Dynamic Modeling & Simulation for Environmentally Benign Cleaning & Rinsing

By J.P. Gong, K.Q. Luo, and Y.L. Huang

Cleaning and rinsing are two key unit operations in achieving high plating quality in an electroplating shop. These two operational steps, however, are identified as major sources of waste, such as wastewater, spent solutions and sludge. In this paper, a set of first principles-based process models are developed for these two steps. The models characterize the dynamic behaviors occurring in cleaning and rinsing units, greatly facilitating the development of accurate waste minimization strategies, while production can be simultaneously optimized. Simulation results demonstrate the desirability of adopting these models in plating lines.

Waste management in the electroplating industry has been greatly improved over the past two decades. This has led to significant cost reduction in waste treatment and disposal. Facing increasingly stringent environmental regulations today, this industry is making a tremendous effort to identify new opportunities for waste minimization (WM). According to the EPA WM hierarchy, source reduction is of the highest priority, comparing with recycle/reuse and source waste pretreatment. A variety of source reduction strategies has been developed that can be classified functionally into the categories of drag-out minimization, bath-life extension, rinse-water reuse, cyanide-free solution substitution, material change, and good operating practice.[1-3]

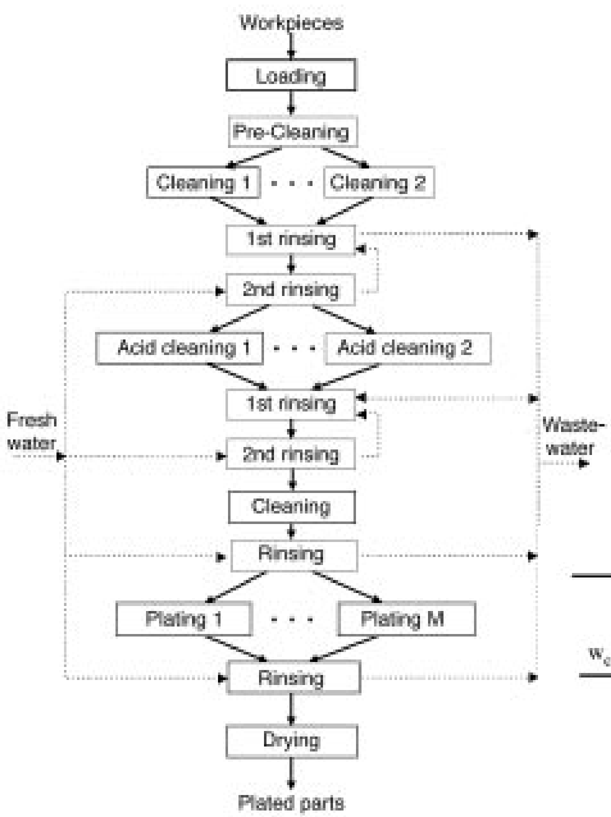

Fig. 1—Typical electroplating process.

Successful implementation of the source reduction strategies requires extensive knowledge, ample experience, and sufficient process information. Because of process complexity and a lack of sensors, the description of process behaviors is always imprecise, and the expertise for WM is frequently available locally. This has led to very limited success in implementing existing strategies in the industry.[4] To help platers utilize these strategies in a systematic and efficient way, a PC-based intelligent decision support system, namely WMEP Advisor, has been developed.[5,6] The system contains numerous WM rules, and can provide strong technical assistance and basic economic analysis for fighting waste.

Recently, Load *et al.* pointed out that using process analysis is a key for implementing controlled changes to incorporate new technology and to comply with regulatory requirements.[7] Moreover, they indicate that controlling changes are key to optimizing processes, particularly when the mandates required by WM are to be effectively addressed. They are among the earliest in this industry to suggest the use of process systems engineering approaches for comprehensive source reduction. Obviously, deep process analysis and optimization for WM must rely on precise process information; this information should be obtained from reliable process models.[8] The models, whenever possible, should be first principles-based and dynamic.

In this paper, process dynamic models for a general cleaning-rinsing system are developed. We focus on the modeling for barrel plating processes. Extensive simulation using these models demonstrates the attractiveness for accurate WM in any cleaning-rinsing systems.

Process Description

In an electroplating process, parts in barrels pass through three types of process units (*i.e.*, cleaning tanks, rinsing tanks, and plating tanks, see Fig. 1). A plating process consists of a number of cleaning-rinsing systems for removing different kinds of dirt and chemical residues. The operational efficiency of cleaning and rinsing largely determines plating quality.

As observed, the processing time in tanks may vary considerably. For instance, it may take four min for a barrel to be processed in a soak cleaning tank, one min in two consecutive rinsing tanks, and 40 min in a plating tank. The processing time can be determined through experiment, but mainly

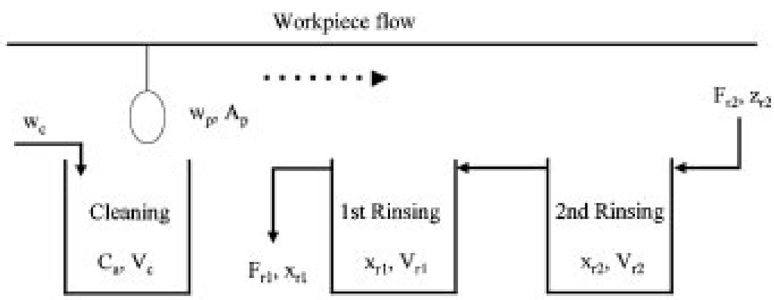

Fig. 2—Sketch of a general cleaning-rinsing process.

needs adjustment based on experience. In practice, it is set quite conservatively in shops because process dynamic behaviors are often unknown. This not only inhibits the improvement of process efficiency, but blocks the reduction of chemical and water consumption as well. For example, extensive rinsing may not improve a given rinsing quality noticeably, but increase water consumption substantially. Over-cleaning may decrease a production rate and increase chemical consumption. A chemical concentration higher than optimum may lead to increments of operating cost and pollutants in sludge and wastewater. To realize WM effectively, the optimal operational mode in each tank must be identified. This requires the development of process dynamic models.

