CHEMICAL ENGINEERING TRANSACTIONS

VOL. 70, 2018

A publication of AIDIC

The Italian Association of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Timothy G. Walmsley, Petar S. Varbanov, Rongxin Su, Jiří J. Klemeš
Copyright © 2018, AIDIC Servizi S.r.l.
ISBN 978-88-95608-67-9; **ISSN** 2283-9216

DOI: 10.3303/CET1870280

A New Targeting Approach for Large Scale Interplant Heat Integration

Bo Li[a], Yufei Wang[a,*], Xiao Feng[b], Guiyuan Jiang[a]

[a]State Key Laboratory of Heavy Oil Processing, China University of Petroleum, Beijing 102249, China
[b]School of Chemical Engineering, Xi'an Jiaotong University, Xi'an, Shaanxi, 710049, China
wangyufei@cup.edu.cn

In recent years, inter-plant heat integration has been widely studied. Direct Heat Integration using process streams and Indirect Heat Integration using intermediate fluid are both researched. Up to now, for large scale problem, most of published work concentrated on Indirect Heat Integration through steam system. Due to complexity of large scale problem, very few works have been done to consider Direct Heat Integration. However, the twice heat transfer nature of Indirect Heat Integration limits energy saving potential. In order to solve the bottleneck of heat integration in interplant heat integration, Direct Heat Integration should be considered. Moreover, applying Direct Heat Integration can provide more cascade utilization opportunities of energy. To overcome the complex problem in solving large scale interplant heat integration, in this paper, a new targeting approach is proposed to determine the maximum energy recovery and optimal match between plants. The approach is based on Particle Swarm Optimization (PSO) and Multi-Verse Optimizer (MVO) to randomly match all the plants. Pinch Approach is used to determine the energy target for each pair of plants, and then the total energy target can be found. The optimal match of plants with maximum energy recovery can be found when the terminal condition for PSO is met. A case study is used to illustrate the capacity of solving large scale problem of the proposed methodology, and significant energy recovery can be obtained compared with Indirect Heat Integration.

1. Introduction

Inter-plant heat integration has been widely studied for many years as it can bring significant energy recovery. There are two forms of inter-plant heat integration. Interplant Heat Integration through intermediate fluid such as steam or hot water is called Indirect Heat Integration (Hui and Ahmad, 1994). On the contrary, using process stream to recover heat is called Direct Heat Integration. Dhole and Linnhoff (1993) extended Pinch Technology from single process to multiple processes through a central utility system, and they defined such heat integration through large scale industrial zone as total site heat integration. Klemeš et al. (1997) developed Total Site Profile and Site Utility Grand Composite Curve to target total site energy savings. Bandyopadhyay et al. (2010) proposed a Site Level Grand Composite Curve to maximum possible indirect integration and estimate the cogeneration potential. An improved Total Site Sensitivity Table is proposed by Peng et al. (2013) to characterize the effects of a plant maintenance shutdown, and determine the operational changes needed for the utility production and to plan mitigation actions. Hipólito-Valencia et al. (2014) proposed a design methodology for interplant trigeneration systems, not only the Inter-Plant Heat Integration is considered, but also a large utility system is considered to be optimized. Nemet et al. (2016) simultaneously considered integration within and between plants (at the plant and at the Total Site levels) using the superstructure optimization approach.
Bagajewicz and Rodera (2002) compared the two integration patterns in their work. It was found that Direct Heat Integration pattern can recover more heat compared with indirect pattern because it experiences heat transfer only once. The energy target shown in Figure 1 indicates the ultimate energy saving for each inter-plant heat integration method. Because the minimum temperature difference for Direct Heat Integration is smaller, the energy consumption can be reduced. Although steam system is simpler, lower in investment and widely accepted, the lower energy saving target limits the possibilities for further energy recovery. Wang et al. (2014)

