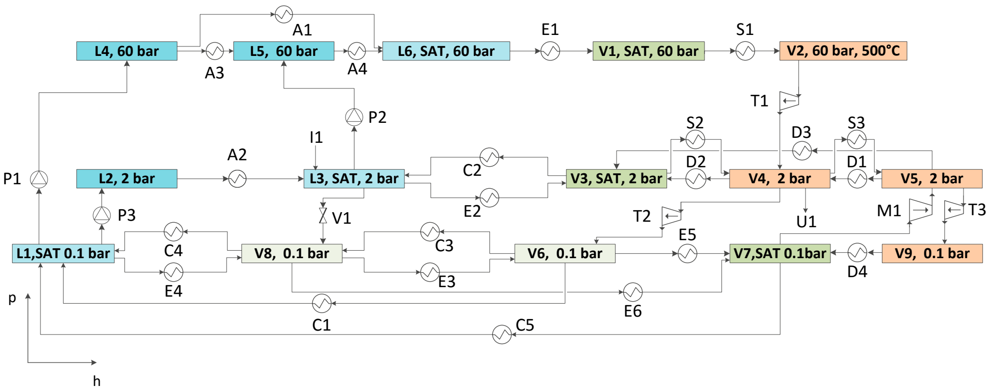

Figure 1: A general Rankine Cycle superstructure for wet-expansion fluids (e.g., H_2O, NH_3). Pressures and temperatures shown in the figure are just exemplary.

The superstructure is composed by liquid (L) and vapor (V) headers that can be connected by different process units, namely, compressors (M), valves (V), pumps (P), turbines (T) and heat exchangers (economizer (A), evaporator (E), superheater (S), condenser (C), desuperheater (D)). I and U denote input/output of liquid and vapor taken/sent to the process. The user defines the list of possible headers and process units connecting them. Alternatively, the set of process units between headers can be automatically generated by applying simple rules (e.g., valves can be installed only from a header at higher pressure to a header of lower pressure). Although systematic, the automatic generation procedure may lead to useless components which considerably increase the size of the optimization problem.

The superstructure shown in Fig. 1 features the minimum number of process units to reproduce different Rankine cycles for wet-expansion fluids (e.g., water) including inverse Rankine cycles (for refrigeration or heat pumps):

- single pressure level steam cycles (at 60 bar: V2-V4-V6-L1-L4-L6-V1, at 2 bar without reheat: V4-V6-L1-L2-L3-V3, at 2 bar with reheat: V4-V5-V9-V7-L1-L2-L3-V3, with back-pressure steam turbine between 60 bar and 2 bar: V1-V2-V4-V3-L3-L5-L6);
- two-pressure level steam cycle (i.e., composition of two single-pressure steam cycles at 60 bar and 2 bar);
- steam cycle with extraction and condensing turbine (i.e., composition of the single pressure steam cycle at 60 bar and the steam cycle with back-pressure steam turbine);
- heat pump (V7-V5-V3-L3-V8).

Moreover, the model can reproduce any hybrid configuration of the cycle, respecting the mass and energy balances at each header. Although the superstructures represented in the figures are specific, the cycle building blocks developed in these examples can be used to create a wide range of possible customized cycle configurations to match an arbitrary heat source, such as cycles with/without regenerator, cycles with multiple pressure levels, as well as heat pumps, etc. For the sake of space and consistency, in this work we show only examples with ORCs. Examples featuring heat pumps and steam cycles will be shown in an extended version under preparation.

The superstructure shown in Fig. 2 features the minimum number of process units to reproduce different Rankine cycles for dry-expansion fluids (e.g., nPentane), such as: single pressure level steam cycles (at 8.3 bar with superheating: V2-V5-V7-L1-L4-L6-V1, at 8.3 bar without superheating: V1-V9-V7-L1-L4-L6, at 4.1 bar with superheating: (V4-V5-) or (V8-V9-) V7-L1-L2-L3-V3, at 4.1 bar without superheating: V3-V6-V7-L1-L2-L3, between 8.3 bar and 4.1 bar: V1-V2-V4-V3-L3-L5-L6), with/without regenerator (the regenerator can be automatically obtained in the HEN optimization by matching a desuperheater with an economizer); two-pressure level steam cycle (i.e., composition of two single-pressure level steam cycles at 8.3 bar and at 4.1 bar) with turbines in series, parallel or tandem [23]. Fig. 3 shows all the thermodynamic transformations considered by the Rankine cycle superstructure of Fig. 2