Dynamic Modeling

A cleaning-rinsing system usually consists of a cleaning tank, followed by one or more rinsing units, as illustrated in Fig. 2. The cleaning tank maintains the chemical concentration in a specified range. In the cascade rinsing system, there is countercurrent flow of rinsewater against parts. The models for this system should provide the following time-variant information:

(a) the surface cleanness of the parts in any tank; this is critical to the determination of processing time.
(b) the chemical concentration in a cleaning tank; this is crucial to the generation of energy for dirt removal, and for control of chemical addition.
(c) the pollutant composition in a rinsing tank; this is helpful for adjusting water flow rates and estimating the quantity of pollutants in effluent streams.
(d) the sludge accumulation and composition in a cleaning tank; this is necessary for knowing when and how the tank should be cleaning.

In the system, chemical addition to a cleaning tank, the water flow rate in a rinsing tank, and the processing time in each tank are identified as environmentally sensitive. In the modeling, therefore, their cause-effect relationships must be appropriately established.

Cleaning Tank Model

In a cleaning tank, parts are cleaned, and the dirt (soil, oil, and other solid particles) on the surface is removed by applying to it certain types of energy, such as mechanical, chemical, thermal, electrical, and/or radiation energy. A certain amount of the loose dirt on parts sinks to the bottom of the tank as sludge. The remaining dirt is carried over together with drag-out to succeeding tanks.

Dirt Removal Model

The amount of dirt on parts is negatively proportional to a dirt removal rate with time variable. This rate is determined by the type of chemicals used and their concentration, and the type and amount of the dirt on parts. Mathematically, the process can be described by the following first-order differential equation,

$$A_p \frac{dw_{p_c}(t)}{dt} = -r_{p_c}(t) \qquad (1)$$

$$r_{p_c}(t) = \gamma_c(t) C_a(t) w_{p_c}(t) \qquad (2)$$

$$\gamma_c(t) = \gamma_0 \left(1 - e^{-\alpha(t-t_0)}\right) \qquad (3)$$

where A_p is total surface area of the parts in a barrel (cm^2)
$C_a(t)$ is chemical concentration in the cleaning tank at time t (gal-chem/gal-soln)
$r_{p_c}(t)$ is dirt removal rate in the cleaning tank at time t (g/min)
$w_{p_c}(t)$ is amount of dirt on parts at time t (g/cm^2)
α is a constant
$\gamma_c(t)$ is looseness of the dirt on parts at time t ($cm^2 \cdot$ gal-soln/gal-chem $\cdot$ min)
γ_0 is the kinetic constant ($cm^2 \cdot$ gal-soln/gal-chem $\cdot$ min)

Chemical Consumption Model

The amount of chemical in the tank changes with consumption or replenishment. The relationship can be modeled as:

$$V_c \frac{dC_a(t)}{dt} = -\frac{r_{p_c}(t)}{\mu} + w_c(t) \qquad (4)$$

where V_c is capacity of the cleaning tank (gal-soln)
$w_c(t)$ is flow rate of the chemical added to the cleaning tank at time t (gal-chem/min)
μ is chemical capacity for dirt removal (g-dirt/gal-chem)

To run these models, the amount of dirt on the parts in the barrel before cleaning (*i.e.*, the initial dirt ($w_{p_c}(t_0)$), must be obtained through experiment or estimated based on experience. The barrel-based initial chemical concentration in the tank ($C_a(t_0)$) can be measured or computed by applying the model to the preceding barrel. The kinetic constant (γ_0) and the chemical capacity for dirt removal (μ) can be determined by the type of chemical used. The larger the value of μ, the more efficient the dirt removal.

Rinsing Tank Model

After cleaning, the loose dirt on parts and in the drag-out should be washed out in the rinsing step. The efficiency of the dirt removal is largely dependent on the cleanness of the rinsewater, the dirtiness of parts, and the uniformity of the rinsewater in the tank.

Dirt Removal Model

The amount of dirt on the parts, which includes the dirt residue after cleaning and the drag-out from the cleaning tank, in a rinsing tank is negatively proportional to the dirt removal rate. The cleaner the rinsewater, or the dirtier the parts, the faster the dirt removal. This gives rise to the following models.

$$A_p \frac{dw_{p_r}(t)}{dt} = -r_{p_r}(t) \qquad (5)$$

$$r_{p_r}(t) = k_r \gamma_c(t_e)[\theta(w_{p_r}(t) - w_{p_c}(t_e)) - x_r(t)] \qquad (6)$$

where k_r is the mass transfer coefficient (gal-chem-gal-water/gal-soln$\cdot cm^2$)
$r_{p_r}(t)$ is dirt removal rate in the rinsing tank at time t (g/min)
$w_{p_r}(t)$ is amount of dirt on parts when the barrel is in a rinsing tank at time t (g/cm^2)
$W_{p_c}(t_e)$ is amount of dirt on parts when leaving the cleaning tank at time t_e (g/cm^2); t_e is the time at which the barrel is withdrawn from the preceding cleaning tank

