CLEANER PRODUCTION EVALUATION MODEL FOR SURFACE FINISHING PLANTS*

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The evaluation of an electroplating facility as compared to best available practice can prove a challenge as the obtaining of detailed data is a problem. This availability of data could compromise the evaluation process and would also result in drawn out time frames. Various models exist which are either over simplified and do not reflect the true status of the company or are too complex and require a high level of skill and huge time investments. It is aimed to present a model that uses fuzzy evaluation systems together with process models to determine the operational status of the company. Minimum data is required as compared to previous models. The system would then generate a profile of the company as compared to best available practice.

1. Introduction

The surface plating industry has been the subject of many auditing systems, which range from simple half hour questionnaires[1-3], , to detailed studies, which require up to three weeks to complete[4]. The outputs from these studies represent a basic or a detailed view of the operation of a surface finishing facility. It has been noted that local municipalities require a simple audit for permitting of companies while cleaner production audits require detailed chemical, water and operational statistics. The objectives of the latter studies are normally to compare the companies operation to some known best practice principals.

The challenge is to determine accurate data from small to medium size enterprises where such detailed information is not normally recorded. This would imply using a highly skilled auditor and an informed individual representing the company spending a considerable amount of time on sourcing and sorting of data. The data would then need to be captured into an auditing tool. This tool should ideally compare the company data to best available practice. The tool would then have to churn out a comparative company status. This seems like a difficult enough task without considering the variety of processes for surface treatment. The system cannot be generic and the auditor needs to know the different processes.

The aim of this paper is to develop a user friendly system to conduct a detailed environmental audit at metal finishing companies so as to serve as an indication of the company's status relative to best available practice. The aim of development of such a model is to reduce the skills level for an environmental review to a plant operator. This would be achieved by using fuzzy logic and basic computer software.

2. Existing systems

A search for auditing systems reveals a variety of system. These systems differ greatly in that some are over simplistic[1-3] and ineffective to systems that are detailed but require large amounts of inputs[4]. The most comprehensive system is Flemming. This system is based on European standards and limits. The system is spreadsheet based and requires detailed understanding of both the evaluation system and the company.

The greatest challenge for system development is representation of the process as "seen" by plant personnel, in other words verbal inputs. The system must also be able to consider multivariables and conduct decision-making, based on operator inputs. Hence it was decided to use fuzzy logic to capture information. Fuzzy logic can be considered due to the “soft” linguistic system variables. It is ideally applied to systems with a continuous range of truth-values.

The system also needs to be user friendly and spreadsheets as an interface is less than ideal, hence a visual basic program was developed for user interface. The relevant questions are asked under the different categories. A different visual basic screen represents each category.

2.1 Approach

Development of a single fuzzy logic system for the entire plant would be an almost impossible task hence the plant can be categorized into subsections. For the purpose of this system the plant was categorized into the following sections:

- *Sludge*-Sludge generated plant-wide and handled at the wastewater treatment facility. The amount of sludge is proportional to plating chemical losses.
- *Waste water treatment plant chemicals*-Chemicals used for treatment of wastewater at the wastewater treatment facility. This is an indication of the chemical losses from the plant.
- *Wastewater treatment plant equipment*- The equipment used at the wastewater treatment plant must be effective in measurement and control. Calibration is also a key factor.
- *Process Chemical*-Process chemicals must be used for the plating process and not contribute to waste generation. Optimum management is required.
- *Occupational health and safety*-The employee’s health is a major concern especially since such hazardous chemicals are being used.
- *State of the rinsing system*- The configuration of the rinsing system at a surface finishing plant could result in low or very high water consumption.
- *Water consumption*- The actual water flow is an important factor in an audit of a plating plant. Excessive water could result in an oversized treatment process.
- *Production*-The way things are done. Good operational practices imply a reduction in rejects and waste thus ensuring optimal use of resources.

The final output from the model would represent these categories of the company as key focus areas.

3. Multiobjective decision-making

The scope of this paper would include all of the above categories but the rinse tables would be used to illustrate fuzzy logic multi-objective decision function procedure[5,6]. The objective of the rinse tables being, determining the water consumption rating of the company[7].

