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Design of flexible multiperiod heat exchanger networks with debottlenecking in subperiods

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HIGHLIGHTS

- A three-stage method for flexible multiperiod heat exchanger network is proposed.
- Parametric fluctuations in subperiods are considered.
- Multiperiod operation and flexibilities in subperiods are satisfied simultaneously.
- Operational flexibility and economic efficiency of multiperiod network are ensured.

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ABSTRACT

In order to accommodate potential fluctuations of uncertain parameters, a systematic three-stage method for the design of flexible multiperiod heat exchanger networks (HENs) is proposed, which satisfies not only the requirement of the multiperiod operation but also the flexibility of the subperiod operation. In the first stage, an initial multiperiod HEN is constructed based on the synthesis of the single period HEN. In the second stage, the structure and heat transfer area arrangement of the initial multiperiod HEN are modified and optimized by considering both the multiperiod operational characteristics and the subperiod operational flexibilities. In the third stage, the flexibilities of the modified multiperiod HEN in each subperiod are examined and improved by solving a subperiod debottlenecking model. A case study of a HEN in a vacuum gas oil hydrotreating unit is carried out to illustrate the application of the proposed method. Results indicate that the heat transfer areas and total annual cost of the multiperiod HEN will be underestimated if the parametric fluctuations in subperiods are neglected. A cost-effective multiperiod HEN with sufficient flexibility in subperiods can be obtained by using the proposed method when the parametric fluctuations are taken into consideration.

1. Introduction

In process industries, heat exchanger networks (HENs) link the industrial process with utility sub-systems and generally possess a large fraction of both the overall plant capital cost and operating costs in terms of energy consumption (Escobar et al., 2014; Verheyen and Zhang, 2006). The changes in external environment conditions, such as shocks of demand and supply, process improvement and seasonal changes, and internal process parameters, such as variations in kinetic parameters, heat transfer coefficients, and startup and shutdown of equipment, cause fluctuations in the operating parameters of HENs (Kang et al., 2016). In general, the recurrent operation conditions are partitioned into a finite number of discrete subperiods with constant operational parameters (Kang and Liu, 2014), which is referred as a multiperiod synthesis problem.

Methods for the synthesis of the multiperiod HEN can be either sequential (Floudas and Grossmann, 1986; Floudas and Grossmann, 1987) or simultaneous (Verheyen and Zhang, 2006; Kang et al., 2016). For the sequential methods (Floudas and Grossmann, 1986), a linear programming (LP) model, a mixed-integer linear programming (MILP) and a nonlinear programming (NLP) model are usually solved in sequence to target energy consumption, amount of heat transfer units and capital cost accordingly. Although these decomposition-based methods are helpful for the solution generation of multiperiod HENs, the interactions between the capital cost and operation cost of multiperiod HEN are often ignored. In principle, this shortcoming can be overcome by solving a simultaneous model of the multiperiod HEN (Verheyen and Zhang, 2006) on the basis of the stage-wise

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Nomenclature

Indices
- i hot streams
- j cold streams
- k stages in SWS model
- p subperiods
- s critical points

Parameters
- β cost exponent of heat transfer area
- c_f, c_a cost efficient of heat transfer units/areas
- d the ratio of durations of subperiods over the whole operating time
- F^N nominal values of heat capacity flow rates
- g inequality constraints
- g_A constraint of heat transfer areas
- h equality constraints
- M a big number
- sgn direction of deviation from nominal point towards critical point
- T_{in} nominal values of inlet temperatures
- $\Delta\theta$ the expected variations of the uncertain variables
- θ^N nominal values of uncertain variables

Variables
- A^I, A^{II}, A^{III} heat transfer areas of the initial/modified/flexible multiperiod HEN
- A_m heat transfer area of any single stream match
- F heat capacity flow rates of process streams
- q_{cu}, q_{hu} heat loads of cooling utility/heating utility
- T temperature
- T_{in} inlet temperatures of process streams
- $\mathbf{z}^{com}$ common structure set
- $\mathbf{z}^{pot}$ potential structure set
- $\mathbf{z}^0$ optimal structure of the HEN in subperiod
- z^{I}, z^{II}, z^{III} structure of the initial/modified/flexible multiperiod HEN
- δ flexibility index
- ΔA newly increased heat transfer areas
- Δz newly added stream matches
- θ uncertain variables