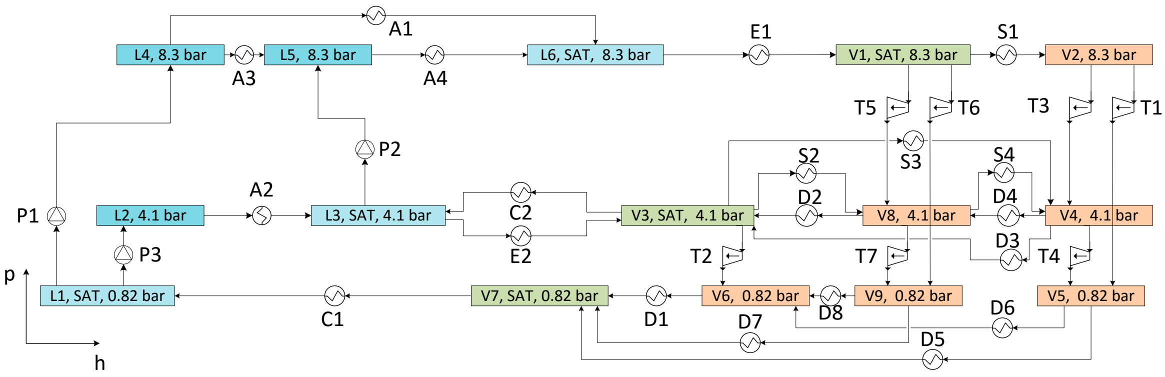

Figure 2: A general Rankine cycle superstructure for dry-expansion fluids. Pressures shown in the scheme refer to the case studies for nPentane.

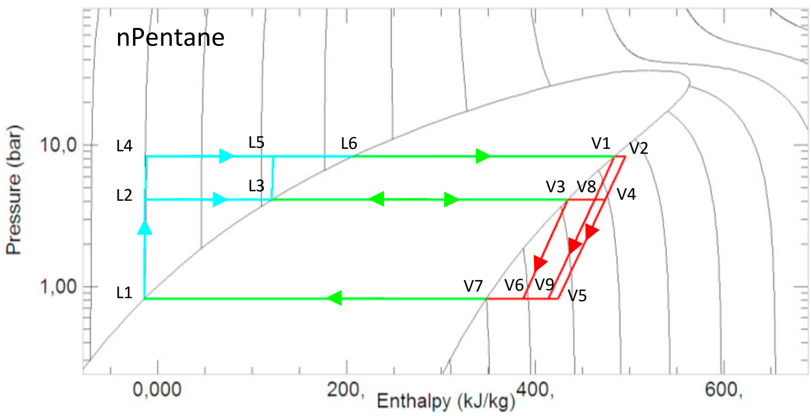

Figure 3: Pressure-enthalpy (p-h) diagram of the possible thermodynamic transformations considered in the superstructure in Fig. 2 (nPentane).

The underlying ideas of the superstructure are:

- Each header is associated to the stream condition (pressure, temperature and enthalpy) of the cycle on the p-h diagram. Pressure, temperature and enthalpy of each header are fixed parameters.
- Headers are graphically arranged like on the p-h diagram (horizontally ordered with growing enthalpy and vertically ordered with increasing pressures).
- Non-isothermal mixing can occur in the headers.
- Import/export of working fluid at determined conditions or output of mechanical/electric power to satisfy process requirements can be imposed.
- Different Rankine cycles can be represented simultaneously in the superstructure.
- Configuration, components' activation and sizing, and stream mass flow rates of the Rankine cycle are numerically optimized (yielding a Mixed Integer Non Linear Program).

3. Algorithm for cycle optimization + HEN synthesis

Following the approach recently devised by Martelli et al. [24], the general superstructure for Rankine cycles is integrated with the well-known SYNHEAT superstructure of heat exchanger networks proposed by Yee and Grossmann [12], based on temperature stages. The extended superstructure for Rankine cycle + HEN synthesis is shown in Fig. 4.

