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# Participant Plants and Streams Selection for Interplant Heat Integration among Three Plants

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Interplant heat integration is an efficient way of energy saving for industry zones. In past few decades, many researches of this topic were proposed, which brings significant energy savings. However, in many previous studies, either all process streams or waste heat source/sink of individual plants were used for integration. This paper introduced a new selection strategy of participant plants and streams before integration, which can reduce the number of participant streams and calculation burden while the energy targets almost keep unchanged. The proposed method can consider both pinch and threshold problems. The parallel structure is selected for integration between three plants, since it can always achieve the largest energy saving than split and series structures and it might be more reliable when considering flow rate or temperature fluctuation in individual plants. A case study is used to show the effectiveness of the strategy.

## 1. Introduction

Interplant heat integration can further save energy after the heat integration of each plant has carried out. The first effort about interplant heat integration was introduced by Dhole and Linnhoff (1993) and further elaborated had been done by Hu and Ahmad (1994). The research topic still receives considerable attentions. Both Pinch Analysis (PA) and Mathematical Programming (MP) have been applied to it (Klemeš and Kravanja, 2013). For PA, Total Site Profiles (TSP, Klemeš et al., 1997) was widely used to solve this problem. Bandyopadhyay et al. (2010) and Bade and Bandyopadhyay (2014) introduced the concept of Site Grand Composite Curve (SGCC) to estimate the possibility of heat recovery across plants. Wang et al. (2014) proposed a graphical methodology for determining the energy target of interplant heat integration with different connection patterns. Recently, Song et al. (2016) investigated a way to achieve almost maximum possible heat recovery for indirect heat integration between two plants without basically changing the existing heat exchanger networks (HENs). For MP, Rodera and Bagajewicz (1999) introduced a mathematical model to target energy savings for heat integration across plants and showed that in certain problems, removing of "pockets" from the Grand Composite Curves (GCC) reduces the energy recovery potential. In subsequent work, Bagajewicz and Rodera (2000) extended the mathematical models proposed from two plants to multi-plants heat integration. Chang et al. (2014) established a Mixed Integer Nonlinear Programming (MINLP) model to achieve the optimal economic solution for indirect heat integration between two plants using hot water as the intermediate medium. Recently, Nemet et al. (2015) developed a stochastic multi-period MINLP model for the synthesis of a Total Site (TS) and the optimization of its heat recovery in order to consider also future utility prices.The optimal economical solution for implementation of interplant heat integration can be obtained by MP. However, it is usually difficult to find out the optimal results, especially for the complex problems which may have a lot of plants and streams get involved.
The current work provide a procedure for selecting plants and hot/cold streams for interplant heat integration among three plants, which can reduce the number of participant hot/cold streams before integration, while the energy targets almost keep unchanged.

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## 2. Methodology

For the interplant heat integration, both Pinch and threshold problem may appear between the heat source and sink plants. However, the problem types were usually ignored in the previous studies. Actually, these two problems should be treated with different strategies when we choose the participant heat source and sink plants for interplant heat integration. In this paper, three plants (one heat source plant and two heat sink plants) are chosen for illustration. The combination of two heat source plants and one heat sink plant can be implemented in a similar way.

### 2.1 Pinch problem

Linnhoff and Vredeveld (1984) firstly introduced the “Plus-Minus Principle” for single HEN, which can increase the energy targets of the HEN through process modification. This method is shown in Figure 1 and below guidelines.

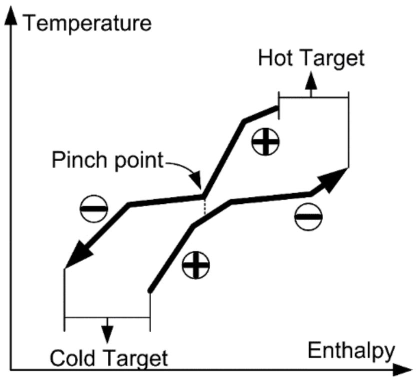


*Figure 1: The energy targets can only be modified if the process stream enthalpy changes are modified*

Guidelines of “Plus-Minus Principle”:
1. Increase hot stream duty above the pinch.
2. Decrease cold stream duty above the pinch.
3. Decrease hot stream duty below the pinch.
4. Increase cold stream duty below the pinch.

