CHEMICAL ENGINEERING TRANSACTIONS
VOL. 61, 2017
A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet
Guest Editors: Petar S Varbanov, Rongxin Su, Hon Loong Lam, Xia Liu, Jiří J Klemeš

ISBN 978-88-95608-51-8; **ISSN** 2283-9216
DOI: 10.3303/CET1761077

Heat-Integrated Water Allocation Network Synthesis for Industrial Parks

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Industrial parks can achieve the cooperative utilization of resource among multiple enterprises, and have become a major trend of process industry. Concerning the combined consumption issue of water and energy in industrial parks, this paper presents a methodology for interplant heat-integrated water allocation network (IHIWAN) synthesis, to explore the potential of water and energy conservation in industrial parks. The novel model proposed takes both direct and indirect schemes of cross-plant water reuse into consideration, and develops strategies for Heat Integration specific to industrial parks. The economically optimal overall IHIWAN is pursued by mathematical programming under the objective of minimum total annual cost (TAC). Based on superstructure, a non-linear programming (NLP) model is formulated containing two sub-networks: water allocation sub-network and heat exchanger sub-network. Regarding the two sub-networks, the overall network is synthesized in two solution approaches respectively: sequential design and simultaneous design. Through the comparison between these two approaches, it is indicated that simultaneous design presents preferable result, despite the higher requirement on solution process. The effectiveness of the proposed methodology is illustrated by a case study of an industrial park including three plants.

1. Introduction

Over the past decades, considerable efforts have been made on the synthesis of water allocation network (WAN) and heat exchanger network (HEN), which are efficient means to reduce the consumption of water and energy respectively. In recent years, industrial parks have become a major trend due to the advantage in industrial symbiosis among multiple plants. Yet, most of the works on water and energy integration are carried out either separately or within a single plant, which limits the potential of resource conservation. Consequently, it is crucial to achieve the cooperative integration of water and energy in the scale of industrial parks.

The study on individual synthesis of WAN and HEN in industrial parks started in the 1990s, with mathematical programming as the major approach. Chew et al. (2008) classified interplant water integration into two schemes: direct and indirect integration, wherein the former directly via cross-plant pipelines and the latter via a centralized utility hub. Liu et al. (2016) presented a plant-based mode of water allocation in industrial parks to restrict the number of interplant streams and thereby reduce complexity. As for Heat Integration, Chang et al. (2015) developed a two-step methodology for interplant Heat Integration via Heat Recovery Loop considering additional factors associated with distance between plants.

Combining WAN and HEN, whilst utilizing the interactions between these two sub-networks, water and energy consumption can be further reduced. So far, heat-integrated water allocation network (HIWAN) synthesis has been widely studied and the optimization approaches mainly follow two routes: sequential design and simultaneous design. The former is a stepwise strategy, dividing the problem into two sub-problems (concerning water and energy respectively) and solving sequentially; while the latter takes the optimization problem as a whole, and all the trade-offs are balanced within the model, which is optimized under one objective covering both water and energy.

However, most of the works only focus on the HIWAN synthesis within a single plant, whereas interplant HIWAN synthesis in the scale of industrial park has not been adequately investigated. Boix et al. (2011) addressed the water and energy management for an industrial park involving three plants, yet detailed issues such as network

Please cite this article as: Song H., Liu L., Du J., 2017, Heat-integrated water allocation network synthesis for industrial parks, Chemical Engineering Transactions, 61, 475-480 DOI:10.3303/CET1761077

structure and interplant distribution mode were not discussed. Zhou et al. (2012) presented the design of interplant water-allocation and heat-exchange network in a mixed integer nonlinear programming (MINLP) model based on multi-scale state-space superstructure, involving various scenarios of regeneration and redistribution. Still, relevant works are quite few and the methodologies are yet to be further explored.
In this work, a methodology for the economically optimal design of IHIWAN is presented to reduce water and energy consumption in industrial parks. Based on superstructure approach, a mathematical model is presented and strategies for interplant integration specific to industrial parks are developed. It's worth noting that, to simplify the model and reduce the computation load, all the discrete variables are eliminated and the problem is formulated as an NLP model rather than an MINLP model.

