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Modified Deterministic Algorithm for Automated HEN Design in Waste-to-Energy Applications

Vojtěch Turek*, Zdeněk Jegla
Institute of Process and Environmental Engineering, Faculty of Mechanical Eng., Brno University of Technology, UPEI-VUT, Technická 2, 616 69 Brno, Czech Republic
turek@upei.fme.vutbr.cz

Majority of process plants contain heat exchanger networks. These facilitate heat exchange between hot and cold process streams and thus lower demand for energy of the entire plant. As a result, this leads not only to lower operational costs but can also cause an abatement of emissions plants produce.
The aim of this paper is to provide a multi-objective optimization algorithm that can be used for automated synthesis of small-scale heat exchanger networks commonly used in waste-to-energy process plants. This algorithm employs two optimization models, first of which is an MILP (Mixed-Integer Linear Programming) model that does not support stream splitting or any other feature requiring non-linear constraints. Optimum design of a simple HEN is always quickly reached due to model's linearity. The other model is a more sophisticated MINLP (Mixed-Integer Non-Linear Programming) one which contains non-linear constraints and therefore its computational requirements are relatively high. Both models are based on previous work of Turek et al. (2009) and are enhanced with the emphasis on obtaining a global solution within a reasonable time frame. Also, an existing heat exchanger network is analyzed in the paper and possible improvements are discussed.

1. Introduction

At first, sequential algorithms dividing heat exchanger synthesis problem into a set of sub-problems solved successively in order of decreasing significance and thus reducing the computational demand were developed. These, however, usually yielded "nearly optimal" solutions only (Floudas et al. 1986, Linnhoff and Hindmarsh 1983) which led to the development of simultaneous synthesis algorithms. First papers describing such algorithms were presented in the beginning of the 1990s (e.g. Yee and Grossmann 1990, Ciric and Floudas 1991). Main disadvantage of the simultaneous approach is that it does not perform any decomposition and finds the solution directly, which results in computationally much more intensive tasks. Therefore, various simplifying assumptions are made very often, even though a recent paper by Toffolo (2009) demonstrated that synthesis of networks with unconstrained topology is possible using a two-level hybrid optimization methodology. Modern sequential algorithms, however, can also perform quite well (Anantharaman et al., 2010). Interactive approaches to the studied problem

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(Laukkanen et al., 2010) exist as well, but these require presence of a decision maker and thus synthesis cannot be fully automated. As for global optimization approach to non-linear models of heat exchanger networks, Adjiman et al. (1997) were one of the first researchers who investigated it.

Although pinch analysis (Kemp, 2006) is still one of the most commonly used methods in practice, a variety of simultaneous mathematical programming algorithms based on superstructure representations of heat exchanger networks start to become very popular. Based on the fact that HEN synthesis is NP-hard in the strong sense (Furman and Sahinidis, 2001), Errico et al. (2007) proposed a deterministic algorithm. However, considering small to medium-size HENs, it has not been investigated much since then and therefore the authors further generalize and extend it within the scope of their research. Typically, one of the following optimization criteria is used:

- Maximum energy recovery (MER), or
- Minimum total heat exchange area, or
- Minimum total annual costs (TAC) in case of maximum energy recovery.

Although some (e.g. Trivedi et al. 1997) argue that reaching MER may lead to sub-optimal network designs, this is remedied by finding more solutions instead of a single one and implementing an additional mechanism that evaluates suitability of the obtained solutions.

2. Optimization algorithm

In this section, a modified global optimization algorithm is presented. This algorithm is being developed using GAMS (General Algebraic Modelling System; cf. www.gams.com) together with global MINLP solver BARON (Branch-And-Reduce Optimization Navigator; cf. http://archimedes.cheme.cmu.edu/baron/ baron.html). Since it turned out that the way this system accesses individual elements of matrices is far from being efficient, any additional post-processing of obtained solutions is performed outside GAMS with a custom Java™ application while the necessary data exchange is carried out using GDX I/O API (GAMS Data Exchange I/O Application Programming Interface.

2.1 General representation of network structure

Let us consider the problem once again: a robust yet efficient enough optimization model must be built such that it would allow for virtually any reasonable HEN structure. A general way to represent a wide range of networks is to use superstructures consisting of one or more "repetitive units" proposed by Yee and Grossmann (1990). Layout of a repetitive unit (including the way streams are split) is given by the number of hot and cold process streams. Although stream splitting can in some cases improve overall performance of a heat exchanger network, it also increases costs and network complexity which, in consequence, can lead to higher vulnerability of the entire structure. Splitting is therefore avoided if possible.