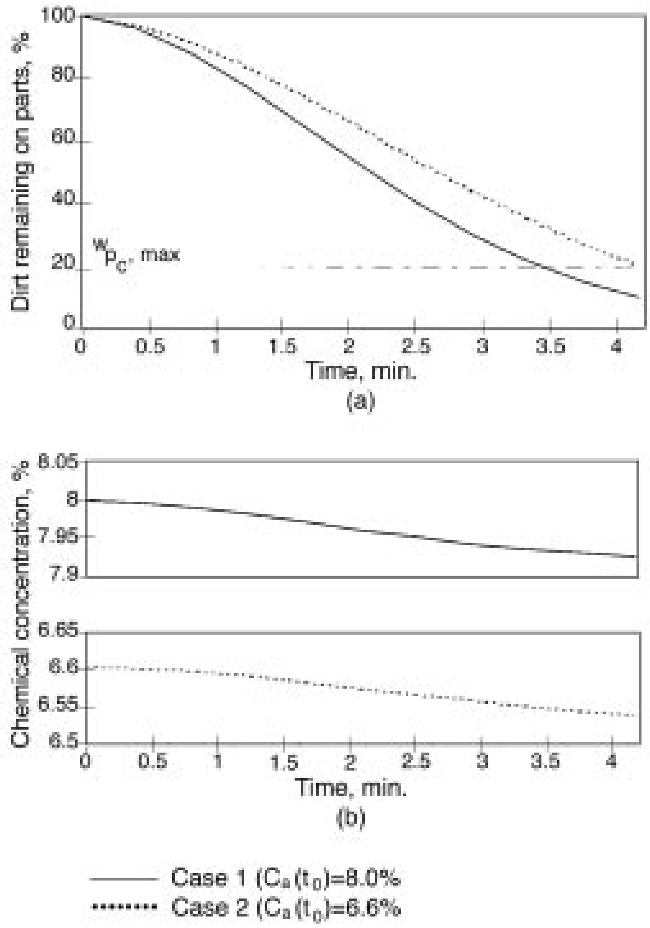

Fig. 3—Cleaning of a barrel of parts: (a) dirt removal from the parts; (b) chemical concentration in the tank.

$x_r(t)$ is pollutant composition in rinsewater at time t (g/gal-water)
$\gamma_r(t_e)$ is looseness of dirt on parts when leaving the cleaning tank at time t_e ($cm^2 \cdot$ gal-soln/gal-chem $\cdot$ min)
θ is unit conversion factor (cm^2/gal-water)

Water Pollution Model

The effluent water stream of the rinsing tank contains various pollutants, such as dirt, chemicals, and metal particles. The quantity of pollutants is related to the rinsing efficiency, water flow rate, the initial dirtiness of parts, and the cleanness of the influent rinsewater. Assume that water in the tank is well mixed. The pollutant composition in the tank should then be the same as that of the effluent water. Accordingly, the following model can be derived

$$V_r \frac{dx_r(t)}{dt} = r_{p_r}(t) + F_r(t)\left(z_r(t) - x_r(t)\right) \quad (7)$$

where $F_r(t)$ is flow rate of rinsewater at time t (gal-water/min)
V_r is capacity of the rinsing tank (gal-water)
$Z_r(t)$ is pollutant concentration in influent rinsewater at time t (g/gal-water)

In the above equations, the initial amount of the dirt on parts ($w_{p_r}(t_0)$) can be estimated from the computation of the models for the cleaning tank. The dirtiness of influent rinsewater $z_r(t)$ can be easily measured. Note that we assumed the amount of contaminant in the water is negligible for mass balance in Eq. (7).

After the barrel is withdrawn from the rinsing tank, the tank is in idle mode. Rinsewater, however, still flows through the tank. This will reduce the pollutant concentration in the tank for the next rinsing. The model for this mode can be derived as follows:

$$V_r \frac{dx_r(t)}{dt} = F_r(t)\left(z_r(t) - x_r(t)\right) \quad (8)$$

Simulation

The models described above have been used to investigate the operations of an individual tank, as well as an entire cleaning-rinsing system. The simulation based on the models facilitates greatly the identification of opportunities for WM and optimal production.

Cleaning Unit Characterization

Single Barrel Cleaning

When an initial operating condition in a tank is known, the model in Eqs. (1) through (4) can provide all information on the dirt removal on the parts in a barrel and the chemical solution dynamics.

Dynamics. We simulate the cleaning of a barrel of 200 kg of parts with a total surface area (A_p) of 20.6 m^2. The estimated initial dirt on the parts ($w_{p_c}(t_0)$) is 0.0035 g/cm^2. It is required that the dirt residue on the parts after cleaning ($w_{p_c, max}$) be not greater than 0.0007 g/cm^2. This is equivalent to 80 percent of dirt removal, which corresponds to 20 percent of permissible dirt residue. If the initial chemical concentration ($C_a(t_0)$) of the solution is 6.6 percent and no chemical is added during cleaning, we obtain the curves in Fig. 3 (see dotted lines). It can be found that after 4.16 min of cleaning, 80 percent of the dirt on parts is removed (Fig. 3a), and chemical concentration is reduced to 6.54 percent ($C_a(t_e)$) (Fig. 3b), which means chemical consumption of 0.19 gal. Note that the processing time for a barrel can be decreased as the chemical concentration, $C_a(t_0)$, is increased. If this concentration is increased to 8.0 percent, only 3.45 min are necessary for the same level of cleaning (Fig. 3a). If the cleaning continues to 4.16 min, the parts become even cleaner, with 9.50 percent of dirt residue; this is far below $w_{p_c, max}$ (20%). Correspondingly, $C_a(t_e)$ is reduced to 7.93 percent (Fig. 3b). If the concentration ($C_a(t)$) is maintained at 8.0 percent during cleaning, parts cleaning is not distinguishable as compared with the case in which $C_a(t_0)$ is only 8.0 percent.

The simulation reveals that the lower the initial chemical concentration, the slower the dirt removal. Moreover, dirt removal is nearly the same when the initial chemical concentrations are the same, regardless of chemical addition during one-barrel cleaning.

