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Synthesis of Interplant Water-Allocation and Heat-Exchange Networks. Part 1: Fixed Flow Rate Processes

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ABSTRACT: This paper is part 1 of a series dealing with the design of integrated interplant water-allocation and heat-exchange networks (IWAHENs), a special case of interplant network synthesis with multiple physical properties. Traditionally, the tasks of optimizing water-allocation networks (WANs) and heat exchange networks (HENs) were either performed individually or studied within a single plant. In this paper, a novel multiscale state−space superstructure is developed to capture all possible network configurations for the fixed flow rate (FF) IWAHEN designs with both direct and indirect integration schemes. In addition, our model has been simplified to deal with the interplant HEN design where the optimal utility network can be determined simultaneously. By properly addressing the interactions between different plants as well as the WAN and HEN subsystems, lower total annualized cost (TAC) can be obtained in all examples by solving the corresponding mixed-integer nonlinear programming (MINLP) model.

1. INTRODUCTION

Water and energy are two of the most essential resources for process industries. A large amount of water is needed not only as an effective mass-separating agent in separation operations (such as absorption and extraction) but also to be consumed in the utility systems to produce steam and/or cooling water as heat carriers. In the aforementioned usages, both wastewater-treatment units and a large amount of energy in the form of cooling and heating utilities are needed to satisfy both the concentration and temperature requirements for the operating conditions. At the moment, escalating costs of energy, effluent treatment, and freshwater have created increased incentives to use an integrated approach for designing cost-effective integrated water-allocation and heat-exchange networks (WAHENs). This gives rise to the development of WAHEN synthesis, which can facilitate simultaneously the optimal distribution of water resources and energy consumption to satisfy process demands as well as environmental regulations at minimum total cost.

Although the issues of water and energy management in chemical processes are always highly related, the design problems of water-allocation networks (WANs) and heat-exchange networks (HENs) have been considered separately in the past. In continuous water network design, the problem is categorized as either a fixed contaminant-load (FC) problem,[1−7] in which water-using units are modeled as mass transfer process with a fixed contaminant-load transferred to a stream, or a fixed flow rate (FF) problem[8−13] where all process streams only exist as an output or input. A considerable amount of research has been presented for water network synthesis using both the insight-based pinch analysis technology and the mathematical-based optimization approach. Research in water network synthesis with pinch analysis has evolved from the targeting of minimum freshwater and wastewater flow rates[1,8] to the targeting of minimum regeneration[9,10] and wastewater treatment flow rates.[2,12,13] In addition, various mathematical optimization approaches have been developed to deal with more complex problems, such as multicontaminant systems,[3,4,6,7] limiting connections between water-using processes,[5] and process uncertainty.[6] Detailed and comprehensive reviews of the available techniques have been reported by Bagajewicz,[14] Foo,[15] and Jezowski.[16] On the other hand, two major methodologies have also been proposed for the HEN design, namely the sequential[17−19] and the simultaneous approaches.[20−22] While the sequential approaches are essentially based on pinch design methods,[18] in which targets for the minimum utility requirement, the minimum number of exchanger units, and the minimum capital cost of the network are obtained sequentially, simultaneous approaches formulate the HEN synthesis problem as a mixed-integer nonlinear programming (MINLP) problem and can explicitly handle the trade-offs between the capital and operational costs of the network. For a review on methodologies for the synthesis of HENs, the reader is referred to the paper by Furman and Sahinidis.[23]

Savulescu and Smith[24] and Savulescu et al.[25,26] first proposed a conceptual design method to solve the combined WAHEN optimization problem. The so-called "separate system approach" was adopted to create the overall network design with the two-dimensional grid diagram. Although both direct and indirect heat exchange options have been considered in their work,[27] it is very difficult to incorporate all possible network configurations and to identify an optimal solution with the minimum total annualized cost (TAC) using this heuristic approach. On the other hand, Bagajewicz et al.[28] attempted to solve this problem by developing a series of transshipment formulations on the basis of the optimal conditions for water-using networks.[29] However, since the original nonlinear func-

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tions in NLP and MINLP models were linearized, the true optimal design may not be found by using this method. Notice also that the aforementioned two approaches are really not applicable to the multicontaminant problems that are usually encountered in the process industries, and more importantly, these sequential procedures have rendered it difficult and even impossible to balance the trade-offs between capital investments and operating costs. Later, Bogataj and Bagajewicz[30] presented a new MINLP model for the simultaneous synthesis and optimization of integrated WAHENs with treatment units on the basis of both the stage-wise[21] and mixer-unit-splitter (MUS) superstructures.[31] However, stream mixing across stages cannot be achieved in the stage-wise framework, and thus, the superstructure may preclude a family of optimal network structures, where the best cost-optimal scheme may actually lie. In their study, Dong et al.[32] employed a modified state−space concept to address the interactions between WANs and HENs. Not only can such a representation capture all structural characteristics of the integrated WAHENs, but the MINLP model formulated accordingly can almost always identify the global optimal solutions with the proposed hybrid solution strategy, as well.

It is worth noting that in all the above-mentioned works water and heat recovery is carried out through the manipulations within the same plant. The needs of resource integrations and ever-increasing economic potentials have necessitated the interplant optimization of both WANs and HENs. Chew et al.[33] first proposed the direct and indirect integration schemes for interplant WAN design. In this work, while water sources can be integrated directly with sinks in different water networks, a centralized utility hub can also be used to collect and redistribute water indirectly to the individual plants. Then, Chew et al.[34] extended the automated targeting technique for single water network into interplant integration that was developed for FF problems. Later, Chen et al.[35] minimized both freshwater consumptions and TACs of a series of FC processes, where central and decentralized water mains are placed to interconnect the water-using units of the individual plants. Furthermore, by combining pinch insight with mathematical programming, Liao et al.[36] targeted freshwater usage and cross plant connection conditions are obtained first without considering the detailed network design. Subsequently, a mixed-integer linear programming (MILP) model is established for the design of flexible water networks of individual plants. With the limitation to a single component, the proposed approach can be applied for both FC and FF operations. In their study, Chew et al.[37,38] described both assisted and unassisted methods for targeting minimum fresh resource and waste flow rates for an interplant resource conservation network, which enables the reuse of the excess process sources among different networks and reduces the consumption of fresh resources and the generation of waste. In interplant HEN synthesis, early studies by Ahmad and Hui[39] developed some understanding on this issue by dividing the process plants into separate regions with their own process tasks. Then, the scheme for designing the minimum energy networks that feature few interconnections between the areas of integrity was proposed. Later, Rodera and Bagajewicz[40] developed a systematic sequential approach of heat integration across plants either by directly using process streams or indirectly using intermediate fluids. In their work, models that account for maximum energy savings by direct and indirect heat integration, including in this last case the location of the fluid circuits, were presented, and such a method was then extended to the consideration of a total site composed of several plants.[41,42] In addition to determining the target energy savings, they also presented a methodology to design multipurpose HENs that can realize these savings and function in the two scenarios, integrated and not integrated.[43] However, one serious limitation of these works[40−43] is that the economic optimality of these resulting networks cannot be guaranteed because of the inability of these sequential procedures to balance the capital and operating costs.

In the aforementioned studies, the tasks of synthesizing interplant WANs and HENs were examined individually. However, as the industrial practices have necessitated the management of both quality and temperature of water across plants, there is a need for considering simultaneously both WANs and HENs for the conceptual design on a interplant scale. In this series of papers, the multiscale state−space superstructure, a framework that takes all intra- and interplant network topologies into account, is presented for the interplant synthesis of integrated interplant water-allocation and heat exchange networks (IWAHENs) with direct and indirect integration schemes. Considering both FF-based and FC-based processes, as well as the interactions between these two processes, the overall problems are formulated as an MINLP model. In part 1 of the series, we focus our study on the IWAHEN designs with FF-based water-using operations where two different integration schemes, direct integration with process streams and indirect integration with central junctions, are considered. Besides, our model has also been adapted for the one-step design of interplant HEN synthesis with optimal associated utility network, a topic which has never been addressed before. Since (1) the multiscale state−space framework does not contain any simplifying assumptions of the network configurations, (2) more possible water reuse/recycle and heat recovery opportunities can be exploited, and (3) the trade-offs between capital and operating costs between different utilities can be properly carried out, it is reasonable to expect that the TAC of the overall IWAHEN can be reduced drastically in comparison with that of stand-alone plants. To describe the design method developed in this work and its applications, the rest of this paper is organized as follows: The FF-based integrated IWAHEN design problem is defined in the next section. All issues pertaining to the multiscale state−space representation and the corresponding MINLP model are introduced in sections 3 and 4, respectively. Several case studies are then presented in section 5 to demonstrate the effectiveness of the proposed method, and the conclusion of this research is provided in the last section.

2. PROBLEM STATEMENT

To facilitate the concise formulation of the mathematical model, several important assumptions are made to simplify this problem: the WAHEN process is continuous; all water consuming and generating units are designated as water sinks and sources with a given flow rate, temperature, and concentration level; the wastewater-treatment units are mass transfer-based operations with fixed removal ratios; external utilities (including fresh water, hot and cold utilities) are available to be purchased to satisfy the requirement of process.

