Profitable Pollution Prevention: Concept, Fundamentals & Development

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Industrial pollution prevention (P2) is a national strategic goal for effective environmental protection. Over the past decade, the electroplating industry has implemented numerous basic P2 techniques that have greatly reduced the quantity and toxicity of end-of-plant waste. In recent years, various new P2 technologies have been developed for technology change, material substitution, in-plant recovery/reuse and treatment. Those new technologies usually require significant capital investment, however. Moreover, how to ensure production competitiveness when using those technologies is not clear. Their applicability to, and acceptance by the industry are therefore yet to be proven.

This paper explores the opportunity for developing a new generation of P2 technologies that can also make profits for plants. The basic feature of these technologies is the promise of both environmental and economic benefits. They can be named P3 (*i.e.*, profitable P2) technologies. The P3 concept can be justified through fundamental study of process operation and deep analysis of waste generation. It will show that the development of P3 technologies should be a new direction of R&D for environmental protection in this decade. These key issues in the development will be discussed in detail. Two P3 technologies are described to show their effectiveness for both P2 and optimal production. It is predicted that the P3 technologies will soon become the most attractive environmental technologies for the metal finishing industry.

The electroplating industry is a major pollutant generator in the manufacturing industries. In electroplating plants, huge amounts of water, chemicals, and energy are consumed daily. The waste generated usually contains more than 100 hazardous or toxic chemicals, metals, and other regulated pollutants. This has cost the industry hundreds of millions of dollars per year for waste treatment and disposal.[1–4] As environmental regulations become increasingly stringent, such as the U.S. EPA Strategic Goals set for 2002, how to effectively reduce waste in the first place has greatly challenged the industry. Platers urgently need the least expensive P2 technologies for maximum waste reduction, so that their economical competitiveness can be maintained.[5]

According to the EPA, pollution prevention (P2) means the maximum feasible reduction of all wastes (wastewater, solid waste, and air emissions) generated at production sites.[1] Over the past decade, numerous P2 technologies have been developed for the electroplating industry. One group of technologies is basic and concerns source reduction, recycling/reuse, and pretreatment. Their implementation is usually easy and simple. Nevertheless, the P2 effectiveness is always limited, since most of them are quite general.[6] For instance, a longer drainage time is preferred for drag-out minimization, but is undesirable for maintaining production rate. Current drag-out minimization techniques cannot determine an optimal drainage time for any plating line. In fact, numerous uncertainties exist in using this group of P2 technologies. In recent years, another group of P2 technologies is being developed that focus on technology change, use of alternative metals, in-plant recovery/reuse and treatment.[7] This group of technologies is much more effective in waste reduction.[5] A significant capital investment, however, is always required in implementation. Those investments for technology change and the use of alternative metals require significant change of processes. In-process recovery/reuse and treatment technologies are essentially not for the reduction of waste from plating lines, but for reduction of waste in the effluent streams from a plant (end-of-plant waste). Rigorously, they belong to in-plant pollution control technologies. Another concern of using this group of technologies is how to maintain plating quality and production competitiveness. Their applicability to and acceptance by the industry, therefore, are yet to be proven.

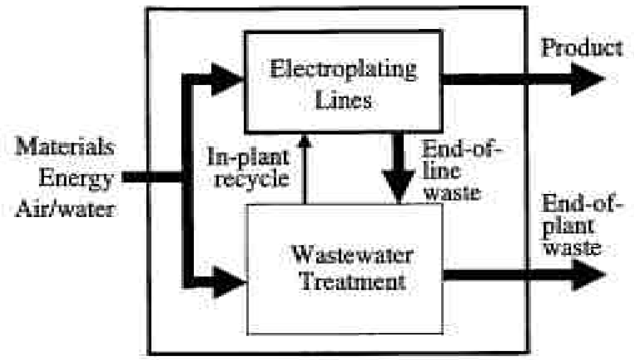

Fig. 1—Conventional approach for waste reduction in electroplating.

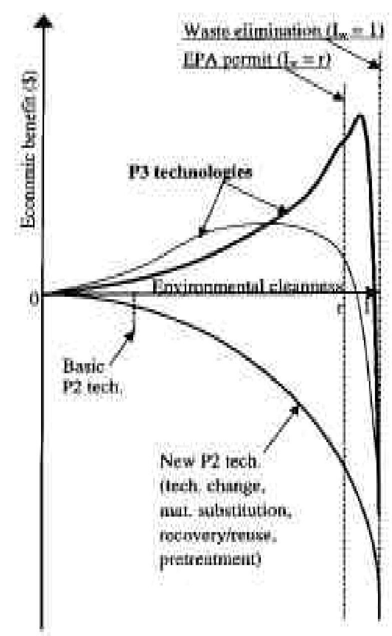

Fig. 2—Analysis of economic impact of P2 and P3 technologies.

