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Design of a Switchable Water Allocation Network Based on Process Dynamics

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Process and manufacturing plants usually consume huge amounts of water in various cleaning and rinsing operations. To couple with environmental regulations, the industries have been seeking effective and affordable technologies for wastewater minimization. This paper presents a design methodology for the most effective water use and reuse in rinsing operations. A unique feature of the methodology is to synthesize of a switchable water allocation network (SWAN) based on the dynamics of a rinse system. This permits water reuse to the maximum extent, while rinse qualities in different rinse steps can be guaranteed scientifically. The efficacy of the methodology is demonstrated by tackling an industrial wastewater minimization problem in an electroplating plant.

Introduction

Wastewater minimization has been a primary concern for pollution prevention (P2) in the process and manufacturing industries. Wastewater streams, if generated from cleaning and rinsing processes, usually contain various hazardous or toxic pollutants that need be strictly controlled. Over the past decades, numerous wastewater reduction and treatment technologies have been developed and practiced in the industries.

Among available wastewater reduction technologies, one type is process design oriented.[1,2] It targets the improvement of the design of each cleaning and rinsing process so that water can be most efficiently used. Wang and Smith[1,3] have developed a water pinch technology. It utilizes the pinch analysis technology that was invented originally for heat integration and then successfully extended to mass integration for P2 by El-Halwagi et al.[4−6] The focal point of the water pinch technology is to maximize water reuse and pollutant concentrations in effluent streams. It can be used to identify the bottleneck of a design problem and to predict the minimum amount of water prior to process flowsheet development.

Industrial practice shows that most of the rinse systems are designed based on experience. Water consumption in each rinse step is almost always much higher than necessary. In operation, process dynamics is usually unknown. Therefore, a plant is often very reluctant to reuse rinse water in the system. Note that excessive water consumption increases not only the operating cost but also the wastewater treatment cost because additional effort for wastewater separation and treatment is needed.

Electroplating is a typical chemical process and a major metal-finishing operation in manufacturing industries. In this nation, there are over 8000 electroplating shops that make numerous types of plated metal and plastic parts for the automotive, aerospace, electronics, and general industries.[7] In an electroplating plant, parts rinsing is a key operation in ensuring cleaning and plating qualities. In a plating line, a huge amount of freshwater is consumed daily, which is almost always much more than necessary. In turn, the amount of wastewater from each plating line is much more than it should be.

A basic concept of optimization and its potential for P2 in electroplating plants were introduced by Load et al.[8] Recently, Lou and Huang[9] introduced a novel concept and theory of what they called profitable P2 (or simply P3). A comprehensive investigation of waste reduction in electroplating has shown that most electroplating lines are operated in a mode far away from optimum. In reality, P2 and optimal production can be simultaneously realized. A key step in this endeavor is to have a deep understanding of process steady-state and dynamic behavior of cleaning, rinsing, and plating operations. In recent years, Huang's laboratory has developed various dynamic models for a general cleaning−rinsing system.[10−12] Comprehensive qualitative and quantitative analyses were conducted on process dynamics and environmental impacts under different operating conditions.[13] Furthermore, Huang and coworkers introduced a new design technology for wastewater reduction.[14,15] The methodology is for the evaluation and modification of existing rinse systems in a plating line. A water use and reuse network (WURN) is then designed to maximize the direct reuse of used rinse water in different rinse steps. Applications to real processes have demonstrated its feasibility and attractiveness to the industry.[9,16]

A WURN is designed using a superstructure-based optimization technique. Ideally, a superstructure is a process structure that consists of all possible connections among all process units.[17] This implies that all feasible WURNs are included in such a structure. A nonlinear optimization technique is then used to remove all undesirable connections among the rinse tanks based on the design objective as well as process and engineering constraints.[18] Note that although its concept is

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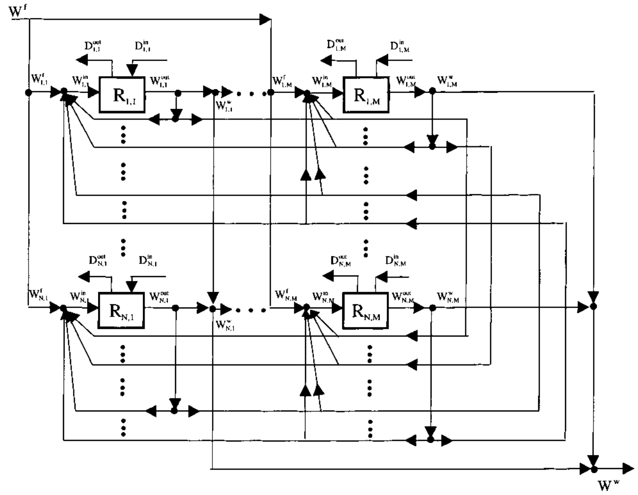


Figure 1. Superstructure for the rinse system of an electroplating line.

sound a superstructure may not be complete in the sense that it may miss some connections among certain rinse tanks. In this case, a final solution identified from the incomplete superstructure may not be optimal.[15]

In this paper, we extend the WURN design methodology by Yang et al.[14,15] in three aspects: (i) to develop a more complete superstructure by including the connections of freshwater and used water to all rinse tanks, (ii) to include not only water consumption (operating cost) but also the requirement of repiping and valves (capital cost) and the impact on in-plant wastewater treatment (change of operating cost in wastewater treatment facilities), and, more importantly, (iii) to take the rinse dynamics into account for maximum wastewater reduction. In this text, a new type of wastewater reduction system to be designed is named the switchable water allocation network (SWAN).

Complete Superstructure for a SWAN Design Problem

As stated, a superstructure for a design problem should contain all possible water flows in the rinse system of an electroplating line. Figure 1 depicts a superstructure of the rinse system that consists of N rinse steps, each of which contains M rinse tanks. Usually, the number of rinse steps is equal to the number of cleaning steps plus a plating step. In this superstructure, freshwater can be sent to *every* rinse tank $R_{i,j}$, and the effluent water stream from $R_{i,j}$ can be reused in *all* rinse tanks or sent to an in-plant wastewater treatment facility. Thus, this superstructure contains all possible design solutions of water allocation networks (WANs). The solution identification from this superstructure is a mixed-integer nonlinear programming (MINLP) problem.

