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Heat Exchanger Network Synthesis without stream splits using parallelized and simplified simulated Annealing and Particle Swarm Optimization

Leandro Vitor Pavão, Caliane Bastos Borba Costa, M.A.S.S. Ravagnani*

Department of Chemical Engineering, State University of Maringá, Av. Colombo, 5790, Bloco D90, CEP 87020900 Maringá – PR, Brazil

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ABSTRACT

Much attention has been paid to heat exchanger network (HEN) synthesis and optimization by using meta-heuristic approaches. In general, Simulated Annealing (SA) is able to provide good solutions, but with large computational efforts. In the present work, a two-level no-split HEN synthesis hybrid method is presented. SA is used for topology optimization, while continuous heat load variables are handled with Particle Swarm Optimization (PSO). SA is simplified and only one type of move is used (single heat exchanger addition), along with group optimizations to improve PSO performance. A parallel processing technique is also presented in order to improve local search performance. The method is tested in 4 medium and large scale benchmark case studies and the no-splits results are compared to literature solutions with and without splits. The solutions presented have lower Total Annual Costs (TAC) when compared to other no-split HENs, and even to some HENs with splits. The proposed method is able to present near-optimal solutions by more efficiently exploring the search space and using simple moves for local searches.

1. Introduction

Heat exchanger network (HEN) synthesis is a sort of problem widely investigated by engineers and researchers. This huge interest is readily explained when one observes capital and energy costs reduction presented by authors and designers along the years of HEN synthesis research. Besides the economic savings, optimal HEN may also lead to reduction in greenhouse gases emissions, an issue whose importance and research interest is constantly growing due to global warming and other natural damages. Such motivations make optimal HEN design a promising field of research. However, obtaining cost optimal HEN is not a trivial task. Formulations and superstructure options may vary, increasing the problem complexity. To solve those models, which are non-convex and nonlinear and contain a large number of variables, numerous solution approaches have been proposed in the literature based mainly in heuristics, mathematical programming and stochastic optimization.

Stochastic or meta-heuristic methods have been used extensively in combinatorial and continuous optimization problems. Most of these methods are attractive for being mainly computational, requiring no derivatives or other advanced mathematical concepts to guide their search. However, even though those algorithms demonstrate efficiency in obtaining optimal or near-optimal solutions, they usually may require high computational effort. This is mostly due to the fact that these methods may work with populations of solutions or perform a massive amount of calculations in local searches. The aforementioned methods may have a constructive profile, where solutions are built from an empty solution according to a set of rules, or an improvement profile, where the neighborhood of a solution is extensively explored in attempts to obtain better results. Some methods might work better in a given sort of problem. In HEN synthesis, algorithms which have an improvement profile, such as Simulated Annealing (SA) or Genetic Algorithms (GA), proved efficient in obtaining topologies which lead to near-optimal solutions after the continuous variables are optimized.

In this work, Simulated Annealing (SA) is used from an empty solution, and the only move it performs repeatedly is to add a single random heat exchanger. Then that single topology is optimized via Particle Swarm Optimization (PSO), a continuous domain optimization method. Heat exchanger removal is performed automatically when PSO finds an optimal solution where heat load for that heat transfer device is zero. Hence, the algorithm profile begins as constructive, and acquires more of improvement characteristics as more heat exchangers are added in local searches after good solutions are achieved. The method, in fact, simulates a slow manual randomized HEN design performed by adding heat exchangers, optimizing heat loads and automatically removing those which do not contribute to costs minimization. The approach is applied to a HEN model with no stream splits. Although this formulation presents fewer variables and is likely

* Corresponding author.
E-mail address: massravagnani@uem.br (M.A.S.S. Ravagnani).

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to lead to slightly higher total annual costs (TAC) than more complex models, it also leads to HEN with simpler configurations, which directly imply in fewer costs with piping and flow controlling valves.

As pointed out by Peng and Cui (2015), Simulated Annealing is known for being a slow method when compared to more recent strategies. However, the solution quality is generally better. In this paper, a parallelization scheme is also presented in order to cover a larger search space and increase the probabilities of finding optimal solutions earlier.

1.1. Literature review

Several authors have presented different approaches to tackle the HEN synthesis problem. The first methods which must be highlighted were presented by Linnhoff and co-workers in many publications (Linnhoff and Ahmad, 1990; Linnhoff and Flower, 1978; Linnhoff and Hindmarsh, 1983; Linnhoff et al., 1979). Their Pinch Analysis method and its variants were mainly based in thermodynamic and heuristic rules and were able to establish and achieve maximum energy recovery goals. However, cost optimal solutions were not ensured, and the HEN synthesis relied much on the designer's experience. Later, many authors focused on modeling HEN synthesis as a mathematical programing problem. Papoulias and Grossmann (1983a, 1983b, 1983c) developed a sequential approach based on the transshipment model and a Linear Problem (LP) problem formulation to achieve minimum utilities goals, a MILP problem formulation for the minimum number of units, and a Non-Linear Programming (NLP) to obtain minimum costs. In the work of Floudas et al. (1986), solutions were automatically generated in a model which led to minimal utilities costs and heat exchanger units. Floudas and Grossmann (1987a, 1987b) proposed a complex NLP superstructure formulation where all the possible HEN configurations were possible, including design options such as stream split, mixing and bypassing. Later Yee and Grossmann (1990) developed a simplified superstructure based on stages. Their stage-wise superstructure (SWS) had all possible matches in single stream branches in every stage. The original Mixed Integer Nonlinear Programming (MINLP) model also presented the assumption of isothermal mixing.