Note that most of the more than 8,000 electroplating jobshops and captive shops in the nation are medium or small

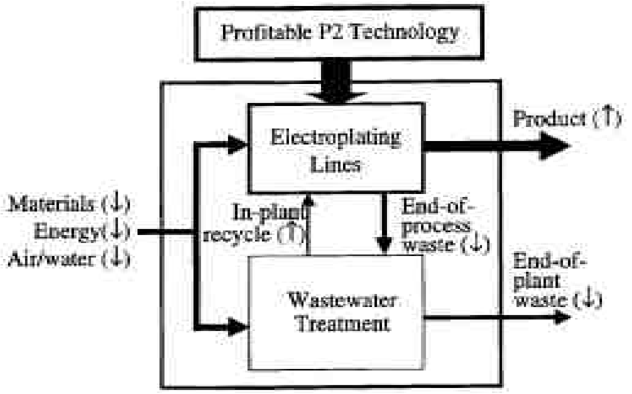

Fig. 3—New P2 approach for maximum waste reduction and optimal production.

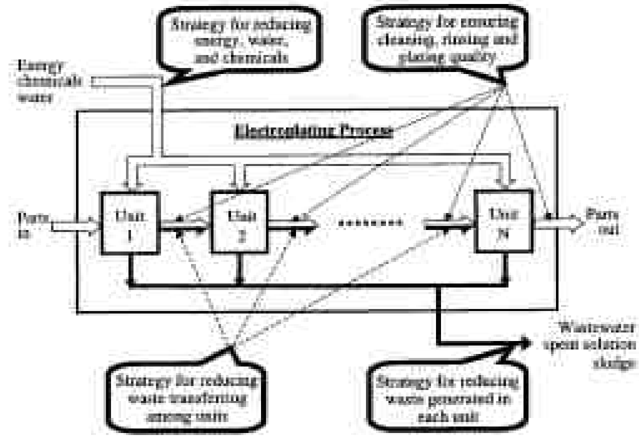

Fig. 4—Strategy revision for P3 technology development.

in size. They usually lack P2 expertise and do not have adequate funds to invest in P2 projects. In recent years, some of the states have launched P2 loan programs for small business. While this will help the industries improve their P2 practice, it also sends a message that effective P2 needs significant funds and that it is an economic burden for platers. In principle, P2 is to prevent pollution, but not to preclude economic benefits. According to the conservation law, if the waste generation mechanism is dismantled, chemicals, water, and energy consumed for waste generation can be saved. This basic economic fact indicates that P2 should not be an economic burden for any industry. P2 should provide industries with both environmental and economic benefits.

In this paper, a novel concept known as profitable pollution prevention (or P3 for short), is introduced. This concept extends the conventional P2 concept significantly by adding a new dimension (*i.e.*, economics), to it. The P3 concept is then elaborated through fundamental study of the P3 theory, using basic process systems engineering principles. The key issues in the development of P3 technologies are discussed. Finally, two P3 technologies are illustrated, with applications to show the effectiveness in P2 and optimal production in plants.

From P2 to P3

Societal expectation about P2 in a plant is to minimize the quantity and toxicity of the effluent streams from it. Because waste is generated in production lines and improper waste reduction methods may strongly affect normal production, a safe P2 effort that most plants prefer is the installation of wastewater pretreatment facilities (WTF), if it is affordable. Figure 1 shows the general structure of an electroplating plant that consists of electroplating lines and WTF. Chemicals, energy, and water are consumed in cleaning, rinsing, and plating operations in the plating lines, and for treatment and recovery in the WTF. In the plant, waste is generated from the tanks in the plating lines (end-of-line waste) and WTF (end-of-plant waste). Obviously, the reduction of end-of-line waste is the focus for the most effective P2. One way to do this is to change plating technologies, and to use alternative metals and other materials as substitutes. It is impractical and uneconomical, however, to ask most plants to do so, even if the technologies are available. To platers, maintenance of production competitiveness is of utmost importance. It is understandable that the current major development emphasis in P2 technologies is on the reduction of end-of-plant waste, because it will not negatively influence production. An easy way for effective P2 is, therefore, to enhance WTF and to improve material recovery for potential reuse. This is a passive way for P2, however.

Figure 2 depicts the analysis of environmental and economical impacts by different P2 technologies. In the figure, environmental cleanness is quantified by the index, I_w, which ranges from 0 (completely unacceptable) to 1 (waste elimination). As indicated, the use of basic, low-cost P2 technologies can only reach a limited waste reduction standard. If new P2 technologies (those for technology change, the use of alternative metals, etc.) are also used, then EPA regulations can be complied with, but it is costly. This analysis is depicted by the dashed curve in the figure. An EPA permit is assigned a value (r) for I_w. This value has been increased, as the environmental standard becomes more stringent. The capital investment requirement for P2 has therefore risen rapidly. As indicated in the preceding section, the conservation law shows that there must be various opportunities for simultaneous reduction of waste and operating/capital cost. Where are the opportunities? How can we grasp the opportunities and make them a reality? The opportunities can be found from the process where waste is generated. Only when the channels of waste generation are blocked, can the end-of-line waste be minimized or even eliminated. At the same time, the chemicals, water, and energy consumed in generating and treating the waste can be saved. This kind of P2 strategy must be the most effective and be the first consideration. It requires no, or very low, capital investment, and should cut operating cost significantly. Moreover, the improvement of product quality and production rate will offer real opportunities. This is the foundation of P3. The economic and environmental incentives are depicted in Fig. 2 (solid curves). It is expected to suggest the P3 technologies that make profits as high as possible.