Environmental impact. The above simulation shows an opportunity for WM through optimizing the cleaning operation. It is probably true that the consumption of chemical remains the same for removing the same amount of dirt, regardless of cleaning time. Over-cleaning, however, requires additional chemicals and leads to lower facility usage. For instance, if the cleaning time remains 4.16 min in the above example, then the parts are too clean when leaving the cleaning tank (9.50 percent of dirt residue (see Fig. 3a). Calculation shows an extra amount of 0.032 gal of chemicals are needed. The accumulation of the extra chemicals through continuous operations in the cleaning tank must eventually lead to a significant increment of chemical concentration in

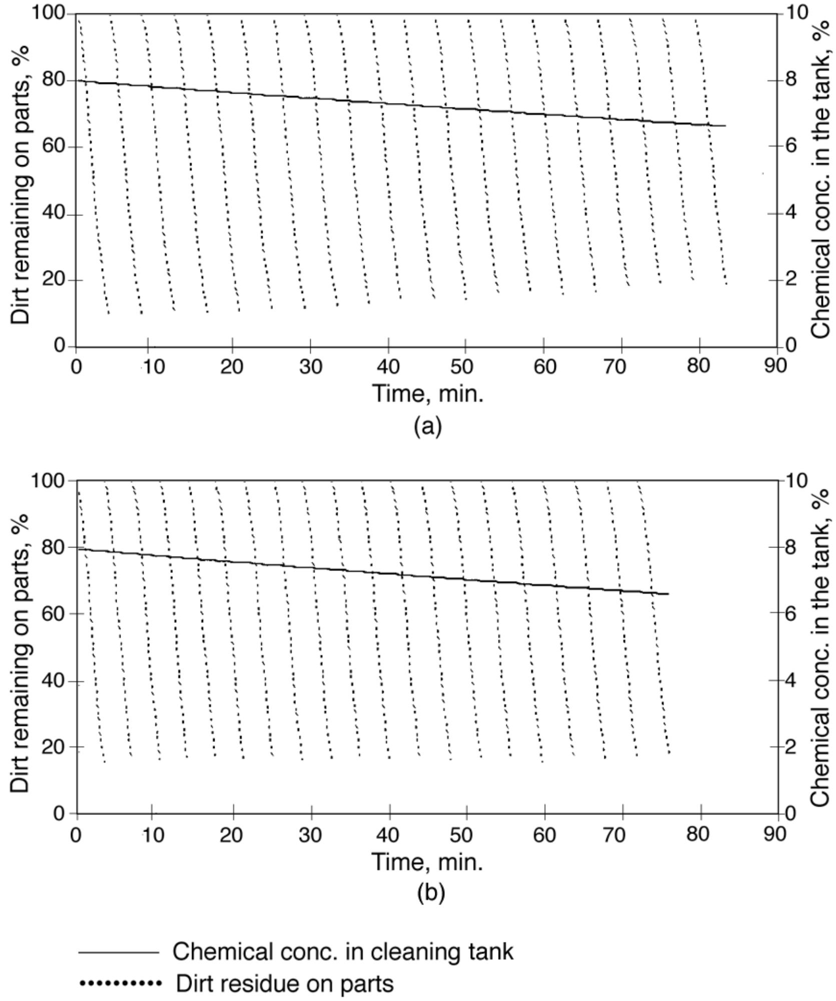

Fig. 4—Cleaning of 20 barrels of parts: (a) before optimization, (b) after optimization.

spent solutions. Moreover, extensive cleaning means reduction of the production rate. To have an environmentally benign cleaning operation, therefore, we must choose the optimal cleaning time and chemical addition, based on the model in Eqs. (1) though (4). The general rule is that chemical consumption and cleaning time must be minimized whenever possible.

Multi-Barrel Cleaning

With the cleaning model, we can simulate the operation of processing any number of barrels sequentially in the tank.

Dynamics. Assume that 20 barrels of parts are to be cleaned sequentially, and each barrel is equally loaded (200 kg) and with the same initial dirtiness: ($w_{p_i}(t_0)$ = 0.0035 g/cm^2). The initial chemical concentration ($C_a(t_0)$) is set to 8 percent. It is required that 80 percent of the dirt for each barrel be removed after cleaning. If the operating mode for each barrel is the same ($t_{e_i} = t_{e_{i+1}}$ = 4.16 min, i = 1, 2, ..., 19), then the model gives the dynamic response in the tank, as in Fig. 4a. The chemical concentration is essentially decreased exponentially for each barrel cleaning, and nearly linearly for all barrel cleaning. At the end of cleaning, the concentration ($C_{a20}(t_e)$) is reduced to 6.6 percent. This implies total chemical consumption of 4.20 gal for 20 barrels. It is clear that the earlier a barrel is cleaned, the cleaner it is.

Environmental impact. From Fig. 4a, it can be found that the dirt residue of the first barrel is only 9.5 percent, and that of the 20th barrel is 19.3 percent. Apparently, the barrels cleaned earlier are too clean, which is surely unnecessary. This over-cleaning requires extra consumption of chemicals, which implies a significant increment of pollutant in effluent waste streams. The situation can be easily changed if the operation is optimized. To alleviate environmental problems, we may have at least the following strategies:

(a) Change cleaning time, and try for the same cleanness for each equally loaded barrel. During cleaning, no additional chemical will be added.
(b) Change the load of a barrel, and try for the same cleanness in the same cleaning period. During cleaning, no additional chemical will be added.
(c) Maintain same chemical concentration by adding chemical when ever necessary. Cleaning time for each equally loaded barrel is the same.

Figure 4b depicts the simulation results of implementing Strategy (a). To simplify the operation, the processing time is changed after every five barrels, rather than after every barrel. For each time setting, the operation is optimized so that the fifth barrel in each group meets the cleaning requirement (20 percent or less of dirt remaining). The simulation shows that the optimal processing time sequence is 3.75, 3.92, 4.08, and 4.14 min for the four groups of barrels. After finishing the cleaning of the 20th barrel, the chemical concentration in the tank is 6.67 percent, which is higher than 6.60 percent, as shown in Fig. 4a. This implies a chemical reduction of 0.23 gal, which will surely lead to the reduction of waste by nearly the same amount.