2. Problem statement

Given an industrial park including several plants, each plant containing a set of water generating and consuming units (assimilated as water sources and sinks) with specific flowrate, temperature and contaminant concentration, the objective is to synthesize an economically-optimal IHIWAN for the industrial park with minimum total annual cost whilst meeting all the process requirements. Regeneration operation is available with required operating temperature and fixed removal ratio of contaminant.

3. Superstructure

The superstructure for IHIWAN synthesis in industrial park is shown in Figure 1. The solid blocks denote the single plants in the park, and the dotted blocks denote the water allocation and Heat Integration subsystems within each plant. As can be seen, plants are correlated by inter-plant water streams and a shared regeneration unit enables the centralized operation in the park. The water allocation subsystem is revised from the “plant-based” WAN superstructure in our recent work (Liu et al., 2016). All the possible intra-plant matches between water sources (including fresh water) and sinks (including waste effluent) are taken in, as well as inter-plant reuse opportunities in both direct and indirect scheme.

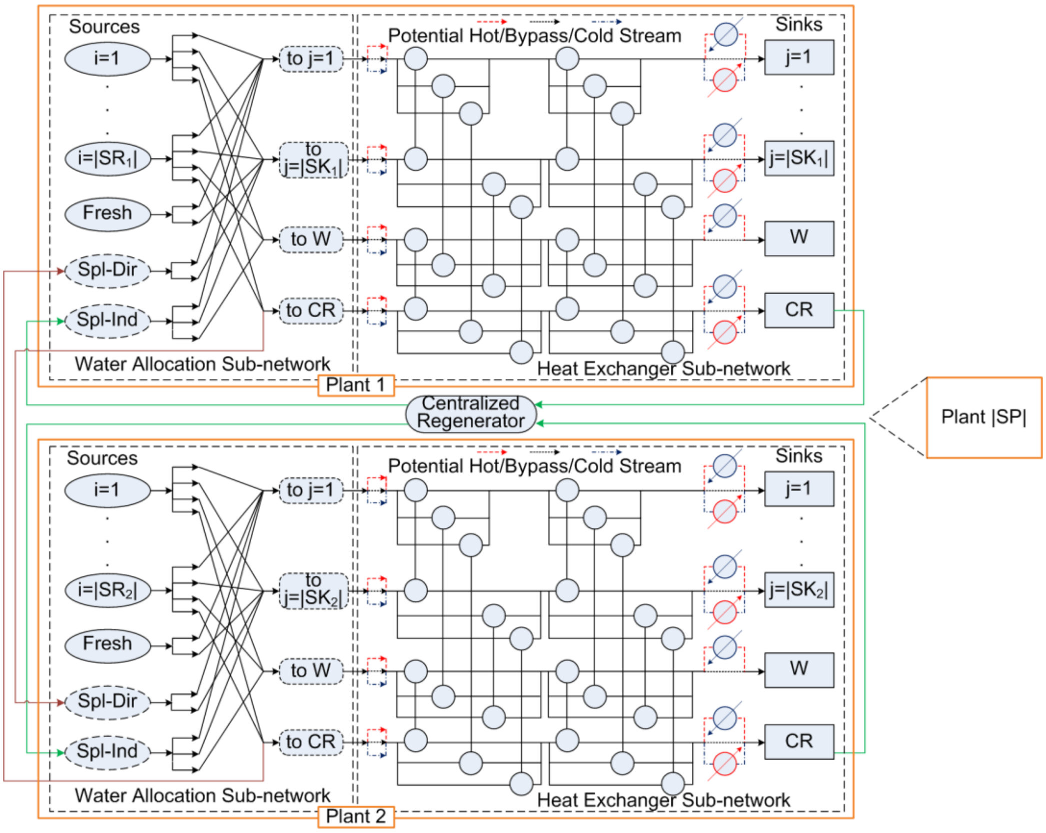

Figure 1: IHIWAN superstructure for industrial park

As for Heat Integration subsystem, heat exchange is allowed among the streams within and entering/leaving the same plant. Specifically, streams of direct interplant reuse participate in the HEN of target plant. In each plant, the water streams to the same target unit (sinks/effluent/central regenerator) are non-isothermally mixed into one single stream before entering the HEN, to make the most of direct heat exchange and reach the minimum number of streams involved in Heat Integration subsystem. Consequently, utility consumption is lowered and the HEN structures are relatively less intricate. Detailed design of HENs is based on the modified stage-wise HEN superstructure. The existence and role (hot/cold/bypass) of the potential streams in HEN are identified in the synthesis procedure. Note that the inlet stream of waste effluent shall not be heated by hot utility if identified as cold stream, since only the upper temperature limit is required for effluent discharge.