The IWAHEN design problem addressed in this work can be stated as follows: Given a set of processes, as well as utility sources and sinks, a set of interplant junctions, and a set of available wastewater-treatment units, it is desired to synthesize

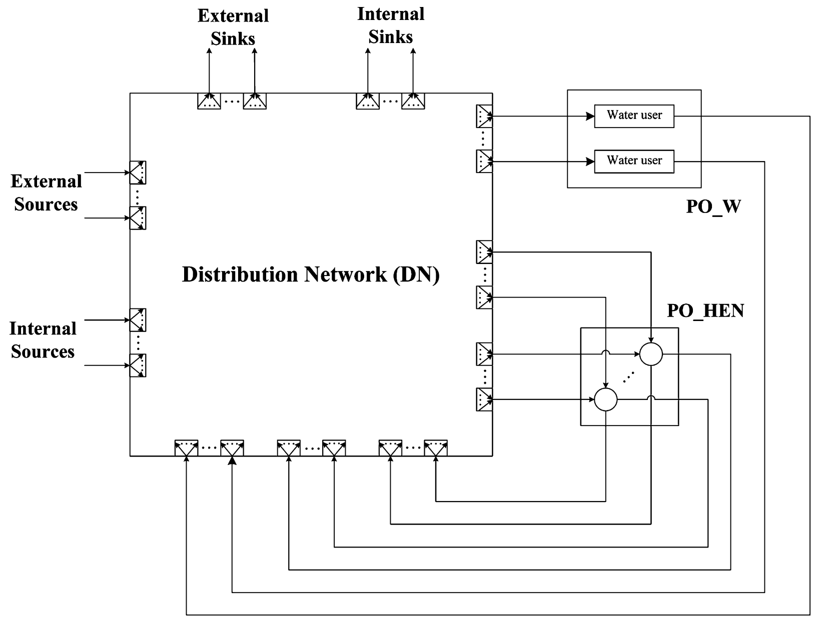

Figure 1. State−space superstructure for stand-alone WAHEN.

a cost-optimal IWAHEN that can satisfy the concentration, temperature, and flow rate constraints imposed at various locations in the network. More specifically, the given model parameters of this optimization problem include: (1) the design specifications of every source (i.e., its operating temperature, its outlet flow rate, and the corresponding concentrations for all contaminants), (2) the design specifications of each sink (i.e., its operating temperature, its inlet flow rate, and the corresponding maximum concentrations for all contaminants), (3) the design specification of each treatment unit (i.e., its operating temperature and its removal ratio for all contaminants), (4) the costs of utilities (i.e., the unit cost of freshwater and hot and cold utilities), (5) the cost parameters of heat exchangers, treatment units, central junctions, and pipelines, and (6) the heat capacities of all streams and the estimates of overall heat-transfer coefficients in all heat exchangers. The resulting IWAHEN design should include: (1) the throughput of every treatment unit, (2) the number of heat exchangers and their duties, (3) the consumption rates of freshwater and the hot and cold utilities, (4) the concentrations of all components at the inlet of all process sinks, and (5) the complete network configuration and the flow rate and temperature of each branch stream.

3. MULTISCALE STATE−SPACE SUPERSTRUCTURE

The state−space superstructure was proposed by Bagajewicz and Manousiouthakis[44] and Bagajewicz et al.,[45] and it has been used as an alternative representation of the mass and heat exchange networks.[46] This framework has been modified in a series of works for WAN designs,[47,48] HEN designs,[22] and integrated WAHEN[32] and separation network designs.[49] In previous publications, no existing superstructure clearly illustrates both intra- and interplant structures as well as the very integrated nature between water-using and heat-transfer processes. As a result, the authors either rely on the MUS representation, which is difficult to incorporate water-using and heat exchange operations in a single and comprehensive flowsheet, or have to use separate frameworks for WAN and HEN designs to address the complex integrations between water-using and heat exchange processes.[30,50] Since the state−space superstructure has proved to be highly effective in handling the synthesis of network with multiple physical properties, such as water and heat, mass and energy, this superstructure has been improved to incorporate intra- and interplant design options to deal with the IWAHEN design. In the subsections below, a state−space superstructure for stand-alone plant WAHEN design is introduced, and this whole structure that characterizes the intraplant structure is then embedded into another state−space representation, which is used to illustrate all connections between different plants. These two steps will be introduced in the sequel.

3.1. State−Space Superstructure for Individual WAHEN.

The overall integrated WAHEN superstructure for stand-alone plant is viewed as a system of two interconnected blocks (see Figure 1). One is referred to as the distribution network (DN), where all corresponding splitters and mixers for each source and sink of the overall network are embedded, and the other block is the so-called process operator (PO). While all direct heat and mass transfer processes are carried out in the mixers of DN, PO_HEN provides all indirect heat exchange opportunities in the network. In this superstructure, while water sources for FF-based operations are represented by the splitters attached on the left side of the DN, the sinks for such operations are denoted by the mixers attached on the upper side of the DN. For FC-based water-users, we use the operator PO_W to represent these units. It can be seen in this figure that there are one splitter and one mixer attached on DN to denote the inlet and outlet of these FC units. Furthermore, in this superstructure, the given input and output streams of the individual plant are considered as internal sources and sinks; all other process and utility streams entering to or exiting from this plant are considered as the external sources and sinks, which are either transferred from or released to other plants. Every input source to DN is then split into several branches at the splitting node and each of them is connected to a mixing node at the exit leading to PO blocks or to the sinks. Like our previous work,[49] all flows are identified with the splitting and/or mixing nodes (i.e., the splitters and/or mixers in DN) which are divided into several groups depending upon the original identities of streams or their connections with the PO block. Here,

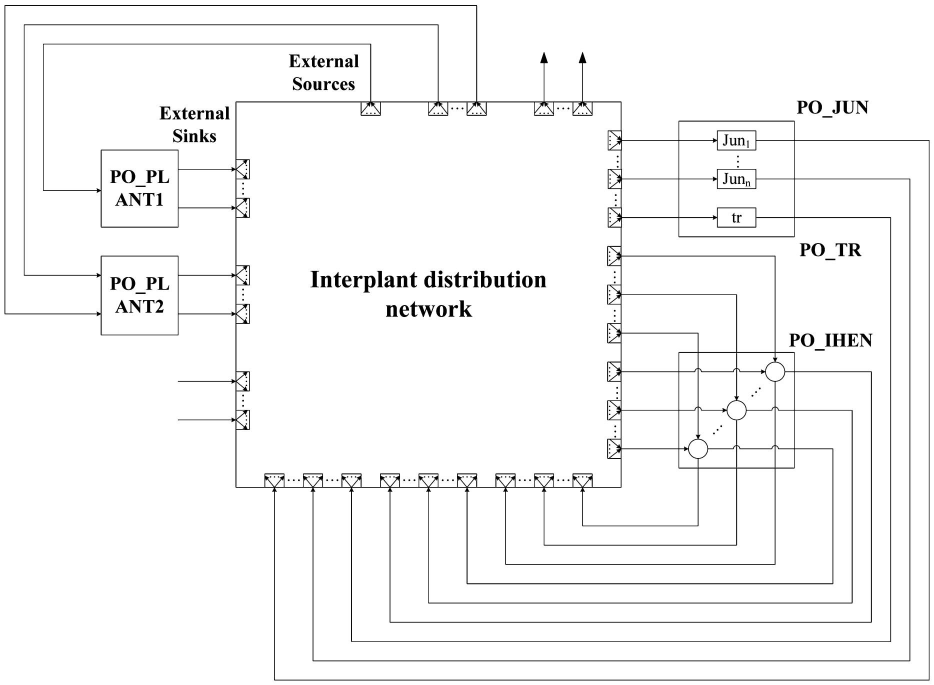

Figure 2. Multiscale state−space superstructure for interplant WAHEN.

it is worth noting that while the presence of every internal source and sink is dictated by process requirements, the numbers of external sources and sinks are all subject to optimization.

3.2. State−Space Superstructure for IWAHEN. By incorporating additional process operators, the IWAHEN superstructure can also be built with the state−space concept. Although this superstructure (see Figure 2) shares great similarity with the one for single plants, there are stark distinctions between them. One apparent disparity is the PO blocks, which is made up of PO_PLANT, PO_JUN, PO_TR, and PO_IHEN. Specifically, the whole set of DN and POs of individual plant is encapsulated into the operator in PO_PLANT, and such a nested structure provides the interactions between stand-alone plant and overall interplant network. On the other hand, while PO_JUN and PO_TR are introduced to facilitate direct stream mixings and water regenerations, interplant heat exchangers are embedded in PO_IHEN to provide indirect heat exchange opportunities across plants. To be consistent with the descriptions for the superstructure for individual plant, in this interplant representation, we characterize all the input streams emanated from and output streams to PO_PLANT as external sinks and sources.

Finally, the use of our superstructure for each different scheme of integrations is described as follows. In direct IWAHEN integration with process streams, streams from different plants are allowed to be directly mixed, and as a result, the PO_JUN and PO_IHEN are removed from the IWAHEN superstructure. On the other hand, indirect integration constitutes a significant distinction from the direct counterpart, since such methods necessitate the need for PO_JUN and/or PO_IHEN. Specifically, in indirect IWAHEN integrations, any of PO_JUN, PO_TR, and PO_IHEN can be used depending on the needs for applications. On the contrary, in indirect HEN integration with associated utility networks, all direct heat exchange opportunities are ruled out, and hence, only PO_IHEN is needed in the previous superstructure.

4. MATHEMATICAL MODEL

The overall integrated mathematical model is made up of two modules. One of the modules focuses on DNs and the other on POs. For the sake of clarity and simplicity, the following definitions are first introduced.

1. Indices

   i, i' = index of sources
   j, j' = index of sinks
   p, p' = index of all DNs (including DN for individual plant and interplant representation)
   $p1$ = index of DNs for individual plant

2. Sets

   K = components
   HE = heat exchangers
   H = heaters
   C = coolers
   JUN = junctions
   TR = wastewater treatment units
   I_P = the splitting nodes for source i in DN p
   J_P = the mixing nodes for sink j in DN p
   NI_P = all forbidden mixing nodes of stream from node I_P
   HIN_{HE}, CIN_{HE} = the hot and cold streams entering to heat exchanger HE
   $HOUT_{HE}$, $COUT_{HE}$ = the hot and cold streams released from unit HE
   HS1, HS2 = the hot nonisothermal and isothermal streams
   CS1, CS2 = the cold nonisothermal and isothermal streams

With these definitions, all the mathematical models are summarized as follows.