Comparison of these two types of operational procedures

Table 1
Comparison of Two Cleaning Cases for 20 Barrels

Parameter	Case 1	Case 2
Tank capacity (gal)	320	320
Number of barrels simulated	20	20
Cleaning time (min)	4.16	varied for every 5 barrels (3.75-4.14)
Initial chemical conc. (vol %)	8.0	8.0
Chem. conc. after cleaning (vol %)	6.60	6.67
Wt % dirt remaining after cleaning	9.5-19.3	17.2-19.9

Table 2
Comparison of Three Cases for a Barrel Processed in a Rinse Tank

	Case 1	Case 2	Case 3
Tank capacity (gal)	220	220	220
Rinse time (min)	0.42	0.42	0.42
Rinsewater flow rate (gal/min)	5	6.5	3.5
Initial dirt before rinsing (wt %)	36.40	36.40	36.40
Initial pollut. conc. in tank (g/L)	0.062	0.074	0.060
Dirt remaining after rinsing (wt %)	23.7	26.8	23.6
Rinsewater consumption (gal)	20.8	14.6	27.0

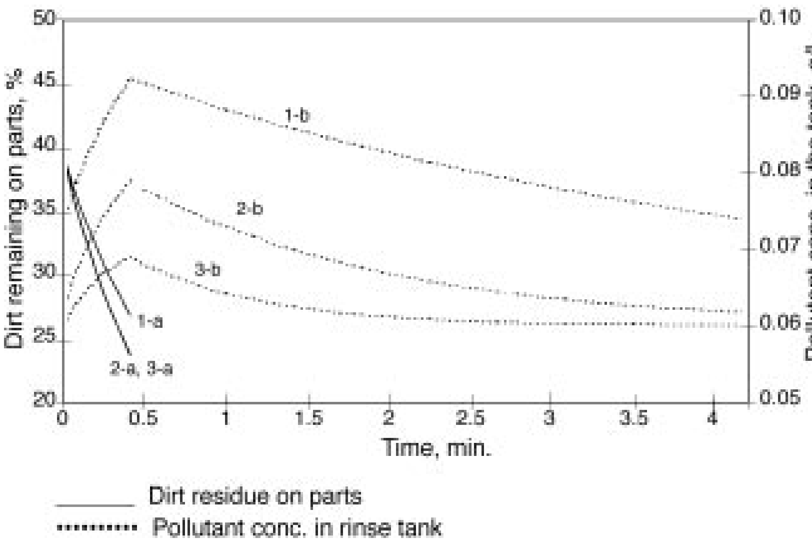

Fig. 5—Rinsing of a barrel of parts (F_{in} = 3.5, 5.0, and 6.5 gal/min for Cases 1, 2, and 3, respectively).

is summarized in Table 1. The only "disadvantage" of implementing this operational strategy is uneven processing time of each group of barrels. Apparently, this disadvantage does not exist if the process is automatically controlled. This suggests that process-model-based automatic control can provide a variety of opportunities for significant waste reduction and production optimization.

Rinsing Unit Characterization

One-step rinsing

A rinsing tank has two operation modes—rinsing and idle. In the rinsing mode, a barrel of parts is rinsed when rinsewater continuously flows through it. After the barrel is withdrawn, the rinsing tank is in idle mode. Rinsewater still flows to reduce the pollutant concentration in the tank.

Dynamics. The rinsing efficiency can be characterized by dirt removal from the parts and water consumption. Using the model in Eqs. (5) through (8), we can accurately show how the dirtiness of parts is decreased and how pollutants in the tank are accumulated. As an illustrative example, consider simulation of the rinsing of a barrel of parts (200 kg). The parts contain 0.00136 g/cm^2 of dirt, which is equivalent to 39.5 percent of total dirt residue, based on the original dirt content before rinsing. In the simulation, three cases with different water flow rates are investigated. Figure 5 shows the dynamic responses under different operating conditions.

In Case 1, the rinsewater is set to 3.5 gal/min, the initial pollutant concentration in the tank is 0.074 g/L, and the dirt residue on the parts is 39.5 percent before rinsing. After 0.42 min of rinsing, the dirt residue is decreased to 26.8 percent (curve 1-a in Fig. 5). After withdrawal of the barrel, the pollutant concentration is reduced to 0.074 g/L within 3.75 min as a result of the continuous water flow. This final pollutant concentration is the same as that before rinsing, which allows the next barrel to be rinsed under the same conditions. The cleaning quality in this case is not acceptable, however, because it is higher than the required 24 percent.

To resolve the rinsing problem, the influent rinsewater is increased to 5 gal/min (Case 2). The stabilized pollutant composition is reduced to 0.062 percent, compared to 0.074 percent in Case 1. Curve 2-a in Fig. 5 shows that after 0.42 min of rinsing, the dirt residue on the parts is reduced from 39.5 percent to 23.6 percent, while the pollutant composition in the tank is increased from 0.062 g/L to 0.080 g/L (curve 2-b).

Environmental impact. The minimization of wastewater relies on minimization of the consumption of rinsewater. When the initial dirtiness of parts, the size of the rinsing tank, and the cleanness of incoming rinsewater are given, water consumption is determined by water flow rate and rinsing time. If the water flow rate is further increased to 6.5 gal/min (Case 3), the dirt residues on the parts are the same as in Case 2, after 0.42 min of rinsing (see curves 2-a and 3-a in Fig. 5). Note that the pollutant composition in the tank in this case is decreased to 0.060 g/L (curve 3-b). For the same cleaning quality, the water consumption for rinsing a barrel in Case 3 (27.0 gal.) is 30 percent higher than in Case 2 (20.8 gal.). Apparently, the operation shown in Case 3 is not desirable. This simulation shows that an optimal flow rate of rinsewater can be uniquely

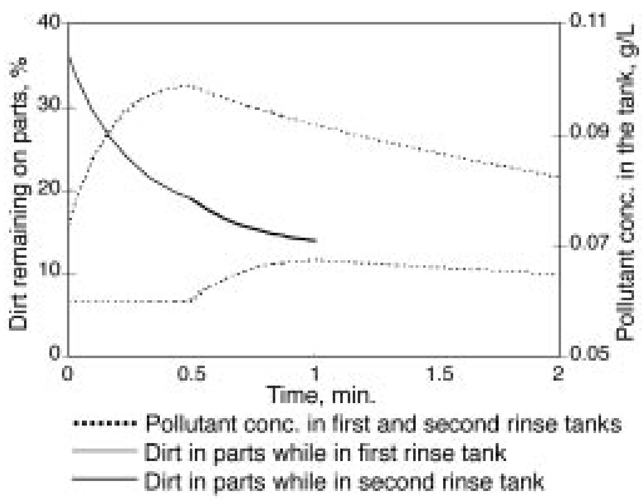

Fig. 6—Rinsing of a barrel of parts in two rinse tanks.