4. Mathematical model

Based on the superstructure, an NLP model is accordingly formulated to solve the problem. Compared with the generally used MINLP model, continuous variables $u=f/(f+\delta)$ and $z=q/(q+\delta)$ (δ is an infinitesimal number) are used to indicate the existence of potential water streams and heat exchangers respectively instead of binary variables, which significantly lowers computation complexity and facilitates the search for more desirable result. The model is divided into the following three sections. The objective function is the minimum TAC of the overall IHIWAN, which is the summation of the two subsystems.

$$TAC_{\text{obj}}^{\text{IHIWAN}} = \min\left(TAC^{\text{WAN}} + TAC^{\text{HEN}}\right) \tag{1}$$

4.1 Water allocation subsystem

The model for water allocation subsystem is basically revised from our recent work (Liu et al., 2016), including flowrate balance for water sources and sinks, contaminant concentration limit for water sinks, flowrate and contaminant load balance for inter-plant water streams, flowrate and contaminant load balance for centralized regenerator, and upper/lower bounds for flowrate. The TAC of water allocation subsystem consists of the cost of fresh water, regeneration and cross-plant pipeline, as shown in Eq(2).

$$\begin{aligned} TAC^{\text{WAN}} &= cost^{\text{fresh water}} + cost^{\text{regeneration}} + cost^{\text{pipeline}} \\ &= \sum_p \sum_j \left(f_{j,p}^{\text{fw}} \times uc^{\text{fw}}\right) \times AWH + \alpha_{\text{reg}}^{\text{cap}} \times \left(\sum_p f_p^{\text{ind,out}}\right)^{\beta_{reg}} \times AF + \alpha_{\text{reg}}^{\text{op}} \times \sum_p f_p^{\text{ind,out}} \times AWH \\ &\quad + AF \times D_{\text{dis}} \times \left(\begin{aligned} &\alpha_{\text{pl}}^{\text{var}} \times \sum_p \frac{f_p^{\text{cp}}}{3.6 \times \rho v} \\ &+\alpha_{\text{pl}}^{\text{fixed}} \times \left(\frac{\sum_p u_p^{\text{ind,out}} + \sum_p u_p^{\text{ind,in}}}{2} + \sum_p \sum_{p'} u_{p,p'}^{\text{dir}} \right) \end{aligned} \right) \quad \forall j \in SK_p, \forall p \in SP, \forall p' \in SP, p \neq p' \end{aligned} \tag{2}$$

where SP is the set of single plants in the park; SK_p is the set of water sinks in plant p; f denotes the flowrate of water stream; uc denotes unit cost; D_{dis} denotes inter-plant distance; AWH denotes annual working hour.