4.1. Model for DNs. At every splitter and mixer, the mass and energy balances must all be satisfied, that is,

$$f_{i_p}^{\text{out}} = \sum_{j_{p'}} fs_{i_p,j_{p'}} \quad \forall\ i_p \in I_P \tag{1}$$

$$f_{j_p}^{\text{in}} = \sum_{i_{p'}} fs_{i_{p'},j_p} \quad \forall\ j_p \in J_P \tag{2}$$

$$f_{j_p}^{\text{in}} t_{j_p}^{\text{in}} = \sum_{i_{p'}} fs_{i_{p'},j_p} t_{i_{p'}}^{\text{out}} \quad \forall\ j_p \in J_P \tag{3}$$

$$f_{j_p}^{\text{in}} c_{j_p,k}^{\text{in}} = \sum_{i_{p'}} fs_{i_{p'},j_p} c_{i_{p'},k}^{\text{out}} \quad \forall\ j_p \in J_P,\ k \in K \tag{4}$$

where $f_{i_p}^{\text{out}}$ and $f_{j_p}^{\text{in}}$ represent respectively the outlet and inlet flow rate at each splitting and mixing node; $t_{i_p}^{\text{out}}$ and $t_{j_p}^{\text{in}}$ respectively stand for the outlet and inlet temperature at each splitting and mixing points; $c_{j_p,k}^{\text{in}}$ and $c_{i_p,k}^{\text{out}}$ denote respectively the concentration of pollutant k at each mixing and splitting point; and fs_{i_p,j_p} stands for the flow rate from i_p to j_p. Because the inlet and outlet flow rates and concentrations of internal sources and sinks for each individual plant are given, we have

$$f_{i_{p1}}^{\text{out}} = F_{i_{p1}}^{\text{out}} \quad \forall\ i_{p1} \in I_{P1} \tag{5}$$

$$f_{j_{p1}}^{\text{in}} = F_{j_{p1}}^{\text{in}} \quad \forall\ j_{p1} \in J_{P1} \tag{6}$$

$$t_{i_{p1}}^{\text{out}} = T_{i_{p1}}^{\text{out}} \quad \forall\ i_{p1} \in I_{P1} \tag{7}$$

$$t_{j_{p1}}^{\text{in}} = T_{j_{p1}}^{\text{in}} \quad \forall\ j_{p1} \in J_{P1} \tag{8}$$

$$c_{i_{p1},k}^{\text{out}} = C_{i_{p1},k}^{\text{out}} \quad \forall\ i_{p1} \in I_{P1},\ k \in K \tag{9}$$

$$c_{j_{p1},k}^{\text{in}} \le C_{j_{p1},k}^{\text{in}} \quad \forall\ j_{p1} \in J_{P1},\ k \in K \tag{10}$$

where $F_{i_{p1}}^{\text{out}}$ and $F_{j_{p1}}^{\text{in}}$, $T_{i_{p1}}^{\text{out}}$ and $T_{j_{p1}}^{\text{in}}$, and $C_{i_{p1},k}^{\text{out}}$ and $C_{j_{p1},k}^{\text{in}}$ are all given parameters and bounds regarding the flow rates, temperatures, and concentrations of process streams. Furthermore, as not all streams are allowed to mix at certain mixing points, the following constraints should be enforced:

$$fs_{i_p,j_p} = 0 \quad \forall\ i_p \in I_P,\ j_p \in \text{NI}_P \tag{11}$$

$$nfs_{i_p,j_p} = 0 \quad \forall\ i_p \in I_P,\ j_p \in \text{NI}_P \tag{12}$$

where nfs_{i_p,j_p} are binary variables that stand for the existence/nonexistence of the flow between nodes i_p and j_p and NI_p is a subset of J_p and is determined by the different mechanisms of integration. Here, it should be noted that constraint 12 can be omitted. Finally, a negligible amount of flow is not allowed in the optimal operating policy and such an uneconomic amount can be eliminated by the addition of the following constraint:

$$fs^{\min} nfs_{i_p,j_{p'}} \le fs_{i_p,j_{p'}} \le fs^{\max} nfs_{i_p,j_{p'}} \quad \forall\ i_p \in I_P,\ j_{p'} \in J_{P'} \tag{13}$$

where $fs^{\max}$ and $fs^{\min}$ specify the upper and lower bounds of the flow rates in DN.

4.2. Model for POs. Notice that for a given design problem the number of splitting and mixing nodes (also the number of heat exchangers) attached on DN must be selected before solving the corresponding model. The appropriate number of these nodes attached on DN and PO block can be determined with the heuristic rules in section 3.2 of our previous work.[49] All mathematical constraints for the POs are written as follows.

a. PO_HEN and PO_IHEN. Mass and Heat Balances for Each Heat Exchange Unit. The flow rate and mass balances around each heat exchange unit can be written as the following equalities:

$$f_{\text{hin}_e}^{\text{in}} = f_{\text{hout}_e}^{\text{out}} \quad \forall\ \text{hin}_e \in \text{HIN}_E,\ \text{hout}_e \in \text{HOUT}_E,\ e \in \text{HE} \cup \text{H} \cup \text{C} \tag{14}$$

$$f_{\text{cin}_e}^{\text{in}} = f_{\text{cout}_e}^{\text{out}} \quad \forall\ \text{cin}_e \in \text{CIN}_E,\ \text{cout}_e \in \text{COUT}_E,\ e \in \text{HE} \cup \text{H} \cup \text{C} \tag{15}$$

$$c_{\text{hin}_{\text{he}},k}^{\text{in}} = c_{\text{hout}_{\text{he}},k}^{\text{out}} \quad \forall\ \text{hin}_{\text{he}} \in \text{HIN}_{\text{HE}},\ \text{hout}_{\text{he}} \in \text{HOUT}_{\text{HE}}\quad k \in K \tag{16}$$

$$c_{\text{cin}_{\text{he}},k}^{\text{in}} = c_{\text{cout}_{\text{he}},k}^{\text{out}} \quad \forall\ \text{cin}_{\text{he}} \in \text{CIN}_{\text{HE}},\ \text{cout}_{\text{he}} \in \text{COUT}_{\text{HE}}\quad k \in K \tag{17}$$

where $f_{\text{hin}_e}^{\text{in}}$ and $f_{\text{hout}_e}^{\text{out}}$ are the flow rates of hot streams entering to and exiting from unit e; $f_{\text{cin}_e}^{\text{in}}$ and $f_{\text{cout}_e}^{\text{out}}$ stand for the flow rates of cold streams entering to and exiting from unit e; $c_{\text{hin}_{\text{he}},k}^{\text{in}}$ and $c_{\text{hout}_{\text{he}},k}^{\text{out}}$ denote the compositions of k in hot streams entering to and exiting from unit he; and $c_{\text{cout}_{\text{he}},k}^{\text{in}}$ and $c_{\text{cin}_{\text{he}},k}^{\text{out}}$ represent the compositions of k in cold streams entering to and exiting from unit he. Constraints 14–17 are obvious because all flow rates and concentrations are identical around each heat exchange unit.

b. Heat Load of Each Heat Exchanger. To determine the existence and the heat load of each heat exchanger, the following equations are needed:

$$f_{\text{hin}_{\text{he}}}^{\text{in}} Cp_{\text{hin}_{\text{he}}} (t_{\text{hin}_{\text{he}}}^{\text{in}} - t_{\text{hin}_{\text{he}}}^{\text{out}}) = f_{\text{cin}_{\text{he}}}^{\text{in}} Cp_{\text{cin}_{\text{he}}} (t_{\text{cin}_{\text{he}}}^{\text{out}} - t_{\text{cin}_{\text{he}}}^{\text{in}}) = q_{\text{he}} \quad \forall\ \text{he} \in \text{HE},\ \text{hin}_{\text{he}} \in \text{HS1},\ \text{cin}_{\text{he}} \in \text{CS1} \tag{18}$$

$$F\lambda_{\text{hin}_{\text{he}}}^{\text{cond}} = f_{\text{cin}_{\text{he}}}^{\text{in}} Cp_{\text{cin}_{\text{he}}} (t_{\text{cin}_{\text{he}}}^{\text{out}} - t_{\text{cin}_{\text{he}}}^{\text{in}}) = q_{\text{he}} \quad \forall\ \text{he} \in \text{HE},\ \text{hin}_{\text{he}} \in \text{HS2},\ \text{cin}_{\text{he}} \in \text{CS1} \tag{19}$$

$$F\lambda_{\text{cin}_{\text{he}}}^{\text{evap}} = f_{\text{hin}_{\text{he}}}^{\text{in}} Cp_{\text{hin}_{\text{he}}} (t_{\text{hin}_{\text{he}}}^{\text{in}} - t_{\text{hin}_{\text{he}}}^{\text{out}}) = q_{\text{he}} \quad \forall\ \text{he} \in \text{HE},\ \text{hin}_{\text{he}} \in \text{HS1},\ \text{cin}_{\text{he}} \in \text{CS2} \tag{20}$$

$$f_{\text{hin}_c}^{\text{in}} Cp_{\text{hin}_c} (t_{\text{hin}_c}^{\text{in}} - t_{\text{hin}_c}^{\text{out}}) = f_{\text{cin}_c}^{\text{in}} Cp_{\text{cin}_c} (t_{\text{cin}_c}^{\text{out}} - t_{\text{cin}_c}^{\text{in}}) = q_c \quad \forall\ c \in C,\ \text{hin}_c \in \text{HS1},\ \text{cin}_c \in \text{CS1} \tag{21}$$

$$F\lambda_{\text{hin}_\text{h}}^{\text{cond}} = f_{\text{cin}_\text{h}}^{\text{in}} Cp_{\text{cin}_\text{h}} (t_{\text{cin}_\text{h}}^{\text{out}} - t_{\text{cin}_\text{h}}^{\text{in}}) = q_\text{h} \quad \forall\ h \in H,\ \text{hin}_\text{h} \in \text{HS2},\ \text{cin}_\text{h} \in \text{CS1} \tag{22}$$

$$Q_{\text{he}}^{\min} w(\text{hin}_{\text{he}},\ \text{cin}_{\text{he}}) \le q_{\text{he}} \le Q_{\text{he}}^{\max} w(\text{hin}_{\text{he}},\ \text{cin}_{\text{he}}) \quad \forall\ \text{hin}_{\text{he}} \in \text{HS1} \cup \text{HS2},\ \text{cin}_{\text{he}} \in \text{CS1} \cup \text{CS2} \tag{23}$$

$$Q_{\text{h}}^{\min} w(\text{hin}_{\text{h}},\ \text{cin}_{\text{h}}) \le q_{\text{h}} \le Q_{\text{h}}^{\max} w(\text{hin}_{\text{h}},\ \text{cin}_{\text{h}}) \quad \forall\ \text{hin}_{\text{h}} \in \text{HS1} \cup \text{HS2},\ \text{cin}_{\text{h}} \in \text{CS1} \cup \text{CS2} \tag{24}$$

$$Q_{\text{c}}^{\min} w(\text{hin}_{\text{c}},\ \text{cin}_{\text{c}}) \le q_{\text{c}} \le Q_{\text{c}}^{\max} w(\text{hin}_{\text{c}},\ \text{cin}_{\text{c}}) \quad \forall\ \text{hin}_{\text{c}} \in \text{HS1} \cup \text{HS2},\ \text{cin}_{\text{c}} \in \text{CS1} \cup \text{CS2} \tag{25}$$