Please cite this article as: Li B., Wang Y., Feng X., Jiang G., 2018, A new targeting approach for large scale interplant heat integration , Chemical Engineering Transactions, 70, 1675-1680 DOI:10.3303/CET1870280

combined direct and Indirect Heat Integration and found that the combined pattern can be used to reduce the heat exchange area, heat exchange circuit and energy consumption.
Although inter-plant heat integration has been widely studied, very few works have been done to consider large scale Direct Heat Integration. In large scale problem, the number of streams is huge, and it is difficult to directly determine the heat integration match between plants. In order to achieve more energy saving through inter-plant heat integration, this work considers a method to target the match between plants and the relative energy saving based on Direct Heat Integration. Concerning the complexity of heat integration between too many plants, the number of plants in each plants match is set as a constraint. PSO-MVO is used to find the optimal match between plants and the energy target can be found by Pinch Approach.

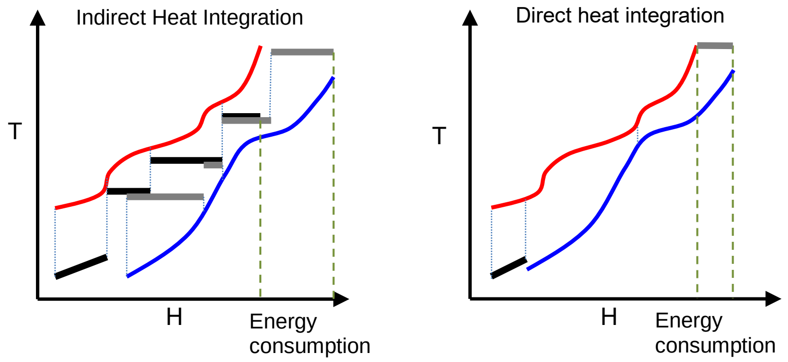

Figure 1: Energy target for different Inter-Plant Heat Integration methods

2. Methodology

Generally, a large scale factory or a chemical industrial park consists of a number of plants. When Direct Heat Integration is considered among plants at Total Site level rather than at the process level, the first task is to determine which plant should be integrated with which one. In this work, authors defined the plants directly integrated with each other as plant match. Different matches between plants will have various energy targets. In order to reduce the complexity of the task, in this paper, all the streams in one plant match are regarded as from the same plant, which means the distance between plants in one plant match is ignored. However, it is a very difficult integration task to put too many plants in one plant match. So, the maximum number of plants in one plant match is set as constraint. (In case study, this number is set to be 3). When Direct Heat Integration is adopted among 2 or 3 plants, the energy target can be calculated by Pinch Approach. But finding the optimal match is a complex task. The complexity of the model is significantly increased by the higher number of plants. In this paper, PSO and MVO algorithm are used to find the optimal match with the minimum total energy target. The targeting approach can be described as the following steps.
Step 1: Acquire hot and cold streams data of all plants, including supply temperature, target temperature and the heat duty of each stream.
Step 2: Sequence all the plants randomly.
Step 3: Divide the permutation in Step 2 into groups randomly. The number of plants in each group is less than 3 considering feasibility.
Step 4: Calculate the energy target of each group using Pinch Approach under the minimum temperature difference to obtain total energy target.
Step 5: If the total energy target meets the set value or the maximum number of iterations is reached, then the optimal match is found, otherwise initialize the parameters of MVO (MVO is the surrounding loop), and generate several universes. Each universe is a sequence of plants.
Step 6: Under the current sequence, initialize the parameters of PSO (PSO is the inner loop), generate several particle swarms. Each particle swarm is a group of the current sequence.
Step 7: Calculate the fitness value of each particle, if it is better than the current fitness value, then update it, otherwise maintain the current fitness value.
Step 8: If the termination condition of PSO is met, then stop the inner loop and return the optimal fitness value and corresponding group to the surrounding loop, otherwise return to Step 7.
Step 9: Take the fitness value returned by the inner loop as the expansion rate of the current universe. Calculate the expansion rate of each universe in turn. If the expansion rate is better than the current value, then update it, otherwise maintain the current universe.

Step 10: If the termination condition of MVO is met, then stop the surrounding loop and the optimal match is found, otherwise return to Step 5.
The algorithm flow chart of this targeting approach is shown in Figure 2.

