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Costs and environmental impacts multi-objective heat exchanger networks synthesis using a meta-heuristic approach

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HIGHLIGHTS

- A multi-objective optimization model for HEN synthesis is proposed.
- The formulation aims to minimize environmental impacts and energy and capital costs.
- The solution scheme is based on an efficient meta-heuristic method.
- It is able to find near-Pareto solutions in HEN medium and large scale case studies.
- Costs competitive solutions but with lower environmental impacts are obtained.

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ABSTRACT

Heat Exchanger Network (HEN) synthesis approaches based on total annual costs (TAC) optimization can reduce CO_2 emissions and electricity used in plants, since the use of utilities is reduced with a cost-optimal design. However, environmental impacts (EI) are not explicitly addressed in such methods. Life cycle assessment (LCA) metrics can quantify EI and can be used as objective function. This work proposes a meta-heuristic approach to perform a multi-objective optimization (MOO) of TAC and EI in medium and large-scale HEN. The method developed efficiently achieves near-Pareto fronts for four industrial-size case studies. Optimal-TAC and optimal-EI solutions, as well as configurations with low EI but still competitive TAC are presented. Cost-optimal solutions reported in the literature are compared with non-dominated solutions obtained in this work with similar TAC. In all cases, the approach developed is able to achieve solutions with remarkably lower EI, demonstrating the importance of multi-criteria optimization in HEN synthesis.

1. Introduction

One of the most extensively studied subjects in process systems engineering is the synthesis of Heat Exchanger Networks (HEN). Optimal HEN designs yield lower capital and operating costs, the latter via utility requirement reduction. A process less demanding on utilities is likely to be also more environmentally friendly. So far, most of the published studies on HEN synthesis use costs as the only objective function in the search for optimal designs, while few studies in the field comprised direct assessments of environmental impacts.

The methods for solving HEN synthesis problems have evolved over decades of research. The first schemes were basically a list of sequential heuristics to be applied, and, among these approaches, works of Linnhoff and co-workers [1,2] on Pinch Technology pioneered the topic. Although these approaches may require some experience from the designer, they are able to establish clear energy goals and lead to near-optimal HEN. A more automatic HEN synthesis task may be achieved using mathematical programming formulations. Some important studies among these approaches are the complex hyper-structure models by Floudas et al. [3], and the stage-wise superstructure (SWS) by Yee and Grossmann [4]. However, HEN synthesis problem is a complex mathematical programming problem even with the most simplified formulations. In particular, the nonlinearities, non-convexities and use of binary variables may lead to local-optima trapping. Such characteristics make necessary the use of sophisticated solution strategies. A concept worth noting is the two-level HEN synthesis used in many works, stated firstly by Lewin [5] and characterized by the use of two separated algorithms to solve a HEN synthesis formulation. The first level concerns the binary

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variables, to which a combinatorial optimization strategy is applied (*i.e.*, deciding which heat exchangers are present in the topology). The second level regards continuous variables, and a continuous optimization method is applied to a topology in order to find optimal heat loads and stream fractions distributions. Important non-deterministic schemes (or hybridizations of stochastic and deterministic methods) presented in the literature, most being two-level or similar schemes, use tactics such as one form of Simulated Annealing (SA) with moves in both levels [6], SA with Sequential Quadratic Programming (SQP) [7], Genetic Algorithms (GA) with GAMS/DICOPT [8,9], GA with Pinch heuristics [10], Differential Evolution (DE) in both levels [11], Evolutionary Algorithms and SQP [12], GA, SA and other strategies [13,14], Particle Swarm Optimization (PSO) [15], Harmony Search (HS) and SQP [16], GA and PSO [17], stream arrangement prior to Powell Method [18], SA and a continuous SA [19], GA and PSO with Parallel Processing (PP) [20], SA and PSO with PP [21], and SA with Rocket Fireworks Optimization (RFO) [22]. Moreover, some works in the literature incorporate other factors to HEN synthesis cost optimization models, such as the detailed design of heat exchangers [23–25], the simultaneous optimization of work and heat [26–28], the HEN synthesis in cases with batch streams [29] and the use of rigorous fouling models for retrofitting [30].

Aiming for more environmentally friendly industrial designs, Life Cycle Assessment (LCA) [31], a widely used method to quantify environmental impacts, may be used as one of the objectives in multi-objective optimization (MOO), in order to provide decision-makers with good solutions [32,33]. Several works were published with such approaches applied to different industrial case studies, such as hydrodealkylation of toluene [34], pollution control in coal-fired power plants [35,36], absorption cooling systems [37], heat integration and simulation of the production of bio-fuels [38], hydrogen infrastructures [39], reverse osmosis plants [40] and central solar heating plants with seasonal storage [41].

