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Simultaneous Synthesis of Property-Based Water Reuse/Recycle and Interception Networks for Batch Processes

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A systematic technique is introduced for the synthesis of cost-effective batch water networks with the placement of interception devices. Utilizing the new concept of property integration, a property-based approach is adopted. The water streams (sources) are characterized by a number of key properties, and water-using units (sinks) are bound with property constraints. The problem also considers a number of interception devices that can be used to modify the properties of the streams to optimize the reuse/recycle of process streams and minimize fresh resources. A source-tank-interception-tank-sink representation is developed. Storage tanks are used throughout the network to enable mixing, storage, and dispatch of the reused/recycled water streams. The procedure is supported by an optimization formulation whose solution identifies optimal allocation of sources to tanks, interception devices, and sinks. The solution also determines an optimal policy for operating the water network. A case study is solved to illustrate the important aspects of the devised procedure. © 2008 American Institute of Chemical Engineers *AIChE J*, 54: 2624–2632, 2008

Keywords: batch water network, interception, optimization, property integration, water minimization

Introduction

As industry endeavors to prevent pollution and conserve resources, there is an increasing emphasis given to the optimal management of water usage and wastewater discharge. Additionally, the growing public awareness toward environmental and economic aspects associated with waste treatment and discharge has stimulated the process industries to search for alternative and competitive methods to reduce waste generation. In this context, reuse/recycle strategies play an instrumental role for simultaneously reducing fresh water consumption and wastewater generation. The water streams from process units (termed as *sources*) may be directly reused/recycled to water-using units (termed as *sinks*). In some cases, the water streams may be intercepted/treated/purified in *interception* devices to adjust its composition and other properties before it is reused/recycled to the sinks. Via water reuse/recycle and interception, there is a potential to achieve substantial reduction in both fresh water usage and wastewater discharge. Therefore, the area of water network synthesis has received considerable research interest. Over the past decade, numerous research contributions have been

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made to systematically address in-plant water reuse/recycle, ranging from graphical pinch analysis techniques to mathematical-based optimization approaches, for both continuous and batch water networks.

Wang and Smith[1] developed an insight-based pinch analysis technique for water network synthesis in continuous mode with focus on mass-transfer water-using units such as scrubbing and cleaning (often known as the *fixed load problem*). Additional research works have investigated the more generalized *fixed flow rate problem* that also considers non-mass-transfer processes such as reactor byproduct formation, cooling tower makeup and boiler blow down.[2–24] In addition to insight-based pinch analysis approaches, mathematical optimization approaches have also received much attention from the research community. Early works in this area were reported by Takama and coworkers.[25–27] Later works on deterministic approaches were reported.[28–48] Other than the deterministic mathematical optimization approaches, stochastic optimization approaches have been developed. These include genetic algorithm,[49–52] random search optimization approaches,[51] and particle swarm optimization.[54–57] Reviews on various techniques in water network synthesis problem can be found in literature.[56–60] In order to enhance the targets for the extent of water recycle, research work has been undertaken to provide partial treatment of water sources, or *water regeneration*. Significant amount of work has also seen in this area.[1,6,14–15,61–68]

While the majority of research efforts on water networks have focused on continuous steady-state systems, much less attention has been given to water management in batch processing. Several insight-based approaches were reported for fixed load[69,70] and fixed flow rate problems.[71] Other contributions have focused on mathematical optimization approaches.[72–81] Additionally, batch water networks with regeneration was addressed by Shoaib et al.[81] who proposed a three-stage hierarchical approach for the synthesis of batch water networks.

