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Transshipment Type Model for Total Site Heat Integration Using Non-Isothermal Utility Loop

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There is a growing interest in developing Total Site Heat Integration methods, since Total Site Heat Integration offers an energy-saving opportunity across multiple plants beyond the traditional intra-plant plant integration. Total Site heat integration can be achieved indirectly by non-isothermal utility loop, such as hot water and thermal oil. The parameters of non-isothermal utility loop, interconnectivity patterns directly determine the energy saving and the capital cost. In this work, a transshipment type Total Site heat exchanger network (HEN) model using non-isothermal utility loop is developed. A new representation method of non-isothermal utility loop is proposed based on transshipment type HEN model to avoid non-linear terms. The model is formulated as a MINLP problem with all linear constraints. The operating cost, capital cost of heat exchangers, pumping and piping cost are holistically considered and optimized. The case study demonstrates the effectiveness of the proposed model.

1. Introduction

Process industry is an energy intensive industry, where large amounts of fossil fuels are consumed. The increasing price of fossil fuels and the growing environmental concern drive process industry to use energy efficiently. In the past decades, heat integration method has been recognized as a systematical and effective approach for energy conservation. More energy saving opportunities can be explored by Total Site Heat Integration, which has received attentions from both researchers in academic and practitioners in industry.

The systematic methods for heat integration can be classified into two categories: Pinch Analysis (PA) and Mathematical Programming (MP). PA was first introduced by Linnhoff and Hindmarch (1983), which provided insight of potential energy saving opportunities in an individual plant. Ahmad and Hui (1991) extended PA to find minimum energy consumption for separate plant regions by the overlapping of Grand Composite Curves. Both direct heat integration using process streams and indirect heat integration using different levels of steam were studied. Then, Hui and Ahmad (1994) further extended this method to identify a network considering the overall cost tradeoff between energy, heat exchange area and the number of interconnections. Although PA methods rely on heuristics and cannot provide the optimal design, up to now, researchers are still developing PA based methods owing to the advantage of physical insights. Varbanov et al. (2012) proposed a modified Total Site targeting procedure, allowing temperature differences ($\triangle T_{min}$) are specified for each process. Chang et al. (2015) introduced a two-steps methodology for inter-plant heat integration using non-isothermal utility loops, by combining graphical targeting and mathematical programming. Liao et al. (2016) developed a new graphical tool, namely H-F diagram, to design HENs with parallel structures. Song et al. (2016) used Interplant Shifted Composite Curve (ISCC) to determine the maximum feasible heat recovery potential. Recently, Tarighaleslami et al. (2017) developed a new unified Total Site Heat Integration targeting methodology for isothermal and non-isothermal utilities. Song et al. (2017) proposed a novel screening algorithm to divide large-scale problems into several smaller sections, based on PA and the theoretical maximum inter-plant heat

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recovery potential. Hong et al. (2018) developed a new conceptual tool, namely Heat Transfer Block Diagram. The utility targets and cost-effective HENs can be obtained by analyzing heat surpluses and deficits on the diagram.

Mathematical programming approaches can generate solutions automatically by optimizing single or multiple objective functions. As is well known, two HEN models, the stage-wise superstructure (Yee, Grossmann, 1990) and the transshipment model (Papoulias, Grossmann, 1983), were widely adopted in the researches about heat integration. Based on the transshipment model (Papoulias, Grossmann, 1983), Rodra and Bagajewicz (1999) developed a systematic procedure to target maximum energy savings for both direct and indirect heat integration across multiple plants. Besides, they proposed a mixed integer linear programming (MILP) model to determine the optimum location of non-isothermal utility loop. Bada and Bandyopadhypy (2014) developed a linear programming (LP) model to minimize the flowrate of thermal hot oil for indirect heat integration. However, other factors, such as piping cost and pumping cost, were not considered in the model. Recently, Chang et al. proposed a mixed integer non-linear programming (MINLP) model for inter-plant direct heat integration (Chang et al., 2017b) and a MINLP model for indirect heat integration (Chang et al., 2017a), based on the stage-wise superstructure (Yee, Grossmann, 1990). Energy cost, heat exchanger cost, piping cost and pumping cost were simultaneously considered in these two models. However, the non-isothermal mixing in the stage-wise superstructure (Yee, Grossmann, 1990) would cause non-linear terms, which will cause heavy computational burdens. Although the transshipment model (Papoulias, Grossmann, 1983) is linear, it was only applied to target energy consumption and determine the location of non-isothermal utility loops (Rodera, Bagajewicz, 1999).