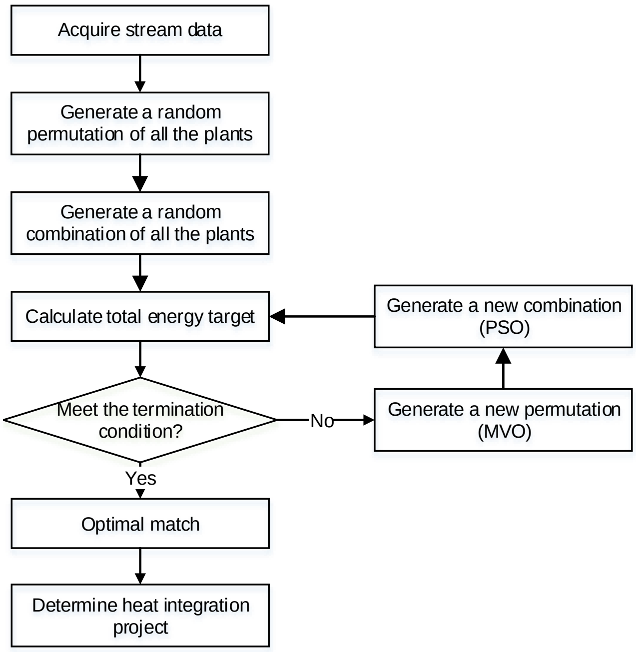

Figure 2: Algorithm flow chart of this targeting approach

Multi-Verse Optimizer (MVO) is a novel meta-heuristic algorithm proposed by Mirjalili et al (2016). The main inspirations of MVO algorithm are based on three concepts in astrophysics: black hole, white hole and wormhole. The mathematical models of these three terms are developed to exploitation, perform exploration, and local search, respectively. Because MVO has less parameters, better stability, and better global optimization capability, it is competitive in solving large scale optimization problems. MVO algorithm can be described as the following steps.
Step 1: Initialize the number of universe n, maximum number of iterations L, variable interval [lb, ub], and position of the universe.
Assume that

$$U = \begin{bmatrix} x_1^1 & x_1^2 & \cdots & x_1^d \\ x_2^1 & x_2^2 & \cdots & x_2^d \\ \vdots & \vdots & \vdots & \vdots \\ x_n^1 & x_n^2 & \cdots & x_n^d \end{bmatrix} \tag{1}$$

where U is a randomly created universe, d is the number of variables, and n is the number of universes.
Step 2: Array the universe by the expansion rate and choose a white hole through the roulette wheel mechanism.

$$x_i^j = \begin{cases} x_k^j & r_1 < NI(U_i) \\ x_i^j & r_1 \ge NI(U_i) \end{cases} \tag{2}$$

where x_i^j is the j^{th} parameter of the i^{th} universe, U_i is the i^{th} universe, $NI(U_i)$ is the normalized expansion rate of the i^{th} universe, r_1 is a random number in [0, 1], and x_k^j is the j^{th} parameter of the k^{th} universe selected by turntable mechanism.
Step 3: Update the wormhole existence probability (WEP), traveling distance rate (TDR) according to Eq(3) and Eq(4) and check the bounds.

$$WEP = \min + l \cdot \left(\frac{\max - \min}{L} \right) \tag{3}$$

$$TDR = 1 - \frac{l^{1/p}}{L^{1/p}} \tag{4}$$

where min (0.2 in this paper) and max (1.0 in this paper) are the minimum and maximum values of *WEP*, *l* is the current iteration, L is the maximum number of iteration, and *p* (6 in this paper) defines the iterative precision in this development process.
Step 4: Calculate the expansion rate, if the expansion rate is better than the current value, then update it, otherwise maintain the current universe.
Step 5: Update the position of universe, and search the optimal individual based on Eq(5).

$$x_i^j = \begin{cases} \begin{cases} X_j + TDR \times ((ub_j - lb_j) \times r_4 + lb_j) & r_3 < 0.5 \\ X_j - TDR \times ((ub_j - lb_j) \times r_4 + lb_j) & r_3 \geq 0.5 \end{cases} & r_2 < WEP \\ x_i^j & r_2 \geq WEP \end{cases} \tag{5}$$

where X_j is the j[th] parameter of the current optimal universe, ub_j and lb_j are the upper and lower bounds of the j[th] variable, and r_2, r_3 and r_4 are random numbers in [0, 1].
Step 6: Termination condition determination. If the termination condition is met (maximum number of iterations is reached, or an expected universe is found), then output the results, otherwise return to Step 2.
The flow chart of MVO algorithm is shown in Figure 3.