The key objectives for the effective rinsing and water consumption at a surface finishing facility would be those factors that impact on water consumption and effective rinsing off, of chemicals. The output has to be a function representing all the objectives with consideration to their levels of importance. The fuzzy logic multi-objective decision function would assist in determining the weighing of each objective. This shall be used to determine the water consumption rating for the company.

The key variables (A), which contribute to water consumption, are:

- Drip times (DT)- The time the components are allowed to drip above the tank before being moved to the next tank
- Hanging (HG)- The orientation of the components on a jig.
- Agitation (AG)-The liquid movement created in a tank by air or jig movement.
- Inlet (IN)- The water flow inlet and outlet of a rinse tank
- Back mix (BM)- The mixing of process rinses due to connections of the tanks
- Flow control (FC)- The regulation of water to a rinse tank

Hence defining set A:

$$A = \{ DT, HG, AG, IN, BM, FC\}$$

The fuzzy logic multi-objective decision function is tasked with determining the weighted importance of each variable in $\{ A\}$. This would be done using a set of criteria, say $\{ O\}$, that is important in the decision-making. The decision function essentially represents a mapping of the alternates in A to a set of ranks. This process would require subjective information from the decision authority concerning the importance of each objective $\{ O\}$.

The objectives for the rinse water problem are:

- Production (P)- The impact of rinsing on the rate of production, e.g. a longer drip time would result in increased production time.
- Cost(C)- The cost implications of the variables e.g. a longer drip time would result in a reduction in dragout chemicals and hence reduced chemical cost.
- Chemical Consumption (CC)- The impact the variables would have on the consumption of chemicals. The reduction in dragout would result in a reduction of chemical consumption.
- Water consumption (WC)- The water consumption is directly dependent on the rinsing required.

The set for the objective function can be defined as:

$$O = \{ P,C,CC,WC)$$

Let the degree of membership of DT in { O} be denoted as μ_{oi} (DT) and is the degree to which DT satisfies the criteria specified for this objective. The decision function D must satisfy all the decision objectives. The decision function is hence the intersection off all the objective sets.

$$D= P \cap C \cap CC \cap WC$$

And hence the grade of membership that the decision function, D, has for each alternate in { A} , is given by:

$$\mu_D (a) = \min [\mu_P(DT), \mu_C(DT), \mu_{CC}(DT), \mu_{WC}(DT)]$$

The optimum decision, a^*, will then be the alternate that satisfies:

$$\mu_D (a^*) = \max (\mu_D(a))$$

Where $a \in A$

The set of preferences { P} , which are values, which can be described as linguistic or intuitive with values in the interval [0,1]. These preferences are attached to each of the objectives to quantify the decision maker’s feelings about the influence that each objective should have on the chose alternate. Let the parameter, b_i, be contained on the set of preferences, { P} , where i =1,2,3,4. Hence we have the level of importance of each objective to the decision maker for each decision.

The form of the decision function, D, now changes to represent a combination of the weight and the objective function.

$$D = M(P,b_1) \cap M(C,b_1) \cap M(CC,b_1) \cap M(WC,b_1)$$

The decision measure for a particular alternative, a, can be replaced with:

$$M(P_i(a),b_i) = b_i \rightarrow P_i\,(a) = \bar{b}_i \vee P_i\,(a)$$

The statement "b_i implies P_i" indicates a unique relationship between a preference and its associated objective function. Hence a reasonable decision model will be the joint interaction of r decision measures:

$$D = \bigcap_{i=1}^{r} (\bar{b}_i \cup O_i)$$

And the optimum solution, a^*, is the alternate that maximizes D. If we define:

$$C_i = \bar{b}_i \cup O_i$$

Hence

$$\mu_{ci}\,(a) = \max\,[\mu_{bi}\,\text{–}(a),\ \mu_O\,(a)]$$

This implies that the optimium solution, expressed in membership form, is:

$$\mu_d\,(a^*) = \max[\min\{\mu_{ci}\,(a),\ \mu_{c2}\,(a)\ldots\ldots\ \mu_r\,(a)\}\ ]$$

The model is intuitive in that as the *ith* object becomes more important in the final decision, b_i increases, causing $\bar{b}_i$ to decrease which in turn causes C_i (a) to decrease, thereby increasing the likelihood that C_i (a) $=O_i$ (a), where O_i (a) will be the value of the decision function, D, representing alternate a. This process is repeated and a choice optimum a* is found.