The Rankine cycle streams are included in the HEN superstructure as hot or cold streams (respectively red and blue lines in Fig. 4): economizers, evaporators, and superheaters are cold streams (to be heated up) while the heat sources (hot gases), condensers and desuperheaters are hot streams. The cooling water is modelled as a cold utility (placed at the cold side of the superstructure) collecting all the waste heat. Combustion boilers can be modelled either as hot utilities (if their internal arrangement of heat exchangers must not be optimized) or as hot streams.

Thanks to the combination of the two superstructures (Rankine cycle and HEN), (1) all heat integration options between heat sources/sinks (even if multiple) and ORC can be considered, (2) the configuration, components, mass flow rates and temperatures of the Rankine Cycle can be optimized, (3) the trade-off between efficiency, equipment costs and heat transfer area cost can be rigorously considered. In Fig. 4 a possible selection of heat exchangers (black vertical lines connecting hot and cold streams) is shown; the streams of the Rankine cycle superstructure that are not selected are represented as dotted lines. The objective function is the Total Annual Cost (TAC) of the system (Rankine cycle + heat exchangers). The mathematical model features both binary variables (for the activation of the heat exchangers between hot and cold streams and for the selection of Rankine cycle components) and real variables (heat transferred, area and temperatures at inlet/outlet of each heat exchanger, mass flow rates of all streams of the Rankine cycle). The resulting optimization problem is a challenging nonconvex MINLP which calls for the development of an ad hoc algorithm. Martelli et al. [24] proposed a two-stage algorithm with the Variable Neighbourhood Search (VNS) for the optimization of the binary variables and the Sequential Quadratic Programming algorithm of SNOPT® for the real variables. The fluid properties for the cycle streams (enthalpy and temperature) are calculated with REFPROP®.

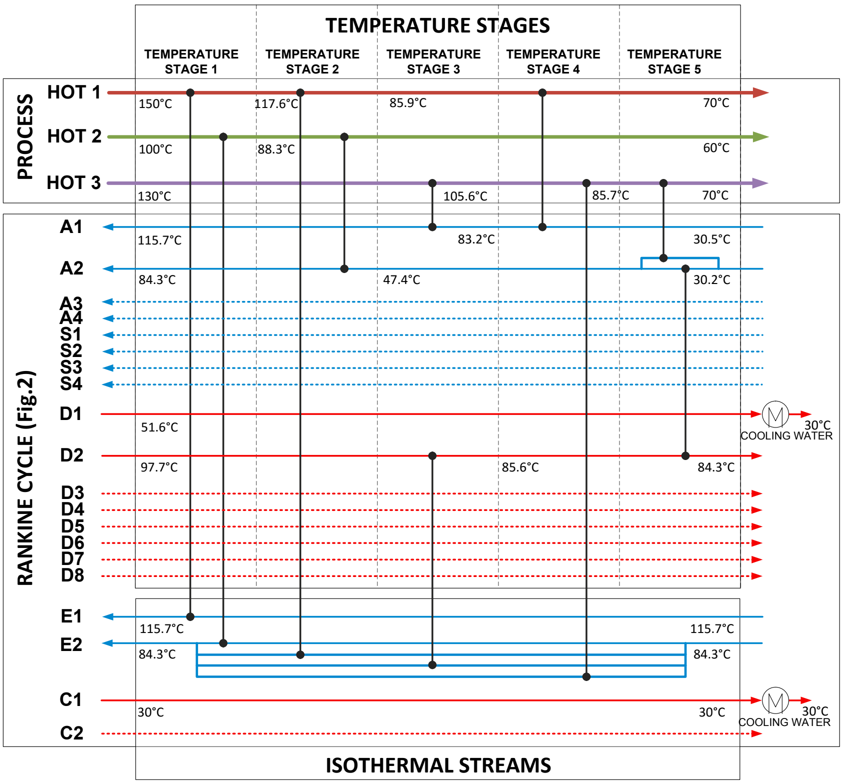

Figure 4: Scheme of the superstructure for integrated HEN and Rankine cycle. The represented example refers to the best solution of Test case 2 (nPentane). Black vertical lines represent active heat exchangers. Dotted horizontal lines represent Rankine cycle streams that were not selected.