The development of P3 has a broad industrial basis. In fact, the end-of-line waste in most plants is generated on a larger scale than it should be.[7~9] Note that most plants still don't have in-depth understanding of process principles, and don't know exactly how production and waste minimization are correlated. Even today, the following questions, which are critical to both optimal production and P2, remain unanswered in the industry:

- What are the cleaning and rinsing standards for parts? Or more specifically, what is the maximum permissible dirt residue on parts before plating?
- What is the optimal setting of chemical solvent concentration in a soaking, electrocleaning, or pickling tank?
- What is the minimum water flow rate for each rinsing step?

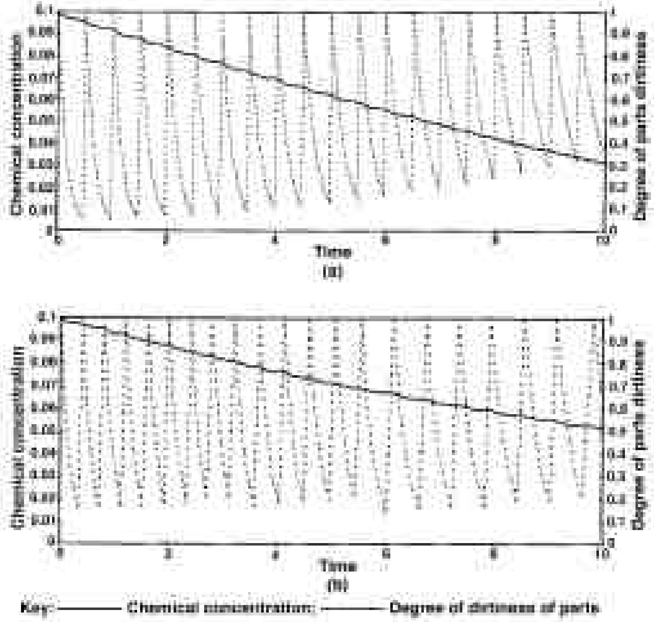

Fig. 5—Simulation results for a cleaning tank: (a) process dynamics of the original operation; (b) process dynamics of optimal operation.

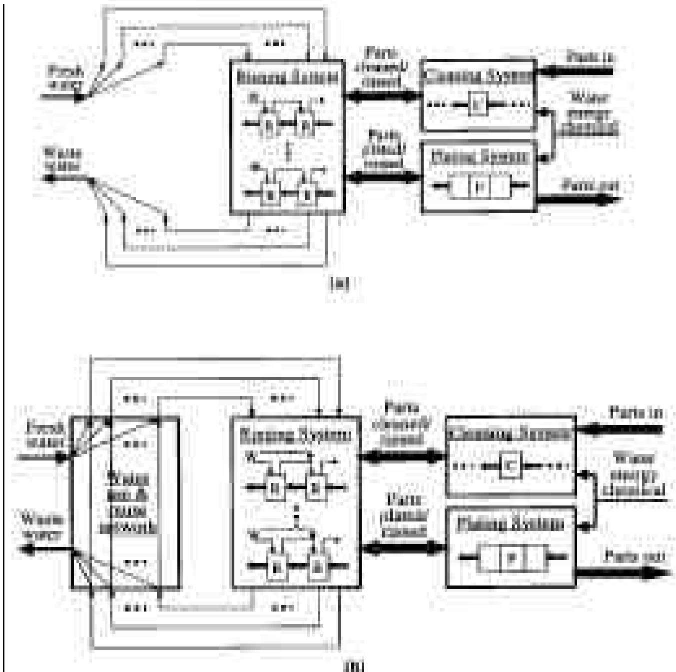

Fig. 6—Water use in an electroplating plant: (a) conventional water distribution configuration; (b) integration of a WURN into electroplating processes.

- What is the minimum processing time needed for a barrel of parts in a cleaning, rinsing, or plating tank?
- How does a rinsing system configuration affect both rinsing quality and wastewater minimization?
- To what extent can sludge in a cleaning or plating tank be reduced?