Recently, Chew (2015) firstly applied this principle on TSP to select beneficial process modification options that would increase the energy conservation. However, the process modification options are usually difficult to implement and not always available. Actually, we can apply this principle on interplant heat integration to select heat source and/or sink plants which can get involved in an existing interplant heat integration system. It will be an easy and always feasible strategy.

For instance, based on the “Plus-Minus Principle”, for an interplant heat integration between two plants which is a Pinch problem, whether another heat sink plant can get involved in this integration system should follow below guidelines:

1. If all the cold streams’ temperature ranges of this heat sink plant sit above the original Pinch point, the energy recovery potential between these three plants will definitely not increase compared to previous integration between two plants.
2. If there are one or more cold streams in this heat sink plant whose temperature ranges sit below or cross the original Pinch point, the energy recovery potential will increase through compositing them with the cold streams of another heat sink plant in a T-H diagram, until the new Pinch point appears.

### 2.2 Threshold problem

The situation where only one utility is required is called a “threshold problem”. Threshold problem falls into two broad categories, where only hot or cold utility is required which are shown in Figure 2(a) and 2(b), respectively.

For an interplant heat integration between two plants which is a threshold problem, another heat sink plant can get involved in this integration system should follow below guidelines:

1. If the threshold problem is the situation of Figure 2(a), it will be a vain attempt that another heat sink plant get involved in this integration system, since all the heat in the heat source plant have been already recovered. In this case, it will be a feasible solution to substitute another heat sink plant which will lead a lower total annual cost (TAC) for the original one.

2. If the threshold problem is the situation of Figure 2(b), another heat sink plant can get involved in this integration system to further increase the interplant heat recovery potential, until a Pinch point appears in the interplant composite curves.

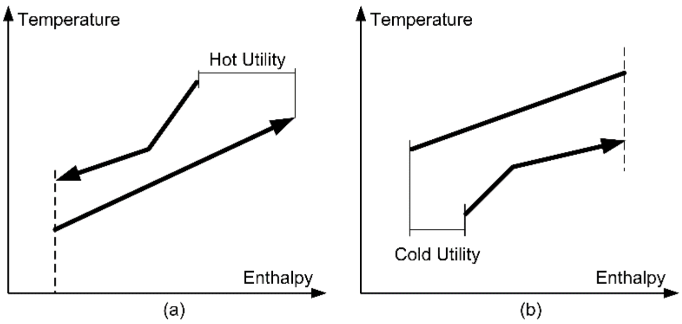


*Figure 2: Two types of threshold problem*

**2.3 Prescreen of hot/cold streams participated in interplant heat integration**

Wang et al. (2014) discussed the different energy targets with different connection patterns among three plants. Based on this research, in this paper, the parallel structure is selected for interplant heat integration among three plants, since it can always achieve the largest energy savings than split and series structures and it might be more reliable when considering flow rate or temperature fluctuation in individual plants.

Three plants (one heat source plant and two heat sink plants) are chosen for integration. To make the problem more general, we assume that Pinch problem appears between heat source plant A and one heat sink plant B, while threshold problem appears between heat source plant A and another heat sink plant C. Note that in this paper, each plant is used only as heat source or heat sink, which uses the waste heat source/sink in the individual plants. In addition, intermediate medium is used to transfer heat between heat source and heat sink plants. The minimum temperature difference of plant A, B and C are $\Delta T_{\min}^{A}$, $\Delta T_{\min}^{B}$ and $\Delta T_{\min}^{C}$, respectively.

Firstly, in order to compose all the heat source/sink streams in one T-H diagram, the temperature ranges of all the hot streams in plant A are shifted down by $\Delta T_{\min}^{A}$, while the temperature ranges of all the cold streams in plant B and C are shifted up by $\Delta T_{\min}^{B}$ and $\Delta T_{\min}^{C}$, respectively.

Based on the method proposed by Wang et al (2014), the simplified composite curves are applied to both heat sinks, as shown in Figures 3 and 4, respectively.

The maximum heat recovery potentials of Pinch and threshold problems are defined as $Q_{recovery}^{pinch}$ and $Q_{recovery}^{threshold}$, respectively. The heat capacity flowrates of two simplified composite curves are defined as $CP_{pinch}$ and $CP_{threshold}$, respectively. The supply temperatures of two simplified composite curves are defined as $T_{s}^{pinch}$ and $T_{s}^{threshold}$, respectively.