4. Case studies

The methodology is used to optimize the ORC design and the HEN of two different test cases with data reported in Table 1. A high electricity selling price equal to 140 $/MWh is considered to account for financial incentives to ORC plants. The economic assumptions for heat exchanger and machinery costs are taken from [24]. However, it should be noticed that the focus of this work is the methodology, so a simplified economic analysis is performed.

Table 1. Process stream data for the three case studies considered here (Case 1/2).

Process stream	$\dot{m}c_P$ [kW/K]	T_{IN} [°C]	T_{OUT} [°C]	h [kW/m²K]
HOT 1	125	150	70	0.5
HOT 2	-/62.5	-/100	-/60	0.5
HOT 3	-/50	-/130	-/70	0.5
CW	variable	15	20	1.5

Exchanger capital cost [$/m²] = 100 + 400*500*(Area[m²]/500) ^0.6
Convective heat transfer coefficient h [kW/m²K] = 1.0 (liquid)/ 10 (two-phase boiling)/ 0.6 (superheating)/ 2.0 (two-phase condensing);
Data for turbines/pumps: specific cost = 430/100 $/kW at the reference size of 4000/1000 kW, scale factor = 0.67;
Isentropic efficiency of turbines/pumps = 0.82/0.7, mechanical/electric efficiency of generator = 0.99/0.98.
Electricity selling prices = 140 $/MWh; annualization factor (CCR) = 0.2/y; equivalent operating hours = 7000 h/y; multiplication factor for costs due to engineering, procurement & construction = 2.5; cooling water cost = 20 $/kWyear.

4.1 Test case 1

The first test case features a single hot stream with temperatures typical of a binary geothermal power plant. According to [25], the most promising working fluids are nPentane and nButane. Both these fluids have a dry expansion, thus the scheme of the cycle superstructure shown in Fig. 2 is considered. As far as the HEN superstructure is concerned, 5 temperature stages have been considered yielding 256 binary variables. The computational time on a single-core computer is about 1h for 20000 function evaluations of the Variable Neighborhood Search (VNS) algorithm. The optimization has been repeated ten times for each fluid. The results of the best solutions found are reported in Table 2 and the optimal plant scheme with nButane in shown in Fig. 5.

Table 2. Best solutions found for test case 1.

Results	nPentane	nButane
Type of ORC	two-pressure level with turbines in tandem	one-pressure level
Selected components (Fig. 2)	A1, A2, E1, E2, D1, D2, C1, T5, T2, P1, P3	A2, E2, D1, C1, T2, P3
Mass flow rate of HP level	13.87 kg/s	0 kg/s
Mass flow rate of LP level	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**

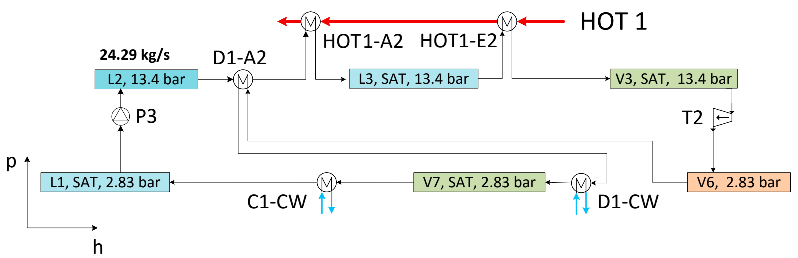

Figure 5: Scheme of the best solution found for Case 1 with nButane.

The objective function value (Total Annual Cost of the plant, TAC) of the best solutions found are respectively equal to -0.321 M$/y (being a negative value, it is a revenue) and -0.331 M$/y. It is important to note that, if a random starting point was used for the VNS algorithm, the returned solutions would be considerably worse (owing to the higher risk of finding local optima). In the nPentane case the selected configuration is a two-pressure level with turbines in tandem; in the nButane case only the low pressure (LP) level is activated. The scheme of the best solution found for Case 1 is shown in Fig. 5 for the case with nButane as working fluid. In the represented solution, the high-temperature heat available from hot process stream HOT 1 is used first to evaporate, then to economize the LP fluid. One regenerator (D1-A2 in Fig. 5) is used to preheat feedwater.