Recently, a transshipment type HEN model (Hong et al., 2017) was proposed to optimize the total annual cost of intra-plant HEN, allowing non-isothermal mixing while keeping all constraints linear. In this work, this transshipment type HEN model is extended to the synthesis of Total Site HEN. Unlike hot and cold process streams, the parameters of non-isothermal utility loops are unknown, such as temperature and flowrate. Thus, a new representation method of non-isothermal utility loop is proposed. The model is formulated as a MINLP model, while keeping all constraints linear. The literature example is adopted to illustrate the effectiveness of the proposed approach.

2. Problem Statement

The general problem of Total Site HEN synthesis can be stated as follows. Given are several individual plants (P) segregated in different location. It is assumed that the local HEN in each plant is well established. In each plant, a set of hot process streams (HP) with coolers, a set of cold process streams (CP) with heaters, a set of hot utilities (HU) and a set of cold utilities (CU) are given, as well as their corresponding parameters. The objective is to design the inter plant HENs using non-isothermal utility loops by minimizing the total annual cost, including the operating cost, the capital cost of heat exchangers, the piping cost and the pumping cost.

3. Mathematical Programming

This section presents the mathematical formulations for the transshipment type Total Site HEN model. It is known that Total Site Heat Integration can be achieved by either directly using process streams or indirectly through non-isothermal utility loops. Compared to direct integration, indirect integration using non-isothermal utility loops is more practical, considering several problems likes schedule, controllability and complexity. The parameters of non-isothermal utility loops, such as flowrate and temperature, and interconnectivity pattern between different plants, directly determine the utility consumption and the capital cost of heat exchangers, pipes, and pumps. However, the flowrates and temperatures of non-isothermal utility loops are unknown, which generally lead to non-linear terms in energy balance equations. In this work, a new representation method of non-isothermal utility loops on transshipment model is developed, while keeping all constraints linear.

3.1 Non-isothermal utility loops

The temperature intervals are constructed according to the starting and ending temperatures of all process streams. It is known that the temperature of non-isothermal utility loops must be lower than the maximum temperature of temperature intervals and higher than the minimum temperature of temperature intervals. Theoretically, the non-isothermal utility loop can exist in the entire temperature intervals, as shown in Figure 1. The hot utility loop (li) and the cold utility loop (mi) can exchange heat with cold and hot process streams in all plants respectively. Several heat exchange matches are shown in Figure 1. The energy balance in each temperature interval is illustrated in the dotted line circle of Figure 1, while the formulations are given by Eq(1) and Eq(2):

$$flisk_{li,ls,k} \times (tn_n - tn_{n+1}) \times c_p + rqhis_{li,ls,n} - rqhis_{li,ls,n+1} - \sum_{(p,m,ms)\in CMS} qlim_{p,li,ls,m,ms,k} = 0 \ \forall (li,ls) \in ILS, n \in TL \quad (1)$$

$$fmisk_{mi,ms,k} \times (tn_n - tn_{n+1}) \times c_p + rqcis_{mi,ms,n+1} - rqcis_{mi,ms,n} - \sum_{(p,l,ls) \in HLS} qlmi_{p,l,ls,mi,ms,k} = 0 \ \forall (mi,ms) \in IMS, n \in TL \quad (2)$$

where the variables $rqhis_{li,ls,n}$ and $rqcis_{mi,ms,n}$ represent the residual energy of hot and cold utility loops at temperature level n respectively. The big-M constraints for heat loads between process streams and utility loops are given by Eq(3) and Eq(4):

$$qlim_{p,li,ls,m,ms,k} \le U_{li,m,k} \times z_{p,li,ls,m,ms,k} \ \forall (li,ls) \in ILS, (p,m,ms) \in CMS, k \in TK \quad (3)$$

$$qlmi_{p,l,ls,mi,ms,k} \le U_{l,mi,k} \times z_{p,l,ls,mi,ms,k} \ \forall (mi,ms) \in IMS, (p,l,ls) \in HLS, k \in TK \quad (4)$$