4.2 Heat Integration subsystem

The model for Heat Integration subsystem mainly includes overall heat balance for each stream, heat balance at each stage in superstructure, assignment of initial temperature in superstructure, feasibility constraints for temperatures, and constraints for heat transfer approach temperature. The TAC of Heat Integration subsystem consists of the cost of heat exchangers (fixed charge + area cost) and utilities, given by Eq(3).

$$\begin{aligned} TAC^{\text{HEN}} &= cost^{\text{heat exchangers}} + cost^{\text{utilities}} \\ &= \sum_p \left\{ \begin{aligned} &\alpha_{\text{he}}^{\text{fixed}} \times \left(\sum_h \sum_c \sum_k z_{h,c,k,p}^{\text{hc}} + \sum_c z_{c,p}^{\text{HUc}} + \sum_h z_{h,p}^{\text{hCU}} \right) \\ &+\alpha_{\text{he}}^{\text{area}} \times \left(\begin{aligned} &\sum_h \sum_c \sum_k \left(A_{h,c,k,p}^{\text{hc}}\right)^{\beta_{\text{he}}^{\text{area}}} \\ &+\sum_c \left(A_{c,p}^{\text{HUc}}\right)^{\beta_{\text{he}}^{\text{area}}} + \sum_h \left(A_{h,p}^{\text{hCU}}\right)^{\beta_{\text{he}}^{\text{area}}} \end{aligned} \right) \\ &+\left(uc^{\text{HU}} \times \sum_c q_{c,p}^{\text{HUc}} + uc^{\text{CU}} \times \sum_h q_{h,p}^{\text{hCU}} \right) \end{aligned} \right\} \quad \forall h \in HS_p, \forall c \in CS_p, \forall p \in SP, \forall k \in ST \end{aligned} \tag{3}$$

where HS_p and CS_p are the sets of hot and cold streams in the HEN of plant p; ST denotes the stages in HEN superstructure; q denotes the heat load exchanged in each unit; A denotes the area of heat exchanger. Note that the cost of hot utility and heater related to waste effluent streams is excluded from TAC^{HEN} in practical solution process since it is invalid as stated in Section 3.

4.3 Interconnections between the two subsystems

As mentioned in Section 3, according to the superstructure, the water streams to the same target unit are pre-mixed into one stream, which participates in the HEN to reach the required temperature before entering the target unit. The energy balance of the pre-mixing is shown by Eq(4) - Eq(7), from which the temperatures after mixing can be calculated and then assigned to the inlet temperatures of the streams in HEN in the order of sinks-effluent-regenerator, as shown in Eq(8). Whilst the outlet temperatures of the streams in HEN equal to the required temperature of corresponding units.

$$T_p^{\mathrm{mix,cp}} \times f_p^{\mathrm{cp}} = \sum_i \left(T_{i,p}^{\mathrm{sr}} \times f_{i,p}^{\mathrm{exp}} \right) \quad \forall i \in SR_p, \forall p \in SP \tag{4}$$

$$T_p^{\mathrm{dir,in}} \times f_p^{\mathrm{dir,in}} = \sum_{p'} \left(T_{p'}^{\mathrm{cp}} \times f_{p,p'}^{\mathrm{dir}} \right) \quad \forall i \in SR_p, \forall p \in SP, \forall p' \in SP, p' \neq p \tag{5}$$

$$T_{j,p}^{\mathrm{mix,sk}} \times F_{j,p}^{\mathrm{sk}} = \sum_i \left(T_{i,p}^{\mathrm{sr}} \times f_{i,j,p}^{\mathrm{in}} \right) + f_{j,p}^{\mathrm{fw}} \times T^{\mathrm{fw}} + f_{j,p}^{\mathrm{impd}} \times T_p^{\mathrm{dir,in}} + f_{j,p}^{\mathrm{impi}} \times T^{\mathrm{cr}} \quad \forall i \in SR_p, \forall j \in SK_p, \forall p \in SP \tag{6}$$

$$T_p^{\mathrm{mix,e}} \times \left(\sum_i f_{i,p}^{\mathrm{e}} + f_p^{\mathrm{impe}} \right) = \sum_i \left(T_{i,p}^{\mathrm{sr}} \times f_{i,p}^{e} \right) + f_p^{\mathrm{impe}} \times T^{\mathrm{cr}} \quad \forall i \in SR_p, \forall p \in SP \tag{7}$$

where SR_p is the set of water sources in plant p; $T_{j,p}^{\mathrm{mix,sk}}$, $T_p^{\mathrm{mix,e}}$, $T_p^{\mathrm{mix,cp}}$ are the inlet temperatures of the pre-mixed stream to sinks, effluent and centralized regenerator.

