

## A Fuzzy-Logic-Based Approach to Cleaner Production Evaluation for Surface Finishing Plants

by Arnesh Telukdarie\*, Chris Brouckaert and Yinlun Huang

**The evaluation of environmental cleanliness of an electroplating facility, as compared to the best available practice, has been a challenge, particularly in small or mid-sized plants. This is mainly due to the fact that the detailed plant data necessary for evaluation is always difficult to obtain completely and precisely. To alleviate the data-scarce and lack-of-skill related problems in environmental performance evaluation for cleaner production, a fuzzy-logic-based decision analysis approach is introduced in this paper. The attractiveness of the approach is illustrated by the analysis of rinse system management. The approach is general and thus is suitable for any type of environmental cleanliness problems in the electroplating industry.**

The electroplating industry is regarded as one of the most polluting industries worldwide.<sup>1-3</sup> In plants, electroplating processes generate continuously huge amounts of hazardous or toxic wastes. Needless to say, applications of effective pollution prevention strategies in plants have been considered an urgent and continuous effort for cleaner production (CP).<sup>4,5</sup> Here, we are referring not to the cleaning processes used in electroplating plants, but rather increased cleanliness in the entire operating regime. According to the United Nations Environment Program, CP is defined as "the continuous application of an inte-

grated preventive environmental strategy to processes, products and services, so as to reduce the risks to humans and the environment".<sup>6</sup>

A critical step towards CP is environmental impact assessment, which requires a systematic evaluation of process operation and management, so that specific needs for improving operational efficiency and waste reduction can be identified.<sup>7,8</sup> Industrial practice has shown that the electroplating industry has been the subject of many types of environmental auditing, ranging from a simple half-hour questionnaire survey to a sophisticated month-long detailed study.<sup>8-10</sup> Local municipalities usually require a simple audit for monitoring general compliance for environmental permits in plating companies, while a CP audit may need much more detailed information on chemical, water and energy consumption, along with operational statistics. The detailed studies are normally performed to compare the company operations to some known best practice.

A detailed environmental evaluation always expects the availability of a large amount of quite accurate data. This is usually difficult for most small or medium-sized plating companies to provide. With limited data, only highly skillful auditors may be able to extract valuable information about plant environmental performance and to conduct adequate evaluation. Needless to say, if such expert knowledge can be encoded into a computer-aided tool, then environmental auditing with limited data can be performed in a much more systematic and effective way for wide applications. In this paper, a fuzzy-logic-based approach is introduced to represent and manipulate expert knowledge and to provide satisfactory evaluation results. A case study on rinse system management is presented to

### Nuts & Bolts: What This Paper Means to You

Evaluating environmental cleanliness in a plating plant is challenging. Much of this analysis is subjective. A unique mathematical approach, using "fuzzy logic," is a useful tool for such analysis. Despite the whimsical term, which finds use in another context in election campaigns, the math allows one to rate various factors "on a scale of 1 to 10," and get meaningful assessments of what factors are most important in obtaining clean production. An eye-opening example is given for rinsing.

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demonstrate the effectiveness of the approach and the attractiveness in computerized environmental auditing.

## Process and environmental concerns

Figure 1 depicts a typical electroplating process, where major process operations (such as cleaning, rinsing and plating), process inputs (such as metal parts, water, chemicals and electricity) and outputs (such as plated parts and waste) are detailed. In operation, the parts, either in barrels or on racks, are cleaned and activated in alkaline and acidic solutions in steps before plating. After each step of cleaning or plating, parts are rinsed in a system that may contain one or more rinse units. In the plating unit, the metal coating is electrodeposited on the surface of parts. The plated parts undergo post processing before leaving the line. The operations generate chemical- and metal-containing waste in almost all the operational steps. According to Lou and Huang<sup>5</sup> and Luo, *et al.*,<sup>11</sup> the waste can be classified into two categories: unavoidable and avoidable. While the former comes from dirt removal from the surface of parts after using chemicals, energy and water, the latter is generated from excessive use of chemicals and water. Waste reduction in an electroplating plant is essentially the minimization of the avoidable waste. In this regard, process optimization and management improvement are the key for CP.<sup>12,13</sup>

To determine the efficiencies of chemical, water and energy use, or to identify the bottleneck of waste minimization in production, all operational units shown in Figure 1 should be carefully evaluated. To facilitate this evaluation, a proper system categorization would be of great help. In this work, the following categories, together with their justification, are used:

**1. Process chemical consumption.** Large amounts of chemical solutions are consumed daily in cleaning and electroplating operations. The chemicals must be optimally used so that chemical consumption can be minimized while the cleaning and plating qualities are also guaranteed.