Next, these two simplified composite curves are composed in one T-H diagram and get pinched with the shifted hot composite curve, as shown in Figure 5. Here, the maximum heat recovery potential through parallel connection pattern can be easily found which is defined as $Q_{recovery}^{\max}$. Note that, the Pinch point may change during this process.

As the connection pattern and energy targets have been determined, the number of participant cold streams in one heat sink plant could be reduced, which will not change the energy targets. For instance, if we try to reduce the the number of participant cold streams in plant C while keeping the maximum heat recovery potential $Q_{recovery}^{\max}$ unchanged, the prescreen temperature for cold streams in plant C can be calculated with Eq(1).

$$T_{prescreen}^{threshold} = \frac{Q_{recovery}^{\max} - Q_{recovery}^{pinch}}{CP_{threshold}} + T_{s}^{threshold} \quad (1)$$

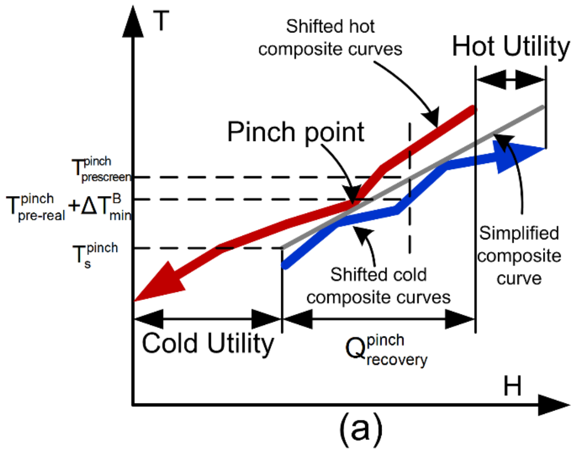


*Figure 3: Shifted and simplified composite curves of Pinch problem*

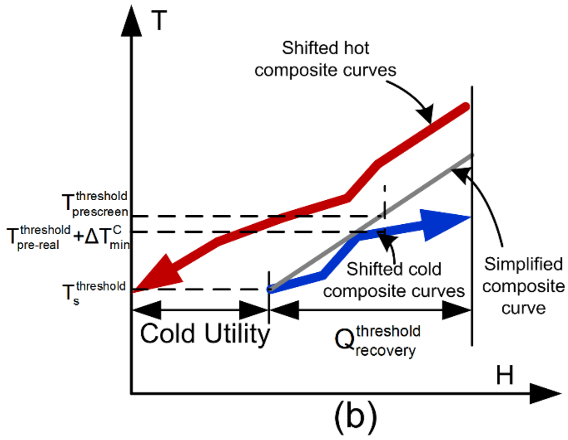


*Figure 4: Shifted and simplified composite curves of threshold problem*

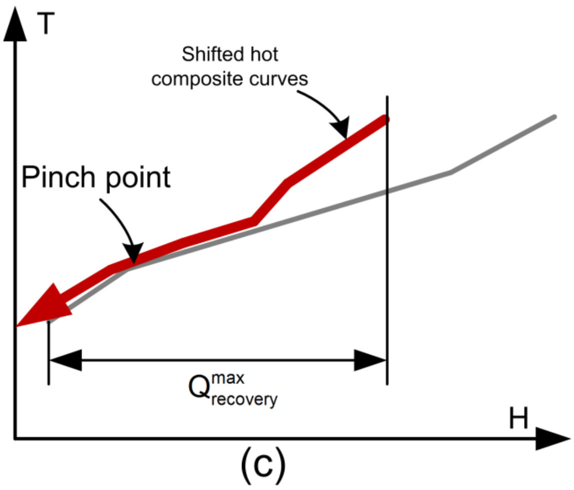


*Figure 5: The maximum heat recovery potential through parallel connection pattern among three plants*

Note that, it is the temperature in the simplified composite curve of plant C. Drawing a vertical line from this point and intersecting with the shifted cold composite curves of plant C, the real prescreen temperature $T_{pre\text{-}real}^{threshold}$ for cold streams in plant C can be obtained, as shown in Figure 4. Any cold streams in plant C, whose temperature ranges sit above $T_{pre\text{-}real}^{threshold}$, can be excluded from calculation, which will not change the $Q_{recovery}^{max}$.
Similarly, the prescreen temperature for cold streams in plant B can be calculated with Eq(2).

$$T_{prescreen}^{pinch} = \frac{Q_{recovery}^{max} - Q_{recovery}^{threshold}}{CP_{pinch}} + T_s^{pinch} \quad (2)$$

By the same method above, $T_{pre\text{-}real}^{pinch}$ can be easily obtained. After that, all the excluded cold streams will be directly heated by hot utility.
Note that under the same $Q_{recovery}^{max}$, there are numbers of assemblies for selection of participant cold streams. Here, we just provide two feasible ones.