$$Ts_{s,p}^{\mathrm{in}} = \begin{cases} T_{j,p}^{\mathrm{mix,sk}} & \forall s \in ES_p, \forall j \in SK_p, \forall p \in SP, s = j \leq \left| SK_p \right| \\ T_p^{\mathrm{mix,e}} & \forall s \in ES_p, \forall p \in SP, s = \left| SK_p \right| + 1 \\ T_p^{\mathrm{mix,cp}} & \forall s \in ES_p, \forall p \in SP, s = \left| SK_p \right| + 2 \end{cases} \tag{8}$$

where ES_p is the set of potential streams to be involved in the HEN of plant p, $Ts_{s,p}^{\mathrm{in}}$ is the inlet temperature of potential heat-exchange stream s in plant p; $| SK_p |$ is the number of sinks in plant p.

When it comes to the simultaneous design of the two subsystems, the outlet temperature of pre-mixing nodes (i.e. inlet temperature in Heat Integration) is unknown before the HEN synthesis. The method from Yan et al. (2016) is adopted to identify the role (hot/cold/bypass) of the streams in HEN and allocate the corresponding rational value to their inlet temperatures, given by Eq(9) and Eq(10), which cooperate with the feasibility constraints of temperatures to guarantee the validity of the identification.

$$\left(Th_{h,p}^{\mathrm{in}} - Ts_{s,p}^{\mathrm{out}} \right) \times \left(Tc_{c,p}^{\mathrm{in}} - Ts_{s,p}^{\mathrm{out}} \right) = 0 \quad \forall h \in HS_p, \forall c \in CS_p, \forall s \in ES_p, \forall p \in SP, h = c = s \tag{9}$$

$$Ts_{s,p}^{\mathrm{in}} = Th_{h,p}^{\mathrm{in}} + Tc_{c,p}^{\mathrm{in}} - Ts_{s,p}^{\mathrm{out}} \quad \forall h \in HS_p, \forall c \in CS_p, \forall s \in ES_p, \forall p \in SP, h = c = s \tag{10}$$

where $Th_{h,p}^{\mathrm{in}}$ and $Tc_{c,p}^{\mathrm{in}}$ are the inlet temperatures of hot stream h and cold stream c in the HEN of plant p.

5. Case study

To illustrate the application of the proposed method, a theoretical industrial park containing three plants is investigated. The process data are listed in Table 1. The centralized regenerator features a fixed removal ratio of 90 % and shall be operated at 30 °C, cost parameters $\alpha_{\mathrm{reg}}^{\mathrm{cap}}$, β_{reg} and $\alpha_{\mathrm{reg}}^{\mathrm{op}}$ are set at 12,600, 0.7 and 0.0067, respectively. Pipeline cost parameters $\alpha_{\mathrm{pl}}^{\mathrm{fixed}}$ and $\alpha_{\mathrm{pl}}^{\mathrm{var}}$ are set at 250 and 7,200. Fresh water (0.375 \$/t) is supplied at 20 °C. Effluent shall be discharged at no higher than 30 °C. Inlet and outlet temperatures of cold utility are 10 °C and 20 °C, with unit cost 189 \$/(kW·y); the temperature of hot utility (low pressure steam) is 120 °C, with unit cost 377 \$/(kW·y). Heat exchanger cost parameters $\alpha_{\mathrm{he}}^{\mathrm{fixed}}$, $\alpha_{\mathrm{he}}^{\mathrm{area}}$ and $\beta_{\mathrm{he}}^{\mathrm{area}}$ are set at 8,000, 1,200 and 0.6; overall heat transfer coefficient is fixed at 0.833 and 0.5 kW/(m^2·°C) for matches with/without steam. AWH, AF and D_{dis} are 8,000 h/y, 10 % and 180 m. The mentioned optimization approaches, namely sequential design and simultaneous design, are employed for the synthesis of the overall network. The problem is implemented in GAMS using BARON as solver.