3.1 Application of Multiobjective decision making to the rinse tables

The rinse tables determine the state of the rinsing system. The variables that would be considered would be:

First the alternatives had to be defined. For rinsing the alternatives are:

A = { Drip times (DT), Hanging (HG), Agitation (AG), Inlet (IN), Back mix (BM), Flow control (FC)}

Then the main objectives in evaluating and controlling the rinses were determined:

O = { Production, Cost, Chemicalconsumption, Water consumption}

The ranking for each of the above objectives will be rated as preferences:

$$P = \{ b_1, b_2, b_3, b_4\} \longrightarrow [0,1]$$

So inputting the relationship between each one of the alternatives and the objectives.

$$\underset{\leftrightarrow}{O}_1 = \frac{0.25}{DT} + \frac{0.2}{HG} + \frac{0.15}{AG} + \frac{0.15}{IN} + \frac{0.1}{BM} + \frac{0.2}{FC}$$

$$\underset{\leftrightarrow}{O}_1 = \frac{0.3}{DT} + \frac{0.15}{HG} + \frac{0.2}{AG} + \frac{0.15}{IN} + \frac{0.1}{BM} + \frac{0.1}{FC}$$

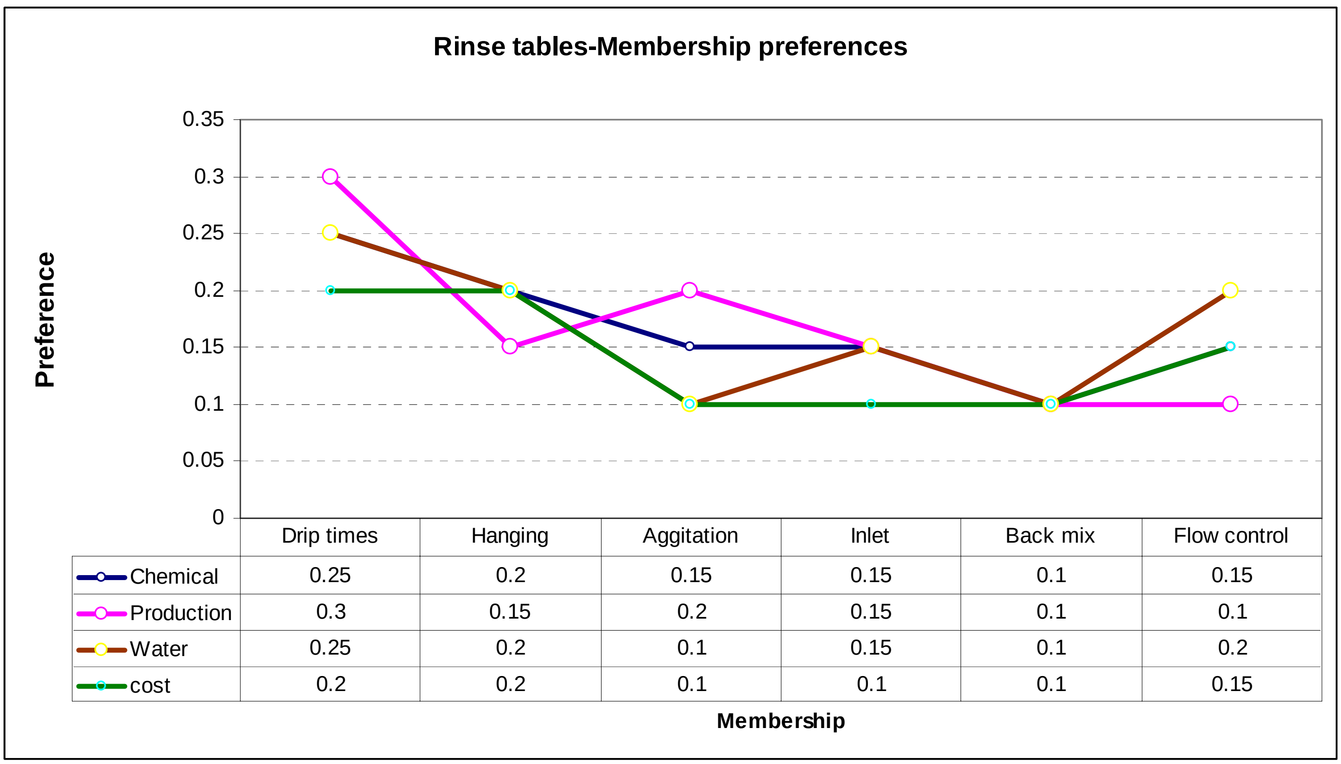
$$\underset{\leftrightarrow}{O}_1 = \frac{0.25}{DT} + \frac{0.2}{HG} + \frac{0.1}{AG} + \frac{0.15}{IN} + \frac{0.1}{BM} + \frac{0.2}{FC}$$

