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Optimization of heat integration with variable stream data and non-linear process constraints

Chi-Wai Hui *

Chemical and Biomolecular Engineering Department, Hong Kong University of Science and Technology, Clear Water Bay, Hong Kong

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ABSTRACT

Two novel formulations for the optimization of heat integration of chemical processes with variable stream data and non-linear process constraints are proposed. An NLP formulation utilizes a concept of pseudo stream temperatures and the Plus/Minus Principles simplifies the formulation with tight constraints. The NLP model is efficiency but the use of bi-linear constraints might sometimes deteriorate the solution quality comparing to the conventional Big-*M* disjunctive model. To overcome this, a Multi-*M* model is proposed that applies the same concepts as in the NLP model together with a set of Multi-*M* constraints. The Multi-*M* model significantly reduces the number of binary variables and minimizes the size of *M*s for the use in the Multi-*M* constraints. Results show that the NLP model spends least time in solution but sometimes converges too soon at near or local optimum. The Multi-*M* model is the most robust and still maintains a high efficiency in solution quality and speed. For problem with non-linear process constraints, both NLP and Multi-*M* models perform much better than the traditional Big-*M* model.

1. Introduction

Designing and optimizing of heat recovering systems with variable stream data such as stream temperature, flowrate or heat capacity is one of the most important topics in heat integration study. Duran and Grossmann (1986) defined a general model that simultaneously optimizes heat integration and process flowsheet in the following form:

$$\min F(w,x) + C_H Q_H + C_C Q_C$$

$$\begin{aligned} s.t.\quad & h(w,x) = 0 \\ & g(w,x) \le 0 \\ & \Phi(Q_H, Q_C, x) \le 0 \\ & Q_H, Q_C \ge 0 \\ & x \in X \subset R_+^m, \quad w \in W \subset R_+^n \end{aligned}$$

The objective of this model is to minimize the overall cost of a flowsheet of which utility costs ($C_H Q_H + C_C Q_C$) and other processing costs $F(w,x)$ are considered. The model considered single hot/cold utility. The vector of w represents process variables such as pressure, temperatures, flowrates and binary variables for the existence of process equipment. The vector of x includes flowrates, heat capacities and temperatures of the process streams that require cooling or heating. The vectors of h and g represent material and energy balance, design specifications, etc. excluding the heat integration constraints that determine the amount of heating (Q_H) and cooling (Q_C) required for a given set of condition x and a given heat recovery approach temperature *HRAT*. For a problem where the process variables (w) are fixed, the problem is reduced to just minimizing utility cost with either fixed or variable stream data.

Former approaches such as pinch design method of Linnhoff and Hindmarsh (1983), transportation formulation of Cerda and Westerburg (1983) that requires fixed stream temperatures and flowrates, or a pre-determined temperature intervals, had difficulties to handle problems with variable stream data. Duran and Grossmann (1986) proposed a non-linear programing (NLP) model that does not require pre-determined temperature intervals in their formulation. By observing that the process pinch is always located at a supply temperature of a hot or a cold stream, they proposed to obtain energy balance above each candidate pinch point T_k^p, $k \in K$. The overall heat available from the hot streams and heat required by the cold streams above a candidate pinch point k is calculated as $QSOA(x)^k$ and $QSIA(x)^k$ respectively. An example shown in Fig. 1 below is used to illustrate the energy targeting method proposed by

* Tel.: +852 2358 7137; fax: +852 2358 0054.
E-mail address: kehui@ust.hk

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Nomenclature

Indexes
- i hot stream
- j cold stream
- k for both hot and cold steam

Parameters
- $F_i(F_j)$ flowrate of hot (cold) stream
- $Cp_i(Cp_j)$ heat capacity of hot (cold) stream
- $HRAT$ heat recovery approach temperature
- M Big-M
- $M_{i,k}(M_{j,k})$ Multi-M used for each pair of cross-pinch constraint
- $mCp_i(mCp_j)$ heat capacity flowrate of hot (cold) stream
- $T_i^{in}(T_j^{in})$ actual inlet temperature of a hot (cold) stream
- $T_i^{out}(T_j^{out})$ actual outlet temperature of a hot (cold) stream
- $T_{i,max}^{in}(T_{j,max}^{in})$ the maximum pseudo inlet temperature of a hot (cold) stream
- $T_{i,max}^{p}(T_{j,max}^{p})$ the maximum pinch temperature created by a hot (cold) stream
- TM the mean value of a variable stream temperature

Continuous variables
- Q_H hot utility demand
- Q_C cold utility demand
- $QHOT(x)$ heat content of hot process streams
- $QCOL(x)$ heat content of cold process streams
- $QSOA(x)^k$ heat source above candidate pinch k
- $QSIA(x)^k$ heat sink above candidate pinch k
- $F_i(F_j)$ flowrate of hot (cold) stream
- $T_{i,k}^{in}(T_{j,k}^{in})$ Pseudo inlet temperature of a hot (cold) process stream corresponding to a pinch k
- $T_{i,k}^{out}(T_{j,k}^{out})$ Pseudo outlet temperature of a hot (cold) process stream corresponding to a pinch k
- T_k^p pinch temperature created by the inlet temperature of a stream k
- $Z_{i,k}$ ($Z_{j,k}$) 0–1 variable, 1 if the inlet temperature hot (cold) stream is above the pinch k
- Ω difference of heat content between hot and cold process steams