**2. Water consumption.** The actual water flows in all the rinse steps must be evaluated. This is critical for identifying the best opportunities for water use and reuse.

**3. Rinse management.** The rinse effectiveness must be ensured as it is directly related to the use of the minimum amount of water necessary to rinse the chemical solutions carried into the rinse units from the proceeding cleaning or plating units.

**4. Production.** The measurement and control of production (*e.g.*, the total surface area of the parts to be coated) are crucial for CP effectiveness.

**5. Wastewater treatment plant (WWTP) chemicals.** The efficiency of chemical treatment of wastewater in a WWTP is directly related to waste reduction and thus should also be evaluated.

**6. WWTP equipment.** The availability and operational status of the equipment in the WWTP are crucial for waste treatment effectiveness.

**7. Sludge reduction.** The areas where sludge is generated and managed must be checked to ensure minimal sludge generation for disposal.

**8. Occupational health and safety (OHS).** This is to evaluate the employee's health and safety. The impact of the types of chemicals and working environment must be investigated.

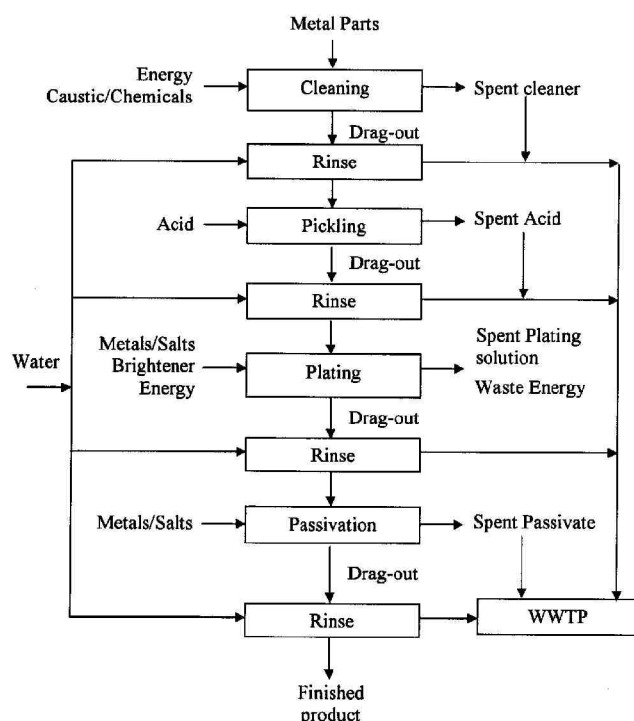


Figure 1—Plating process materials in and out.

## Fuzzy logic-based cleaner production evaluation approach

While evaluations of the eight categories listed above are essential, the data availability and quality in each category are always questionable. Fuzzy logic can be a viable tool in CP evaluation when the available information is imprecise, incomplete and uncertain.<sup>14,15</sup> Fuzzy logic utilizes rigorous fuzzy mathematics to process and manipulate non-ideal information or ill-defined data in a systematic way. By fuzzy logic, expert knowledge, particularly expert's heuristic knowledge, can be readily represented and integrated in a consistent way into a CP evaluation system.<sup>16</sup> The resulting fuzzy models can be used to effectively weigh the factors in each category in evaluation. A total impact of the factor importance on CP can be reasonably assessed. In the following text, a fuzzy-logic-based decision-analysis method is introduced by resorting to a fuzzy-logic-based multi-objective decision making method.<sup>17</sup>

Assume that there are  $N$  objectives to be considered for CP, *e.g.*, minimum process chemical consumption and minimum sludge generation. The set of objectives,  $O$ , can be defined as:

$$O = \{o_1, o_2, \dots, o_N\} \quad (1)$$

Also assume that there are  $M$  factors for CP evaluation. These factors are defined as the set,  $A$ .

$$A = \{a_1, a_2, \dots, a_M\} \quad (2)$$

In evaluation, the impact of each factor ( $a_i$ ) on each individual objective ( $o_j$ ) is first defined by a fuzzy membership function,  $\mu_{o_j}(\alpha_i) \in [0, 1]$ ,

where  $i = 1, 2, \dots, M$

and  $j = 1, 2, \dots, N$ .