The advantage of superstructure representation of heat exchanger networks is that it can be used regardless of properties of the actual heat exchanger units. In other words, no matter which types of heat exchangers (shell and tube, plate, spiral, etc.) are chosen in the end, models based on this representation will still be valid.

2.2 Built-in optimization models

The algorithm implements models presented in (Turek et al., 2009). The first model for networks without stream splitting is a quite simple MILP one maximizing energy recovery and can be used directly without any changes. The second (MINLP) model supporting stream splitting was simplified to maximize energy recovery instead of direct minimization of total annual cost of the entire network combined with MER. This way complexity of the problem becomes notably lower and thus also optimization times shorten significantly (approximately to one twentieth of the original value).

2.3 The algorithm

The optimization algorithm evaluates all possible networks with the number of repetitive units between one and their maximum allowed count. Due to the combinatorial nature of the problem there usually is more than one solution with the same value of objective function and thus a user-specified number of solutions are found for each configuration. To avoid non-linearities, feasibility check of heat exchange areas is done afterwards before total annual costs are computed for each solution. Any solution with TAC exceeding the maximum allowed value or with at least one heat exchanger having larger than the maximum allowed heat exchange area is ignored and marked so in the GAMS optimization log file. Then, all feasible solutions are passed to an external application for evaluation of heat transfer verticality using driving force plots (Linnhoff and Vredeveld 1984). For details related to the actual algorithm see (Turek et al., 2009, Section 2.3). Finally, post-processing results are loaded back into GAMS, solutions are sorted according to chosen criteria and a protocol file containing the results including all available data is created with the first solution listed therein being the best one. Flow chart of the algorithm is shown in Figure 1.

Considering cost estimation models, many different ones can be used. For instance, to estimate total annual cost of a shell and tube heat exchanger, the algorithm uses the formula presented in (Ahmad et al., 1990), i.e.,

$$Cost = (fixed\ cost) + (cost\ of\ 1\ m^2) \cdot (heat\ exchange\ area)^{(area\ cost\ exponent)} \quad (1)$$

Other relations suitable also for different types of heat exchangers can be found for instance in (Couper et al., 1990, Hall et al., 1990, or Peters et al., 2002). All prices are converted to current levels using the Nelson-Farrar Refinery Construction Cost Index.

As for the sort criteria, usually total annual cost is preferred to be minimal while energy recovery is kept at its maximum possible value with the indicator of verticality of heat transfer being taken into account.

3. A real-world example

An existing heat exchanger network in a plant processing sludge from pulp and paper production was analyzed. Currently, the network contains two hot streams, three cold streams, two double U-tube heat exchangers and one common tubular exchanger. Total heat duty of the network is 4,614 kW with total annual cost converted to current price level being 1,582,000 USD. The overall heat transfer verticality indicator for the entire HEN is 0.165 (the closer to zero the better).