Table 1: Process data for case study

Plant	Water Source	Flowrate (t/h)	Contaminant concentration (ppm)	T (°C)	Water Sink	Flowrate (t/h)	Contaminant concentration upper limit (ppm)	T (°C)
1	1-1	72	100	40	1-1	72	0	40
	1-2	360	100	100	1-2	360	50	100
	1-3	144	800	75	1-3	144	50	75
	1-4	36	800	50	1-4	36	400	50
2	2-1	360	100	100	2-1	360	50	100
	2-2	144	800	75	2-2	144	50	75
	2-3	600	1,100	100	2-3	600	800	100
3	3-1	68	250	40	3-1	209	20	44.8
	3-2	169	100	43	3-2	972	20	43.9
	3-3	1,130	150	46	3-3	190	20	43.1
	3-4	436	150	48	3-4	36	20	81
	3-5	832	160	46	3-5	432	148	49
					3-6	1,332	20	44.8

5.1 Sequential design

Sequential approach synthesizes the IHIWAN in two steps. First, water allocation sub-network is designed based on the WAN part of the superstructure and mathematical model, under the objective of minimum TAC^{WAN}. And an economically optimal WAN is obtained with the TAC^{WAN} of 2,299,729 \$/y. On the basis of this WAN, the inlet temperatures of the pre-mixed streams to each target unit are obtained by Eq.(4)-Eq.(8). Comparing to the corresponding temperature specifications, the streams in demand for heat exchange are identified with determinate role, flowrate and temperature, which are to be involved in HENs. 4 hot streams and 12 cold streams are incorporated from 40 water streams. Then, the optimal heat exchanger sub-network with minimum TAC^{HEN} (34,985,946 \$/y) is designed based on stage-wise HEN superstructure. Thereby, an IHIWAN for the industrial park with the TAC^{IHIWAN} of 37,285,675 \$/y is eventually obtained.

5.2 Simultaneous design

Sequential design is able to reduce the resource consumption and minimize the cost of the two sub-networks respectively, but the interaction between the two subsystems is not fully explored. Simultaneous design treats the whole system as one single problem and directly minimizes the overall TAC^{IHIWAN}. Accordingly, the economically-optimal IHIWAN with the minimum TAC^{IHIWAN} of 28,286,147 \$/y is obtained, as shown in Figure 2. Detailed cost terms of the two approaches are listed in Table 2. Compared to sequential design, it is clear that simultaneous design presents preferable results, with a reduction of 24.14 % on *TAC*. This is mainly due to the instinct limitation of sequential approach that the internal trade-offs are not adequately processed, especially when Interplant Integration is involved. Although simultaneous design features higher fresh water consumption, yet the significantly lower utility consumption (especially for Plant 2) still leads to better overall performance, which implies that the optimal WAN might not be the most suitable one for Heat Integration. Yet, it should be noted that simultaneous design features much heavier computation load,and requires more appropriate initial points to search for solution.

Table 2: Results of case study

	Sequential design				Simultaneous design			
Cost terms (M\$/y)	Plant 1	Plant 2	Plant 3	Total	Plant 1	Plant 2	Plant 3	Total
Fresh water	0.216	0	1.392	1.608	1.494	0.761	0	2.256
Regeneration	-	-	-	0.556	-	-	-	0.502
Cross-plant pipeline	-	-	-	0.136	-	-	-	0.124
TAC, WAN subsystem	-	-	-	2.300	-	-	-	2.881
Heat exchangers	0.422	0.504	0.578	1.503	0.419	0.455	0.535	1.409
Hot utility	3.512	7.212	13.352	24.076	3.163	2.714	12.200	18.078
Cold utility	1.602	3.616	4.189	9.406	0.487	0.530	4.901	5.918
TAC, HEN subsystem	5.536	11.331	18.119	34.986	4.069	3.700	17.636	25.405
TAC, overall IHIWAN	-	-	-	37.286	-	-	-	28.286