It is worth noting that the foregoing research efforts have been restricted to "*chemo-centric*" *or composition-based* systems, where the characterization of the streams and constraints on the sinks are described in terms of the composition of pollutants. Other than the composition of pollutants, there may be other important characteristics that should be considered. Indeed, there are many applications that require the consideration of *properties*. For instance, the use and discharge of water streams may be dependent on various characteristics, such as pH, conductivity, turbidity, toxicity, theoretical oxygen demand (ThOD) and color. Moreover, systems with numerous components (e.g., petroleum, coal, pulp and paper) can be characterized by finite properties that are easier to track than attempting to track the numerous components. Therefore, in order to address design problems that are governed by functionalities and properties, the framework of property integration has been recently proposed. It is defined as "*a functionality-based, holistic approach to the allocation and manipulation of streams and processing units, which is based on the tracking, adjustment, assignment, and matching of functionalities throughout the process*".[82] Graphical, algebraic and optimization techniques have been developed for property-based recycle/reuse network,[83–88] and for simultaneous process and molecular design.[89,90] It is worth noting that these research efforts have been limited to steady-state continuous processes. Grooms et al.[91] developed a technique for synthesizing interception networks that involve the use of steady-state and dynamic separation devices.

The objective of this work is to develop a systematic, property-based procedure for the synthesis of cost-effective batch water networks. This synthesis tasks involve the optimal allocation and interception of water sources, while satisfying all the property-based process constraints. In addition, the procedure should determine the number and assignment of storage tanks used for scheduling. A structural representation of the problem is introduced to embed all potential network configurations, and is solved by an optimization formulation. The solution provides the optimal allocation of sources, storage, interception and network configuration. A case study is presented to show the usefulness of this newly developed procedure.

Problem Statement

The following section defines the problem of the property-based batch water network. Consider:

- A batch process with a cycle time (τ).
- A set of water sources (referred to as SOURCES) composed of process water streams that may be reused/recycled or discharged. Each source has a flow rate profile, $f_{source}(t)$, where the subscript *source* is an index for the sources. Each source is characterized by a set of properties: PROPERTIES $= \{q | q = 1, 2, ..., N_{\text{properties}}\}$. The dynamic profiles of the properties of the sources are designated by $p_{source,q}(t)$, and t is the time from the beginning of the cycle ($0 \leq t \leq \tau$).
- A set of process sinks (referred to as SINKS). Sinks are process units that can accept the sources. The index for sinks is referred to as *sink* (subscript). Each sink requires a flow rate, $g_{sink}(t)$ and property values $p_{sink,q}(t)$, that satisfy the following constraints

$$p_{sink,q}^{\min} \leq p_{sink,q} \leq p_{sink,q}^{\max} \quad sink \in \text{SINKS}, \quad q \in \text{PROPERTIES} \quad (1)$$

where $p_{sink,q}^{\min}$ and $p_{sink,q}^{\max}$, are given lower and upper bounds on acceptable properties to *sink*.

- A set of interception devices: INTERCEPTORS $= \{k | k = 1, 2, ..., N_{\text{Interceptors}}\}$. Interception devices are units that may be added to the process to change the source properties. The interception devices are operated dynamically with the following performance

$$p_{k,q}^{\text{int}} = f\left(p_{source,q}^{\text{in}}, z_k, r_k, t\right) \quad (2)$$

- A set of fresh water: FRESH $= \{m | m = 1, 2, ..., N_{\text{Fresh}}\}$ that may be purchased at a cost C_m^{Fresh} to supplement the use of process sources. The properties of the fresh water are designated by $p_{m,q}^{\text{Fresh}}$.

A mixing rule is needed to define all possible mixing patterns among these individual properties. One such form for mixing is the following expression[83]

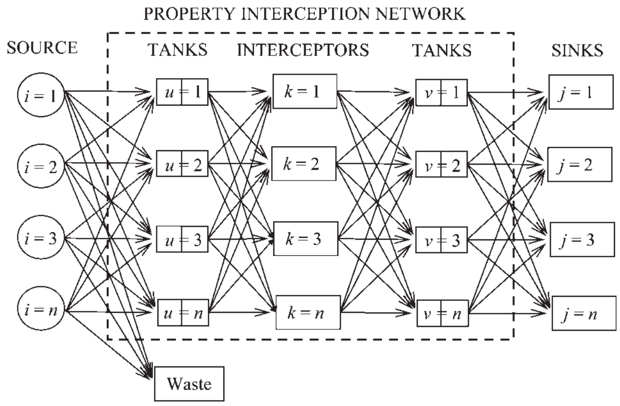

Figure 1. Source-tank-interception-sink representation.

$$\psi(\bar{p}_q) = \sum_l x_l \psi(p_{l,q}) \tag{3}$$

where $\psi(p_{l,q})$ and $\psi(\bar{p}_q)$ are operators on property $p_{l,q}$ and mixture property $\bar{p}_q$, respectively, and x_l is the fractional contribution of stream l of the total mixture flow rate (for continuous representations) or flow/quantity (for the discretized representations).