Regarding HEN, when one compares environmental impacts of a plant that uses only utilities for heating and cooling, without heat integration, to the same plant with a cost optimal HEN, environmental impacts are likely lower on the second case. However, recent studies have proved that these objectives become conflictive, and there are trade-off solutions among them.

López-Maldonado et al. [42] have presented a mathematical programming formulation to simultaneously optimize Total Annual Costs (TAC) and Environmental Impact (EI). They used a stage-wise superstructure (SWS) with the possibility of heaters and coolers in every stage, which differs slightly from the classic SWS, proposed by Yee and Grossmann [4]. They developed a Mixed Integer Nonlinear Programming (MINLP) formulation, and used the ε-constraint and the goal method with DICOPT, CONOPT and CPLEX on GAMS. The authors used the Eco-indicator 99 to calculate the EI and different utilities combinations were analyzed. In their model, only impacts from hot and cold utilities were considered. Vaskan et al. [43] proposed a MINLP formulation based on the SWS [4] to simultaneously optimize TAC and EI. Their model also covered environmental impacts associated with the construction of the heat exchangers (*i.e.*, stainless steel). The authors made overall and individual analysis of different impacts from Eco-indicator 99 in order to address which were more important in different plant lifetimes. Ravagnani et al. [44] applied a meta-heuristic approach to optimize EI and TAC in HEN synthesis. They incorporated EI to their method using SimaPro software and used a modified Particle Swarm Optimization scheme to solve a stage-wise superstructure based model and obtain Pareto fronts. Kang et al. [45] focused on CO_2 emissions during both construction and operation stages of the plant. They proposed a sequential method based on a preliminary Pinch Analysis stage and further evaluation of optimal solutions for a range of $\Delta T_{\min}$ (heat exchanger minimal approach temperature) to identify where objectives conflict. They used ε-constraint method and evaluation function method, which transforms the MOO problem into a single-optimization case by using a function reconstructed from the original objectives, to obtain Pareto fronts. Optimal solutions were obtained with the same constraints used in the SWS [4] by using BARON, CPLEX and SNOPT on GAMS. Kang and Liu [46] also used CO_2 as environmental impact indicator. Their work presented a MOO model for retrofitting a given HEN configuration by finding the optimal location and operation parameters for heat pumps that must be added to the system in order to reduce TAC and emissions simultaneously. To solve their model, the authors used CPLEX, DICOPT and CONOPT on GAMS.

The synthesis of a HEN is a challenging problem to solve even with simplified models for costs single optimization. Such difficulties probably led the aforementioned works on HEN multi-objective optimization (MOO) to present case studies smaller (in terms of number of process streams) than the cases usually presented in single costs optimization. Real-world cases might comprise a larger number of streams, and to the best of authors' knowledge, such industrial scale problems were not yet approached with bi-criteria formulations for assessing costs and environmental impacts trade-offs. In that sense, this work aims to tackle such industrial scale problems, allowing for the assessment of environmental *versus* economic performance trade-offs and providing decision-makers with different low-costs and eco-friendly solutions. Presenting good performance when employed in larger case studies may be an indicator for the applicability of such methodologies at early stages of industrial design.

In the present work, a meta-heuristic hybrid method based on SA and Rocket Fireworks Optimization (RFO), which was originally developed for HEN costs optimization, is adapted to handle larger HEN multi-optimization cases using a strategy based on the ε-constraint method. The approach is implemented in C++. In order to perform a more complete analysis, besides the near-Pareto fronts, data related to each design, such as number of units, splits and utilities required, are presented for all solutions in each case. Such design features are also important for decision-making. Some configurations might entail intricacies in piping and controllability given their large number of stream splits or heat exchanging units. These features must be evaluated in order to select a configuration that has reasonable economic and environmental performance, and is not problematic to implement and operate.

The present paper is divided into two major parts. The first (Section 2) regards mainly technical features: LCA and its use in tailoring an objective function to be coupled with the HEN synthesis model for bi-criteria optimization; the technical outline of the solution algorithm; and the features added to it in order to handle bi-criteria optimization. The second part (Section 3) concerns the applicability of the developed mathematical model and solution algorithm to four case studies and the evaluation of the results obtained regarding their environmental *versus* economic performances and design features.

2. Methodology

2.1. Life cycle analysis

There is still no consensus in the literature regarding methods to quantify Environmental Impacts (EI). A method which has proved efficient and been applied in many works is Life Cycle Assessment (LCA). In such methodology, all the impacts of an activity, "from cradle to grave" are considered and categorized, weighted and interpreted. At the end, impacts are translated into eco-points.