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Game-theory based optimization strategies for stepwise development of indirect interplant heat integration plans

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ABSTRACT

Since the conventional design strategies for interplant heat integration usually focused upon minimization of the overall utility cost, the optimal solutions may not be implementable due to the additional need to distribute the financial benefits "fairly." To resolve this profit sharing issue, a Nash-equilibrium constrained optimization strategy has already been developed to sequentially synthesize heat exchanger networks (HENs) that facilitate direct heat transfers across plant boundaries. Although this available approach is thermodynamically viable, the resulting network may be highly coupled and therefore inoperable. To address the operability issues in any multi-plant HEN, the present study aims to modify the aforementioned strategy by considering only *indirect* interplant heat-exchange options. Two separate sets of mathematical programming models are developed in this work for generating the total-site heat integration schemes with the available utilities and an extra intermediate fluid, respectively. The negotiation powers of the participating plants are also considered for reasonably distributing the utility cost savings and also shouldering the capital cost hikes. Finally, extensive case studies are presented to demonstrate the effectiveness of the proposed procedures and to compare the pros and cons of these two indirect heat-exchange alternatives.

1. Introduction

The total operating cost of almost every chemical plant can be largely attributed to the needs for heating and cooling utilities. The heat exchanger network (HEN) embedded in a chemical process is usually configured for the purpose of minimizing the utility consumption rates. A HEN design is traditionally produced with either a simultaneous optimization strategy [1] or a stepwise procedure for determining the minimum utility consumption rates and the minimum match number first [2] and then the network structure [3]. The former usually yields a better trade-off between utility and capital costs, but the computational effort required for solving the corresponding mixed-integer nonlinear programming (MINLP) model can be overwhelming. On the other hand, although only suboptimal solutions can be obtained in the latter case, implementing a stepwise method is much easier. For this very reason, a sequential approach is often adopted to configure the inner-plant heat-exchange networks in three steps. In the first two steps, a linear program (LP) and a mixed-integer linear program (MILP) are solved respectively to determine the minimum total utility cost and to identify the minimum number of matches and their heat duties [2]. A nonlinear programming (NLP) model is then solved in the final step for synthesizing the cost-optimal network [3].

Driven by the belief that significant extra benefit can be reaped by expanding the feasible region of any optimization problem, a number of studies have been carried out to develop various interplant heat integration schemes, e.g., see Bagajewicz and Rodera [4] and Anita [5] and Liew et al. [6]. The available synthesis methods for total site heat integration (TSHI) can be classified into three kinds: the insight-based pinch analysis [7], the model-based methods [8] and the hybrid methods [6], while the required interplant energy flows may be either realized with direct heat exchanges between process streams or facilitated indirectly with the extraneous fluids [9].

The main advantages of insight-based pinch analysis can be attributed to its target setting strategy and flexible design steps. Matsuda et al. [10] applied the area-wide pinch technology which incorporated the R-curve analysis and site-source-sink-profile analysis to TSHI of Kashima industrial area. For the fluctuating

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renewable energy supply, Liew et al. [11] proposed the graphical targeting procedures based on the time slices to handle the energy supply/demand variability in TSHI. In addition, a retrofit framework was proposed by the same research group [12] and the framework showed that energy retrofit projects should be approached from the total-site context first. Furthermore, Tarighaleslami et al. [13] developed a new improved TSHI method in order to address the non-isothermal utilities targeting issues.

On the other hand, the model-based methods are more rigorous and thus better equipped to identify the true optimum. Zhang et al. [14] proposed to use a superstructure for building a MINLP model to synthesize multi-plant HEN designs. Chang et al. [8] presented a simultaneous optimization methodology for interplant heat integration using the intermediate fluid circle(s). Wang et al. [9] adopted a hybrid approach for the same problems. The performances for heat integration across plant boundaries using direct, indirect and combined methods were analyzed and compared through composite curves, while the mathematical programming models were adopted to determine the optimal conditions of direct and/or indirect options [9].