The objective is to develop a systematic procedure for the synthesis and scheduling of the batch water network, so as to optimize the allocation and interception of water sources to tanks, interception devices, and sinks in a cost-effective manner, while satisfying all the property-based constraints on water reuse/recycle.

Solution Approach

For convenience, a multiperiod representation is adopted, whereby the cycle time is discretized into N_{periods} intervals (or time periods). The duration of each period is defined so as to capture important dynamic characteristics of the sources or the constraints on the sinks. At the limit when $N_{\text{periods}} \rightarrow \infty$, the multiperiod representation becomes a continuous representation. Over each time interval, the flow rate, f_{source} is integrated (to give flow or quantity $F_{source,n}$), and the property is averaged $p_{source,q,n}$, as shown by the following equations

$$F_{source,n} = \int_{t_n^s}^{t_n^e} f_{source}(t)\ dt \tag{4}$$

$$p_{source,q,n} = \frac{\int_{t_n^s}^{t_n^e} f_{source}(t) p_{source,q}(t)\ dt}{F_{source,n}} \tag{5}$$

where t_n^s and t_n^e are the starting and ending times of the n-th time period.

To simplify the symbols and the representation, each pair of indices (*source*, n) is mapped to an index i, which is used to represent all discretized and integrated sources. Hence, the values of the integrated flows and averaged properties for the sources are designated by F_i and $p_{i,q}$ respectively, where i = 1 corresponds to Source 1 in period 1; while i = 2 corresponds to Source 1 in period 2, and so on until i index reaches $i = N_{sources} \times N_{periods}$, which corresponds to the last source in the last period.

A similar discretization and integration are carried out for the sinks with the result of yielding flows (or quantities) and properties for the sinks designated by G_j and $p_{j,q}$, respectively, with j-th being an index representing all discretized and integrated sinks.

The problem can be represented by a source-tank-interception-tank-sink allocation, as shown in Figure 1. Each source i, is assigned to tanks u before interceptors k. Each set of tanks consists of two tanks. This is because the role of the tanks will alternate after each cycle between storage and dispatch. One tank will first be used for collection of water sources, while the other tank is used to dispatch the stored water. Meanwhile, in the subsequent cycle, their roles are reversed. The main purpose of having a set of tanks for storage and dispatch is to ensure that the properties in the tank achieve the desired values prior to being dispatched to interception devices or sinks. In the cases when both sources and sinks are not overlapping in the same discretized time interval, only one storage tank is required, because the same tank can be operated as storage and dispatch at different discretized time intervals. In addition, in some special cases, no tanks are required if the sources over a time interval are steady-state streams with steady properties, and are operating along with interception devices, tanks and sinks at the same time interval. Figure 2 shows the usage of the storage tanks in the water network. In this work, it is assumed that a standardized size of tank that can accommodate the maximum flow of the water is used to store and dispatch the water; thus, the cost of the tank is referred to as a constant C^T.

Optimization Formulation

The objective function is expressed as:

Minimize total annualized cost =

$$\sum_{m=1}^{N_{\text{Fresh}}} \sum_{j=1}^{N_{\text{Sink}}} C_m^{\text{Fresh}} F_{m,j}^{\text{Fresh}} N_{batches} + \sum_{k=1}^{N_{\text{Interceptors}}} COST_k\left(w_k, \psi\left(p_{k,q}^{\text{in,int}}\right), \psi\left(p_{k,q}^{\text{int}}\right), z_k, r_k\right) + 2\sum_{u=1}^{N_{\text{Tank}\,u}} C_u^{\text{T}} I_u^{\text{Tank I}} + 2\sum_{v=1}^{N_{\text{Tank}\,v}} C_v^{\text{T}} I_v^{\text{Tank II}} \tag{6}$$