The membership functions can be continuous or discrete, and be determined based on engineering knowledge, subjective preference and/or available data.<sup>14</sup>

The task of evaluation is to assess how the pre-defined objectives are achieved. Mathematically, this evaluation can be obtained through defining the following decision function,  $D$ :

$$D = a_1 \cap a_2 \cap \dots \cap a_N \quad (3)$$

Note that the importance of each objective to the overall CP objective may be different in the view of the decision maker. Moreover, data availability and quality for assessment may also be different for each objective-based evaluation. To make the evaluation more reasonable, a set of preference values should be defined as an association with the specific objective set as shown below.

$$B = \{b_1, b_2, \dots, b_N\} \quad (4)$$

where each preference has a value between 0 and 1.

By integrating the preferences, the decision-analysis function in Eq. (3) can be advanced as follows:

$$D = M_1(o_1(a_1), b_1) \cap M_2(o_2(a_2), b_2) \cap \dots \cap M_r(o_r(a_r), b_r) \quad (5)$$

where the decision measure,  $M$ , for the factor,  $a_i$ , is defined below:

$$M_j(o_j(a_i), b_j) = b_j \rightarrow o_j(a_i) = \bar{b}_j \vee o_j(a_i) \quad (6)$$

The evaluation of each decision measure can be conducted as follows:

$$\mu_{M_j}(a_i) = \max[\mu_{\bar{b}_j}(a_i), \mu_{o_j}(a_i)] \quad (7)$$

Or more concisely, the decision-analysis model in Eq. (5) can be rewritten as:

$$D(a_i) = \bigcap_{j=1}^M (\bar{b}_j \vee o_j(a_i)) \quad (8)$$

With this decision function, a fuzzy MIN-MAX algorithm is used to identify the most important factor(s) that are critical for CP evaluation. This algorithm has the following two-step operations:

1. To determine the minimum importance of the objective  $\mu_{M_j}(\alpha_i)$ , for each factor  $a_i$ . This can be accomplished by performing the following MIN operation:

$$\mu_D(a_i) = \min[\mu_{M_1}(a_i) \quad \mu_{M_2}(a_i) \quad \dots \quad \mu_{M_N}(a_i)] \quad (9)$$

or

$$D(a_i) = \bigcap_{j=1}^N \mu_{M_j}(a_i) \quad (10)$$

2. To identify the most important factor for CP by performing the following MAX operation:

$$\mu_D(a^*) = \max[\mu_D(a_1) \quad \mu_D(a_2) \quad \dots \quad \mu_D(a_m)] \quad (11)$$

or

$$D(a^*) = \bigcup_{i=1}^M D(a_i) \quad (12)$$

The two-step decision analysis will lead to the identification of the most important factor,  $a^*$ , for production improvement. In many applications, it is preferred to give a single score as an indicator of

the CP status for the plant. The following formula is suggested for determining the overall CP status.

$$S = \sum_{i=1}^M \mu_D(a_i) V(a_i) \times 100\% \quad (13)$$

where  $V(a_i)$  is a fuzzy number of factor  $a_i$ . The definitions of the fuzzy numbers are based on experience.<sup>16,18-20</sup> In the case study below, a detailed example of defining the fuzzy numbers of all six factors is given.

## Case study on rinse management

The effectiveness of the fuzzy decision analysis approach is illustrated by applying it to a rinse management assessment in an electroplating plant.

*Problem definition.* In this study, the factors critical for rinse management are defined below.

$$A = \{a_1, a_2, \dots, a_6\} = \{DT, HG, AG, IN, BM, FC\} \quad (14)$$

where

$DT$  is the drip time that parts stay above a tank before moving to the next tank,

$HG$  is the orientation of the parts hanging on a rack,

$AG$  is the solution agitation by air or rack movement,

$IN$  is the water flow through a rinse tank,

$BM$  is the back mixing of the rinse due to via interconnecting rinse tanks (counterflow) and

$FC$  is the flow control of rinse water to a rinse tank.

The analysis for CP is performed by focusing on the impacts of the six factors on the four objectives below.

$$O = \{o_1, o_2, \dots, o_4\} = \{CC, P, WC, C\} \quad (15)$$

where

$CC$  is the chemical consumption,

$P$  is the production rate,

$WC$  is the water consumption and

$C$  is the cost for wastewater treatment and due to production loss.