In the model, the residual energy of utility loops can be both positive and negative. When the residual energy $rqhis_{li,ls,n}$ ($rqcis_{mi,ms,n}$) is positive, it means that the temperature of hot (cold) utility loop is larger (smaller) than the temperature of the corresponding temperature level. The binary variables $xlisn_{li,ls,n}$ and $xmisn_{mi,ms,n}$ are used to denote whether the residual energy is positive, given by Eqs(5-8). When the residual energy $rqhis_{li,ls,n}$ ($rqcis_{mi,ms,n}$) is positive, the binary variable $xlisn_{li,ls,n}$ ($xmisn_{mi,ms,n}$) will be 1. Besides, the heat transfer matches are available only when the residual energy is positive, owing to the minimum temperature difference $\triangle T_{min}$.

$$rqhis_{li,ls,n} \le PMlin_{li,ls,n} \times xlisn_{li,ls,n+1} \ \forall (li,ls) \in ILS, n \in TL \quad (5)$$

$$rqhis_{li,ls,n} \ge NMlin_{li,ls,n} \times (1 - xlisn_{li,ls,n+1}) \ \forall (li,ls) \in ILS, n \in TL \quad (6)$$

$$rqcis_{mi,ms,n} \le PMmin_{mi,ms,n} \times xmisn_{mi,ms,n+1} \ \forall (mi,ms) \in IMS, n \in TL \quad (7)$$

$$rqcis_{mi,ms,n} \ge NMmin_{mi,ms,n} \times (1 - xmisn_{mi,ms,n+1}) \ \forall (mi,ms) \in IMS, n \in TL \quad (8)$$

$$z_{p,li,ls,m,ms,k} \le xlisn_{li,ls,n} \ \forall (li,ls) \in ILS, (p,m,ms) \in CMS, k \in TK, n \in TL, k{=}n \quad (9)$$

$$z_{p,li,ls,m,ms,k} \le xlisn_{li,ls,n+1} \ \forall (li,ls) \in ILS, (p,m,ms) \in CMS, k \in TK, n \in TL, k{=}n \quad (10)$$

$$z_{p,l,ls,mi,ms,k} \le xmisn_{mi,ms,n} \ \forall (mi,ms) \in IMS, (p,l,ls) \in HLS, k \in TK, n \in TL, k{=}n \quad (11)$$

$$z_{p,l,ls,mi,ms,k} \le xmisn_{mi,ms,n} \ \forall (mi,ms) \in IMS, (p,l,ls) \in HLS, k \in TK, n \in TL, k{=}n \quad (12)$$