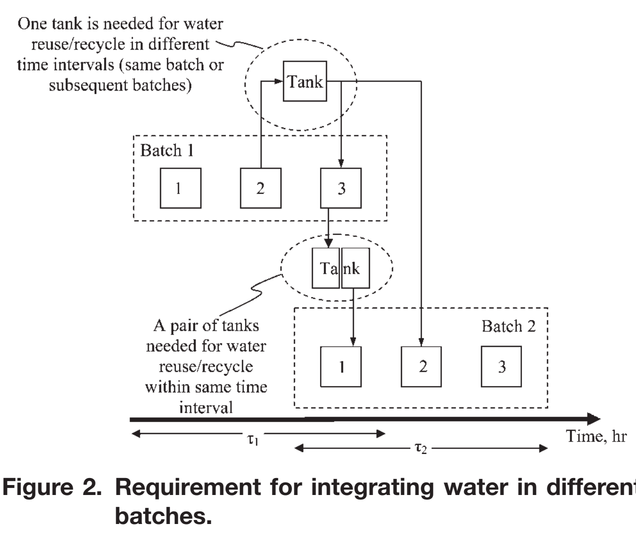

Figure 2. Requirement for integrating water in different batches.

where C_m^{Fresh} is the cost coefficient of the m-th fresh resources, $F_{m,j}^{\text{Fresh}}$ is the m-th fresh resource that is fed into the j-th sink (mass per batch cycle, τ), $N_{batches}$ is the number of batches per year, $COST_k$ is the total annualized cost function associated with interception device k. $COST_k$ is a function of the flow rate w_k, inlet property operator for the q-th property entering the interceptor $\psi(p_{k,q}^{\text{in,int}})$, outlet (intercepted) operators for the q-th property $\psi(p_{k,q}^{\text{int}})$, the vector of design variables z_k, and the vector of operating variables r_k. The parameters C_u^{T} and C_v^{T} are the cost coefficients of tanks u and tank v, respectively. Besides, $I_u^{\text{Tank I}}$ and $I_v^{\text{Tank II}}$ are binary integers that take the value of 0 or 1, designating the absence or presence of tank u and tank v, respectively. The factor 2 is used to indicate the existence of storage and dispatch tanks alternating from one cycle to another. The objective function is formulated to minimize the total annualized cost that is subject to the following constraints.

Splitting of sources to the tanks preceding interception device and waste treatment

$$F_i = \sum_u f_{i,u} + f_{i,\text{waste}} \quad \forall i \tag{7}$$

The combined flow of the mixed sources entering the u-th tank is given by

$$W_u^{\text{Tank I}} = \sum_i f_{i,u} \quad \forall u \tag{8}$$

and property-operator mixing equations

$$W_u^{\text{Tank I}} \times \psi\left(\bar{p}_{u,q}^{\text{Tank I}}\right) = \sum_i f_{i,u} \times \psi\left(p_{i,q}\right) \quad \forall u, q \tag{9}$$

Absence or presence of tank u

$$W_u^{\text{Tank I}} \le W^{Cap} I_u^{\text{Tank I}} \quad \forall u \tag{10}$$

where W^{Cap} is the maximum capacity (mass per batch cycle) of the tank. When the value of $W_u^{\text{Tank I}}$ is positive, the constraint forces $I_u^{\text{Tank U}}$ to take the value of 1. On the other hand, when $W_u^{\text{Tank I}}$ is zero, the constraint allows the value of $I_u^{\text{Tank U}}$ to be 0 or 1. However, the objective function will force $I_u^{\text{Tank U}}$ to be 0.