As indicated in Cheng et al. [15], the aforementioned interplant heat integration arrangements were often not implementable in practice due to the fact that the profit margin might be unacceptable to one or more participating party. This drawback can be primarily attributed to the conventional HEN design objective, i.e., minimization of overall energy cost. Thus, the key to a successful interplant heat integration scheme should be to allow every plant to maximize its own benefit while striving for the largest overall saving at the same time. To address this benefit distribution issue, a game-theory based sequential optimization strategy has been developed by Cheng et al. [15] to generate the “fair” interplant integration schemes via *direct* heat exchanges between the hot and cold process streams across plant boundaries. In addition to a lighter computation load, this approach is justified by the fact that the game theoretic models can be more naturally incorporated into a step-by-step design practice when the same type of decision variables are evaluated one-at-a-time on a consistent basis. To be specific, let us consider their modeling strategy in more detail. After determining the global minimum of total utility cost with the LP model used in the first step of the conventional approach, a NLP model was then constructed for identifying the acceptable interplant heat flows in the given system. Since the commodities to be traded were energies of different grades, this model was formulated as a nonzero-sum matrix game, in which each game strategy was the fraction of heat flow entering/leaving a distinct temperature interval. On the basis of this conceptual analogy, the Nash equilibrium constraints [16] were imposed in the NLP model for solving the game while keeping the overall utility cost at minimum. It should be noted that, although Hiete et al. [17] also treated the benefit-sharing plan for interplant heat integration as a cooperative game, this alternative approach is less rigorous due to the requirements of heuristic manipulations. Finally, note that the game theory has been adopted in various other interplant resource integration applications, e.g., water network designs [18], supply/value chain optimization [19], and multi-actor distributed processing systems [20].

Other than the profit-allocation concerns mentioned above, it is also of critical importance to examine the viable means for facilitating the desired energy flows among plants in practice. In principle, these flows can be materialized via heat exchange(s) either directly between hot and cold process streams located in different plants or indirectly between the process streams and an intermediate fluid (or the heating and cooling utilities). Although the direct heat exchanges are thermodynamically more efficient than their indirect counterparts, the resulting highly-coupled interplant HEN may pose a control problem in the industrial environment. On the other hand, since the indirect heat integration is facilitated with the auxiliary streams (i.e., steam, cooling water and/or hot oil) that do not take part in any production process, a greater degree of operational flexibility can be achieved [21] and, thus, should be regarded as a more practical alternative.

It should be noted that Cheng et al. [7] considered only the impractical direct heat transfers in their studies and, also, ignored the negotiation powers of the participating plants in their models for allocating the cost savings. To improve the practical feasibility of interplant heat integration projects, the present study aims to modify their sequential optimization approach by replacing the direct interplant heat-transfer options with indirect ones. In addition to the advantage of better operability, the resulting HEN design should also be more acceptable to all players of the game because, on the basis of their respective negotiation powers [11] and the Nash equilibrium constraints [8], the utility cost savings and capital cost increases can both be reasonably distributed among all participating members. Extensive case studies are also presented in this paper to illustrate the proposed procedures and to compare the pros and cons of different indirect heat-exchange alternatives.

Finally, on the basis of the above discussion, the novel contributions of this work can be briefly summarized as follows:

- The profit-allocation concerns in interplant heat integration schemes are addressed systematically with the game theoretic models.
- The more viable means of indirect heat exchanges between the process streams and an intermediate fluid (or the heating and cooling utilities) are considered to facilitate interplant heat flows in practical applications.
- A modified version of the sequential HEN synthesis approach is proposed to incorporate the negotiation powers of the participating plants for allocating their cost savings and, also, to reduce the computation effort to a reasonable level.

2. Sequential optimization procedure

For the sake of illustration clarity, let us briefly review the sequential optimization procedure suggested by Cheng et al. [7]:

i. On the basis of given process data, the minimum acceptable total utility cost of the entire industrial park is determined with a linear program (LP).
ii. By incorporating the constraints of minimum acceptable overall utility cost obtained in step i and also the Nash equilibrium in a nonlinear program (NLP), the heat flows between every pair of plants on site and also their fair trade prices can be calculated accordingly.
iii. By fixing the interplant heat-flow patterns determined in step ii, the minimum total number of both inner- and interplant matches and the corresponding heat duties can be determined with a mixed-integer linear programming (MILP) model.
iv. After constructing a superstructure to facilitate the matches identified in step iii, a nonlinear programming (NLP) model can be formulated to generate the HEN configuration that optimally distributes the total annual cost (TAC) savings among all plants.

This study basically follows the same procedure, while each step is modified for synthesizing the indirect interplant heat integration schemes.