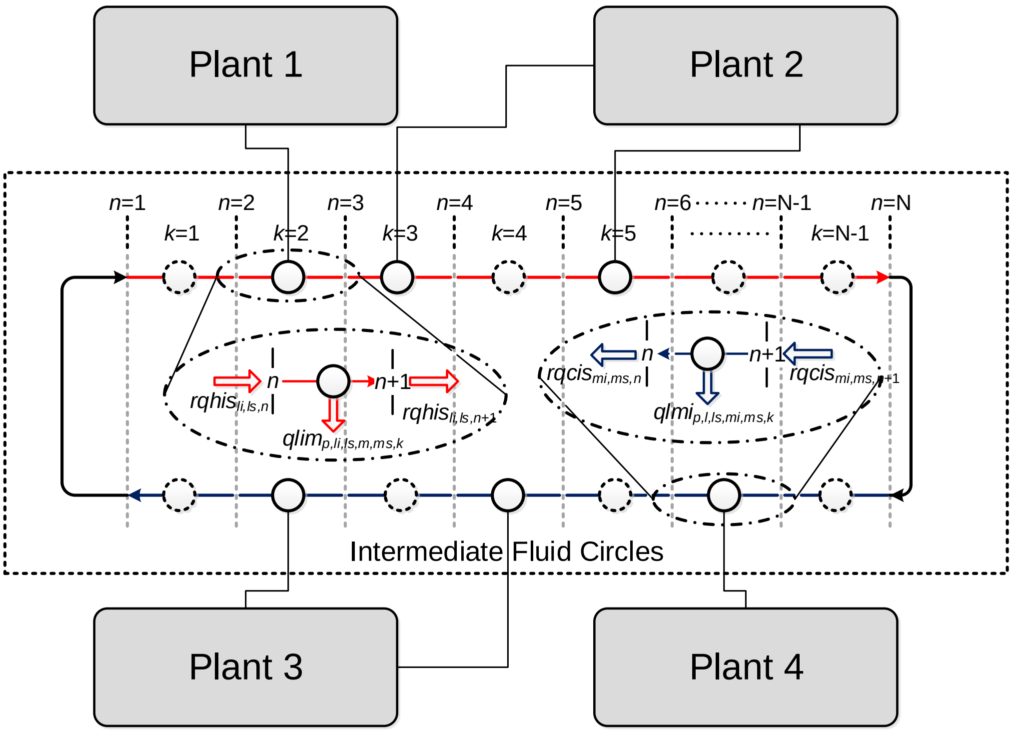

Figure 1: The representation of non-isothermal utility loops

3.2 Objective function

The objective function of the proposed model is defined as the total annual cost (TAC) including the hot utility cost (HUC), the cold utility cost (CUC), the exchangers cost (EXC), the piping cost (PIPC), and the pumping cost (PUMC), given by Eq. 13. The HUC, CUC, EXC, PIPC, and PUMC are given by Eqs(4-18). Note that, the piping cost and the pumping cost formulation are adopted from Chang et al. (2016). Besides, more details about the formulations for the transshipment type HEN can be found in the previous work (Hong et al., 2017).

$$\min TAC = HUC + CUC + EXC + PIPC + PUMC \tag{13}$$

$$HUC = \sum_{l \in \mathrm{HU}} hu_l \times \mathrm{Chu}_l \tag{14}$$

$$CUC = \sum_{m \in \mathrm{CU}} cu_m \times \mathrm{Ccu}_m \tag{15}$$

$$\begin{aligned} EXC = {} & \mathrm{AF} \times \alpha \times \Big(\sum_{(p,l,ls) \in \mathrm{HLS}} \sum_{(mi,ms) \in \mathrm{IMS}} \sum_{k \in \mathrm{TI}} zzlmi_{p,l,ls,mi,ms,k} + \sum_{(li,ls) \in \mathrm{ILS}} \sum_{(p,m,ms) \in \mathrm{CMS}} \sum_{k \in \mathrm{TI}} zzlim_{p,li,ls,m,ms,k} \\ & + \sum_{m \in \mathrm{CP}} zhu_m + \sum_{l \in \mathrm{HP}} zcu_l \Big) + \mathrm{AF} \times \Big(\beta \times \sum_{(l,ls) \in \mathrm{HLS}, l \in \mathrm{HP}} \sum_{(mi,ms) \in \mathrm{IMS}} \Big(\sum_{ns_l \le k < ns_{mi}} \frac{qlmi_{p,l,ls,mi,ms,k}}{U_{l,mi} \times dtlmi_{p,l,ls,mi,ms,k}} \Big)^{\gamma} \\ & + \beta \times \sum_{(li,ls) \in \mathrm{ILS}} \sum_{(p,m,ms) \in \mathrm{CMS}} \Big(\sum_{ns_{li} \le k << ns_m} \frac{qlim_{p,li,ls,m,ms,k}}{U_{li,m} \times dt_{p,li,ls,m,ms,k}} \Big)^{\gamma} \\ & + \beta \times \Big(\sum_{l \in \mathrm{HP}} \Big(\frac{\sum_{ls \in \mathrm{LS}} \sum_{ms \in \mathrm{MS}} q_{l,ls,\mathrm{M},ms,\mathrm{K}}}{U_{l,\mathrm{M}} \times dtcu_l} \Big)^{\gamma} \Big) + \beta \times \Big(\sum_{m \in \mathrm{CP}} \Big(\frac{\sum_{ls \in \mathrm{LS}} \sum_{ms \in \mathrm{MS}} q_{\mathrm{L},ls,m,ms,1}}{U_{\mathrm{L},m} \times dthu_m} \Big)^{\gamma} \Big) \Big) \end{aligned} \tag{16}$$