Splitting from tank u to all interception devices k

$$W_u^{\text{Tank I}} = \sum_k w_{u,k} \quad \forall u \tag{11}$$

Mixing of sources entering the k-th interception device

$$w_k = \sum_u w_{u,k} \quad \forall k \tag{12}$$

and property-operator mixing equations

$$w_k \times \psi\left(p_{k,q}^{\text{in,int}}\right) = \sum_u w_{u,k} \times \psi\left(\bar{p}_{u,q}^{\text{Tank I}}\right) \quad \forall k, q \tag{13}$$

The outlet (intercepted) property operator of the q-th property, leaving the k-th interception device $\psi(p_{k,q}^{\text{int}})$, is a function of the inlet operator $\psi(p_{k,q}^{\text{in,int}})$, flow w_k, as well as the design and operating variables (z_k and r_k) of the interceptor as determined by the following model

$$\psi\left(p_{k,q}^{\text{int}}\right) = f\left(\psi\left(p_{k,q}^{\text{in,int}}\right), w_k, z_k, r_k\right) \quad \forall k, q \tag{14}$$

Splitting of sources from interception device k to all pairs of tanks v for storage and dispatch

$$w_k = \sum_v h_{k,v} \quad \forall k \tag{15}$$

Note that an imaginary interception device may be added to allow for bypass, to cater for source(s) that does not require any property interception.

The combined flow of the mixed streams entering the tank v is given by

$$W_v^{\text{Tank II}} = \sum_k h_{k,v} \quad \forall v \tag{16}$$

and property-operator mixing equations

$$W_v^{\text{Tank II}} \times \psi\left(\bar{p}_{v,q}^{\text{Tank II}}\right) = \sum_k h_{k,v} \times \psi\left(p_{k,q}^{\text{int}}\right) \quad \forall v, q \tag{17}$$

Absence or presence of tank v

$$W_v^{\text{Tank II}} \le W^{Cap} I_v^{\text{Tank II}} \quad \forall v \tag{18}$$

Splitting from tank v to all sinks

$$W_v^{\text{Tank II}} = \sum_j g_{v,j} \quad \forall v \tag{19}$$

Overall material balance around the mixing point of the feed to the j-th sink

$$G_j = \sum_m F_{m,j}^{\text{Fresh}} + \sum_v g_{v,j} \quad \forall j \tag{20}$$

Material property operator constraints around the mixing point of the feed to the sink j

$$G_j \times \psi\left(p_{j,q}^{\text{in}}\right) = \sum_m F_{m,j}^{\text{Fresh}} \times \psi\left(p_{m,q}^{\text{Fresh}}\right) + \sum_v g_{v,j} \times \psi\left(\bar{p}_{v,q}^{\text{Tank II}}\right) \quad \forall j, q \tag{21}$$

Sink constraints

$$\psi\left(p_{j,q}^{\min}\right) \le \psi\left(p_{j,q}^{\text{in}}\right) \le \psi\left(p_{j,q}^{\max}\right) \quad \forall j, q \tag{22}$$

All the unused sources are fed to the waste treatment system before discharge to the environment

$$\text{waste} = \sum_i f_{i,\text{waste}} \tag{23}$$

From the formulation described above, it is noted that the optimization program is a mixed integer nonlinear program (MINLP), which can be solved to determine the minimum total annualized cost for the water network with interception devices. The nature of the interception function, and the bilinear terms involved in the mixing equations lead to nonconvexities. Therefore, the global solver feature in the commercial optimization software Extended LINGO version 10.0 is used to obtain the global solution.

Finally, an inspection step is added after solving the optimization program to remove unnecessary tanks. For the case

Table 1. Data for the Process Sources of the Case Study (*t* is Start Time of the Cycle h)

Source	Function for flowrate (kg/hr)	Function for pollutant composition (ppm)	Function for pH	Start time (hr)	End time (hr)
1	6.0	$20 \times t + 10$	$2 \times t + 8.0$	0	1
2	2.0	30	7.7	3	4

when both sources and sinks are overlapping in the same discretized time interval, two tanks are included; while in cases when sources and sinks are not overlapping in the same discretized time interval, one tank is needed. When sources are assigned directly to sinks, no tanks are needed. On inspection of these conditions, the solution is simplified, and the scheduling scheme is determined.