Rinse Dynamics: A New Opportunity for Maximum Wastewater Reduction

The WURN design methodology developed by Yang et al.[14,15] does not require the knowledge of rinse dynamics. A derived WURN can be operated by meeting the steady-state rinse performance of the whole rinse system. Note that any rinse tank runs in two operating modes: (i) a rinse mode in which a barrel of parts is being rinsed and (ii) an idle mode in which the rinse water in the tank is replenished to ensure that the rinse water quality was acceptable for the next rinse job.

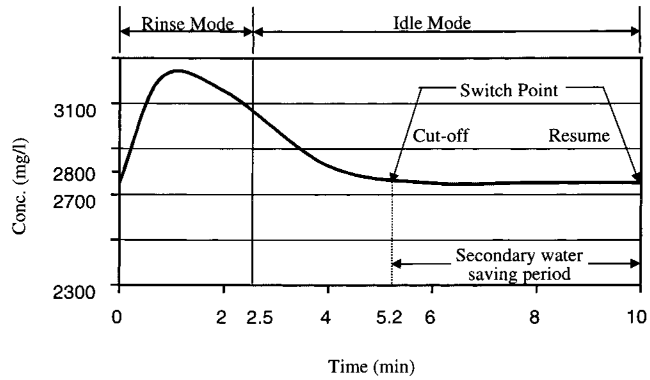


Figure 2. Rinse dynamics and identification of the secondary water-saving period.

In normal operations, the operation cycle of a plating line is fixed, say, at 10 min. This operation cycle applies to every rinse tank. It is counted from the beginning of a rinse mode to the beginning of the next rinse mode. The time distribution of the two modes in a rinse cycle is fixed also, which is determined by production scheduling for a given production rate.

It is found that in an idle mode the rinse water quality in the tank reaches the standard quickly before the end of the mode. Figure 2 illustrates a practical example where the rinse cycle is 10 min, with 2.5 min in operation (for rinsing) and 7.5 min in idle (for water replenishment). The requirement of the pollutant weight concentration in the tank before the next rinse is not higher than 2750 mg/L. The figure shows that the concentration comes back to 2750 mg/L after 2.7 min of water replenishment (between the time at 2.5 min and that at 5.2 min). However, a normal operational practice is that the rinse water continuously flows at a constant flow rate through the tank for the rest of the cycle (i.e., the flow lasts another 4.8 min) to ensure that the tank is ready for the next quality rinse operation. Although understandable, this operational policy is undesirable because it generates excessive wastewater. A better strategy is that at the time of 5.2 min the rinse water is cut off, because the rinse tank is already ready for the next barrel rinse as its contaminant concentration comes down to the standard. Note that once the rinse water is cut off, the water level in the tank is maintained because the outgoing water is only due to overflow according to a rinse tank structure. Nevertheless, it is difficult to develop a systematic strategy for it. First, the rinse dynamics should be fully revealed. Second, if a used rinse water stream to a tank is cut off, where should it go? Third, how should the water be optimally allocated in different rinse tanks? Hence, to realize maximum wastewater reduction, we need to (i) develop a dynamic model for the entire rinse system, (ii) identify whether the rinse water incoming flow can be cut off and, if yes, the cut-off time, and (iii) develop a SWAN that can be operated smoothly in every operation cycle.

Dynamic Modeling

Figure 1 gives a general rinse system that consists of N subsystems, each of which contains M rinse tanks. Dynamic modeling of the whole system can be initiated at the unit level, i.e., the modeling of an individual rinse tank.

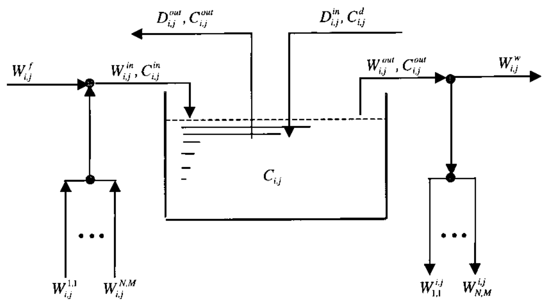


Figure 3. Sketch of a flow rinse tank.

Rinse Tank Model. For clarity, the input and output streams of any rinse tank in Figure 1 are depicted in Figure 3. The cleanness of the rinse water in the tank is determined by the cleanness of the incoming rinse water that is a mixture of freshwater and recycle water and the amount of solution attached on the surface of the parts from the preceding tank (i.e., the drag-in solution). A differential mass balance analysis gives the following model for the rinse tank, $R_{i,j}$.

(a) Water cleanness dynamics

$$\frac{\mathrm{d}C_{i,j}}{\mathrm{d}t} = -\frac{W_{i,j}^{\text{out}} + D_{i,j}^{\text{out}}F_{i,j}(t)}{V_{i,j}}C_{i,j} + \frac{M_{i,j}^{\text{in}}}{V_{i,j}} + \frac{D_{i,j}^{\text{in}}F_{i,j}(t)}{V_{i,j}}C_{i,j}^{\text{d}} \qquad (1)$$

(b) Mixing of freshwater and reused water at the inlet of the tank

$$W_{i,j}^{\text{in}} = W_{i,j}^{\text{f}} + \sum_{k=1}^{N}\sum_{l=1}^{M} E_{i,j}^{k,l}\, W_{i,j}^{k,l}; \quad k \neq i;\ l \neq j \qquad (2)$$

(c) Contaminants in the water stream at the inlet of the tank

$$M_{i,j}^{\text{in}} = \sum_{k=1}^{N}\sum_{l=1}^{M} E_{i,j}^{k,l}\, W_{i,j}^{k,l} C_{k,l}; \quad k \neq i;\ l \neq j \qquad (3)$$