In these equations, $t_{\text{hin}_{\text{he}}}^{\text{in}}$ and $t_{\text{hin}_{\text{he}}}^{\text{out}}$ denote respectively the temperature of hot stream at the inlet and outlet of heat exchanger he; $t_{\text{cin}_{\text{he}}}^{\text{in}}$ and $t_{\text{cin}_{\text{he}}}^{\text{out}}$ represent respectively the temperature of cold stream at the inlet and outlet of heat exchanger he; $F\ \lambda^{\text{cond}}$ and $F\lambda^{\text{evap}}$ are the total latent heat for condensation and evaporation of corresponding streams; the binary variable $w(\text{hin}_{\text{he}}, \text{cin}_{\text{he}})$ is set to one when there is a heat load q_{he} between $Q_{\text{he}}^{\min}$ and $Q_{\text{he}}^{\max}$, which correspond to the lower and upper bounds of heat duties for he. While eqs 18−20 describe the energy balances around each heat exchanger with both isothermal and nonisothermal streams, eqs 21 and 22 express the energy balances around heater and cooler, respectively. From these equations, it can be found that the energy balances for heaters and coolers are only the special cases for the energy balances for heat exchangers with both isothermal and nonisothermal streams.

c. Temperature Differences. The temperature differences in PO_HEN and PO_IHEN are calculated as follows:

$$\Delta t_\text{e}^1 = t_{\text{hin}_\text{e}}^{\text{in}} - t_{\text{cout}_\text{e}}^{\text{out}} \quad \forall\ \text{e} \in \text{HE} \cup \text{H} \cup C,\ \text{hin}_\text{e} \in \text{HS1} \cup \text{HS2},\ \text{cin}_\text{e} \in \text{CS1} \cup \text{CS2} \tag{26}$$

$$\Delta t_\text{e}^2 = t_{\text{hout}_\text{e}}^{\text{out}} - t_{\text{cin}_\text{e}}^{\text{in}} \quad \forall\ \text{e} \in \text{HE} \cup \text{H} \cup C,\ \text{hin}_\text{e} \in \text{HS1} \cup \text{HS2},\ \text{cin}_\text{e} \in \text{CS1} \cup \text{CS2} \tag{27}$$

$$\Delta t_\text{e} = \left[\Delta t_\text{e}^1 \Delta t_\text{e}^2 \left(\frac{\Delta t_\text{e}^1 + \Delta t_\text{e}^2}{2}\right)\right]^{1/3} \quad \forall\ \text{e} \in \text{HE} \cup \text{H} \cup C \tag{28}$$

where Δt_e^1 and Δt_e^2 denote the temperature driving forces at both ends of the heat exchanger he and Δt_e stands for the logarithmic mean temperature difference for heat exchanger he. In particular, Chen's approximation[51] is adopted, as shown in constraint 28. Finally, the temperature of hot and cold streams around every heat exchanger should satisfy the following thermodynamic constraints:

$$\Delta t_\text{e}^1 + \Gamma[1 - w(\text{hin}_\text{e}, \text{cin}_\text{e})] \ge \Delta T^{\min} \quad \forall\ \text{e} \in \text{HE} \cup \text{H} \cup C,\ \text{hin}_\text{e} \in \text{HS1} \cup \text{HS2},\ \text{cin}_\text{e} \in \text{CS1} \cup \text{CS2} \tag{29}$$

$$\Delta t_\text{e}^2 + \Gamma[1 - w(\text{hin}_\text{e}, \text{cin}_\text{e})] \ge \Delta T^{\min} \quad \forall\ \text{e} \in \text{HE} \cup \text{H} \cup C,\ \text{hin}_\text{e} \in \text{HS1} \cup \text{HS2},\ \text{cin}_\text{e} \in \text{CS1} \cup \text{CS2} \tag{30}$$

$$t_{\text{hin}_\text{e}}^{\text{in}} - t_{\text{hout}_\text{e}}^{\text{out}} \ge 0 \quad \forall\ \text{e} \in \text{HE} \cup \text{H} \cup C,\ \text{hin}_\text{e} \in \text{HS1} \cup \text{HS2},\ \text{hout}_\text{e} \in \text{HS1} \cup \text{HS2} \tag{31}$$

$$t_{\text{cout}_\text{e}}^{\text{out}} - t_{\text{cin}_\text{e}}^{\text{in}} \ge 0 \quad \forall\ \text{e} \in \text{HE} \cup \text{H} \cup C,\ \text{hin}_\text{e} \in \text{HS1} \cup \text{HS2},\ \text{cin}_\text{e} \in \text{CS1} \cup \text{CS2} \tag{32}$$

By specifying the minimum temperature difference, $\Delta T^{\min}$, constraints 29 and 30 also ensure that exchangers with infinite sizes do not occur in the network. Furthermore, if a match does not occur, the associated binary variable equals zero and the large positive upper bound Γ renders these two equations redundant.

4.2.2. PO_JUN and PO_TR. Junctions are introduced with the purpose of indirect integration where process sources are not allowed to directly integrate with sinks in other water networks for further water recovery. In such scenarios, junctions act as storage tanks that store and transfer cross-plant flows and can significantly improve controllability and operational flexibility. The relevant mass balance for all junctions can be written as follows:

$$f_{\text{jun}}^{\text{in}} = f_{\text{jun}}^{\text{out}} \quad \forall\ \text{jun} \in \text{JUN} \tag{33}$$

$$c_{\text{jun},k}^{\text{in}} = c_{\text{jun},k}^{\text{out}} \quad \forall\ \text{jun} \in \text{JUN},\ k \in K \tag{34}$$

$$t_{\text{jun}}^{\text{in}} = t_{\text{jun}}^{\text{out}} \quad \forall\ \text{jun} \in \text{JUN} \tag{35}$$

where $f_{\text{jun}}^{\text{in}}$and $f_{\text{jun}}^{\text{out}}$ denote the inlet and outlet flow rates of jun; $c_{\text{jun},k}^{\text{in}}$ and $c_{\text{jun},k}^{\text{out}}$ represent the inlet and outlet concentrations of pollutant k of jun; and $t_{\text{jun}}^{\text{in}}$ and $t_{\text{jun}}^{\text{out}}$ are respectively the inlet and outlet temperatures of jun. It is worth noting that the centralized junction among plants can serve as the function of water regeneration units where the water source quality is improved before it is sent to other plants. The models for fixed removal ratio wastewater treatment units are formulated as follows:

$$f_{\text{tr}}^{\text{in}} = f_{\text{tr}}^{\text{out}} \quad \forall\ \text{tr} \in \text{TR} \tag{36}$$

$$f_{\text{tr}}^{\text{in}} c_{\text{tr},k}^{\text{in}} (1 - r_{\text{tr},k}) = f_{\text{tr}}^{\text{out}} c_{\text{tr},k}^{\text{out}} \quad \forall\ \text{tr} \in \text{TR},\ k \in K \tag{37}$$

$$t_{\text{tr}}^{\text{in}} = t_{\text{tr}}^{\text{out}} = T_{\text{tr}} \quad \forall\ \text{tr} \in \text{TR} \tag{38}$$

where $f_{\text{tr}}^{\text{in}}$ and $f_{\text{tr}}^{\text{out}}$ denote the inlet and outlet flow rates of tr; $c_{\text{tr},k}^{\text{in}}$ and $c_{\text{tr},k}^{\text{out}}$ represent the inlet and outlet concentrations of pollutant k of tr; and $t_{\text{tr}}^{\text{in}}$ and $t_{\text{tr}}^{\text{out}}$ are respectively the inlet and outlet temperatures of tr; $r_{\text{tr},k}$ represents the removal ratio of component k in unit tr. Because we assume that wastewater-treatment units operate isothermally at a fixed and predefined temperature, constraint 38 is therefore enforced.