Case Study

A semibatch chemical process which operates with an eight-hour cycle time is presented to illustrate the proposed approach. The process produces two water sources, and has two sinks that require water usage. The first process source comes from a batch unit, and, therefore, has dynamic characteristics. On the other hand, the second source comes from a steady-state unit. The feed to process sinks is constrained by criteria on flow rate, composition of a sulfur pollutant, and pH. Tables 1 and 2 provide a summary of the pertinent data for the sources and sinks. Using Eq. 4, the flows of Source 1 and Source 2 are determined as 6.0 kg and 2.0 kg, respectively. Utilizing Eq. 5, the averaged sulfur composition and pH of Source 1 are determined as 20 ppm and 9.0, respectively. On the other hand, properties of Source 2 are constants, have the steady-state values of 30 ppm of sulfur concentration and pH = 7.7.

In order to adjust the pH of the process streams, neutralization units using an acid (pH = 5, cost = \$0.2/kg) or an alkali (pH = 11, cost = \$0.1/kg) may be used as interceptors. For sulfur removal, activated carbon adsorption may be used for interception (removal efficiency = 90%, cost = \$0.05/kg intercepted water). Fresh water (zero content of the pollutant and a pH of 7.0, cost = \$0.01/kg) may be used as needed. The total annualized cost of a tank (including pumping and piping) is \$15,000 per year.

In this case, the mixing rule for composition of sulfur pollutant and pH is given by Eqs. 22 and 23, respectively

$$\overline{C} = \sum_l x_l C_l \tag{24}$$

$$10^{-\mathrm{p}\overline{\mathrm{H}}} = \sum_l \left(x_l \times 10^{-\mathrm{pH}_l} \right) \tag{25}$$

Figure 3 shows the superstructure of this case study. Note that, all the process sources are sent to storage tank set *u*, i.e., U1 and U2 (with two tanks for each set), before the process water is treated by interception device *k*. Note also that an artificial interception device (K2) with zero cost, and no property adjustment is included in the formulation, which enables the bypass of process source(s) when interception is not necessary. The intercepted sources are then sent to storage tank set *v*, i.e., V1 and V2 (with two tanks for each set), before sending to the sink. Note that there will be a total of eight tanks in this superstructure (with two tanks for each set of *u* and *v*) before the optimization is carried out. The excessive tank(s) will be removed by inspection after the model is solved.

In this work, the objective is to synthesize a cost-effective water network and the MINLP model was run on Extended LINGO version 10.0 with a global solver. Global solution is obtained in 16 s on a Pentium (R) 4 desktop, with 3.00 GHz CPU and 512 MB RAM, resulting in the water network as shown in Figure 4. Following the proposed inspection step, only one storage tank is needed in both sets *u*1 and *v*1, as water sinks and sources do not overlap in their respective time intervals (hence, the use of two tanks for breaking the dynamic behavior is not needed here). Note also that tank sets *u*2 and *v*2 is completely removed. Hence, the inspective step identify that only two tanks are necessary, out from eight tanks proposed in the superstructure in Figure 3. As shown, both Source 1 and Source 2 are stored in Storage Tank u_1 prior to interception. In 3–4 h, 3.84 kg/s of water from Storage Tank u_1 is treated with 0.026 kg/s of acid (pH = 5.0), prior sending to Storage Tank v_1. Besides, 2.682 kg/s of water from Storage Tank u_1 bypasses the interception device prior storing in the Storage Tank v_1. The stored water in Storage Tank v_1 is then sent to fulfill the requirement of Sinks 1 and 2 at a later time. Figure 4 also shows that a total of 2.979 kg/s of fresh water is used to fulfill the requirement of Sinks 1 and 2.

Following the result from the optimization coupled with the inspection step (for excessive storage tank removal), the minimum total annualized cost of the system is determined as \$167,456/yr. Note that numerous network designs may achieve the minimum total annualized cost, with Figure 4 being one of the alternatives.