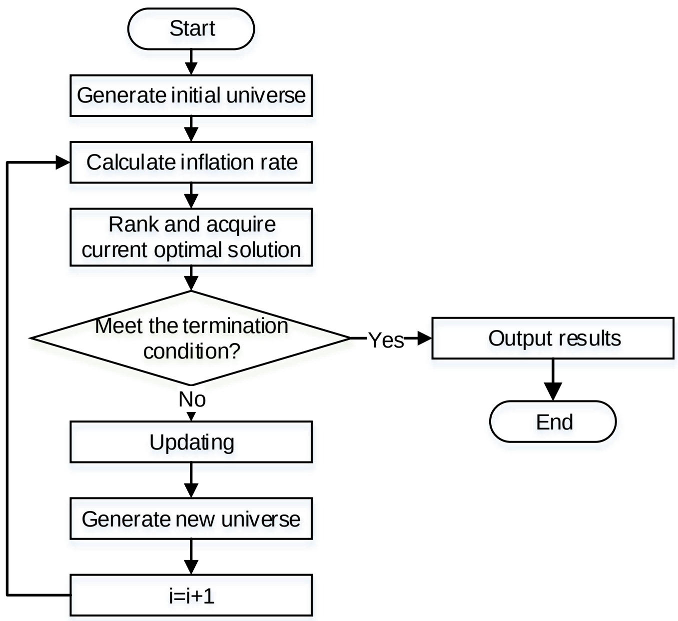

Figure 3: Flow chart of MVO algorithm

3. Case study

To make the case more practical, the data of process streams in this case is taken from a real Chinese refinery. There are 12 plants as well as a traditional utility system in the case. The name of 12 plants are listed in Table 1. The supply temperature, target temperature and the heat duty of each stream is extracted from the plant flowsheet. In total, there are 116 process steams.
The steam system contains: low pressure steam (0.45 MPa, 155 °C), medium pressure steam (1.0 MPa, 180 °C) and high-pressure steam (3.5 MPa, 240 °C). The minimum temperature difference in this case study is 10 °C. Because Indirect Heat Integration requires twice heat transfer, the minimum temperature is doubled compared with Direct Heat Integration. And if the intermediate fluid is steam, it is much easier to be get pinched with

process streams because steam uses latent heat. The existing heat exchanger network is based on Indirect Heat Integration by the steam system.

In this case, the streams of these plants can be integrated directly. By using PSO-MVO algorithm and Pinch Approach, the optimal match with the minimum total energy target can be found. First, the maximum number of plants in one plant match is set to be 2. And in the second case, it is set to be 3. For the first case, the optimal match of Direct Heat Integration of these 12 plants is (1,12), (2,3), (4,10), (6,7), (8,9), (5,11). For the second case, the optimal match is (1,12), (2,8), (3,4,7), (5,6,9), (10,11). The detail results are shown in Table 2. The comparison between the existing Indirect Heat Integration project and optimized Direct Heat Integration in this work indicates that the Direct Heat Integration project obtained by this approach has significant energy recovery. When Direct Heat Integration is adopted between 2 plants (Case 1), the steam consumption, steam generation and furnace duty decrease significantly because the direct heat exchange of the process streams between two plants brings more heat recovery opportunities. The furnace duty decreases by 45.1 %, and the energy consumption of whole area reduces by 30.2 % compared with Indirect Heat Integration, which means less fuel consumption and simpler steam system. When Direct Heat Integration is adopted among 3 plants (Case 2), the heat recovery further increases. The furnace duty decreases by 51.5 %, and the energy consumption reduces by 40.4 % compared with Indirect Heat Integration. The result illustrates the significant energy recovery of this approach.