Binary variables
- $Y_{i,k}^1(Y_{j,k}^1)$ 1 if a hot (cold) stream is above a pinch k
- $Y_{i,k}^2(Y_{j,k}^2)$ 1 if a hot (cold) stream across a pinch k
- $Y_{i,k}^3(Y_{j,k}^3)$ 1 if a hot (cold) stream below a pinch k
- $Y_{i,k}(Y_{j,k})$ 1 if the pseudo inlet temperature of a hot (cold) stream equals to its actual inlet temperature; 0 if the pseudo inlet temperature of a hot (cold) stream falls onto the pinch

Sets
- H hot process streams
- C cold process streams
- ST hot and cold process streams

Vectors
- w vector of process parameters
- x vector of flowrates and temperatures of process streams

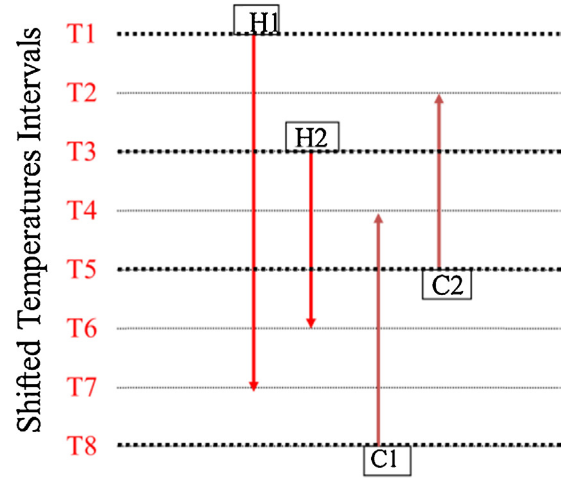

Fig. 1. A four-stream example.

Duran and Grossmann (1986). As other energy targeting methods that require per-determined temperature intervals, Fig. 1 shows a process with 2 hot and 2 cold streams in their shifted temperatures (the cold streams temperature are shifted upward of a value of $HRAT$).

Since the process pinch is formed at one of the inlet temperatures of a hot or a cold stream, the pinch candidates are at T1, T3, T5 and T8. To obtain the utility targets, Q_C and Q_H, the hot utility target at each candidate pinch k is first calculated by subtracting $\text{QSOA}(x)^k$ from $\text{QSIA}(x)^k$. For instance, at the candidate pinch T5, which is at the shifted inlet temperature of C2, $\text{QSOA}(x)^{\text{T5}}\text{QSIA}(x)^{\text{T5}}$ is the summation of heat contents of H1 and H2 and the summation of heat requirements of $C1$ and $C2$ respectively at above T5. The hot utility target at this candidate pinch equals to $(\text{QSIA}(x)^{\text{T5}} - \text{QSOA}(x)^{\text{T5}})$. Each candidate pinch results in a different hot utility target. The maximum among these targets (Eq. (6)) will be the actual hot utility target, Q_H. Once when the hot utility target is determined, with the overall energy balance obtained from all hot and cold streams (Eqs. (3)–(5) and Eq. (7)), the cold utility target Q_C can be obtained. Following is the mathematical model proposed by Duran and Grossmann (1986):

Minimize $C_H Q_H + C_C Q_C$ (objective)

Subject to:

$$QSOA(x)^k = \sum\nolimits_{i \in H} F_i Cp_i \{\max(0, T_i^{in} - T_k^p) - \max(0, T_i^{out} - T_k^p) \tag{1}$$

$$QSIA(x)^k = \sum\nolimits_{j \in C} F_j Cp_j \{\max(0, T_j^{out} - (T_k^p - HRAT)) - \max(0, T_j^{in} - (T_k^p - HRAT))\} \tag{2}$$

$$QHOT(x) = \sum\nolimits_{i \in H} F_i Cp_i (T_i^{in} - T_i^{out}) \tag{3}$$

$$QCOL(x) = \sum\nolimits_{j \in C} F_j Cp_j (T_j^{out} - T_j^{in}) \tag{4}$$

$$\Omega(x) = QHOT(x) - QCOL(x) \tag{5}$$

$$Q_H = \max_{k \in K}(QSIA(x)^k - QSOA(x)^k) \tag{6}$$

$$Q_C = \Omega(x) + Q_H \tag{7}$$

Where the pinch candidate temperatures are given by:

$$T_k^p = T_i^{in} : k = i \in H, \quad T_k^p = T_j^{in} + HRAT : k = j \in C \tag{8}$$

and

$$Q_C, Q_H, QSIA, QSOA, F_i, F_j, T_i, T_j \geq 0 \tag{9}$$