Table 2. Data for the Process Sinks of the Case Study

Sink	Minimum flowrate demand (kg/hr)	Maximum flowrate demand (kg/hr)	Minimum allowable pollutant composition entering the sink (ppm)	Maximum allowable pollutant composition entering the sink (ppm)	Minimum pH entering the sink	Maximum pH entering the sink	Start time (hr)	End time (hr)
1	8.0	8.5	0	17	6.0	7.20	5	6
2	3.0	3.2	0	20	7.35	7.50	7	8

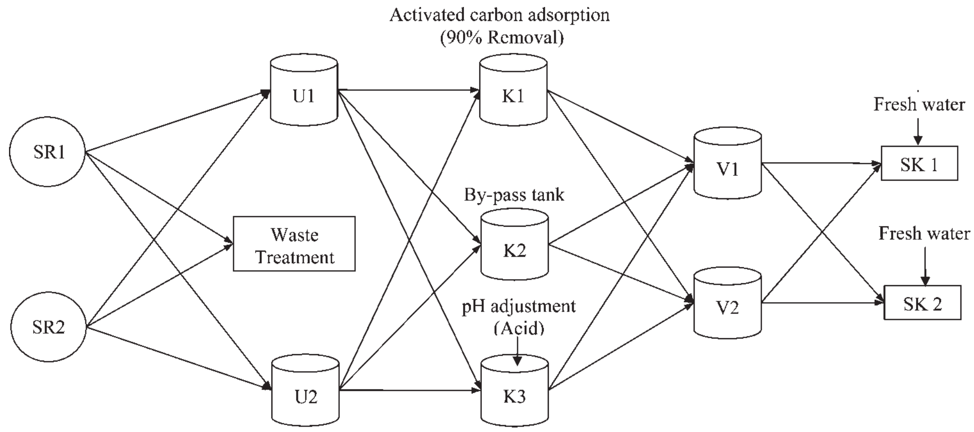

Figure 3. Superstructure for the case study.

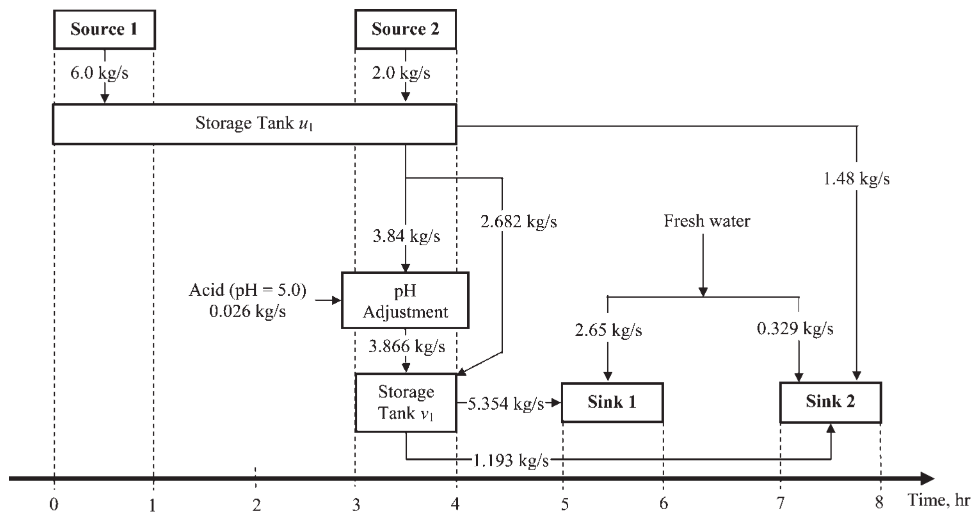

Figure 4. Network design for the case study.

Conclusion

A systematic property-based procedure has been developed for the synthesis, operation, and scheduling of batch water networks. Property-based characterization of sources and constraints for the sinks are used. A source-tank-interception-tank-sink representation was used to incorporate potential configurations of interest. Then, a mathematical-programming approach was used to formulate the design, operation, and scheduling tasks as an optimization problem. The solution of this optimization program determines the duty and location of each interception device, the assignment of source to interception devices, tanks, and sinks, and the operation of the synthesized network. A case study was solved to illustrate the usefulness of the developed approach.