Without correct answers to these questions, production can never be optimal, and P2 can never be complete. The reality in plants now is that chemicals, energy and water are over-consumed, and waste generation is always more than it should be. It is urgent, therefore, to conduct a fundamental study of these concerns.[10]

P3 Fundamentals

As stated, the merit of P3 is the simultaneous realization of waste reduction (environmental impact) and improvement of production (economic incentive). This can be expressed as,

$$\text{P3} = \text{Waste}\downarrow + \text{Production}\uparrow \tag{1}$$

The waste reduction and production improvement in Eq. (1) can be elaborated as:

$$\text{Waste}\downarrow = \text{Dirt removed}\downarrow + \text{Chemicals}\downarrow + \text{Water}\downarrow + \text{Energy}\downarrow \tag{2}$$

$$\text{Production}\uparrow = \text{Product quality}\uparrow + \text{Production rate}\uparrow + \text{Operating cost}\downarrow + \text{Capital cost}\downarrow \tag{3}$$

It is clear that the reduction of chemicals, water, and energy consumed in a production line in Eq. (2) must lead to the direct reduction of operating cost and indirect reduction of capital cost in Eq. (3). The key to waste reduction is the control of production quality. A reduction in dirt removal from parts can directly contribute to waste minimization, and the reduction of chemicals, water, and energy in equation (2) leads directly to reduction in operating costs in Eq. (3). Moreover, it will shorten the processing time in cleaning tanks and thus improve the production rate in Eq. (3). A critical concern is again the cleaning and rinsing quality as included in Eq. (3). This analysis has shown that thorough understanding of the process is the key to ensuring both environmental and economic benefits.

The fundamental component of P3 is the process principles that explain how parts are cleaned, rinsed and plated, and how waste is generated in various operations. These principles are nothing more than mass and energy balances, thermodynamics, and kinetics. They can be used to study process steady-state and dynamic behavior and to develop P3 strategies. For instance, if the process dynamics is derived, the parts cleaning, rinsing and plating operations can be fully understood, and the waste generation mechanism clearly revealed. Then the P3 opportunities can be readily identified. The end-of-line waste can be divided into two groups: unavoidable and avoidable. The unavoidable waste is generated by removal of the minimum amount of dirt from the surface of parts, according to the cleaning quality. The main portion of the waste is stationary, remaining in the cleaning tanks. The rest is mobile that can enter succeeding tanks and finally enter wastewater. Through drag-in/drag-out, a certain amount of chemical and plating solutions is also carried over to rinsing systems and finally enters the wastewater. This should be avoided to the maximum extent possible. Another type of avoidable waste is related to parts cleaning, rinsing, and plating. We all know that it is clearly unreasonable to ask for completely dirt-free parts before plating. In reality, dirt-free cleanness is not necessary for parts before plating. There must be an upper limit of dirt residue, below which plating quality will not be affected. In production, the dirt residue on parts before plating varies significantly. That is, many barrels of parts are overly cleaned, while many others are not clean enough for quality plating. Obviously, we should avoid over-cleaness; or, we want to have the parts as dirty as possible, as long as the dirt residue is below the upper limit. If we can successfully do this, the consumption of chemicals and water, and the processing time in relevant tanks can all be reduced. The focal point of the operational strategy is identification of the upper limit and the way of controlling the process by following this restriction.

The above analysis shows that current P2 focuses on waste, not process. By contrast, P3 focuses on both waste and process. Figure 3 shows that when P3 technologies are applied to the plating line, the chemicals, energy, and air/water consumed in the process and WTF will be reduced, the end-of-line waste will be reduced, the waste load of the WTF will be reduced; thus the end-of-plant waste from the WTF will be reduced and production will be improved.

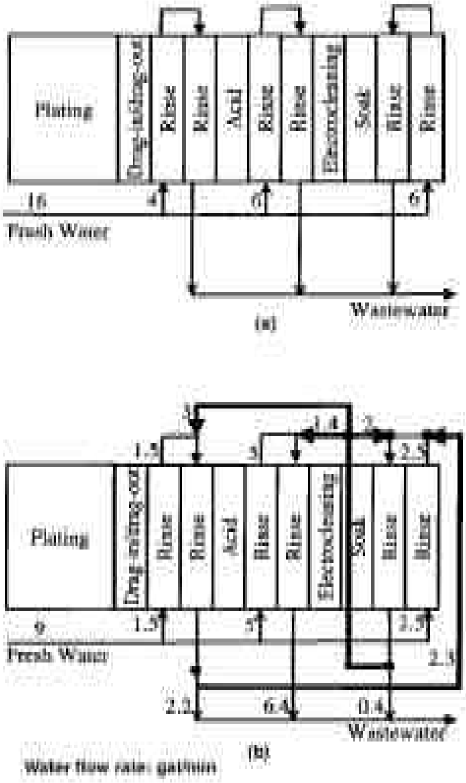

Fig. 7—Water use and reuse in a plating line: (a) original process flow sheet; (b) new process flow sheet with an embedded WURN.

P3 Technology Development

Because the plating process is the focus of P3, the development of P3 technologies must be for clean and cost-effective process design, as well as for clean and optimal process operation. To be effective, P3 technologies must consist of at least four types of strategies. Figure 4 indicates the functionality of these strategies that must be developed based on the parts processing flow, the energy, chemical, and water flow, as well as the waste flow. The functionality of each P3 strategy is delineated below.