(d) Water mass balance for the tank

$$W_{i,j}^{\text{in}} + D_{i,j}^{\text{in}} = W_{i,j}^{\text{out}} + D_{i,j}^{\text{out}} \qquad (4)$$

where $W_{i,j}^{\text{f}}$= freshwater flow rate into tank $R_{i,j}$, $W_{i,j}^{\text{in}}$= total water flow rate into tank $R_{i,j}$, $M_{i,j}^{\text{in}}$= total amount of contaminants in the inlet stream of tank $R_{i,j}$, $W_{i,j}^{\text{out}}$= water flow rate out of tank $R_{i,j}$, $W_{i,j}^{k,l}$= flow rate of the recycle from tank $R_{k,l}$ to tank $R_{i,j}$, $E_{i,j}^{k,l}$= integer variable (0 or 1) reflecting the existence of the recycle from tank $R_{k,l}$ to tank $R_{i,j}$, $D_{i,j}^{\text{in}}$= drag-in flow rate into tank $R_{i,j}$, $D_{i,j}^{\text{out}}$= drag-out flow rate out of tank $R_{i,j}$, $C_{i,j}$= contaminant concentration in tank $R_{i,j}$, $C_{i,j}^{\text{d}}$= drag-in contaminant concentration into tank $R_{i,j}$, $V_{i,j}$= capacity of tank $R_{i,j}$, $F_{i,j}(t)$= pulse function [equal to $U(t - t_{i,j}^{\text{din}}) - U(t - t_{i,j}^{\text{dout}})$], $t_{i,j}^{\text{din}}$= time instant at which a barrel enters tank $R_{i,j}$, and $t_{i,j}^{\text{dout}}$= time instant at which the drag-in into tank $R_{i,j}$ ends.

Note that the time period during which the drag-in solution enters the rinse water varies; it is related to the shape of the parts, type of solution, water flow rate, etc. Thus, the drag-in is modeled as an intermittent volumetric flow (a continuous flow times a pulse function) instead of a discrete volume.

Rinse Subsystem Model. Each rinse subsystem has a different task, such as for the rinse after soak cleaning, acid cleaning, electrocleaning, or plating. The subsystem may contain a number of rinse tanks in series. A dynamic model for such a subsystem can be established by lumping unit rinse models together. In matrix form, the ith subsystem can be written as

$$\frac{\mathrm{d}\mathbf{C}_i}{\mathrm{d}t} = \mathbf{A}_i\mathbf{C}_i + \mathbf{B}_i\mathbf{M}_i + \mathbf{G}_i\mathbf{C}_i^{\text{d}}; \quad i = 1, ..., N \qquad (5)$$

where

$$\frac{\mathrm{d}\mathbf{C}_i}{\mathrm{d}t} = \left(\frac{\mathrm{d}C_{i,1}}{\mathrm{d}t}, ..., \frac{\mathrm{d}C_{i,M}}{\mathrm{d}t}\right)^{\mathrm{T}} \qquad (6)$$

$$\mathbf{C}_i = (C_{i,1}, ..., C_{i,M})^{\mathrm{T}} \qquad (7)$$

$$\mathbf{C}_i^{\text{d}} = (C_{i,1}^{\text{d}}, ..., C_{i,M}^{\text{d}})^{\mathrm{T}} \qquad (8)$$

$$\mathbf{M}_i = (M_{i,1}, ..., M_{i,M})^{\mathrm{T}} \qquad (9)$$

$$\mathbf{A}_i = \text{diag}\left\{-\frac{W_{i,1}^{\text{out}} + D_{i,1}^{\text{out}}F_{i,1}(t)}{V_{i,1}}, ..., -\frac{W_{i,M}^{\text{out}} + D_{i,M}^{\text{out}}F_{i,M}(t)}{V_{i,M}}\right\} \qquad (10)$$

$$\mathbf{B}_i = \text{diag}\left\{\frac{1}{V_{i,1}}, ..., \frac{1}{V_{i,M}}\right\} \qquad (11)$$

$$\mathbf{G}_i = \text{diag}\left\{\frac{D_{i,1}^{\text{in}}F_{i,1}(t)}{V_{i,1}}, ..., \frac{D_{i,M}^{\text{in}}F_{i,M}(t)}{V_{i,M}}\right\} \qquad (12)$$

Rinse System Model. The rinse system of an electroplating line consists of N subsystems. A system model for the rinse system can be generated by lumping all subsystem models, each of which is listed in the preceding section. This gives

$$\frac{\mathrm{d}\mathbf{C}}{\mathrm{d}t} = \mathbf{AC} + \mathbf{BM} + \mathbf{GC}^{\text{d}} \qquad (13)$$

where

$$\frac{\mathrm{d}\mathbf{C}}{\mathrm{d}t} = \left(\frac{\mathrm{d}\mathbf{C}_1}{\mathrm{d}t}, ..., \frac{\mathrm{d}\mathbf{C}_N}{\mathrm{d}t}\right)^{\mathrm{T}} \qquad (14)$$

$$\mathbf{C} = (\mathbf{C}_1, ..., \mathbf{C}_N)^{\mathrm{T}} \qquad (15)$$

$$\mathbf{C}^{\text{d}} = (\mathbf{C}_1^{\text{d}}, ..., \mathbf{C}_N^{\text{d}})^{\mathrm{T}} \qquad (16)$$

$$\mathbf{M} = (\mathbf{M}_1, ..., \mathbf{M}_N)^{\mathrm{T}} \qquad (17)$$

$$\mathbf{A} = \text{diag}\{\mathbf{A}_1, ..., \mathbf{A}_N\} \qquad (18)$$

$$\mathbf{B} = \text{diag}\{\mathbf{B}_1, ..., \mathbf{B}_N\} \qquad (19)$$

$$\mathbf{G} = \text{diag}\{\mathbf{G}_1, ..., \mathbf{G}_N\} \qquad (20)$$

In the system model, the state variables are contaminant concentrations in the rinsing tanks, the control variables are the recycle structure and recycle flow rates, and the disturbance variables are the drag-in solutions into the rinsing tanks.

Cost Estimation

A basic strategy for maximum wastewater reduction is to minimize the consumption of freshwater, or equivalently to maximize the reuse of used rinse water in the rinse system prior to wastewater treatment. A direct benefit of implementing this strategy is the reduction of in-plant waste treatment cost due to reduced volume of wastewater. However, the implementation should be restricted by rinse qualities in different rinse steps and capital investment because of the requirement of additional piping and valves. Hence, the design of a SWAN is an optimization task, which can be formulated below.