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Notation

Sets

Fresh = set of fresh resources
Interceptors = set of interception devices
Properties = set of properties
Sinks = set of water sinks
Sources = set of water sources

Indices

k = index for interception device
i = index of discretized and integrated sources
j = index of discretized and integrated sinks
m = index for fresh water
n = index of time period
q = index for property
sink = index for sink
source = index for source

u = index for storage and dispatch tanks before interception device
v = index for storage and dispatch tanks after interception device

Variables

C_l = concentration in l-th stream
$\overline{C}$ = mean concentration
$COST_k$ = total annualized cost of k-th interception device
F_i = integrated flows of i-th source
$f_{i,u}$ = flow rate of i-th souce to u-th tank
$f_{i,waste}$ = flow rate of i-th souce to waste
$F_{m,j}^{\mathrm{Fresh}}$ = flow rate of m-th fresh water to j-th sink
f_{source} = water flow rate of *source*
$F_{source,n}$ = water flow of *source* within n-th time period
G_j = integrated flows of j-th sink
g_{sink} = water flow rate of *sink*
$g_{v,j}$ = flow rate of v-th tank to j-th sink
$h_{k,v}$ = flow rate of k-th interceptor to v-th tank
$I_u^{\mathrm{Tank\,I}}$ = binary integers that indicate absence or presence of u-th tank
$I_v^{\mathrm{Tank\,II}}$ = binary integers that indicate absence or presence of v-th tank
$\mathrm{p}\overline{H}$ = mean pH
pH_l = pH in l-th stream
$p_{i,q}$ = averaged of q-th property of i-th source
$p_{j,q}$ = averaged of q-th property of j-th sink
$p_{j,q}^{\mathrm{in}}$ = q-th property entering the j-th sink
$p_{l,q}$ = q-th property in l-th stream
$p_{m,q}^{\mathrm{Fresh}}$ = q-th property of m-th fresh water
$p_{sink,q}$ = q-th property of water *sink*
$p_{source,q}$ = q-th property of water *source*
$p_{source,q,n}$ = averaged of q-th property within n-th time period
$p_{source,q}^{\mathrm{in}}$ = q-th property for water *source* entering interceptor
$\overline{p}_{u,q}^{\mathrm{Tank\,I}}$ = mean q-th property in u-th tank
$\overline{p}_{v,q}^{\mathrm{Tank\,II}}$ = mean of q-th property in v-th tank
$\overline{p}_q$ = mean of q-th property
r_k = operating variable for k-th interceptor
t = time from the beginning of the cycle
t_n^s = starting time of the n-th time period
t_n^e = ending times of the n-th time period
τ = cycle time
w_k = flow rate entering k-th interceptor
$W_u^{\mathrm{Tank\,I}}$ = combined flow of the mixed sources entering the u-th tank
$W_v^{\mathrm{Tank\,II}}$ = combined flow of the mixed sources entering the v-th tank
$w_{u,k}$ = flow rate of u-th tank to k-th interceptor
x_l = fractional contribution of l-th stream of the total mixture flow rate
z_k = design variable for k-th interceptor
ψ = property operator

Parameters

C_m^{Fresh} = cost of m-th fresh water
C^{T} = cost of tank
C_u^{T} = cost of tank u
C_v^{T} = cost of tank v
N_{Fresh} = total number of fresh waters
$N_{\mathrm{Interceptors}}$ = total number of interceptors
N_{periods} = total number periods
$N_{\mathrm{properties}}$ = total number of properties
N_{sink} = total number of sinks
$N_{\mathrm{Tank}\ u}$ = total number of tank u
$N_{\mathrm{Tank}\ v}$ = total number of tank v
$p_{j,q}^{\min}$ = lower bound on acceptable properties to unit j-th *sink*.
$p_{j,q}^{\max}$ = upper bound on acceptable properties to unit j-th *sink*
$p_{sink,q}^{\min}$ = lower bound on acceptable properties to unit *sink*.
$p_{sink,q}^{\max}$ = upper bound on acceptable properties to unit *sink*
τ = cycle time
W^{Cap} = maximum capacity (mass per batch cycle) of tank

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