4.3. Objective Function. The objective function in this model is to minimize the TAC, taking into account, (1) the cost of freshwater, (2) the cost of hot and cold utilities, (3) the installation costs of heat exchange units, (4) the cost of wastewater-treatment units, and (5) the cost of cross-plant pipelines and junctions. The objective function can be written as follows:

$$\begin{aligned}\text{objective function} = {} & \text{cost of freshwater} + \text{cost of utilities}\\ & + \text{cost of treatment unit}\\ & + \text{cost of heat exchangers}\\ & + \text{cost of pipelines and junctions}\end{aligned} \tag{39}$$

$$\text{cost of freshwater} = \sum_{\text{fw}} \text{cost}_{\text{fw}} f_{\text{fw}}^{\text{out}} \tag{40}$$

$$\text{cost of utilities} = \sum_{\text{h}} \text{cost}_{\text{hu}} q_{\text{h}} + \sum_{\text{c}} \text{cost}_{\text{cu}} q_{\text{c}} \tag{41}$$

$$\text{cost of treatment unit} = \text{AF} \sum_{\text{tr}} \text{cost}_{\text{tr}}^{\text{fix}} f_{\text{tr}}^{\alpha} + \sum_{\text{tr}} \text{cost}_{\text{tr}}^{\text{var}} f_{\text{tr}}^{\beta} \tag{42}$$

$$\begin{aligned}&\text{cost of heat exchangers}\\ &= \sum_{\text{he}} \text{cost}_{\text{he}}^{\text{fix}} w(\text{hin}_{\text{he}}, \text{cin}_{\text{he}}) + \sum_{\text{he}} \text{cost}_{\text{he}}^{\text{var}} \left(\frac{q_{\text{he}}}{U\Delta t_{\text{he}}}\right)^{b}\\ &+ \sum_{\text{h}} \text{cost}_{\text{he}}^{\text{fix}} w(\text{hin}_{\text{h}}, \text{cin}_{\text{h}}) + \sum_{\text{h}} \text{cost}_{\text{he}}^{\text{var}} \left(\frac{q_{\text{h}}}{U\Delta t_{\text{h}}}\right)^{b}\\ &+ \sum_{\text{c}} \text{cost}_{\text{he}}^{\text{fix}} w(\text{hin}_{\text{c}}, \text{cin}_{\text{c}}) + \sum_{\text{c}} \text{cost}_{\text{he}}^{\text{var}} \left(\frac{q_{\text{c}}}{U\Delta t_{\text{c}}}\right)^{b}\end{aligned} \tag{43}$$

where cost_{fw}, cost_{hu}, and cost_{cu} denote respectively the annualized unit costs of freshwater, hot and cold utilities; $\text{cost}_{\text{tr}}^{\text{fix}}$ and $\text{cost}_{\text{tr}}^{\text{var.}}$ represent the fixed and annualized variable cost parameters for treatment; $\text{cost}_{\text{he}}^{\text{fix}}$ and $\text{cost}_{\text{he}}^{\text{var.}}$ stand for the annualized fixed and variable cost coefficients for heat exchange unit; α,β, and b are the cost coefficients for treatment unit and heat exchanger; and AF denotes the annualized factor. The capital cost for the cross-plant pipeline in eq 39 is adapted from Kim and Smith,[52] and for the sake of clarity, this term is expressed respectively with both direct and indirect integration schemes. Neglecting the piping cost within stand-alone plants, the fixed and variable costs of pipelines for direct integration with process streams can be expressed as follows:

$$\begin{aligned}\text{cost of pipelines} = \text{AF}&\left[\text{cost}_{\text{pipe}}^{\text{var}} \sum_{i_p \in I_P} \sum_{j_{p'} \in J_{P'}} \frac{D_{i_p, j_p} fs_{i_p, j_{p'}}}{\rho v}\right.\\ &\left.+ \text{cost}_{\text{pipe}}^{\text{fix}} \sum_{i_p \in I_P} \sum_{j_{p'} \in J_{P'}} D_{i_p, j_{p'}} nfs_{i_p, j_{p'}}\right] \quad p \neq p'\end{aligned} \tag{44}$$

where $\text{cost}_{\text{pipe}}^{\text{fix}}$ and $\text{cost}_{\text{pipe}}^{\text{var.}}$ denote respectively the fixed and variable cost parameters of pipelines; $D_{i_p j_{p'}}$ stands for the distance of pipelines from sources i_p to $j_{p'}$; and ρ and ν stand for the density of the fluids and the stream flow rate velocity, respectively. For indirect integration, the interplant piping cost in eq 39 is reformulated as eq 45. Here, the cost of central junctions, which is proportional to the total junction flow rate, is also considered.

$$\begin{aligned}&\text{cost of pipelines and junctions}\\ &= \text{AF}\left\{\left[\text{cost}_{\text{pipe}}^{\text{var}} \sum_{i \in I_P} \sum_{j \in \text{jun} \cup \text{sink}} \frac{D_{i,j} fs_{i,j}}{\rho v}\right.\right.\\ &+ \text{cost}_{\text{pipe}}^{\text{fix}} \sum_{i \in I_P} \sum_{j \in \text{jun} \cup \text{sink}} D_{i,j} nfs_{i,j}\\ &+ \text{cost}_{\text{pipe}}^{\text{var}} \sum_{i \in \text{Jun}} \sum_{j \in J_{P'}} \frac{D_{i,j} fs_{i,j}}{\rho v}\\ &\left.+ \text{cost}_{\text{pipe}}^{\text{fix}} \sum_{i \in \text{Jun}} \sum_{j \in J_{P'}} D_{i,j} nfs_{i,j}\right]\\ &\left.+ \text{cost}_{\text{jun}} \sum_{\text{jun}} f_{\text{jun}}^{\text{in}}\right\} \quad p \neq p'\end{aligned} \tag{45}$$

5. APPLICATION EXAMPLES

Several examples are given in this section to demonstrate the relative merits of the proposed superstructures and models. These examples include the interplant HEN design with optimal utility network and the IWAHEN synthesis with both direct and indirect schemes. All cases are run with a 2.2 GHz Intel Core Duo processor in GAMS environment. In addition, we should note that global optimality of the solutions is not guaranteed due to the nonconvexities introduced in the MINLP. However, random initial values and perturbations were used to try to avoid getting trapped into poor suboptimal solutions. In our work, GAMS/DICOPT with CPLEX as the MILP solver and CONOPT as the NLP solver are used throughout the study.

5.1. Example 1. An example that consists of two plants is first solved to illustrate the proposed approach in interplant HEN design. Table 1 shows the process data for all streams in both plants (taken from Grossmann[53] and Ponce-Ortega[54] respectively). In our example, these two plants are indirectly integrated with cross-plant utility streams, and for simplicity, the cross-plant pipeline costs are not included. The typical MINLP model for this example consists of 1628 variables (with 14 binary variables) and 1566 constraints (including 1482 equality constraints). Solving the MINLP model, which involves eqs 1–3, eqs 5–8, eqs 11–15, eqs 18–32, and eq 39 needs 20 iterations between the MILPs and NLPs with 17.75 s. The resulting network, as shown in Figure 3, features a TAC of \$187 183, which represents a 25.8% reduction compared with the sum of the TACs of the stand-alone plants. Detailed comparisons of key features between our computational results with the original ones are listed in Table 2. Here, the cost reduction with respect to the designs reported in Table 2 can be attributed to the effective design in the associated utility network, which is achieved by exploiting all possible matching opportunities through the PO_IHEN in the multiscale state–space superstructure. Specifically, while cold utility is used across plants in cost-efficient parallel and series manners, the HPS act as an intermediate circuit which significantly reduces the heating and cooling costs for both plants. Compared with

Table 1. Process Data for Example 1

stream	F (kW/K)	inlet temp. (°C)	outlet temp. (°C)	h [kW/(m^{2}K)]	cost ($/kW yr)
		Plant 1[a]			
H1	10	377	97	1	
H2	20	317	97	1	
C1	15	137	377	1	
C2	13	80	227	1	
S1		407	407	5	80
W1		27	47	1	15
		Plant 2[b]			
H3	10	105	25	0.5	
H4	5	185	35	0.5	
C3	7.5	25	185	0.5	
HPS[c]		210	209	5	160
MPS[d]		160	159	5	110
LPS[e]		130	129	5	50
CW[f]		5	6	2.6	10

[a]Annualized cost for each heat exchanger = 5500 + 150 × area (m^2) [b]Annualized cost for each heat exchanger = 238.4 × area (m^2) [c]High pressure steam. [d]Medium pressure steam. [e]Low pressure steam. [f]Cooling water.

previous work,[54] our methods demonstrated in this example can not only determine the selection and placement of multiple utilities, but can also obtain the corresponding utility network with the primary HEN simultaneously.

5.2. Example 2. In this example, IWAHEN designs with three different kinds of integrations are studied. In case 1, two separate WAHENs are synthesized without taking into account interplant integration opportunities. Then, cases 2 and 3 are investigated to demonstrate the effectiveness of both direct integration with process streams and indirect integration with central junctions. Finally, the effectiveness of using central junction as a treatment unit will be demonstrated.

Table 2. Comparison between Stand-Alone and Integrated Designs in Example 1

	stand-alone plants		
	plant 1	plant 2	indirect integration
cost of hot utility	$39 292	$45 757	$47 560
cost of cold utility	$32 117	$7400	$26 335
cost of exchangers	$83 600	$43 922	$113 288
individual TAC	$155 009	$97 079	
overall TAC	$252 088		$187 183

A set of common model parameters used in all cases will be introduced first. Specifically, the inlet and outlet temperature of cooling water are set at 10 and 20 °C; the temperature of hot utility is assumed to be 120 °C; the cost of cold and hot utilities are taken to be 120 and 260 $/(kW yr), respectively; the installation cost of each heat exchanger is set to 8000 + 1200(area)$^{0.6}$, where the heat transfer area (area) is in m^2; for simplicity, all treatment units operate isothermally at 30 °C with an removal ratio of 0.9 for all components, and their annual costs are determined with the formula $12600F_{tr}^{in0.7} + 0.0067F_{tr}^{in}$ (taken from Kuo and Smith[55]); the overall heat transfer coefficient are fixed at 0.833 and 0.5 kW/(m^2 K) for matches with and without steam, respectively; the upper and lower bounds of the cross-plant flow rates (fs^{max} and fs^{min}) are set to 500 kg/s and 3 kg/s, respectively, while the lower bound for all other streams is set to 0 kg/s; the cost parameters with the cross-plant pipelines and junctions, namely, $cost_{pipe}^{fix}$, $cost_{pipe}^{var.}$, ν, ρ, and $cost_{jun}$, are chosen to be 250, 7200, 1 m/s, 1000 kg/m^3, and 4000, respectively; the distances between different plants are assumed to be 180 m in all cases; all streams have constant heat capacity of 4.2 kJ/(kg K); and finally, the annualized factor is set at 10%, and all plant are assumed to be operated continuously for 8000 h a year.