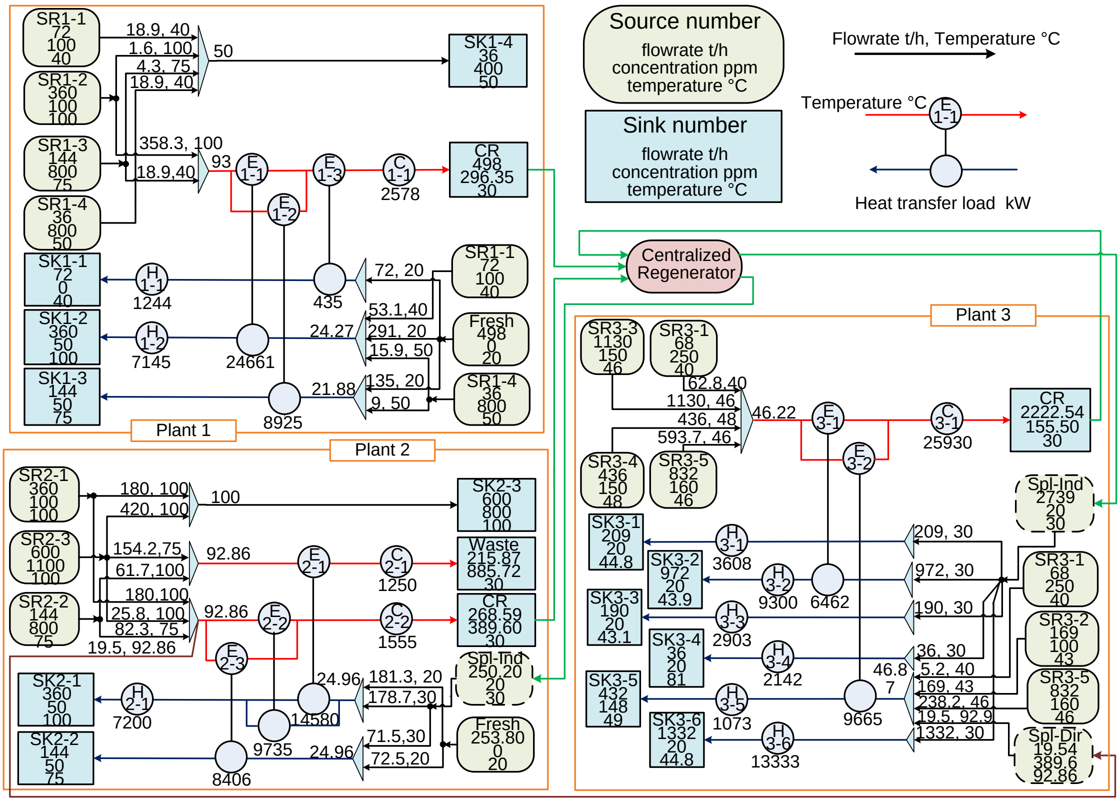

Figure 2: Optimal IHIWAN design of industrial park for case study

6. Conclusions

This paper addresses a methodology for the optimal design of IHIWAN in the scale of industrial park. A combined superstructure specific to industrial parks is presented capturing all the intra-plant and inter-plant possibilities for integration, in which synthesis strategies are incorporated. An NLP model is correspondingly formulated, which is more computational friendly compared to conventional MINLP model. The effectiveness of the method is validated by a case study. Comparing the results v two approaches, it can be concluded that simultaneous design surpasses sequential design with TAC lower by 24.14 %. The method can promote the symbiotic system in industrial parks and contribute to the sustainable development of process industry.

Acknowledgments

The authors gratefully acknowledge the financial support from Natural Science Foundation of China (No. 21406026) and the Fundamental Research Funds for Central Universities of China (DUT16RC(4)07).

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