Capital Cost. An installation of a SWAN requires repiping and installation of some valves for water redistribution and/or recycle. The cost can be expressed as

$$J_{\mathrm{pv}} = \frac{u_{\mathrm{p}}}{q_{\mathrm{p}}}\sum_{k=1}^{N}\sum_{l=1}^{M} E_{i,j}^{k,l}\, L_{i,j}^{k,l} + \frac{u_{\mathrm{v}}}{q_{\mathrm{v}}} N_{\mathrm{v}}; \quad k \neq i;\ l \neq j \tag{21}$$

where $L_{i,j}^{k,l}$ = length of the pipe for the recycle from tank $R_{k,l}$ to tank $R_{i,j}$, u_p = cost of the unit pipe length, q_{p} = useful life of a pipe, N_{v} = number of valves, u_{v} = cost of a valve, and q_{v} = useful life of a valve.

In the above formula, depreciation is estimated by a straight-line depreciation method, and there is no salvage value for used pipes and valves.

Operating Cost. (i) Freshwater. The only operating cost of a SWAN is for freshwater. It can be readily formulated as

$$J_{\mathrm{fw}} = u_{\mathrm{fw}} \sum_{i=1}^{N}\sum_{j=1}^{M} W_{i,j}^{\mathrm{f}} \tag{22}$$

where u_{fw} = unit cost of industrial freshwater and $W_{i,j}^{\mathrm{f}}$ = flow rate of the freshwater into tank $R_{i,j}$.

(ii) Wastewater Treatment. The reduction of wastewater from a plating line can reduce significantly both the capital and operating costs of a wastewater treatment facility (WWTF), even if the total loading of contaminants in wastewater remains the same. The capital cost of most treatment operations is proportional to the total incoming flow of wastewater. In this work, however, we omit the benefits for the capital cost because we assume the use of an existing WWTF. Certainly, it should be more beneficial when we deal with the new design of a WWTF. The operating cost for the treatment decreases with the increased contaminant concentration in the wastewater, if the total contaminants remain the same. This can be expressed as

$$J_{\mathrm{wt}} = u_{\mathrm{wt}} \sum_{i=1}^{N}\sum_{j=1}^{M} \left(1 - \frac{C^{\mathrm{env}}}{C_{i,j}^{\mathrm{out}}}\right) W_{i,j}^{\mathrm{w}} \tag{23}$$

where $W_{i,j}^{\mathrm{w}}$ = wastewater flow rate from tank $R_{i,j}$, $C_{i,j}^{\mathrm{out}}$ = contaminant concentration of wastewater from tank $R_{i,j}$, C^{env} = environmental regulation on the contaminant concentration after treatment, and u_{wt} = unit cost of wastewater treatment.

Note that the unit cost for wastewater treatment varies widely. A valuable reference is provided by Cushnie where a reasonable range is somewhere between \$5 and \$15 per 1000 mg/L.[19]

Optimization Model

The design objective is to minimize the capital and operating costs that are defined above. However, a solution meeting the objective should follow basic mass balance and obey process and environmental constraints. A complete optimization model is as follows.

Objective Function. The objective function is to minimize the total cost of a SWAN, i.e.,

$$\begin{aligned} \operatorname{Min} J &= J_{\mathrm{fw}} + J_{\mathrm{pv}} + J_{\mathrm{wt}} \\ &= u_{\mathrm{fw}} \sum_{i=1}^{N}\sum_{j=1}^{M} W_{i,j}^{\mathrm{f}} + \frac{u_{\mathrm{p}}}{q_{\mathrm{p}}}\sum_{k=1}^{N}\sum_{l=1}^{M} E_{i,j}^{k,l}\, L_{i,j}^{k,l} + \frac{u_{\mathrm{v}}}{q_{\mathrm{v}}} N_{\mathrm{v}} + \\ &\qquad u_{\mathrm{wt}} \sum_{i=1}^{N}\sum_{j=1}^{M} \left(1 - \frac{C^{\mathrm{env}}}{C_{i,j}^{\mathrm{out}}}\right) W_{i,j}^{\mathrm{w}} \end{aligned} \tag{24}$$

Constraints. There are many types of constraints listed below.

(a) Mass balance for each rinse tank

$$W_{i,j}^{\mathrm{in}} + D_{i,j}^{\mathrm{in}} = W_{i,j}^{\mathrm{out}} + D_{i,j}^{\mathrm{out}}; \quad i = 1, ..., N;\ j = 1, ..., M \tag{25}$$

$$W_{i,j}^{\mathrm{in}} = W_{i,j}^{\mathrm{f}} + \sum_{k=1}^{N}\sum_{l=1}^{M} E_{i,j}^{k,l}\, W_{i,j}^{k,l}; \quad i = 1, ..., N;\ j = 1, ..., M;\ k \neq i;\ l \neq j \tag{26}$$

$$W_{i,j}^{\mathrm{out}} = W_{i,j}^{\mathrm{w}} + \sum_{k=1}^{N}\sum_{l=1}^{M} E_{k,l}^{i,j}\, W_{k,l}^{i,j}; \quad i = 1, ..., N;\ j = 1, ..., M;\ k \neq i;\ l \neq j \tag{27}$$

(b) Component mass balance for each rinse tank

$$\sum_{k=1}^{N}\sum_{l=1}^{M} E_{i,j}^{k,l} W_{i,j}^{k,l} C_{k,l}^{\mathrm{out}} = C_{i,j}^{\mathrm{in}} W_{i,j}^{\mathrm{in}}; \quad i = 1, ..., N;\ j = 1, ..., M;\ k \neq i;\ l \neq j \tag{28}$$

$$C_{i,j}^{\mathrm{in}} W_{i,j}^{\mathrm{in}} + C_{i,j}^{\mathrm{d}} D_{i,j}^{\mathrm{in}} = C_{i,j}^{\mathrm{out}} (W_{i,j}^{\mathrm{out}} + D_{i,j}^{\mathrm{out}}); \quad i = 1, ..., N;\ j = 1, ..., M \tag{29}$$

(c) Process constraints

$$C_{i,j}^{\mathrm{lim}} \geq C_{i,j}^{\mathrm{out}} \geq C^{\mathrm{env}} \geq 0; \quad i = 1, ..., N;\ j = 1, ..., M \tag{30}$$

$$C_{i,j}^{\mathrm{in}} \geq 0; \quad i = 1, ..., N;\ j = 1, ..., M \tag{31}$$

$$W_{i,j}^{\mathrm{in}},\ W_{i,j}^{\mathrm{out}} \geq 0; \quad i = 1, ..., N;\ j = 1, ..., M \tag{32}$$

where $C_{i,j}^{\mathrm{in}}$ = contaminant concentration of the rinse water into tank $R_{i,j}$ and $C_{i,j}^{\mathrm{lim}}$ = upper limit of the rinse quality in tank $R_{i,j}$.