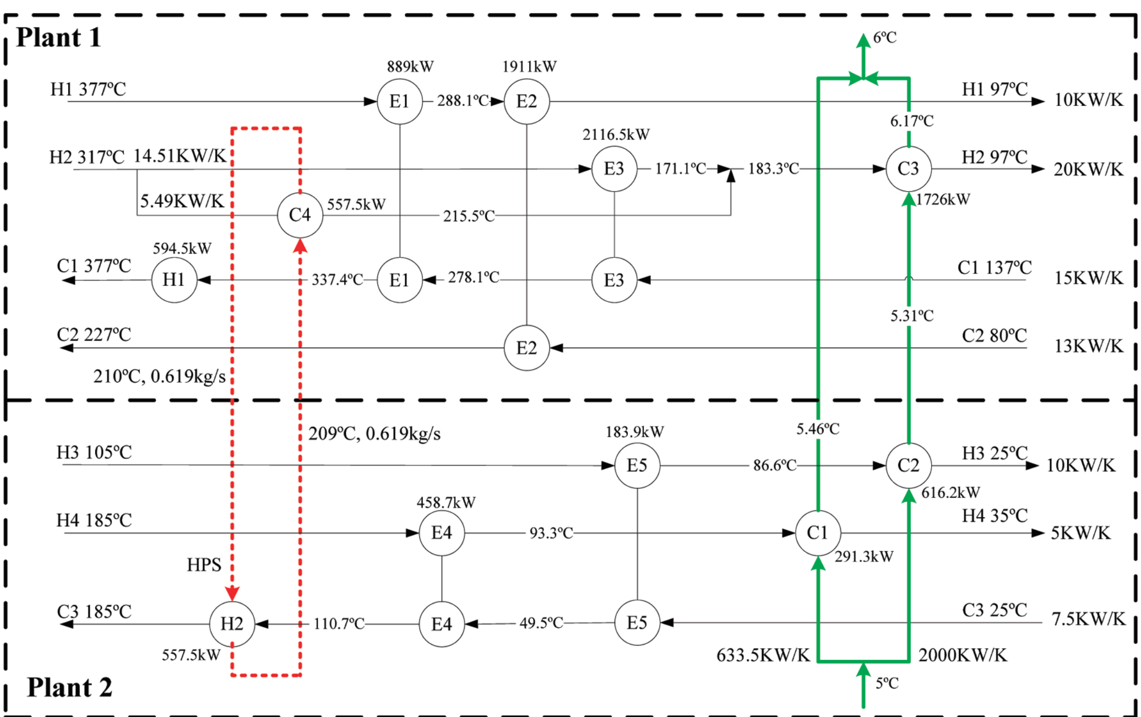

Figure 3. Optimal interplant HEN configuration in example 1.

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Table 3. Process Data for Cases 1−3 in Example 2

source	flow rate (kg/s)	temp. (°C)	concn. (ppm) *k*1	concn. (ppm) *k*2	concn. (ppm) *k*3	sink	flow rate (kg/s)	temp. (°C)	max. concn. (ppm) *k*1	max. concn. (ppm) *k*2	max. concn. (ppm) *k*3
						Plant 1					
1	30	100	100	80	120	1	35	50	50	40	60
2	56	95	60	100	400	2	40	20	40	55	120
3	36	50	80	100	200	3	28	95	40	40	100
4	32	60	50	100	150	4	40	100	30	40	80
fresh water		25	0	0	0	waste sink		30	30	50	100
						Plant 2					
5	40	70	80	80	150	5	32	35	50	50	120
6	30	75	120	100	180	6	45	45	40	60	100
7	55	10	60	110	160	7	45	60	40	70	80
8	38	20	60	80	120	8	42	65	30	60	80
fresh water		25	0	0	0	waste sink		30	30	50	100

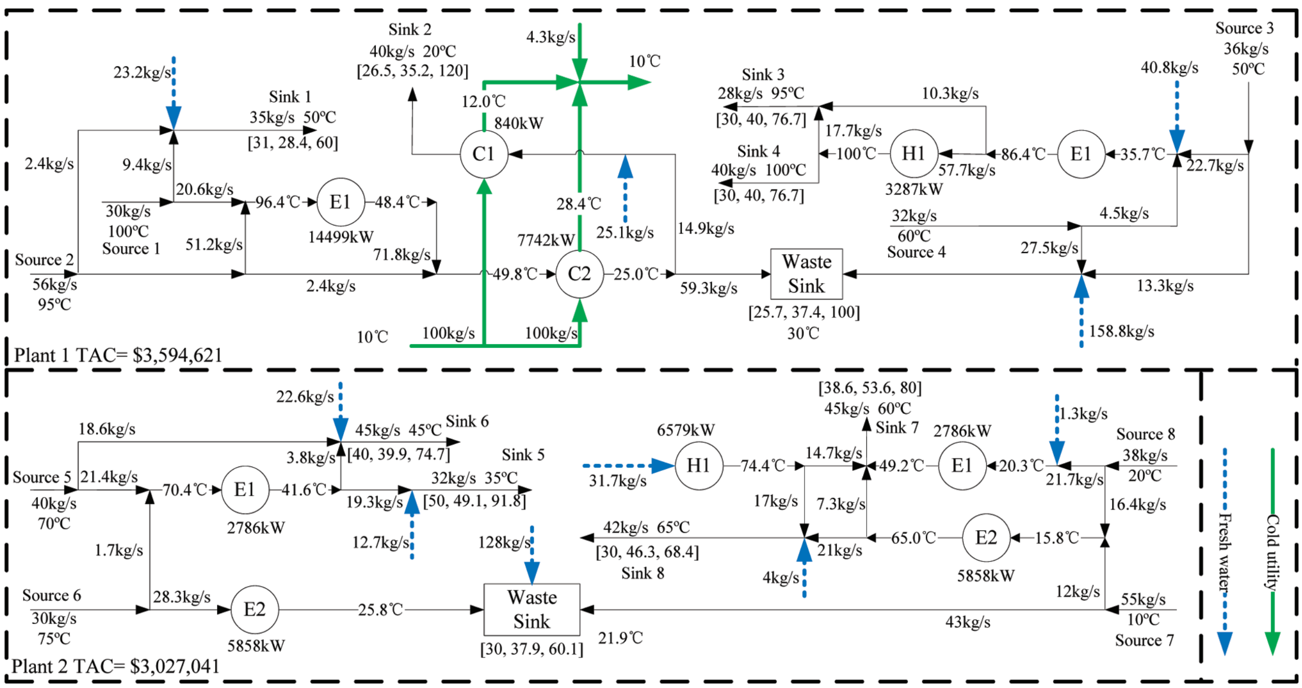

Figure 4. Optimal stand-alone WAHEN designs in case 1 of example 2.

Case 1 WAHEN Design for Stand-Alone Plant. Two individual plants each with a waste sink are studied in this case without considering any form of interplant integration. All the process data are given in Table 3. Let us first assume that the two hot streams in each plant are allowed to be merged and the two cold streams in each plant are also mixable, while the mixing of hot and cold streams is not permitted. In addition, we assume that the price of freshwater is 0.2 \$/ton. In this instance, while the MINLP models (eqs 1−45) for both cases have 587 variables (including 6 binary variables) and 597 constraints (including 561 equalities), 7 major iterations with 7.05 s and 16 major iterations within 14.14 s are needed to generate the optimal network configurations for the two stand-alone plants, as shown in Figure 4, where flow rates, heat loads, and outlet concentrations for sinks are all marked. Notice that the resulting network in plant 1 contains 1 heat exchanger, 1 heater, and 2 coolers, whereas plant 2 consists of 2 heat exchangers and 1 heater. Their TACs were found to be \$3 594 621 and \$3 027 041, respectively, and all cost terms on the right-hand side of eq 39 are given in Table 4. In the following two studies, these two base plants are then used to illustrate both direct integration and indirect integration with central junctions.

Case 2 Interplant WAHEN Design with Direct Integration Scheme. Case 2 is studied to investigate the effects of direct integration with process streams between two plants. To explore the possible cross-plant structure of freshwater supply network, we further assume that freshwater is allowed to be used across plants and that both freshwater source and waste sink of the system are embedded in plant 2. In addition, any hot (or cold) stream is allowed to be merged with another hot (or cold) stream, while the mixing of hot and cold streams is forbidden. With the above assumptions, this MINLP model (eqs 1−45) has 1032 continuous and 366 binary variables, as well as 36 inequality and 820 equality constraints. 8.66 s were needed for 3 iterations of the NLP subproblem and MILP master problem before identifying the optimal solution. The optimal IWAHEN structure with direct integration is shown in Figure 5. As evident from this figure, there are 3 heat exchangers, 1 heater, and 10 cross-plant pipelines (including one

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Table 4. Comparison of Different Design Schemes in Cases 1−3 in Example 2

	stand-alone plants (case 1)		direct integration (case 2)	indirect integration (case 3)
	plant 1	plant 2		
cost of freshwater	$1 427 712	$1 154 294	$2 232 587	$2 142 753
cost of hot utility	$854 495	$1 710 623	$840 686	$567 879
cost of cold utility	$1 029 758	$0	$0	$0
cost of exchangers	$282 656	$162 124	$344 695	$230 398
cost of pipelines and junctions			$455 832	$230 040
individual TAC	$3 594 621	$3 027 041		
overall TAC	$6 621 662		$3 873 800	$3 171 070

pipeline for fresh water, which was not marked in the figure for the sake of clarity) in this resulting network. The corresponding minimum TAC of the two integrated plants reduced significantly to $3 873 800, which represents a 41.5% improvement. Furthermore, although the capital investment has increased, the consumptions of all kinds of utilities have been cut down drastically so as to lower the TAC. Such reductions are achieved with the additional mixing, splitting, and heat exchange opportunities afforded by the direct integration. All relevant costs with regard to this network are summarized in Table 4. In this network, it should be noted that while most interplant streams involve both direct heat and mass transfer, one cross-plant stream from plant 2 passing through E1 also participates in indirect heat exchange. This stream mixes with others streams in plant 1 and then exits to the waste sink in plant 2.