Through the last decades, essentially computational meta-heuristics have demonstrated efficiency in solving combinatorial and continuous linear and non-linear optimization problems. The HEN synthesis problem is basically assigning matches and distributing heat loads optimally among the heat exchangers. Hence, both combinatorial and continuous optimization methods are needed. When properly adapted, these stochastic approaches have demonstrated success in finding optimal and near-optimal solutions to the HEN synthesis problem formulations, and proved an effective alternative to mathematical programming methods. Some works in this field must be highlighted. Dolan et al. (1989) used Simulated Annealing for many randomized moves, such as adding/removing heat exchangers, stream splitting or changing heat loads. Simulated Annealing was also used by Athier et al. (1997), however, the moves were only structural, while the heat load and stream fraction variables were optimized by the Sequential Quadratic Programming (SQP) method. SA approaches usually require too much computational effort. Due to this feature, researchers have focused more on methods able to lead to near-optimal solutions in less time. Lewin (1998) introduced the concept of two level HEN synthesis, using GA for both levels. This concept basically means that first a structure must be proposed in the “upper” level, which comprises a combinatorial optimization problem. Then, in the lower level, a constrained NLP problem is solved in order to obtain heat loads and stream fractions that lead to optimal costs. In such approach, the upper level combinatorial optimization method is not actually searching for the global optimum solution. In fact, it searches for the best solution that the lower level NLP optimization method is able to provide, which may or not be globally optimal. It can be noted that the two level approach was, in fact, already used in the work of Athier et al. (1997). Yerramsetty and Murty (2008) used Differential Evolution (DE) to optimize both levels simultaneously. Ravagnani et al. (2005) used a combination of GA and Pinch Technology. In their method, the heat exchanger minimum approach temperature was previously optimized with a continuous GA variation. Then, GA was applied to find good HEN match combinations using pinch analysis heuristics for the heat loads. Luo et al. (2009) used a GA/SA hybrid method. Fieg et al. (2009) applied a monogenetic algorithm to sub-networks in large scale HEN. Silva et al. (2009) adapted Particle Swarm Optimization for HEN synthesis. Khorasany and Fesanghary (2009) used Harmony Search (HS) for the structural level and SQP for continuous variables. Huo et al. (2013) used a GA/PSO combination with modifications in the classic SWS formulation, in which splits were not considered or considered only in few stages. He and Cui (2013) used a stream arrangement approach to reduce the search space. Peng and Cui (2015) used Simulated Annealing in both levels with heat exchanger addition/removal and substitution by utilities moves.

2. Model formulation

HEN synthesis problem is commonly formulated as a MINLP problem, and the stage-wise superstructure (SWS) (Yee and Grossmann, 1990) is often used. In the original formulation, the SWS allows all possible matches in each stage in single stream split branches with the assumption of isothermal mixing. Such assumption means that, at the outlet of heat exchangers, all branches of the same stream in the same stage have the same temperature. Thus, temperature of all inlet streams of mixers is the same (isothermal mixing assumption).

In this work, a modified SWS is employed (Fig. 1), allowing matches in series between all the process streams, and not allowing stream splits. Such modified SWS has also been used by Huo et al. (2013) in some of their case studies, and by Peng and Cui (2015). Hot and cold utilities are placed at the end of each stream, and matches between streams of the same kind are not allowed. This model is suitable for large scale HEN synthesis, since its solution requires less computational effort. It is also worth bearing in mind that HEN with splits, as mentioned before, also imply in extra piping, valves and flow controlling costs. Such costs are not included in the cost function. Hence, in

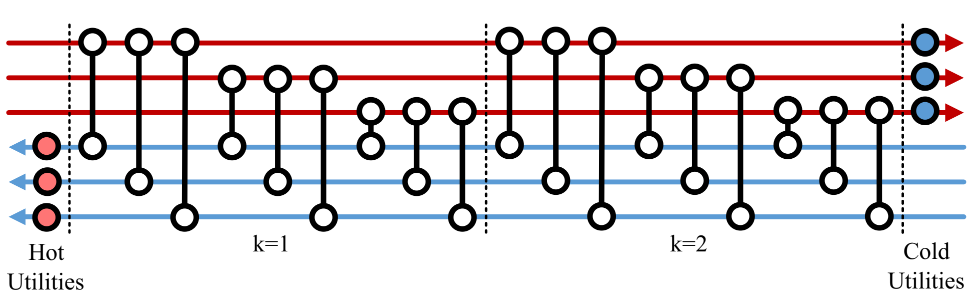

Fig. 1. Modified SWS used in this work.