Note that $C_{i,j}^{\mathrm{out}}$ in any tank is always much greater than C^{env} in real production, according to the rinsing technologies widely used in industry. On the other hand, even if $C_{i,j}^{out}$ can be less than C^{env} in production, the necessary rinsing time for each barrel will be much longer and the amount of water to be consumed will be much greater. This is certainly not acceptable in practice.

Identification of the Secondary System Water-Saving Period

The above optimization model is defined in such a way that every rinse tank can receive freshwater, used water, or their mixture from any rinse tank. The optimization gives only one water allocation network (primary WAN). A SWAN is the one consisting of two networks, the primary WAN and the secondary WAN, that is derived by the same optimization model except for some additional constraints. The additional constraints are for disallowing (fresh and used) water flows into a certain number of rinse tanks for a certain time period. These constraints can be developed by analyzing the dynamic behavior of each rinse tank in the primary WAN using the system dynamic model developed in this work. The basic idea of cutting off water into a rinse tank and then resuming the water flow is shown in Figure 2. We name this period the "secondary water-saving period", as opposed to the primary water-saving period used by the primary WAN. As the figure shows, this second water-saving period starts at the time when the pollutant concentration in the tank reaches the stable point or at least is close enough to that point. The period ends when the next rinse job starts. The dynamic analysis should be performed on every rinse tank, which will generate $N \times M$ secondary water-saving periods to the maximum extent, assuming there are $N \times M$ tanks in the rinse system of the same plating line.

Note that the secondary water-saving periods identified for the rinse tanks are usually different in an operation cycle. From the viewpoint of water reduction, a secondary WAN for each water-saving period can be developed. However, this will lead to the generation of many secondary WANs. Economically and technically speaking, this is certainly undesirable because of high cost, operational complexity, and instability. In this regard, the most valuable secondary water-saving period should be identified for the entire system. This can be accomplished in the following way. First, the intersection period of every two secondary water-saving periods of rinse tanks is evaluated and compared. The intersection period should be larger than a predefined time interval; otherwise, it should be discarded. Then, the qualified intersection period of every combination of secondary water-saving periods needs be analyzed. The most valuable one is the longest intersection period in which the rinse tanks involved are the most. This period is named the "secondary system water-saving period". In this period, the rinse water to a number of rinse tanks need to be cut off. Mathematically, a set of constraints for the exclusion of those rinse tanks in the derivation of the secondary WAN can be derived correspondingly.

Operational Strategy

As stated, a SWAN consists of a primary WAN and a secondary WAN. In each operation cycle, the primary WAN will be operated in the primary system water-saving period, while the secondary WAN will be operated in the rest of the cycle (i.e., the secondary system water-saving period). At the time when the networks are switched, the contaminant concentrations of relevant rinse tanks are stable. This ensures the transition stability of the entire rinse system. Figure 4 delineates the concept of switching of two WANs. This operating mode change repeats in every operation cycle.

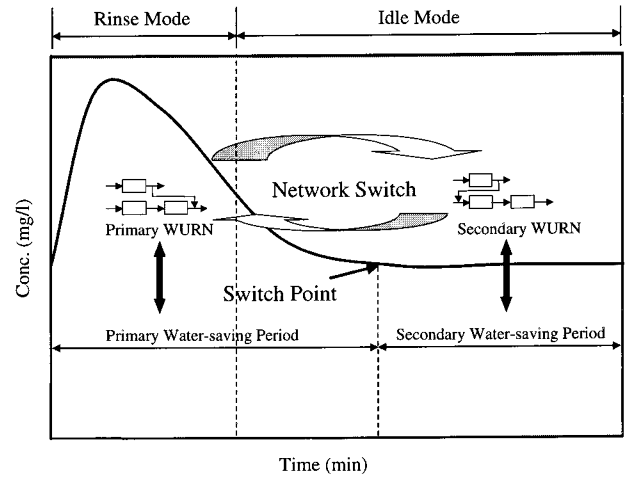


Figure 4. Switch of the two water allocation networks (WAN).

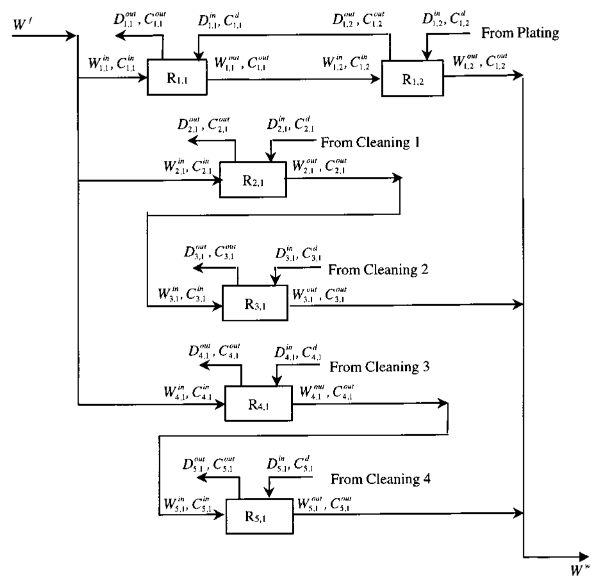


Figure 5. Flowsheet of the original rinse system.

Application

The developed design methodology has been successfully applied to several real-world problems. One application is delineated in this section.

Process Description. The original rinse system of an electroplating line is depicted in Figure 5. This system consists of five rinse subsystems, each of which is operated for a specific rinse purpose, after either a cleaning step or a plating step. In the 1st subsystem, there are two rinse tanks in series ($R_{1,1}$ and $R_{1,2}$). Every other subsystem has only one rinse tank ($R_{i,1}$; $i = 2, ..., 5$). In this rinse system, the used water from the 2nd and 4th subsystems has already been reused entirely by the 3rd and 5th subsystems, respectively.