Case 3 Interplant WAHEN Design with Indirect Integration and Multistream Mixing. The second type of IWAHEN integration scheme addressed in this work is indirect integration where two central junctions are included in the network. In this scenario, direct stream mixing and matching across plants are forbidden and all flows are directed to other plants through central junctions. To simplify the model in dealing with stream mixings in junctions, the assumption that all hot and cold streams are allowed to be mixed is introduced. Yet, given the aforementioned features, we consider in the IWAHEN design, the number of binary variables coupled with extremely limited network connections between the two plants may overwhelm the capabilities of any available solvers. To deal with this problem, we first solve the simplified MINLP model by removing constraints 12 and 13, as well as the binary cost term in the cost of pipelines. Then, we can obtain the exact TAC by adding such fixed cost to the foregoing objective function. As the fixed

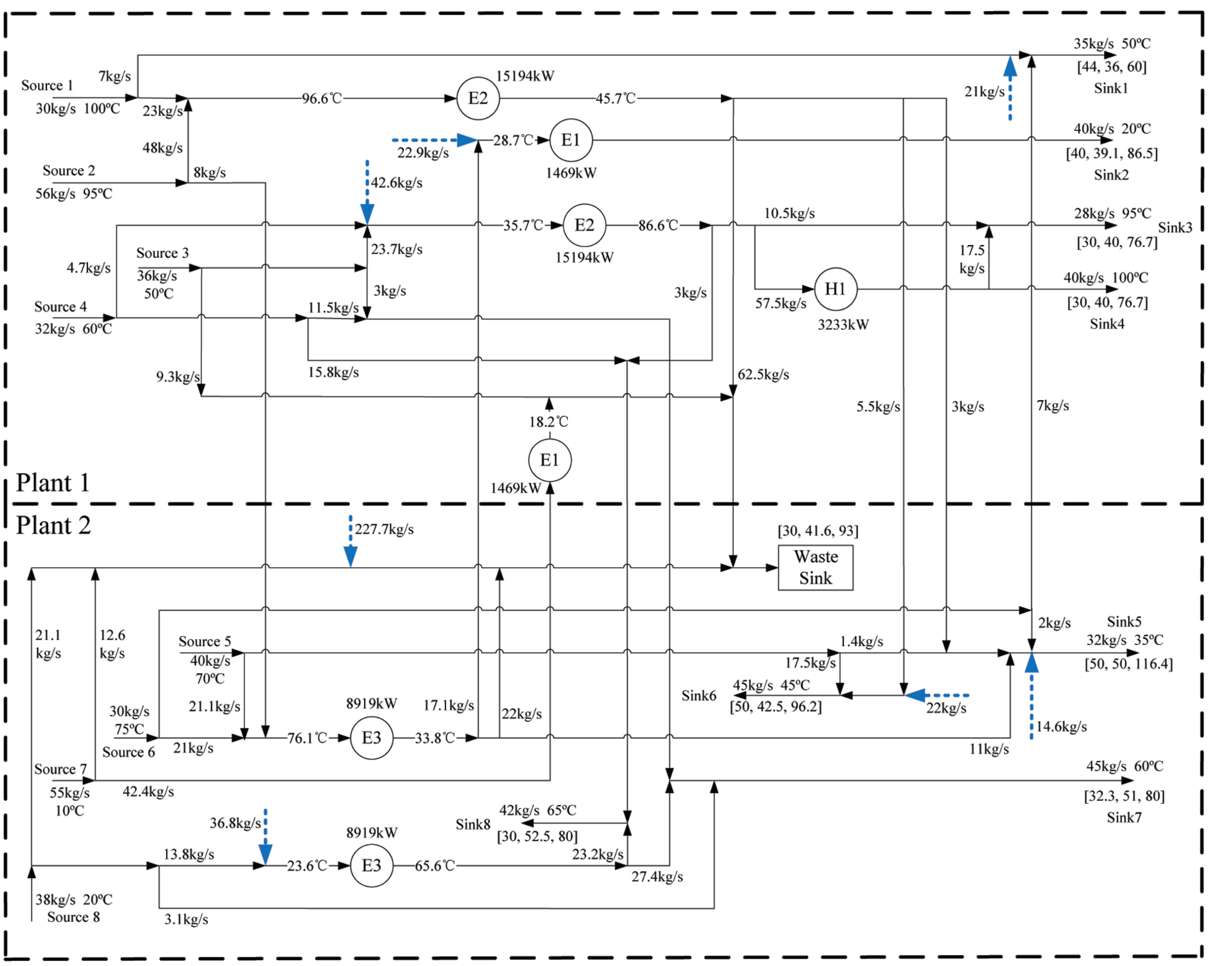

Figure 5. Optimal direct integrated WAHEN design in case 2 of example 2.

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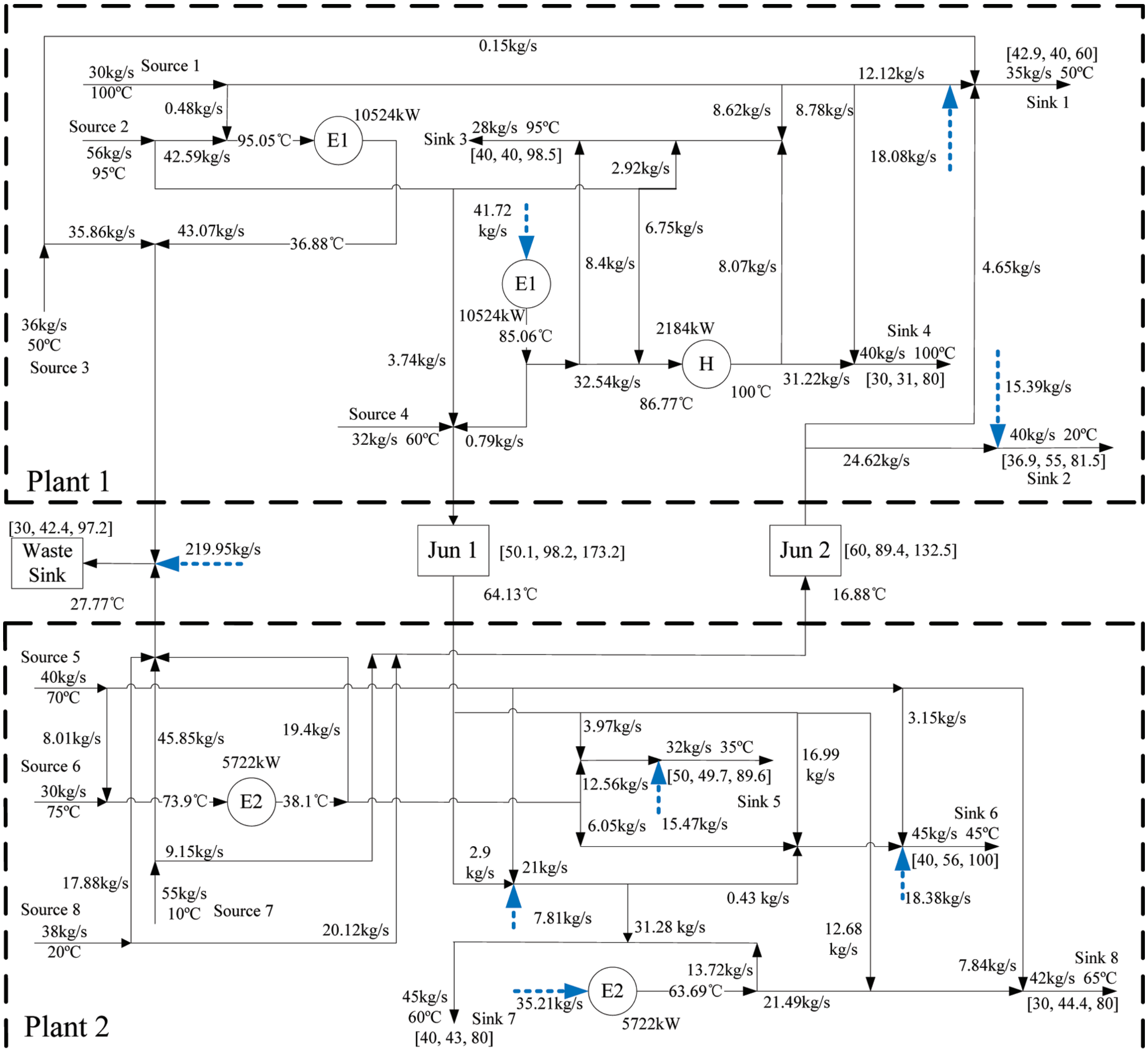

Figure 6. Optimal indirect integrated WAHEN design in case 3 of example 2.

cost for pipelines carries few weights in the final objective function, good local optimal solutions can always be captured with the this approach.

Given the above assumptions and solution strategy, the simplified MINLP model for this case entails 716 constraints (including 680 equalities), as well as 1164 continuous and 6 binary variables. 14.4 s for 10 major iterations between the NLPs and MILPs were required to find the optimal solution. The optimal structure obtained is shown in Figure 6, and the corresponding TAC can be further reduced to $3 171 070 which is only 47.9% of the TAC for stand-alone plants. The total capital expenditures (pipelines and junctions included) and utility cost have also decreased to $460 438 and $2 710 632. Note that only 2 heat exchangers, 1 heater, and 6 cross-plant pipelines are needed in this design. All other key parameters for the network design are provided in Table 4. Here, it should be noted that the TAC of indirect integration alone is usually higher than that of direct integration since there are fewer mixing, splitting, and heat exchange opportunities. However, since the mixing between hot and cold streams are allowed, other classes of more desirable "direct" mixing and heat exchange possibilities are created. Therefore, compared with direction integration in case 2, the decrease of TAC in this case should in fact be attributed to the mixing of hot and cold streams.

