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

Cristina Elsido[a], Alberto Mian[b], Emanuele Martelli[a]*

[a]*Politecnico di Milano, Via Lambruschini 4A, 20156 Milano, Italy*
[b]*Ecole Politechnique Fédérale de Lausanne, Station 9, 1015 Lausanne, Switzerland*

**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.



*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

* Corresponding author. Tel.: +39 02 2399 3908
*E-mail address:* emanuele.martelli@polimi.it

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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.