Based on the present rinse criteria, the contamination level of the water out of $R_{1,1}$ must be under 20 mg/L; that out of $R_{2,1}$ must be limited to under 2500 mg/L. The concentration constraint for tank $R_{3,1}$ is 3000 mg/L. Parts passing through tank $R_{4,1}$ should have the concentration constraint of 600 mg/L. The concentration constraint for tank $R_{5,1}$ is 3000 mg/L. The process data are listed in Table 1. The operation cycle for this plating line is 10 min.

Primary WAN. The developed design methodology should generate the primary WAN first. Commercial optimization software GAMS is used to identify the optimal solution, which is depicted in Figure 6. Structurally, this network improves the original rinse system by recycling completely the used water from tank $R_{1,2}$ to tanks $R_{2,1}$ and $R_{4,1}$. This structural modification leads to a water reduction of 33.3% (from 960 to 640 gal/h). A more detailed cost analysis will be provided later.

Dynamic Modeling and System Analysis. With the structure of the primary WAN, we can derive the following system dynamic model for it.

$$\frac{\mathrm{d}\mathbf{C}}{\mathrm{d}t} = \mathbf{AC} + \mathbf{BM} + \mathbf{GC}^{\mathrm{d}} \tag{33}$$

$$\frac{\mathrm{d}\mathbf{C}}{\mathrm{d}t} = \left(\frac{\mathrm{d}C_{1,1}}{\mathrm{d}t}, \frac{\mathrm{d}C_{1,2}}{\mathrm{d}t}, \frac{\mathrm{d}C_{2,1}}{\mathrm{d}t}, \frac{\mathrm{d}C_{3,1}}{\mathrm{d}t}, \frac{\mathrm{d}C_{4,1}}{\mathrm{d}t}, \frac{\mathrm{d}C_{5,1}}{\mathrm{d}t}\right)^{\mathrm{T}} \tag{34}$$

$$\mathbf{C} = (C_{1,1}, C_{1,2}, C_{2,1}, C_{3,1}, C_{4,1}, C_{5,1})^{\mathrm{T}} \tag{35}$$

$$\mathbf{M} = (0, W_{1,2}^{1,1}C_{1,1}, W_{2,1}^{1,2}C_{1,2}, W_{3,1}^{2,1}C_{2,1}, W_{4,1}^{1,2}C_{1,2}, W_{5,1}^{4,1}C_{4,1})^{\mathrm{T}} \tag{36}$$

$$\mathbf{C}^{\mathrm{d}} = (C_{1,1}^{\mathrm{d}}, C_{1,2}^{\mathrm{d}}, C_{2,1}^{\mathrm{d}}, C_{3,1}^{\mathrm{d}}, C_{4,1}^{\mathrm{d}}, C_{5,1}^{\mathrm{d}})^{\mathrm{T}} \tag{37}$$

$$\mathbf{A} = \mathrm{diag}\left\{-\frac{W_{1,1}^{\mathrm{out}} + D_{1,1}^{\mathrm{out}}}{V_{1,1}}, -\frac{W_{1,2}^{\mathrm{out}} + D_{1,2}^{\mathrm{out}}}{V_{1,2}}, -\frac{W_{2,1}^{\mathrm{out}} + D_{2,1}^{\mathrm{out}}}{V_{2,1}}, -\frac{W_{3,1}^{\mathrm{out}} + D_{3,1}^{\mathrm{out}}}{V_{3,1}}, -\frac{W_{4,1}^{\mathrm{out}} + D_{4,1}^{\mathrm{out}}}{V_{4,1}}, -\frac{W_{5,1}^{\mathrm{out}} + D_{5,1}^{\mathrm{out}}}{V_{5,1}}\right\} \tag{38}$$

$$\mathbf{B} = \mathrm{diag}\left\{\frac{1}{V_{1,1}}, \frac{1}{V_{1,2}}, \frac{1}{V_{2,1}}, \frac{1}{V_{3,1}}, \frac{1}{V_{4,1}}, \frac{1}{V_{5,1}}\right\} \tag{39}$$

$$\mathbf{G} = \mathrm{diag}\left\{\frac{D_{1,1}^{\mathrm{in}}F_{1,1}(t)}{V_{1,1}}, \frac{D_{1,2}^{\mathrm{in}}F_{1,2}(t)}{V_{1,2}}, \frac{D_{2,1}^{\mathrm{in}}F_{2,1}(t)}{V_{2,1}}, \frac{D_{3,1}^{\mathrm{in}}F_{3,1}(t)}{V_{3,1}}, \frac{D_{4,1}^{\mathrm{in}}F_{4,1}(t)}{V_{4,1}}, \frac{D_{5,1}^{\mathrm{in}}F_{5,1}(t)}{V_{5,1}}\right\} \tag{40}$$

The system dynamics of the primary WAN is shown in Figure 7. It can be found that the variations of the contaminant concentrations in tanks $R_{1,1}$, $R_{1,2}$, $R_{3,1}$, and $R_{4,1}$ are too small to be chosen as the secondary system water-saving period. However, for tanks $R_{2,1}$ and $R_{5,1}$, the last 2.5 min can be safely chosen for the secondary period. In this period, the water flowing into these two tanks can be cut off. Certainly, the outflow water from these two tanks is automatically stopped, because there is no overflow water from these two.

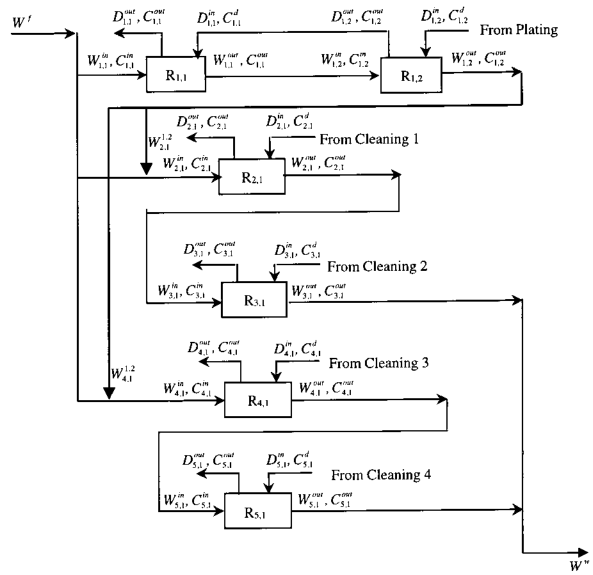


Figure 6. Flowsheet of the primary WAN.