Strategy for Reducing Waste Generated In Each Processing Unit

In operation, all cleaning, rinsing, and plating tanks can generate waste. In cleaning tanks, for example, the waste is generated by dirt removal from parts surfaces. In most plants, part dirtiness varies greatly. In a cleaning tank, chemical solvent is always added periodically and chemical concentration is set based on experience. When the concentration in a tank is below a pre-specified lower limit, solvent should be added to the upper limit. We call the time between two chemical additions a cycle. It is conceivable that the barrels of parts processed at the beginning of the cycle are much cleaner than those processed later in the cycle when the processing time for each barrel is the same. The simple logic is that if the cleanness of the parts processed later is satisfactory for plating, there is no reason for the parts processed early to be that clean.[10,11] This suggests that a basic strategy for reducing waste is to maximize the dirtiness of each barrel of parts after cleaning. Or, we want to have the dirtiest parts after cleaning, with each barrel of parts equally dirty. The bottom line is that the dirt residue must be just below the upper limit.[12] It seems bizarre, but it is a real opportunity. Certainly, the key for the success of this strategy is the establishment of the upper limit for dirt residue, and the estimation of the cleanness of parts in each cleaning tank.

Strategy for Reducing Waste Transferral Among Units

Because barrels of parts are processed sequentially in a plating line and the production rate must be maintained, the drag-out is unavoidable. It contains dirt, solvents, and other pollutants that eventually enter the wastewater. The drag-out must be minimized, therefore, everywhere in the process. As stated in the preceding section, the available drag-out strategies are almost all experience-based. The correlation among drag-out-related variables, such as chemical concentration, viscosity, surface tension, and drainage time, has not been established.[13] In addition to developing operation-related strategies, it is also necessary to study how a rinsing system configuration is related to drag-out minimization. In general, a rinsing system consisting of a static tank followed by a flow tank is an effective way for minimizing mobile waste. Accordingly, a new rinsing system design methodology should be developed.[14]

Strategy for Reducing Chemicals, Water & Energy

The reduction of chemicals, water, and energy is always desirable because it means reduction of operating cost as well as reduction of the volume and contamination of wastewater and sludge. The main concern in this effort is the quality of cleaning, rinsing, and plating. An optimal operational strategy must be developed to ensure minimum consumption of chemicals, water, and energy. This operational strategy is also related to production scheduling. It is a complicated multiple-objective optimization problem.[13,15] It is suggested that large-scale system theory be used to solve it.

Strategy for Ensuring Cleaning, Rinsing & Plating Quality

This strategy consists of two sub-strategies. One is to set the standards for cleaning, rinsing and plating. So far, only general standards are available.[1] More specific standards for each type of cleaning, rinsing, and plating are yet to be developed. A difficulty involved is a system consideration. For instance, presoaking, soaking, electrocleaning followed by a two-step rinsing is a quite common sequence for removing oil, soil, other particles, and for loosening scale. The solvents used in the three cleaning tanks are the same. It is difficult to determine optimal cleaning standards in these tanks. The other type of sub-strategy is control of operations so that these standards can be reached. Although different control systems have been used in plants, they are essentially for open-loop control in terms of parts cleaning, rinsing, and plating quality.[16] For instance, closed-loop control of the concentration of a cleaning tank is not directly related to parts cleanness. Thus, process control of these operations must be advanced.

Process Modeling & Optimization for P3

The four types of P3 strategies discussed in the preceding section are closely related. The central point is understanding of a plating process. This understanding can be obtained through developing plant models. The models should be fundamental and that can reveal precisely the cause-effect relationships among quality, productivity, waste reduction and costs. The models should be dynamic so that process behavior, such as parts processing status, solvent solution cleaning capability, rinsing water contamination level, and plating solution capability at any time can be characterized. Moreover, the models should be plant-wide so that the P3 decisions can be made at the system level, rather than at a specific unit level.

Over the past five years, the authors and students have developed a variety of unit-based process models.[10~15] These include models for soak cleaning, electrocleaning and pickling (acid cleaning), single and concurrent rinsing, and basic plating operations. The pioneering modeling work has proven very valuable for the development of comprehensive P3 technologies. These include the development of environmentally clean design and operational technologies. In this section, the previous modeling is enhanced to plant-wide integrated modeling and model-based optimization.

Plant-Wide Model

A plant-wide model consists of the integrated models for cleaning, rinsing and plating, and a model for sludge prediction.