Table 1: The details of 12 plants

Number	Name of plant	Abbreviation
1	Aromatic Extraction	AMC
2	Wax Oil Hydrogenation	WH
3	Residue Hydrogenation	RH
4	Sulfur Recovery	SUR
5	Acid Water Stripping	AW
6	Fluid Catalytic Cracking	FCC
7	S-Zorb	SZ
8	Crude Oil Fractionation	COF
9	Solvent Regeneration	SOR
10	Continuous Reforming	CR
11	Diesel Hydrogenation	DH
12	Delayed Coking	DC

Table 2: The detail results for case study

	Indirect Heat Integration	Case 1	Case 2
LP consumption (kW)	37,945	23,731	21,282
MP consumption (kW)	33,554	12,512	11,716
HP consumption (kW)	9,946	9,831	8,924
Furnace duty (kW)	48,914	26,840	23,718
LP generation (kW)	10,061	0	0
MP generation (kW)	23,965	8,540	8,118
HP generation (kW)	50,954	32,707	30,473
Q_H (kW)	45,379	31,667	27,049
Q_C (kW)	248,712	235,001	210,972

4. Conclusions

Inter-plant heat integration can bring significant energy saving. Although Indirect Heat Integration based on steam system is simpler, lower investment and widely accepted, Direct Heat Integration can solve the bottleneck of indirect integration due to avoid twice heat transfer and more cascade utilization opportunities of energy. In this work, Direct Heat Integration is considered in a large-scale problem. In case study, by using PSO-MVO algorithm and Pinch Approach, the optimal match of 12 plants is found. The result shows the significant energy saving of Direct Heat Integration. Compared with Indirect Heat Integration through steam system, the energy consumption of whole area reduces by 40.4 % and the furnace duty decreases by 51.5 %, having guiding significance for large scale inter-plant heat integration. The future work is to determine the number of process streams for Direct Heat Integration and the detail design of heat integration.

Acknowledgments

Financial supports from the National Natural Science Foundation of China (No. 21476256) and Science Foundation of China University of Petroleum, Beijing (No. 2462017BJB03) are gratefully acknowledged.

References

Bagajewicz M., Rodera H., 2002, Multiple plant heat integration in a total site, AIChE Journal, 48, 2255-2270.

Bandyopadhyay S., Varghese J., Bansal V., 2010, Targeting for cogeneration potential through total site integration, Applied Thermal Engineering, 30, 6-14.

Dhole V.R., Linnhoff B., 1993, Total site targets for fuel, co-generation, emissions, and cooling, Computers & Chemical Engineering, 17, 101-109.

Hipólito-Valencia B.J., Lira-Barragán L.F., Ponce-Ortega J.M., Serna-González M., El-Halwagi M.M., 2014, Multiobjective design of interplant trigeneration systems, AIChE Journal, 60, 213-236.

Hui C.W., Ahmad S., 1994, Minimum cost heat recovery between separate plant regions, Computers & Chemical Engineering, 18, 711-728.

Klemeš J.J., Dhole V.R., Raissi K., Perry S.J., Puigjaner L., 1997, Targeting and design methodology for reduction of fuel, power and CO_2 on total sites, Applied Thermal Engineering, 17, 993-1003.

Mirjalili S., Mirjalili S. M., Hatamlou A., 2016, Multi-Verse Optimizer: a nature-inspired algorithm for global optimization, Neural Computing & Applications, 27, 495-513.

Nemet A., Čuček L., Kravanja Z., 2016, Procedure for the simultaneous synthesis of heat exchanger networks at process and total site level, Chemical Engineering Transactions, 52, 1057-1062.

Peng Y.L., Alwi S.R.W., Varbanov P.S., Manan Z.A., Klemeš, J.J., 2013, Centralised utility system planning for a total site heat integration network, Computers & Chemical Engineering, 57, 104-111.

Wang Y., Feng X., Chang C., 2014, Heat integration between plants with combined integration patterns, Chemical Engineering Transactions, 39, 1747-1752.