## 3. Case study

According to the above discussions, three plants (one heat source plant A and two heat sink plant B and C) are introduced from an industry zone to implement an interplant heat integration, which can achieve further energy conservation compared to interplant heat integration between two plants.

### 3.1 Input data

The hot/cold stream data are listed in Table 1. The minimum temperature differences of plant A, B and C are 10 ºC, 15 ºC and 10 ºC, respectively.

*Table 1: Stream data*

| Plant | Stream | $T_s$ (ºC) | $T_t$ (ºC) | CP(kW/ ºC) | ΔH(kW) |
|---|---|---|---|---|---|
| Plant A | H1 | 220.0 | 150.0 | 14.86 | 1,040 |
| | H2 | 182.7 | 72.0 | 2.98 | 329.9 |
| | H3 | 163.7 | 38.0 | 0.381 | 47.89 |
| | H4 | 105.0 | 39.0 | 2.44 | 161.0 |
| | H5 | 169.7 | 52.0 | 2.147 | 252.7 |
| | H6 | 113.3 | 36.0 | 14.27 | 1,299 |
| Plant B | C1 | 70.0 | 100.0 | 10 | 300 |
| | C2 | 90.0 | 110.0 | 20 | 400 |
| | C3 | 100.0 | 200.0 | 30 | 3,000 |
| | C4 | 120.0 | 150.0 | 5 | 150 |
| | C5 | 145.0 | 150.0 | 6 | 30 |
| Plant C | C6 | 69.2 | 114.6 | 1.839 | 83.49 |
| | C7 | 149.5 | 164.0 | 10.93 | 158.5 |
| | C8 | 50.0 | 90.0 | 2.5 | 100 |
| | C9 | 152.1 | 160.0 | 23.84 | 188.3 |
| | C10 | 100.0 | 150.0 | 6 | 300 |
| | C11 | 40.0 | 80.0 | 20 | 800 |

### 3.2 Results and discussions

Based on the proposed method above, the results are shown in Table 2.

*Table 2: The calculation results*

| Problem style | $Q_{recovery}^{i}$(kW) | $CP_i$(kW/ ºC) | $T_s^i$(ºC) | $T_{prescreen}^i$(ºC) | $T_{pre\text{-}real}^i$(ºC) |
|---|---|---|---|---|---|
| i=pinch | 1,718.0 | 30.0 | 98.3 | 120.1 | 103.1 |
| i=threshold | 1,630.3 | 11.7 | 50 | 98.3 | 71.3 |

A Pinch problem appears between plant A and B, where the Pinch point of shifted cold streams is 98.3 ºC. A threshold problem which belongs to the situation of Figure 2(b) appears between plant A and C, where the temperature range of simplified composite curves for plant C starts from 50 ºC to 189.3 ºC. According to above discussions, Interplant heat integration among these three plants can further save energy. Actually, it can be easily calculated that the $Q_{recovery}^{max}$ through interplant heat integration among these three plants with a parallel connection pattern is 2,283.3 kW, which is larger than the integration between two plants. According to $T_{pre-real}$, the cold streams C4 and C5 in plant B or C7, C9 and C10 in plant C can be excluded from calculation, which will not change the $Q_{recovery}^{max}$.

## 4. Conclusions

A procedure for selecting plants and hot/cold streams for interplant heat integration among three plants has been developed and demonstrated. It allows us to determine the participant plants which can increase the energy savings before integration. Additionally, a simple method is proposed to reduce the number of participant hot/cold streams, while the energy targets almost keep unchanged. A case study has shown the effectiveness of the proposed method. Interplant heat integration with more than three plants and various connection patterns will be considered in future work.

**Acknowledgments**

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