Integrated Cleaning Model

In a cleaning tank, chemicals are consumed for removing dirt from the surface of parts, and are lost through drag-out. The model is for characterizing chemical solution dynamics in any cleaning tank, such as soaking, electrocleaning, and pickling. A general model structure is,

$$V_{c_i}\frac{dC_{c_i}(t)}{dt}=\sum_{j=1}^{N_c} f_j(C_c,r_c,\mu_c,W_c,E)\big(H_j(t_0)-H_j(t_e)\big) \qquad I=1,\cdots,N_c \tag{4}$$

where $C_c(t)$ is the chemical solvent concentration in the cleaning tank at time t
$r_c(t)$ is the dirt removal rate in the cleaning tank at time t
$W_c(t)$ is the amount of solvent added at time t
$E(t)$ is the amount of energy added at time t
μ_c is the chemical capacity for dirt removal
V_c is the capacity of the cleaning tank
N_c is the total number of cleaning tanks in the plating line
$H(t)$ is the unit step function
t_0, t_e are, respectively, the starting and ending time of parts in a cleaning tank.

Note that the expression $H_j(t_0)$ - $H_j(t_e)$, forms a pulse function that has a value of 1 in the period from t_0 to t_e. The function, f_j , is dependent on the type of cleaning. For instance, the function for either presoak or soak cleaning is:[11]

$$f_i(C_c,r_c,\mu_c,W_c,E)=-\frac{r_c(t)}{\mu_c}+W_c(t) \tag{5}$$

$$r_c(t)=\gamma_c(t)C_c(t)W_P(t) \tag{6}$$

$$\gamma_c(t)=r_0\left(1-e^{-\alpha(t-t_0)}\right) \tag{7}$$

where $W_p(t)$ is the amount of the dirt on parts at time t
$\gamma_c(t)$ is the weight loss of the dirt on parts at time t
r_0 is the kinetic constant
α is the constant.

The model is associated with a number of initial conditions, such as the initial chemical concentration and initial dirtiness of the parts.

Integrated Rinsing Model

A plating line may have a number of rinsing steps, each of which may contain more than one rinsing tank. The model is to characterize the contamination level of rinsing water in any rinsing tank of a plating line. A general model structure is,

$$V_{r_{i,j}}\frac{dC_{r_{i,j}}(t)}{dt}=\sum_{k=1}^{N_r}\sum_{l=1}^{N_{rk}} g_{k,l}(r_r,F_r,C_r,C_{r,in})\big(H_{k,l}(t_0)-H_{k,l}(t_e)\big) \qquad k=1,\cdots,N_r;\ l=1,\cdots,N_{rk} \tag{8}$$

where $C_r(t)$ is the pollutant concentration in the rinsing tank at time t
$r_r(t)$ is the dirt removal rate in the rinsing tank at time t
$F_r(t)$ is the flowrate of rinsing water at time t
$C_{r,in}(t)$ is the pollutant concentration of input rinsing water at time t
V_r is the capacity of the rinsing tank
N_r is the total number of rinses in the plating line
N_{ri} is the total number of rinsing tanks in the *I*-th rinsing system of the plating line
$H(t)$ is the unit step function
t_0, t_e are, respectively, the starting and ending time of a rinsing cycle that includes a rinsing mode and an idle mode.

The function, $g_{i,j}$, has the same structure for either single or multiple rinsing, because the rinsing mechanism is the same. The only difference is the cleanness and flow rate of the incoming water to each rinsing tank. The function can be expressed as:

$$g(r_r,F_r,C_r,C_{r,in})=r_r(t)\big(H(t_0)-H(t_e)\big)+F_r(t)\big(C_{r,in}(t)-C_r(t)\big) \tag{9}$$

$$r_r(t)=k_r\gamma_r(t_0)\big(\theta(W_r(t)-W_r(t_0))-C_r(t)\big) \tag{10}$$

where k_r is the mass transfer coefficient
$W_r(t)$ is the amount of the dirt on parts in a rinsing tank at time t
$W_r(t_0)$ is the amount of the dirt on parts when entering the rinsing tank
$\gamma_r(t_0)$ is the looseness of dirt on parts when entering the rinsing tank is the unit conversion factor.

This model is associated with a number of initial conditions, such as the initial contamination level in the rinsing tank and the initial dirtiness of the parts, that must be specified.

Integrated Parts Processing Model

The dirt or other materials on the surface of parts are removed by using chemical, mechanical, thermal, electrical, and/or radiated energy in cleaning tanks. 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 by drag-out to rinsing tanks. The model is to describe the surface cleanness of parts in any cleaning and rinsing tank at any time t. This is critical to the plating operation in a plating tank. In principle, the dirt removal rate is proportional to the cleanness of the rinse water and the dirtiness of the parts. Thus, we have,

$$A_p\frac{dW_p(t)}{dt}=\sum_{i_c=1}^{N_c} r_{c_i}(t)\big(H_i(t_0)-H_i(t_e)\big)+$$

$$\sum_{i=1}^{N_r} \sum_{j=1}^{N_{r_i}} r_{r i,j}(t)\left(H_{i,j}(t_0) - H_{i,j}(t_e)\right) \tag{11}$$

where A_p is the total surface area of parts in a barrel. All other variables are defined in the preceding equations. The initial conditions for cleaning and rinsing are also stated in those equations.