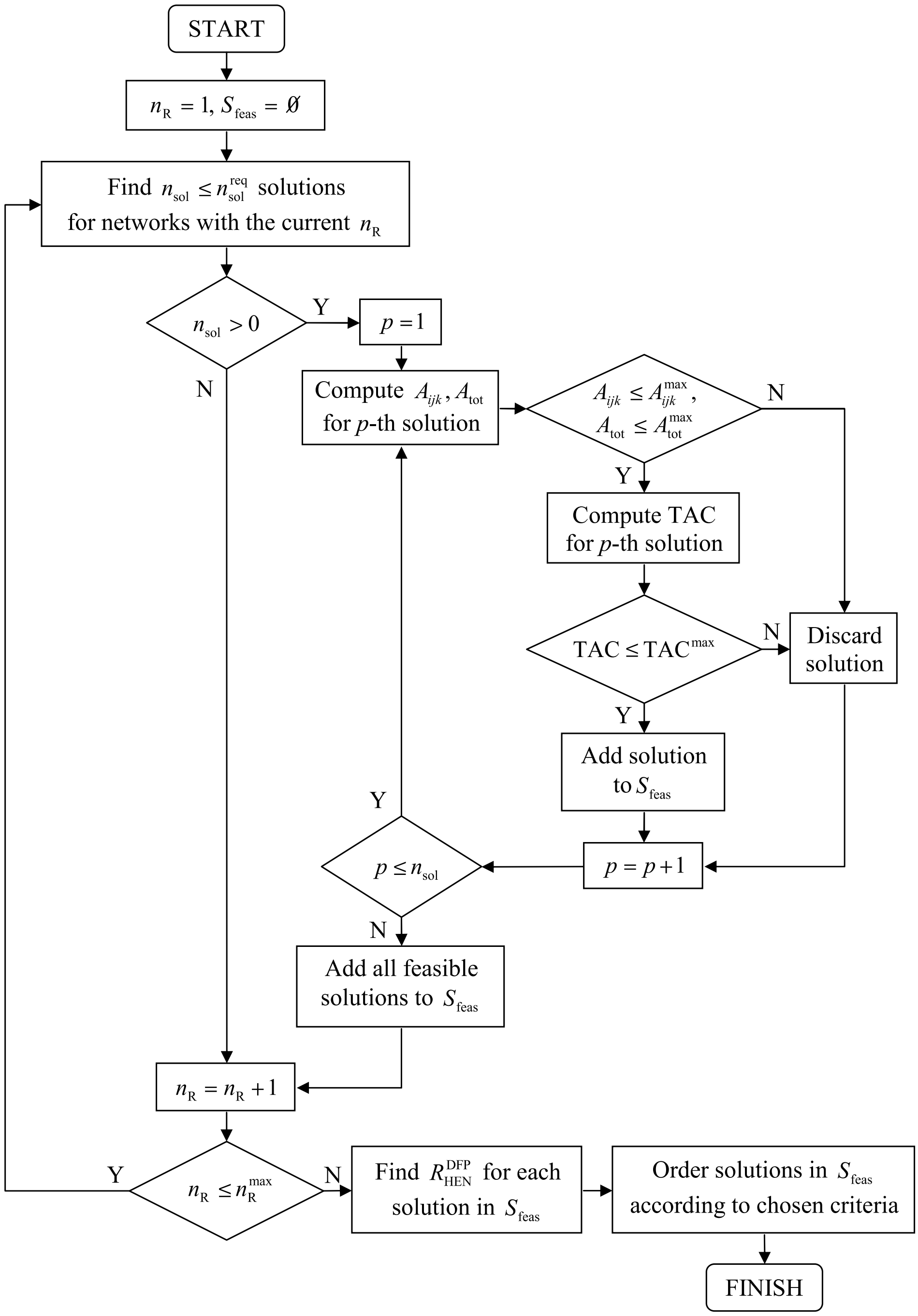

Figure 1: Flow chart of the modified multi-objective optimization algorithm.

Considering networks without stream splitting, the best one according to the proposed optimization algorithm employing the MILP model contains one additional double U-

tube heat exchanger and one cold utility unit (312 kW). This causes heat duty to be distributed better among the exchangers. Energy recovery is 4,302 kW while the total annual cost of this network is 975,000 USD, i.e., approximately two thirds of the original value. The overall heat transfer verticality indicator remains quite low: 0.171. Optimization time necessary to get 20 solutions with the best one among them is approx. 6 s on a MS Windows 7 PC with a single-core AMD Athlon 64 3200+ CPU.
As for networks with split streams, the best possible one contains two splits, five double U-tube heat exchangers, one common tubular exchanger and one cold utility unit (276 kW). Energy recovery is 4,338 kW with total annual cost being 1,354,000 USD. However, the overall heat transfer verticality indicator is worse for this network (0.675) with optimization time being roughly 84 s per 20 solutions. It is obvious that in this case stream splitting is not advisable.

4. Conclusions

A modified multi-objective optimization algorithm for automated synthesis of small-scale heat exchanger networks was presented. This algorithm employs either an MILP or an MINLP model maximizing energy recovery while heat transfer areas, total annual costs, and overall heat transfer verticality indicator are computed afterwards. Due to reduced complexity, optimization times are significantly shortened. Moreover, the algorithm returns a user-specified number of solutions if possible to compensate for the fact that many solutions with the same objective value can exist.
Also, an existing heat exchanger network was analyzed and improved HEN designs were outlined.

Notation

A heat exchange area
n_{R} current number of repetitive units
n_{sol} number of solutions found for the current configuration
$n_{\mathrm{sol}}^{\mathrm{req}}$ minimum required number of solutions to be found
$R_{\mathrm{HEN}}^{\mathrm{DFP}}$ overall heat transfer verticality indicator
S_{feas} set of found feasible solutions
Subscripts: *ijk* heat exchanger connecting *i*-th hot stream with *j*-th cold stream in *k*-th repetitive unit.
tot total amount
Superscript "max" denotes maximum allowed value.

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