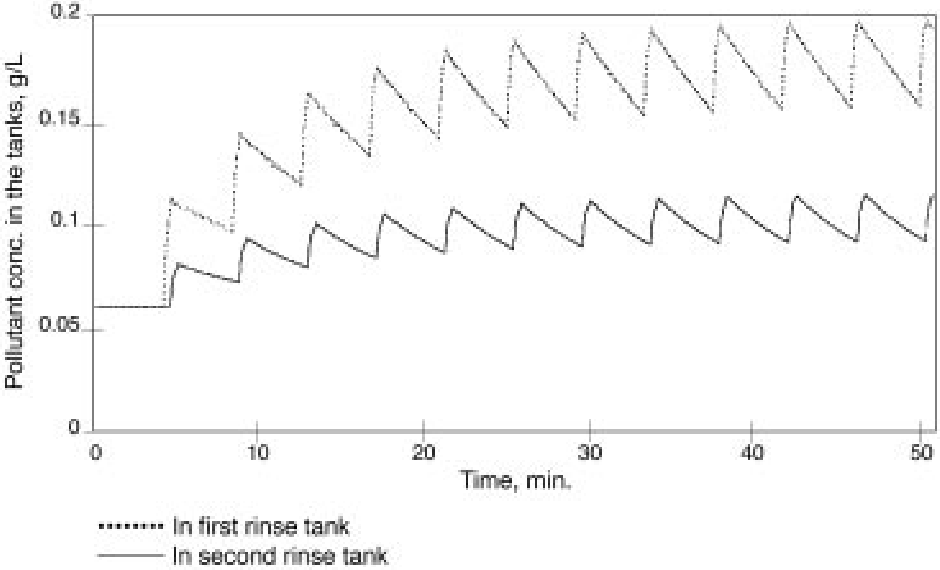

Fig. 7—Pollutant concentration change in the two rinse tanks.

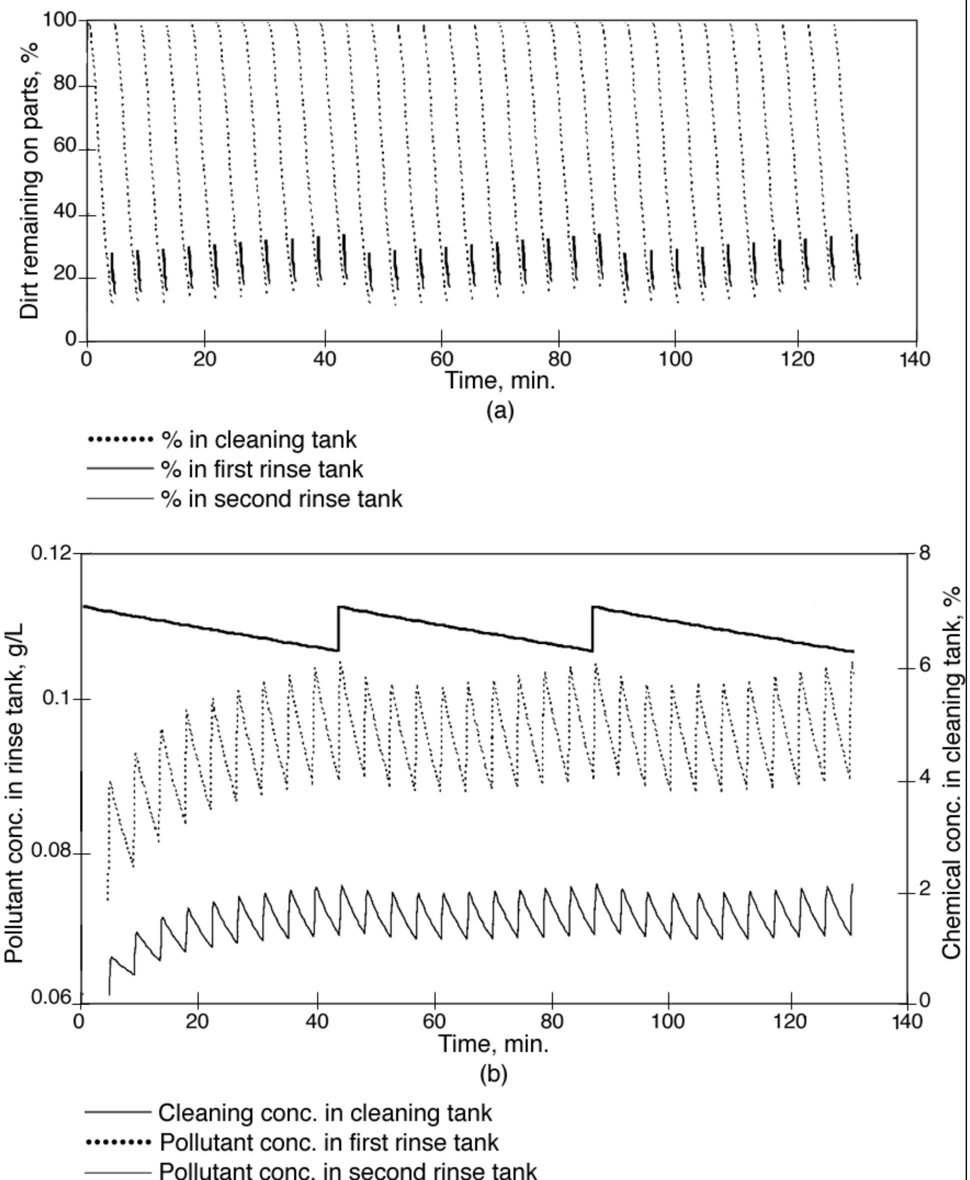

Fig. 8—Processing of 30 barrels in the cleaning-rinsing system (base case): (a) dirt removal from the parts in each barrel; (b) changes of chemical concentration in the cleaning tank and of pollutant concentration in the two rinse tanks.

determined by the model. Table 2 gives the process specification and operation conditions for these three cases.