$$PIPC = AF \times L \times \left(A_1 \times (1300 \times Din^2 + 75.18 \times Din + 0.9268) + A_2 \times Dout^{0.48} + A_3 + A_4 Dout \right) \tag{17}$$

$$PUMC = 2 \times Pe \times Hy \times Qw + AF \times 2 \times \left(\mathrm{a} + \mathrm{b} \times \left(\frac{M \Delta P}{\rho} \right)^{\mathrm{c}} \right) \tag{18}$$

4. Case study

The proposed model is formulated as a MINLP problem, modeled in GAMS 23.3 (General Algebraic Modeling System) on a PC machine (3.2 GHz, 4 G RAM). The DICOPT solver is adopted to solve the proposed model. Inside DICOPT solver, CONOPT is adopted as NLP solver, while CPLEX is adopted as MILP solver. An example adopted from Chang et al. (2016) is presented, including two plants. The stream data is listed in Table 1, while the distance between two plants is : L=1,000 m. The minimum temperature difference $\triangle T_{min}$ for all heat exchangers is set 10 °C. In this example, hot water is assumed as the non-isothermal utility loop. The parameters of hot water are cp = 4.2 kJ/(°C·kg), ρ = 960 kg/m3, μ = 0.0002834 Pa·s and hw = 1 kW/(m^2·°C). The capital cost parameters of heat exchanger are α = 11,000, β = 150, γ = 1. The parameters of pipes are A_1 = 0.82, A_2 = 185, A_3 = 6.8 and A_4 = 295. The parameters of centrifugal pump are a = 8,600, b = 7,310 , c = 0.2, and η = 0.7. The operating time is assumed as Hy = 8000 h/y, while the electric price is Pe = 0.1 $/(kW·h). The annual factor of the capital cost AF is 0.264. The cold utility cost is Ccu = 8 $/(kW·y) and the hot utility cost is Chu = 20 $/(kW·y).

Table 1: Stream data for the example

Stream	F(kW/°C)	T_{in}(°C)	T_{out}(°C)	h(kW/m^2°C)
H1(Plant 1)	311.9	148.1	114.7	1.642
H2(Plant 1)	303.3	145.4	105.6	1.451
H3(Plant 1)	302.6	141.9	98.4	1.754
H4(Plant 1)	307.4	140.8	75.5	1.411
H5(Plant 1)	335.4	135.3	55.3	1.531
H6(Plant 1)	330.2	133.9	42.2	1.721
H7(Plant 1)	331.3	131.9	41.2	1.713
C1(Plant 2)	335.4	78.2	135.7	1.518
C2(Plant 2)	323.3	69.3	108.5	1.631
C3(Plant 2)	305.6	60.5	95.6	1.108
C4(Plant 2)	321.5	59.5	90.3	1.501
C5(Plant 2)	381.5	50.2	79.5	1.203
C6(Plant 2)	311.5	45.9	71.4	1.102
C7(Plant 2)	301.5	42.9	65.4	1.102

The computational result shows that the TAC of this is 1,975,861 $/y, while the hot and cold utility consumptions are 8,000 and 72,392 kW respectively. The Total Site HEN is shown in Figure 2. The results of literature and this work are compared in Table 2. Although less hot and cold utilities are consumed in Figure 2, the flowrate of hot water is larger, which leads to larger piping cost and pumping cost.