Integrated Plating Model

A plating tank usually consists of a number of slots, each of which can accommodate a barrel of parts for plating. A number of plating operations can occur simultaneously in these slots. A plating deposition model can be developed based on basic electrochemical principles. According to Faraday's Law, the amount of metal deposition can be:

$$\frac{dW_m(t)}{dt} = \frac{\mu\, s\, M_w}{n\Im} I(t) \tag{12}$$

where $W_m(t)$ is the mass of metal deposited
M_w is the molecular weight of the metal
$I(t)$ is the applied or induced current
s is the stoichiometric coefficient of the species
n is the number of electrons transferred for each molecule of metal deposited
μ is the current efficiency
ζ is the Faraday constant (96,500 C/g-equivalent).

In the plating mode, the electrolyte concentration dynamics follows the mass balance below.

$$V_p \frac{dC_i(t)}{dt} = F\left(C_{i,in} - C_i\right) + R_{i,chem} \cdot V_p \pm \varepsilon \frac{dW_i}{dt}\left(H(t_0) - H(t_e)\right) \quad I = 1,2,\cdots,N_p \tag{13}$$

where C_i is the mass concentration of substance I in the electrolyte
$C_{i,in}$ is the in-flow mass concentration of substance I
$C_{i,out}$ is the out-flow mass concentration of substance I
$R_{i,chem}$ is the chemical reaction of substance I in the solution
V_p is the volume of the solvent in the plating bath
F is the volumetric water flow rate
ε is the electrochemical reaction coefficient
N_p is the number of slots in a plating tank.

Note that after the plated parts are withdrawn, the tank is in the idle mode, but water continuously flows in. Thus, a pulse function must be applied to reflect this change. Because there are various plating metals, the model parameters and coefficients are different. The basic model structure is applicable to all, however.

Sludge Predictive Model

The base sludge can be found in all tanks. The sludge in cleaning tanks includes the dirt (oil, soil, grease, solid particles, etc.) removed from the surface of parts and that of the chemicals used to remove the dirt. In rinsing tanks, the sludge resulting from natural contaminants in make-up water or rinsewater and that resulting from drag-out from cleaning tanks should be considered. Thus, the total sludge is the sum of all of them. Detailed formulation of each type of sludge can be found in Huang and his associates.[17]

Model-based Optimization

The P3-oriented optimization is two-fold: waste minimization and optimal production. As stated before, these two objectives are consistent. That is, the minimization of the quantity and toxicity of end-of-process waste is equivalent to the minimization of the chemical, water, and energy consumption. This minimization must follow process operational constraints, however, to meet cleaning, rinsing, and plating qualities. A general optimization model structure can be derived as follows:

$$\min\ J = \sum_i \alpha_i Q_{c,i} + \beta \sum_j F_j + \gamma \sum_k E_k \tag{14}$$

where the three terms on the right side are the cost for chemicals used in all cleaning tanks and plating tank, the cost for fresh water, and the cost for the energy consumed in the plating line. The objective function is subject to the following types of constraints.

Quality Constraints

These include the restriction of dirt residue on the parts after each cleaning and rinsing step. It must not be higher than the upper limit. The thickness of the metal coating on the surface of parts must be within a pre-specified range. These restrictions result in a number of inequality constraints.

Process Specification Constraints

The upper and lower limits for solvent concentrations and those for water flow rates, and the processing time for each step of operation should all be expressed as inequalities.

Model Equality Constraints

The prediction of process behavior must be based on the models described above. These models, therefore, become the basis of the optimization.

Environmental Constraints

Constraints on the concentrations of specific pollutants in wastewater must be specified. Note that there will be no need to have a constraint on the quantity of wastewater, because it must be minimized.

Note that it is possible that no feasible solution can be found if the environmental constraints are too strict. In this case, the optimization procedure will suggest the minimum requirement of wastewater treatment capacity to be installed in a plant.

P3 Applications

Over the past years, Huang's research group has developed six P3 technologies that can be used to drastically reduce waste and greatly improve production with no or negligible capital cost. These are listed below.

- Operating technology for optimal chemical concentration determination
- Operating technology for optimal rinse water flowrate determination
- Operating technology for minimum sludge generation
- Design methodology for developing an optimal water use and reuse network
- Design and operating technology for optimal rinsing water neutralization
- Design and operating technology of reversed drag-out for maximum reduction of chemicals, water, and sludge.

The applications of two P3 technologies are briefly described below.

Optimal Solvent Reduction in a Cleaning System

In a soak cleaning tank, the original solvent concentration is 10 percent. Each barrel of parts is scheduled to have four min of processing in the tank. The chemicals are added in about every 20 barrels of the cleaning interval. It is required that the dirt residue on parts surface be no more than 20 percent. It has been found that the last several barrels of parts in every 20-barrel cycle are not clean enough in operation. The plant is seeking an opportunity to improve cleaning quality without increasing chemical consumption and without changing the chemical addition pattern.