Abbreviations
- HEN heat exchanger network
- LP linear programming
- MILP mixed-integer linear programming
- MINLP mixed-integer nonlinear programming
- MIP mixed integer programming
- NLP nonlinear programming
- SWS the stage-wise superstructure model
- TAC total annual cost

superstructure model (SWS) (Escobar et al., 2013), aiming at the lowest total annual cost (TAC).

To facilitate the solution generation of the simultaneous model of the multiperiod HEN, the stepwise methods are often adopted. Examples of these methods include the interval-based method (Isafiade and Fraser, 2010), the representative subperiod method (Kang et al., 2015), the simplified model method (Kang et al., 2016), the time-sharing method (Jiang and Chang, 2013) and their variants (Isafiade and Short, 2016; Isafiade et al., 2015; Miranda et al., 2016). The main idea of these methods is to avoid the solution of the complicated multiperiod HEN model by reducing the number of binary variables (Kang et al., 2016; Isafiade and Fraser, 2010), fixing the values of binary variables (Kang et al., 2015; Isafiade et al., 2015) in multiperiod HEN model or by using the time-sharing mechanism to determine the structure and heat transfer area arrangement of the multiperiod HEN (Jiang and Chang, 2013; Miranda et al., 2016). However, all the above-mentioned methods were developed to achieve cost-effective multiperiod HENs that are solely tailored to specific operational subperiods, even though the variations of the operational conditions are, in fact, continuous. In other words, the resulting optimal structure of the multiperiod HEN may fail to accommodate the fluctuations of the operational parameters in each subperiod, and thus becomes infeasible in practical operations.

An effective way to address this problem is to conduct flexibility analysis and debottlenecking for the multiperiod HEN, where the steps of network synthesis, flexibility analysis and heat transfer area optimization are usually performed. Based on this train of thought, Escobar et al. (2013) proposed a two-stage strategy to synthesize a flexible multiperiod HEN. In their method, a multiperiod network was initially determined at the nominal multiperiod operation point. The heat transfer areas of the multiperiod HEN were then updated by solving a multi-scenario model where the nominal operation point and the critical points that restrict the structure flexibility of the multiperiod HEN are included. Liang et al. (2016) proposed a two-step method, where the initial multiperiod network that satisfies the multiperiod operation requirement was obtained in the first step, and then the flexibility of multiperiod network was examined and improved by expanding device capacities to meet the flexibility requirement in subperiods. Nevertheless, these methods ignored the effect of parametric fluctuations in subperiods on the structure of the multiperiod network, which may exclude some better designs where adjusting the structure is much cheaper than increasing the heat transfer areas. In addition, for the flexibility analysis of the HEN, both the structure and heat transfer areas should be taken as the design variables. However, the constraints of the heat transfer areas are removed in most cases. To solve this issue, Li et al. (2014) suggested a modified procedure, in which the initial multiperiod HEN is updated by topological union of the structures obtained at nominal operation point and those obtained at the selected critical points, and then the heat transfer areas are optimized through an iterative approach. However, this method may cause redundancy of heat transfer units when the structures at the critical points deviate from the nominal point significantly.

Based on the above analysis, it can be concluded that although significant contributions have been made to the synthesis of multiperiod HEN, less attention is paid to the multiperiod HEN synthesis with uncertain disturbances in subperiods. Although the flexibility analysis is available to compensate the fluctuations of the operational parameters in subperiods, the effect of parametric fluctuations in subperiods on the structure of the HEN are ignored. In addition, for the flexibility analysis of the HEN, both the structure and heat transfer areas should be taken as the design variables. However, the constraints of the heat transfer areas are removed in most cases.

To address these problems, a systematic three-stage method for design of flexible multiperiod HEN is proposed, taking the effect of the parametric fluctuations in subperiods on the structure of the multiperiod HEN into consideration. The rest of this paper is