*Available information.* In this application, the importance of each factor to each objective was obtained by the CP evaluators. These data are compiled in the following notation suggested by Zadeh.<sup>21</sup>

$$\alpha_1 = \frac{0.8}{DT} + \frac{0.5}{HG} + \frac{0.2}{AG} + \frac{0.1}{IN} + \frac{0.1}{BM} + \frac{0.15}{FC} \quad (16)$$

$$\alpha_2 = \frac{0.4}{DT} + \frac{0.15}{HG} + \frac{0.2}{AG} + \frac{0.15}{IN} + \frac{0.1}{BM} + \frac{0.1}{FC} \quad (17)$$

$$\alpha_3 = \frac{0.7}{DT} + \frac{0.2}{HG} + \frac{0.1}{AG} + \frac{0.7}{IN} + \frac{0.1}{BM} + \frac{0.8}{FC} \quad (18)$$

$$\alpha_4 = \frac{0.2}{DT} + \frac{0.2}{HG} + \frac{0.1}{AG} + \frac{0.1}{IN} + \frac{0.1}{BM} + \frac{0.15}{FC} \quad (19)$$

In the above notation, the numerator and denominator of each fraction are, respectively, the fuzzy number ( $\mu_{o_j}(\alpha_i)$ ) as the importance to the objective and the corresponding factor ( $a_i$ ); the symbol, “+”, denotes a grouping operation rather than the usual addition operation.

In this application, the importance of each objective to the overall cleaner production evaluation is subjectively provided by a CP evaluator as below:

$$B = \{b_1, b_2, b_3, b_4\} = \{0.9, 0.75, 1.0, 0.65\} \quad (20)$$

The subjective values reflect the following basic analysis for rinse management:

1. The water consumption objective ( $o_3$ ) is the most important ( $b_3 = 1$ )
2. The chemical consumption ( $o_1$ ) is very important ( $b_2 = 0.9$ )
3. The production ( $o_2$ ) due to rinse management is considered fairly important ( $b_2 = 0.75$ ) and
4. The additional cost ( $o_4$ ) is the least important ( $b_4 = 0.65$ ).

*Evaluation.* According to Eq. (8), or more clearly, Eqs. (7) and (9), the following manipulations are performed:

$$D(a_1) = D(DT) = (0.1 \vee 0.8) \wedge (0.25 \vee 0.4) \wedge (0 \vee 0.7) \wedge (0.35 \vee 0.2) = 0.35 \quad (21)$$

$$D(a_2) = D(HG) = (0.1 \vee 0.5) \wedge (0.25 \vee 0.15) \wedge (0 \vee 0.2) \wedge (0.35 \vee 0.2) = 0.2 \quad (22)$$

$$D(a_3) = D(AG) = (0.1 \vee 0.2) \wedge (0.25 \vee 0.2) \wedge (0 \vee 0.1) \wedge (0.35 \vee 0.1) = 0.1 \quad (23)$$

$$D(a_4) = D(IN) = (0.1 \vee 0.1) \wedge (0.25 \vee 0.15) \wedge (0 \vee 0.7) \wedge (0.35 \vee 0.1) = 0.1 \quad (24)$$

$$D(a_5) = D(BM) = (0.1 \vee 0.1) \wedge (0.25 \vee 0.1) \wedge (0 \vee 0.1) \wedge (0.35 \vee 0.1) = 0.1 \quad (25)$$

$$D(a_6) = D(FC) = (0.1 \vee 0.15) \wedge (0.25 \vee 0.1) \wedge (0 \vee 0.8) \wedge (0.35 \vee 0.15) = 0.15 \quad (26)$$

The above evaluation results provide detailed, specific directions for where and to what level the management should be improved.

Also, according to Eq. (12), we have:

$$D(a^*) = 0.35 \vee 0.2 \vee 0.1 \vee 0.1 \vee 0.1 \vee 0.15 = 0.35 = D(a_1) \quad (27)$$

This evaluation indicates that drip time (DT, or  $a_1$ ) is most critical, while chemical consumption (CC, or  $a_3$ ), the production rate (P, or  $a_4$ ) and the water consumption (WC, or  $a_5$ ) are the least important in this case.

If the values of the factors concerned are available in a plant, the rating of the given rinse management system can be evaluated using Eq. (13) as follows:

$$S = (0.35V(DT) + 0.2V(HG) + 0.1V(AG) + 0.1V(IN) + 0.1V(BM) + 0.15V(FC)) \times 100\% \quad (28)$$

The above formula contains six fuzzy variables for all six factors. These fuzzy variables are defined using fuzzy numbers as shown in Tables 1 thru 6. Note that these numbers were selected based on experience, assisted by an existing database system that contained a huge number of data based on the auditing of 20 plants.<sup>20</sup> Table 7 gives the overall ratings for the four cases where the values of the factors are different. The overall rating for each case is listed in the column with the heading of Fuzzy Evaluation. For comparison, the values are compared with those obtained by an existing database system shown in the last column of Table 7.<sup>20</sup>

## Conclusion

Evaluation of cleaner production in an electroplating installation is always very challenging, especially when the available production and environmental data is incomplete, imprecise and uncertain. This is particularly true for evaluation in small or medium-sized plants where environmental auditing expertise is always insufficient. The fuzzy-logic-based decision analysis approach described in this paper demonstrates an effective way for fast and systematic assessment of plant practice for economically sound waste reduction. This approach is applicable to any type of plating line with any capacity.