Table 2: The result comparisons between the literature result and this work

Items	Ref	This work
Hot utility kW	8,724	8,000
Cold utility kW	73,115	72,392
Hot water loop kW/℃	1,092	1,232
HUC $	174,475	160,000
CUC $	584,922	579,142
EXC $	612,319	718,237
PIPC $	318,282	453,969
PUMC $	37,859	64,513
TAC $	1,727,858	1,975,861

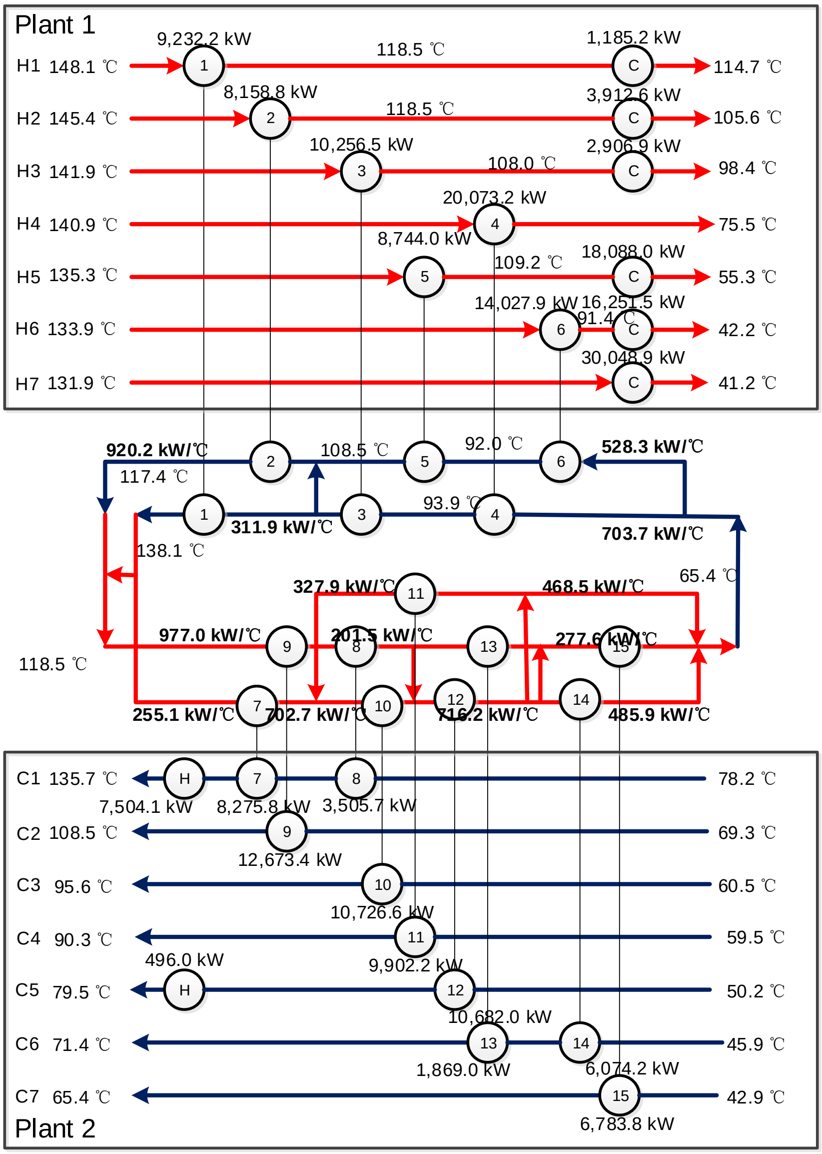

Figure 2: The Total Site HEN of the example

5. Conclusions

In this work, a new transshipment type Total Site HEN model using non-isothermal utility loops is proposed. The utility cost, the capital cost of heat exchangers, the piping cost, and the pumping cost are all considered in the model. A new representation method of non-isothermal utility loops is developed to avoid the non-linear terms caused by the non-isothermal mixing. The model is formulated as a MINLP problem with all constraints linear. Although the result of the proposed model is not better than the one of the literature considering the total annual cost, the case study shows the effectiveness of the proposed transshipment type model. In the future work, the proposed model will be further improved and extended to the synthesis of intra- and inter-plant HEN.

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