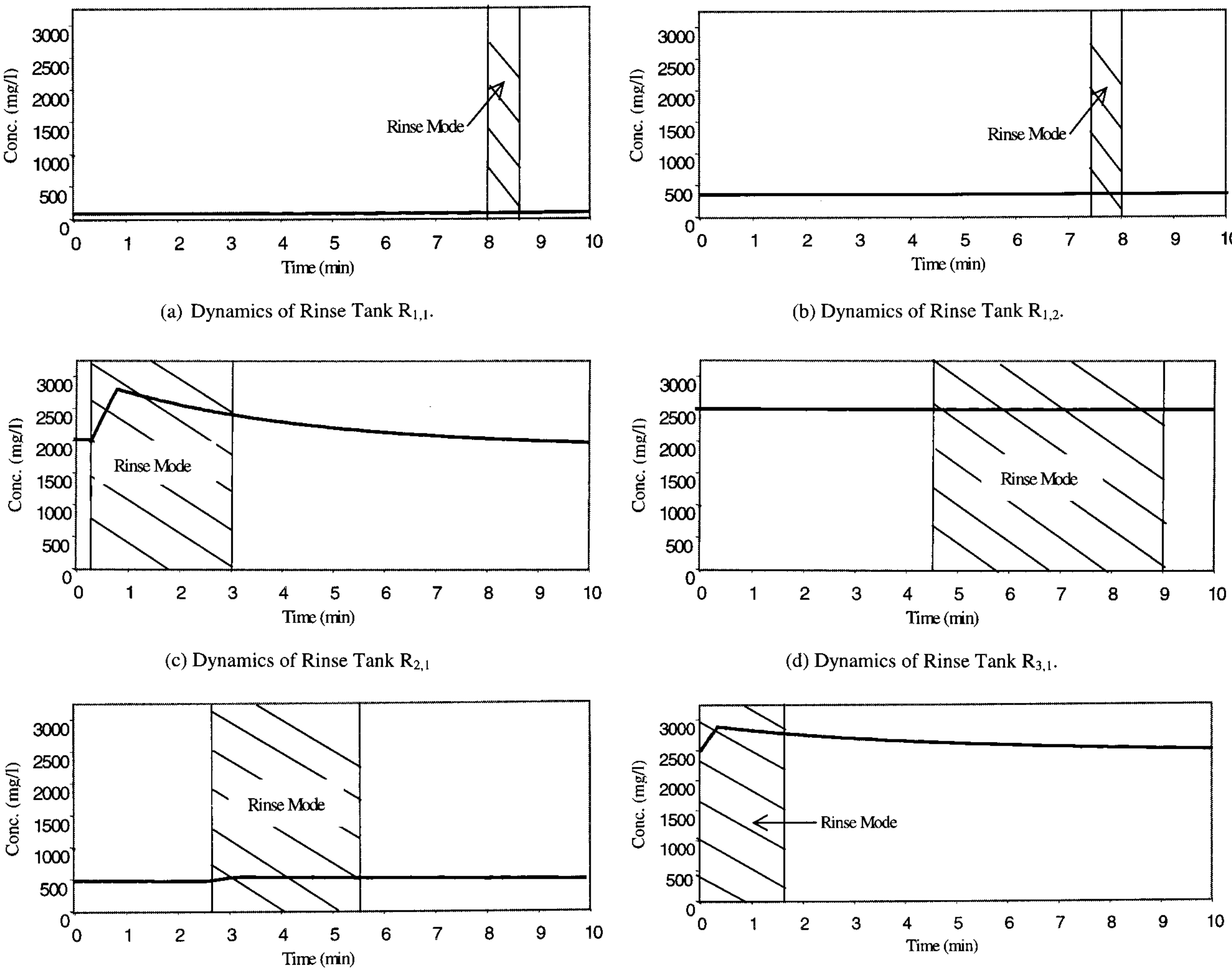
Table 1. Stream Data of the Original Rinse System

symbol	flow rate (GPH)	symbol	concn (mg/L)
$D_{1,1}^{\mathrm{in}}$	4	$C_{1,1}^{\mathrm{d}}$	220
$D_{1,2}^{\mathrm{in}}$	4	$C_{1,2}^{\mathrm{d}}$	10000
$D_{2,1}^{\mathrm{in}}$	4.2	$C_{2,1}^{\mathrm{d}}$	200000
$D_{3,1}^{\mathrm{in}}$	4	$C_{3,1}^{\mathrm{d}}$	50000
$D_{4,1}^{\mathrm{in}}$	3.8	$C_{4,1}^{\mathrm{d}}$	30000
$D_{5,1}^{\mathrm{in}}$	3.75	$C_{5,1}^{\mathrm{d}}$	150000
$W_{1,1}^{\mathrm{in}}$	360	$C_{1,1}^{\mathrm{in}}$	0
$W_{1,2}^{\mathrm{in}}$	360	$C_{1,2}^{\mathrm{in}}$	20
$W_{2,1}^{\mathrm{in}}$	360	$C_{2,1}^{\mathrm{in}}$	0
$W_{3,1}^{\mathrm{in}}$	360	$C_{3,1}^{\mathrm{in}}$	2500
$W_{4,1}^{\mathrm{in}}$	240	$C_{4,1}^{\mathrm{in}}$	0
$W_{5,1}^{\mathrm{in}}$	240	$C_{5,1}^{\mathrm{in}}$	600
$W_{1,1}^{\mathrm{out}}$	360	$C_{1,1}$	20
$W_{1,2}^{\mathrm{out}}$	360	$C_{1,2}$	220
$W_{2,1}^{\mathrm{out}}$	360	$C_{2,1}$	2500
$W_{3,1}^{\mathrm{out}}$	360	$C_{3,1}$	3000
$W_{4,1}^{\mathrm{out}}$	240	$C_{4,1}$	600
$W_{5,1}^{\mathrm{out}}$	240	$C_{5,1}$	3000

Secondary WAN. A secondary WAN can be identified by including tanks $R_{1,1}$, $R_{1,2}$, $R_{3,1}$, and $R_{4,1}$ only. An optimal solution is derived as shown in Figure 8. In the figure, tanks $R_{2,1}$ and $R_{5,1}$ are drawn by dotted lines, showing that they are actually excluded from the solution domain.