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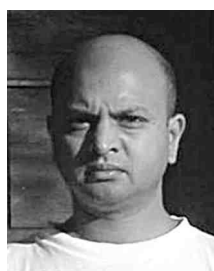
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**Table 1**  
Fuzzy membership definition for drip time

Fuzzy Number	Time Range (sec)
0.05	0-4
0.3	5-9
0.51	10-14
0.7	15-19
1	>20

**Table 2**  
Fuzzy membership definition for parts hanging mode

Fuzzy Number	Liquid Draining Effectiveness
0.05	No cup-shaped parts entraining liquid, flat sheets hung with one corner facing down, draining time less than 3 sec.
0.3	Some liquid entrapment by cup-shaped parts, flat sheets hung with the shortest end facing down, 3 to 8 sec of draining time
0.5	Large liquid entrapment by cup-shaped parts, sheets hung with the shortest end facing down, 8 to 12 sec of draining time
0.83	Large liquid entrapment by cup-shaped parts, sheets hung with a longer side facing down, 12 to 15 sec of draining time
1	Large liquid entrapment by cup-shaped parts, sheets hung with a longer side facing down, draining time greater than 15 sec.

**Table 3**  
Fuzzy membership definition for agitation.

Fuzzy Number	Agitation Status
0.18	No agitation or liquid motion in any tanks
0.3	Visible agitation or rack motion on some cleaning tanks
0.5	Visible agitation or rack motion on all cleaning tanks
0.81	Visible agitation and liquid motion on all process tanks
1	Heavy agitation and liquid motion on all process tanks

**Table 4**  
**Scoring of process inlet/outlet**

Fuzzy Number	Design
0.2	Inlet located at the top of the tank and outlet next to it on the top of the tank
0.3	Inlet located at the top of the tank and the outlet on the top of the tank but on the opposite end
0.6	Inlet located at the top of the tank and the outlet on the bottom of the tank but on the opposite end
0.7	Inlet located at the bottom of the tank and the outlet at the top of the tank but on the opposite end and the tank not agitated
1	Inlet located at the bottom of the tank and the outlet at the top of the tank but on the opposite end and the tank agitated

**Table 5**  
**Fuzzy membership definition for back mixing**

Fuzzy Number	Rinse System Design Related Water Flow
0.05	Rinse tanks linked across the bottom or top, allowing continuous flow of water
0.3	Small pipes linking rinse tanks, resulting in continuous back mixing; high spills between rinse tanks during rack submersion
0.56	Rinse tanks linked across the bottom or top, allowing moderate water flow, or very small water overflows to the next rinse tank during rack submersion.
0.8	Rinse tanks linked across the bottom or top, allowing very little water flow, or some water overflows to the next rinse tank during rack submersion
1	No back mixing, tanks not linked

**Table 6**  
**Fuzzy membership definition for flow control**

Fuzzy Number	Flow Control Design
0.05	Rinse water supplied by non-restricted pipe, separate inlet for each rinse tank
0.3	Rinse water supplied by a valve on the end of a pipe with some control
0.6	Static tanks dumped regularly or with moderate flow control but without rinse recovery system, and no rinse water redirecting
0.72	Static tanks dumped regularly or with moderate flow control but without rinse recovery system, and rinse water redirectable
1	Continuous flow control via predetermined rinse water requirements, all water recovered via low flow rinse back into plating tank

**Table 7**  
**Fuzzy evaluation and comparison with an existing system**

Case No.	Drip Times	Hanging	Agitation	In-Out	Back Mixing	Flow Control	Fuzzy Evaluation	Fleming's Evaluation
1	0.06	0.06	0.30	0.30	0.06	0.05	10.65	6.70
2	0.70	0.30	0.50	0.30	0.30	0.30	46.00	41.70
3	0.51	0.83	0.50	0.70	0.56	0.72	62.80	65.00
4	1.00	0.83	1.00	1.00	1.00	1.00	96.60	96.70