Using the cleaning model developed in the preceding section, computer simulation has resulted in the following: Figure 5a depicts the dynamic responses of the parts cleaning and chemical consumption in the tank, using the original operational procedure. The dotted curves represent the dirt removal of those barrels consecutively. It shows that the first barrel has only four percent of dirt remained after cleaning, while the 20th barrel has a dirt residue of 37 percent. At the end of the cycle, the chemical concentration in the tank is only 3.2 percent. The simulation shows that the last five barrels are not clean enough (> 20% dirt residue). The original procedure is simple, but is proven not acceptable.

This process can be optimized to improve cleaning efficiency and to reduce chemical consumption, while the production rate is kept nearly the same (20.5 barrels after optimization, slightly more productive). As shown in Fig. 5b, the dirt residue of the part surface of each barrel can be controlled to 20 percent or slightly lower; there is no barrel overly cleaned or unqualified. After a cycle of 20.5 barrels of cleaning, the chemical concentration in the tank is 5.2 percent, which is noticeably higher than 3.2 percent. The chemical consumption per barrel cleaning is reduced from 0.328 to 0.26 unit on average. This implies 20.8 percent savings of chemicals, or reduction of waste by nearly the same percentage. The only inconvenience in operation using this improved operational strategy is uneven processing time of each barrel. Apparently, this inconvenience will no longer exist if the process is automatically controlled.

Optimal Design of a Water Use & Reuse Network

A general electroplating process flowsheet is illustrated in Fig. 6a. Fresh water is sent to each rinsing system where countercurrent rinsing is already implemented. The used water from each rinsing system is mixed and sent to a WTF. If there is any water reuse adopted, it is usually based only on experience and thus is usually far below optimal. Recently, Huang's research group has introduced a novel methodology for designing an optimal water use and reuse network (WURN) for rinsing systems in plating lines.[18~20] This methodology is for determination of the optimal distribution of fresh water and used water in different rinsing steps. Figure 6b depicts the general structure of a WURN. The methodology examines the feasibility of every used water stream for potential reuse in appropriate rinsing steps.

The design of a WURN is a complicated optimization problem. The objective of the design is to minimize the total annualized cost for the network. This cost covers freshwater consumption and expense for installing pipes for water distribution. The equality and inequality constraints include the integrated process models described in the previous section, the basic mass balances for stream mixing and splitting necessary for water redistribution, the component mass balances, and other process and environmental constraints. The optimization is solved using the so-called network superstructure concept in order to guarantee global optimality.[18-20]

The design methodology has been used to successfully design a number of WURNs for different plating lines. Figure 7a illustrates a practical industrial example. Detailed information about the process is not included because of confidentiality. It is shown that this plating line contains three rinsing subsystems, each of which has two rinse tanks in series with countercurrent rinsewater flow. The total freshwater flow rate is 16 gal/min. By using the design methodology, an optimal solution is identified as shown in Fig. 7b. With the installation of the WURN, the fresh water consumption is reduced to 9 gal/min, a reduction of about 44 percent of water or wastewater, while rinsing quality is also guaranteed.

Concluding Remarks

Effective P2 always requires significant capital investment. This has hindered wide application of effective but expensive P2 technologies. On the other hand, a large number of P2 technologies focus on the reduction of end-of-plant waste, rather than end-of-line waste. This is really a passive way for P2. In this paper, we introduce a new concept: profitable P2 (*i.e.*, P3). This concept not only inherits the merit of traditional P2, but reflects economic incentives as well. The central point of P3 is the process that generates waste. Thus, the minimization of end-of-process is the focus. Initial applications of the two P3 technologies have demonstrated the attractiveness and opportunities for the industry to simultaneously realize P2 and optimal production. Plants should be able to make profits through implementing P3 technologies. It is believed that full development of P3 technologies will soon become a new direction in environmental protection.

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@inproceedings{Lou2000ProfitablePP, title={Profitable Pollution Prevention: Concept, Fundamentals & Development}, author={H. R. Lou and Yinlun Huang}, year={2000} }. H. R. Lou, Yinlun Huang. Industrial pollution prevention (P2) is a national strategic goal for effective environmental protection. Over the past decade the electroplating industry has implemented numerous basic P2 techniques that have greatly reduced the quantity and toxicity of end-of-plant waste. In recent years, various new P2 technologies have been developed for technology change material substitution, in-plant recovery/re The Pollution Prevention Act (PPA), signed by President George Bush on November 5, 1990, established a national policy, known as the waste management hierarchy, that stated: â— Pollution should be prevented or reduced at the source â— Pollution that cannot be prevented should be recycled in an environmentally safe manner â— Pollution that cannot be prevented or recycled should be treated in an environmentally.Â The following questions address the concept delineated in the Presidential Memorandum, as well as additional opportunities to prevent pollution and reduce waste generation associated with landscaping operations.Â Pollution prevention/environmental impact reduction checklist for landscaping.