Complete Solution. The SWAN for this rinse system is the integration of both the primary WAN and the secondary WAN. The switch of the operational mode will be accomplished by four valves. A complete flowsheet of the SWAN is depicted in Figure 9, where valve positions in different operational modes are also listed. In each operation cycle, the primary WAN runs for the first 7.5 min and the secondary WAN for the next 2.5 min. The water flow comparison between the original rinse system and the SWAN is listed in Table 2.

Economic Incentive. As stated previously, an introduction of an SWAN enables us to reduce not only the operating cost for freshwater but also the operating cost for wastewater treatment. In reality, the capital cost for the installation of the SWAN is very low, as compared with the operating cost. Table 3 provides a detailed comparison between the original rinse system



(a) Dynamics of Rinse Tank $R_{1,1}$.

(b) Dynamics of Rinse Tank $R_{1,2}$.

(c) Dynamics of Rinse Tank $R_{2,1}$

(d) Dynamics of Rinse Tank $R_{3,1}$.

(e) Dynamics of Rinse Tank $R_{4,1}$.

(f) Dynamics of Rinse Tank $R_{5,1}$.

Figure 7. Dynamics of all of the rinse tanks of the primary WAN.

Table 2. Comparison of Water Flows between the Original and the Optimal Rinse Systems

		flow rate (GPH)			
			optimal system		
water stream	symbol	original system	primary WAN (75%)	secondary WAN (25%)	switchable WAN (100%)
freshwater	$W^{f}_{1,1}$	360	360	360	360
	$W^{f}_{1,2}$	0	0	0	0
	$W^{f}_{2,1}$	360	165		123.75
	$W^{f}_{3,1}$	0	0	0	0
	$W^{f}_{4,1}$	240	115	0	86.25
	$W^{f}_{5,1}$	0	0		0
wastewater	$W^{w}_{1,1}$	0	0	0	0
	$W^{w}_{1,2}$	360	0	0	0
	$W^{w}_{2,1}$	0	0		0
	$W^{w}_{3,1}$	360	370	60	292.5
	$W^{w}_{4,1}$	0	0	300	75
	$W^{w}_{5,1}$	240	270		202.5
reused water	$W^{1,2}_{2,1}$		205		153.75
	$W^{1,2}_{3,1}$			60	15
	$W^{1,2}_{4,1}$		155	300	191.25
total freshwater		960		570	

and the SWAN. It shows that the original system costs \$56 829 annually, including the operating cost for wastewater treatment. By contrast, the SWAN costs only \$34 517 annually on the same basis, a 39.3% reduction of the total annualized costs.

Concluding Remarks

Yang et al.[14,15] introduced a design methodology for synthesizing an optimal WURN for any rinsing system in an electroplating plant. In this paper, the design

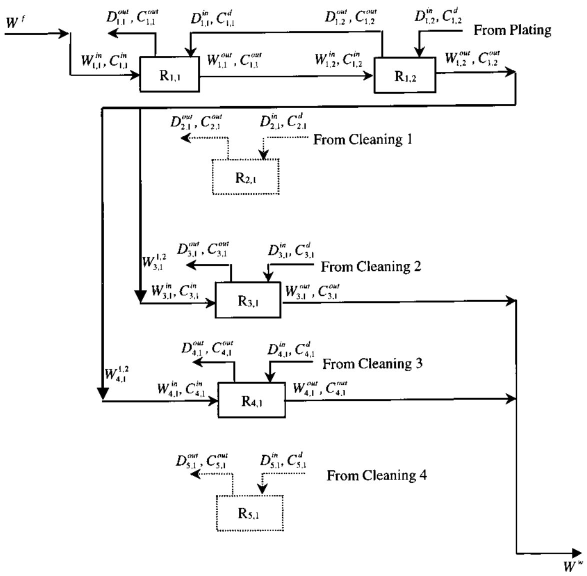
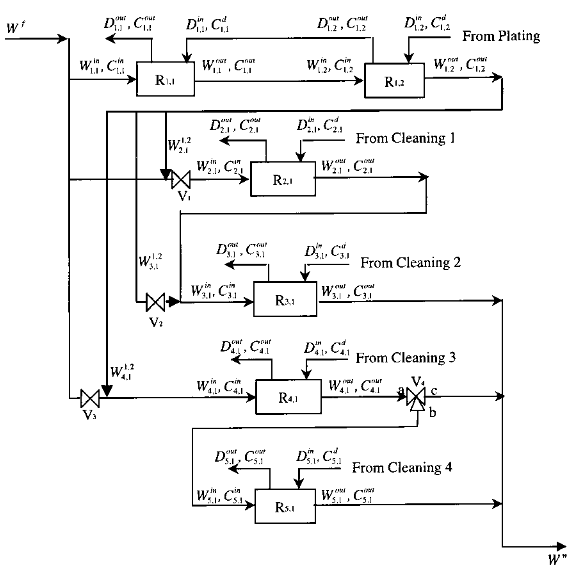


Figure 8. Flowsheet of the secondary WAN.



SWAN	Valve Position				
	V_1	V_2	V_3	V_4 a→b	V_4 a→c
Primary WAN	Open	Close	Open	Open	Close
Secondary WAN	Close	Open	Close	Close	Open

Figure 9. Flowsheet of the SWAN.

Table 3. Cost Analysis of the Original and Optimal Rinse Systems

cost	original system ($/year)	switchable WAN (SWAN) ($/year) primary WAN (75%)	secondary WAN (25%)	subtotal
freshwater	11612	5806	1089	6895
capital		183	43	776[a]
wastewater treatment	45217	22607	4239	26846
total	56829		34517	
cost saving			22312	
cost saving (%)			39.3	

[a] The capital cost for the SWAN includes not only that for repiping but also $550/year for the four valves for water flow change.

methodology has been greatly extended to the one for synthesizing an optimal SWAN, based on the basic characteristics of rinse dynamics. The installation of a SWAN can ensure the maximum water reduction and, thereby, a cost reduction of wastewater treatment. The new design methodology is scientifically sound, technically feasible, and economically attractive. The methodology is so general that it is applicable to any electroplating plant.

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