4.2 Test case 2

This second test case features three heat sources which make possible many cycle and HEN configurations. The presence of multiple waste streams is typical of industrial and chemical process applications, such as oil refineries. Owing to the low temperatures of the hot streams, in this case nPentane, isoPentane, nButane and R245fa are considered and compared as working fluids of ORCs [25]. Being dry-expansion fluids, the superstructure of Fig. 2 is considered for all fluids. A superheating temperature difference of 5°C is assumed.

The results for test case 2 are reported in Table 3. In the two best of the four cases, the optimal solution found by the algorithm is a double pressure level ORC cycle with regenerator (i.e., both high and low-pressure levels are activated by the optimization algorithm). The cycle using isoPentane achieves the best efficiency and economic performance, with net power output of 1.85 MW and total annual cost equal to -0.501 M$/y (being negative, it is a revenue). The scheme of the plant is shown in Fig. 6. An equivalent representation of the solution is shown in Fig. 3. No superheating nor reheating is selected by the optimizer. The stream HOT 1 gives heat to the high and low pressure evaporators E1 and E2, and to the economizer A1. The stream HOT 2 is used to preheat and evaporate the LP steam. The stream HOT 3 gives heat to the economizers A1 and A2 and to the LP evaporator E2. Two regenerators are used to recover heat after the high-pressure expansion, D2-A2 and D2-E2, to preheat and evaporate the LP feedwater. Such highly integrated and efficient configuration is made possible by the enhanced flexibility of the superstructure compared to classic optimization approaches. On the other hand, topology constraints can be easily added to reduce the complexity of the HEN (e.g., forbidden/forced matches between streams, maximum number of heat exchangers).

Table 3. Best solutions found for test case 2.

Working fluid	nPentane	isoPentane	nButane	R245fa
Mass flow rate of HP level	14.63 kg/s	15.59 kg/s	0 kg/s	0 kg/s
Mass flow rate of LP level	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 cycle + HEN)	**-0.501 M$/y**	**-0.480 M$/y**	**-0.404 M$/y**	**-0.374 M$/y**

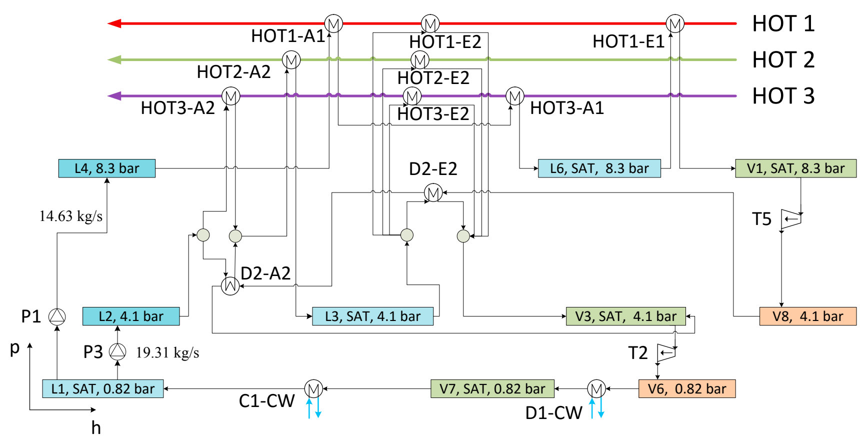

Figure 6: Scheme of the best solution found for Test Case 2 with nPentane.

5. Conclusions

In this work, we presented a superstructure based approach for the techno-economic optimization of ORCs. Compared to other cycle optimization methods, the proposed superstructure is more general as it can reproduce a wide variety of Rankine cycles and it optimizes also the heat exchanger network of the plant. In addition, the method can be applied to problems with multiple heat sources/sinks and can handle both power and inverse cycles, as well as any other combination. The method has been applied to two test cases involving different working fluids and multiple heat sources. The obtained results are cost-optimal HENs and cycle designs which exploit any possible heat integration synergy between process and Rankine cycle while accounting for the best trade-off between efficiency and costs.

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