Two-step Rinsing

A two-step rinsing after cleaning, shown in Fig. 2, is a common practice. The model has been used to simulate this continuous rinsing operation.

Dynamics. Assume that the initial dirt on parts ($w_p(t_0)$) is 0.0013 g/cm^2, which implies a dirt residue of 36.4 percent after cleaning. The barrel is immediately placed in the second rinsing tank after the first rinsing. The influent water to the second rinsing tank has contamination ($z_{r_2}(t)$) of 0.06 g/L. It is assumed that the initial pollutant concentration in the first rinsing tank ($x_{r_1}(t_0)$) is 0.07 g/L, and that in the second rinsing tank ($x_{r_2}(t_0)$) is 0.06 g/L. In Fig. 6, the solid curves demonstrate the dynamic responses of the dirt removal from parts, and the dotted curves depict the changes of pollutants in the two rinsing tanks. It is shown that after the first rinsing of 0.5 min, the dirt on parts is reduced to 19 percent; meanwhile, the contamination of the first tank is increased from 0.07 to 0.1 g/L. In the second tank, the dirt residue percentage is reduced to 13.9 within the next 0.5 min, while the contamination is increased to 0.067 g/L. Note that when the barrel leaves any tank, the contamination level in it will be reduced because rinse water is still flowing in.

Environmental impact. The total amount of pollutants in the effluent streams can be readily estimated by the models. Because the tanks are used continuously, the contamination of each tank will be stabilized. Figure 7 shows the change of contamination level. It is assumed that both tanks have the initial pollutant concentration of 0.06 g/L, which is the same as the concentration of the influent rinsewater into rinse tank 2. The figure contains two zig-zag curves

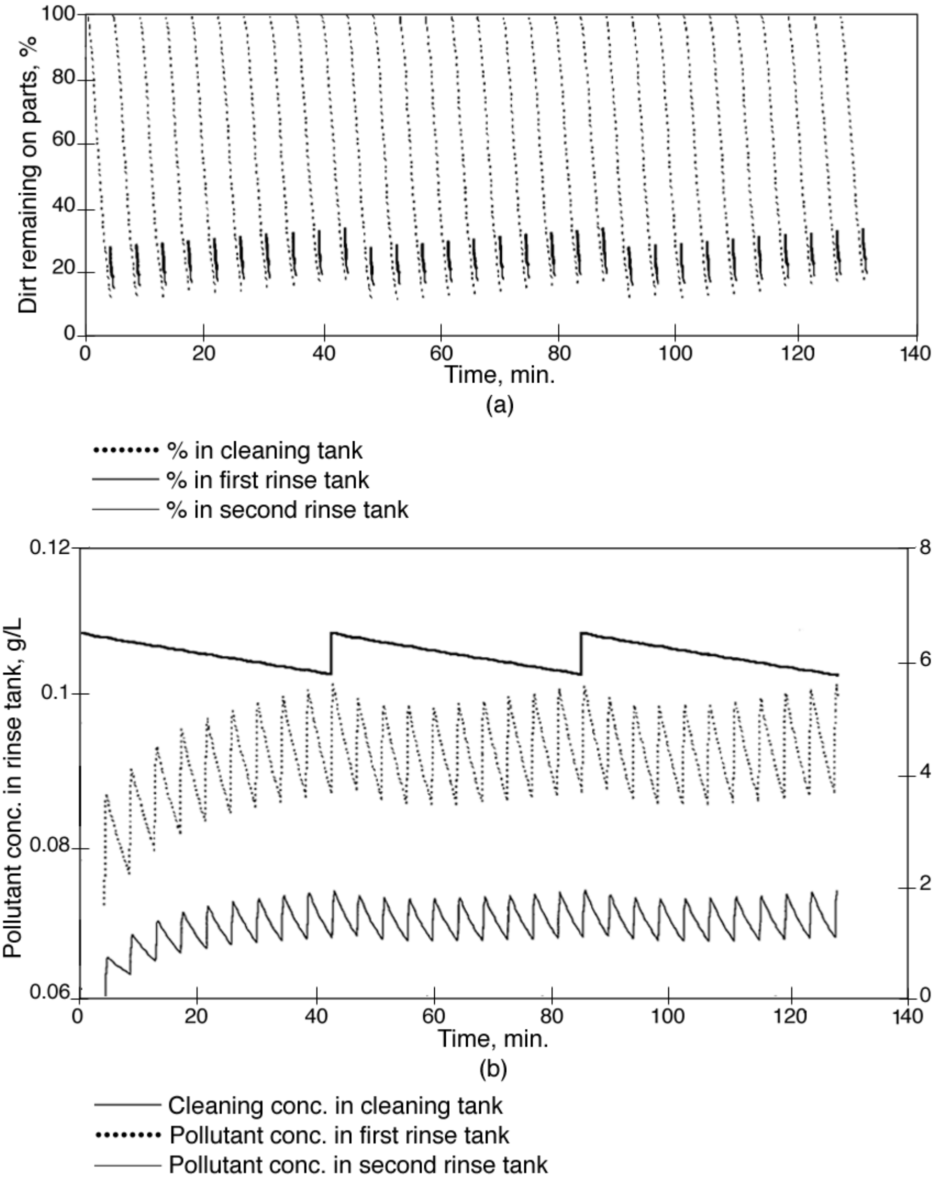

Fig. 9—Processing of 30 barrels in the optimal cleaning-rinsing system: (a) dirt removal from the parts in each barrel; (b) changes of chemical concentration in the cleaning tank and of pollutant concentration in the two rinsing tanks.

should achieve 80 percent dirt removal.