Case 4 Indirect Integration with Centralized Junction as Water Regeneration Units. To demonstrate the capability of the multiscale state–space superstructure for incorporating the wastewater-treatment options in indirect integrations of IWAHEN, process data from another two plants (see Table 5) are used for the comparisons of indirect integration scenarios with and without treatment units. In this case, the price of freshwater is set at 0.375 $/ton. In the first scenario, the aforementioned procedures suggested in case 3 are adopted to integrate the two separate WAHENs indirectly with two junctions. The resulting network structure for this scenario is shown in Figure 7, in which 1 heat exchanger,

Table 5. Process Data for Case 4 in Example 2

source	flow rate (kg/s)	temp. (°C)	concn. (ppm) k1	k2	k3	sink	flow rate (kg/s)	temp. (°C)	max. concn. (ppm) k1	k2	k3
					Plant 1						
1	40	60	250	200	250	1	38	25	50	40	60
2	35	75	120	100	150	2	40	35	40	55	50
3	36	70	150	180	200	3	32	20	50	50	50
fresh water		25	0	0	0	waste sink		30	15	25	40
					Plant 2						
4	35	30	80	80	150	4	30	75	50	50	120
5	40	35	120	100	180	5	45	70	40	60	100
6	29	25	60	110	160	6	30	60	40	70	80
fresh water		25	0	0	0	waste sink		30	15	25	40

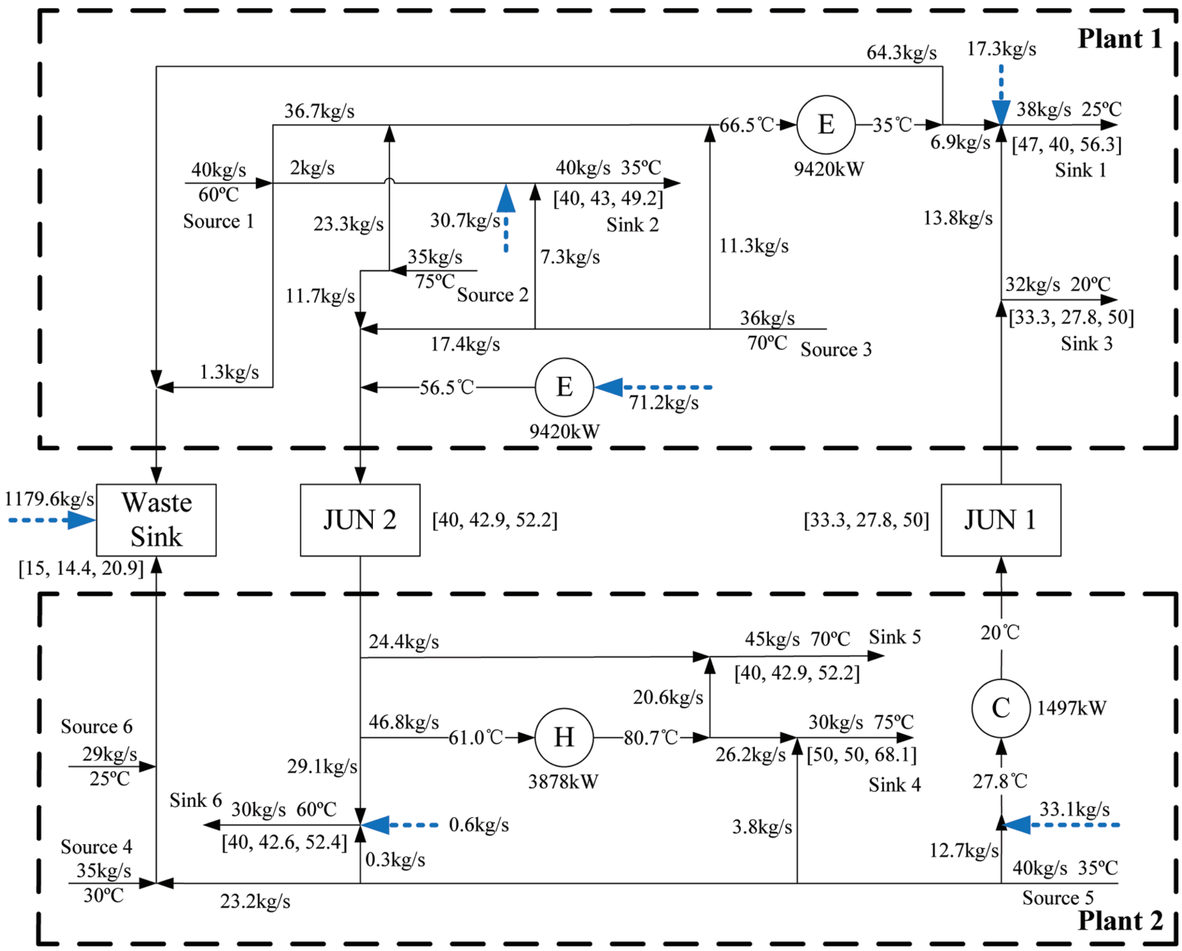

Figure 7. Optimal indirect integrated WAHEN design in case 4 without central treatment.

1 cooler, and 1 heater are included. Its TAC and the corresponding capital investment were found to be \$16 122 892 and \$545 049, respectively. The freshwater flow rate in this design is 1332.5 kg/s, and the consumption rates of cold and hot utilities are 1497 kW and 3878 kW, respectively. In the second scenario, one of the centralized junctions consisting of regeneration unit, where the water source quality is treated before it is sent to other plants for further water recovery, is used to compute the TAC. By constructing the multiscale state−space superstructure and solving the MINLP models with 1044 variables (including 6 binary ones) and 678 constraints (including 642 equality constraints), one can obtain the optimal network configuration (see Figure 8) with three major iterations in 4.35 s. Notice that while the consumption rates of cold utilities and the treatment cost have increased to 5653 kW and \$176 847, respectively, the usage of the freshwater has reduced to 0 kg/s so as to lead to an 86.7% decrease in the overall TAC. A comparison of the key features of the designs obtained in both scenarios is presented in Table 6.

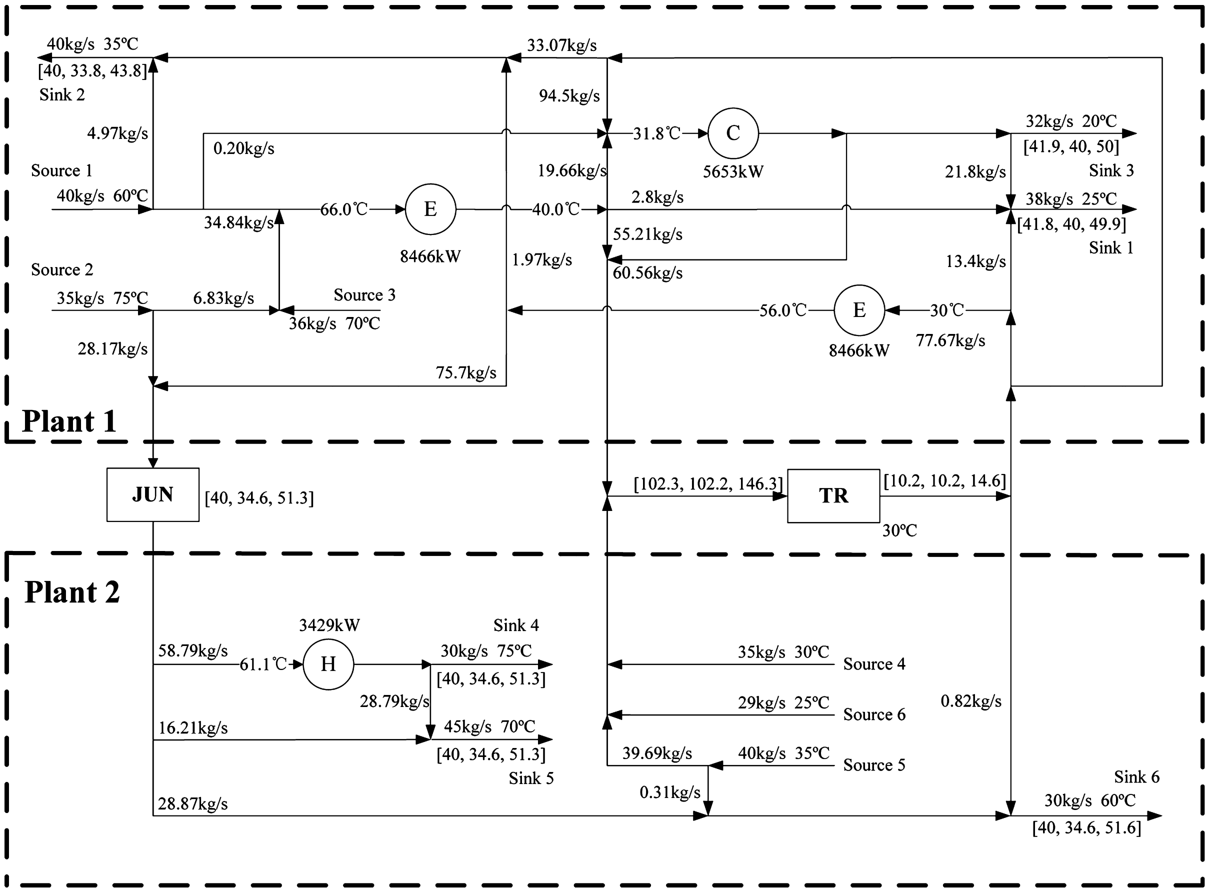

Figure 8. Optimal indirect integrated WAHEN design in case 4 with central treatment unit.

Table 6. Comparison between the Two Scenarios in Case 4 of Example 2

	scenario 1 (without treatment unit)	scenario 2 (with treatment unit)
cost of freshwater	$14 389 980	$0
cost of hot utility	$1 008 186	$891 123
cost of cold utility	$179 677	$678 408
cost of treatment	$0	$176 847
cost of exchangers	$184 349	$210 911
cost of pipelines and junctions	$360 700	$189 664
overall TAC	$16 122 891	$2 146 953

6. CONCLUSIONS

An MINLP model has been presented in this work for the optimization of interplant HENs and IWAHENs with FF operations. The integration of water and heat between each individual plant is rendered possible by resorting to the multiscale state−space superstructure, where all intra- and interplant network configurations are incorporated. To illustrate the advantages and various aspects of our approaches, several examples were presented. From the results obtained, it can be clearly observed that better interplant designs with lower TAC can be generated with the proposed integration schemes.

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Notes

The authors declare no competing financial interest.

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