The simulation for the operating conditions given in Table 2 was implemented. In this case, the dirt residue on the parts through this process must be less than 0.0007 g/cm^2 to ensure the cleaning quality for plating. The initial chemical concentration ($C_a(t_0)$) in the cleaning tank should be 7.6 percent, and no chemical can be added during operation. The flow rate of rinsewater through the two rinsing tanks is kept at 7 gal/min. The dynamics of the cleaning and rinsing operations are depicted in Fig. 8. As shown in Fig. 8a, many barrels are over-cleaned, with the dirt residue much less than 20 percent. For instance, the first barrel after cleaning reaches 9.7 percent of dirt residue. The over-cleaning suggests an opportunity for reducing chemical and rinsewater usage. Corresponding to the dirt removal from parts, Fig. 8b shows the dynamic responses of the chemical concentration in the cleaning tank and pollutant composition in the rinsing tanks.

that characterize different tanks. In each curve, each upward segment represents the rinsing process, and each downward segment represents the idle mode. After about 10 barrels rinsed sequentially in 42 min, the contamination level in each tank becomes stable.

Cleaning-Rinsing System Characterization

The significance of the models is the characterization of an entire cleaning and rinsing system. This can be accomplished by appropriately using these models.

Dynamics. Thirty barrels of parts are to be processed in a simulated cleaning/rinsing system, as shown in Fig. 2. All barrels are equally loaded (200 kg of the same type of parts in each barrel). It is assumed that the dirtiness of each barrel is the same (0.0035 g/cm^2). For each barrel, the cleaning time is set to 4.16 min; the first and second rinsings are set to 0.41 and 0.5 min, respectively. Through this system, each barrel

Environmental impact. To reduce chemical and water consumption, we adopt the strategy of adding chemical to maintain its concentration when the dirt residue after cleaning and rinsing tends to be higher than 20 percent. At the same time, rinsewater flow rate is optimized to keep proper operating conditions. The simulation reveals that if we set the initial chemical concentration to 6.2 percent and the flow rate of rinsewater is changed to 5.8 gal/min, the chemical needs to be added after every 10 barrels of cleaning. In this operating mode, cleaning and rinsing quality can be maintained simultaneously.

Dirt removal from each barrel in different tanks is depicted in Fig. 9a. The first barrel reaches 14.6 percent of dirt residue (85.4 percent of dirt removed). When the 10th barrel leaves the process, its dirt residue approaches 20 percent. Calculation shows that addition of chemical to 6.2 percent in the tank is necessary (Fig. 9b). This figure also shows how the pollutant composition is changed dynamically in the rinsing tanks.

The operating conditions of the base and optimal cases are summarized in Table 3. Compared with the base case, the chemical and water consumption in the optimal mode are reduced by 5.0 and 17.2 percent, respectively.

Table 3
Comparison of Two Cases in a Cleaning-Rinsing System

	Base Case	Optimal
Cleaning tank capacity (gal)	320	320
First rinse tank capacity (gal)	220	220
Second rinse tank capacity (gal)	220	220
Rinsewater flow rate (gal/min)	7	5.8
Initial chemical conc. (vol %)	7.6	6.2
Number of barrels processed	30	30
Chemical consumption (gal/barrel)	0.235	0.223
Rinsewater consumption (gal/barrel)	30.3	25.1

Implementation Practicality

While the extensive simulation described above demonstrated the effectiveness of model-based pollution prevention and optimal operation, model implementation in different (actual) tanks must be carefully considered. In a cleaning tank, it is always desired to maintain a constant chemical concentration in order to have a stable and uniform cleaning operation. The model can tell us when and how much chemical should be added. The maintenance of constant chemical concentration can be readily realized by installing a control system for adding chemicals. For most plating shops, where no control systems are available, we suggest adding the chemicals periodically, based on model computation, as exemplified in the preceding section.

In the simulation, the optimal processing time in either cleaning tank or rinse tank is identified as having precision levels of seconds. For instance, in simulating 30 barrels of parts in a cleaning/rinsing system, the optimal cleaning time is set to 4.16 min, and the first and second rinsings are set to 0.41 and 0.5 min, respectively. The rinsing time difference in these two tanks is only 5 sec. In real operation, this time difference may not have practical significance, especially when a process is manually controlled. We suggest that if minimization of waste and operating cost is strictly targeted, then installation of a model-based control system is strongly recommended. Even for a manually controlled process, however, where slightly different processing periods cannot be effectively implemented, the model can still provide a detailed analysis of environmental and economic impacts. The analytical result can be considered as reliable decision support for operators.

Summary

Accurate pollution prevention must rely on precise information about a process. This information can be obtained from process models, especially dynamic models. A set of the first-principles-based models developed in this work allows us to perform a thorough analysis of the cleaning and rinsing processes. Results of simulation have clearly revealed a great opportunity for minimizing waste generation and maximizing process efficiency in a systematic way. It is hoped that the models can truly help the industry fight waste while optimizing production simultaneously.

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About the Authors


Gong


Huang


Luo

J.P. Gong is a research associate in the Department of Chemical Engineering and Materials Science at Wayne State University. He holds BS, MS and PhD degrees from Zhejiang University, China, all in chemical engineering. His current research interests are in process modeling, simulation, control and optimization, and application to pollution prevention and waste minimization. He has published more than 30 papers in these areas.

Yinlun Huang is an assistant professor in the Department of Chemical Engineering and Materials Science at Wayne State University, 5050 Anthony Wayne Dr., Detroit, MI 48202. He holds a BS from Zhejiang University (China) and an MS and PhD from Kansas State University, all in chemical engineering. He has also been a postdoctoral Fellow at the University of Texas at Austin. His research interests include process design and synthesis, process modeling and control, process simulation and optimization, and industrial process pollution and prevention and waste minimization. His research has been supported by the National Science Foundation, the EPA and AESF.*

K.Q. Luo is a graduate research assistant in the Department of Chemical Engineering and Materials Science at Wayne State University. He holds a BS from East China University of Science and Technology and an MS in chemical engineering from Wayne State University. His research interests include process modeling and optimization, and applications in artificial intelligence and neural networks.

** To whom correspondence should be addressed*