$$\underset{\leftrightarrow}{O}_1 = \frac{0.2}{DT} + \frac{0.2}{HG} + \frac{0.1}{AG} + \frac{0.1}{IN} + \frac{0.1}{BM} + \frac{0.15}{FC}$$

Now each of the preferences has to be rated on a scale of 0-1.

- b_1= 0.75 : The production rate is among the most important preference as this is the main objective of the business. But in the rinsing system it would not be as important as water consumption.
- b_2= 1 Water consumption is the key for the rinse tables. The objective being to achieve effective rinsing with minimum water consumption.
- b_3= 0.7 Cost is always a key variable and enjoys a medium to high rating.
- b_4= 0.6 Chemical consumption is a key objectives as losses implies greater water consumption

A graph can be plotted of each membership with respect to the preferences.



The complement of the preferences is required for the calculations so they are determined and substituted into the Decision making equation:

The decision-making equations:

$$D(a_1) = D(DT) = (\overline{b_1} V O_1)\Lambda(\overline{b_2} V O_2)\Lambda(\overline{b_3} V O_3)\Lambda(\overline{b_4} V O_4)$$

Now substituting into the above for each alternative:

$$D(a_1) = D(DT) = (0.25 V 0.7)\Lambda(0.3 V 0.75)\Lambda(0.25 V 1)\Lambda(0.2 V 0.7)$$
$$D(a_2) = D(HG) = (0.2 V 0.7)\Lambda(0.5 V 0.75)\Lambda(0.2 V 1)\Lambda(0.2 V 0.7)$$
$$D(a_3) = D(AG) = (0.3 V 0.7)\Lambda(0.25 V 0.75)\Lambda(0.1 V 1)\Lambda(0.3 V 0.7)$$
$$D(a_4) = D(IN) = (0.3 V 0.7)\Lambda(0.25 V 0.75)\Lambda(0.15 V 1)\Lambda(0.3 V 0.7)$$
$$D(a_5) = D(BM) = (0.3 V 0.7)\Lambda(0.25 V 0.75)\Lambda(0.1 V 1)\Lambda(0.3 V 0.7)$$
$$D(a_6) = D(FC) = (0.3 V 0.7)\Lambda(0.25 V 0.75)\Lambda(0.2 V 1)\Lambda(0.3 V 0.7)$$

Solving:

$D(a_1)= 0.25$
$D(a_2)= 0.2$
$D(a_3)= 0.1$
$D(a_4)= 0.15$
$D(a_5)= 0.1$
$D(a_6)=0.2$

With a maximum D $(a_1)= 0.25$. These values can now be used to determine the rinsing system environmental status. The final outcome indicates dripping times to be the highest priority. So to configure the output.

We consider the weighing in proportion to the output from the decision making process.

So:

State of the rinsing system =100*(0.25*DT + 0.2*HG + 0.1*AG + 0.15*IN + 0.1*BM + 0.2*FC)…………………………..Equation 1

Thus a rating on the scale of 0-100 would be generated this can be used to determine the potential water savings that can be achieved with changes to the rinsing system. The alternates for the fuzzy model need to be inputted by the operator and fuzzy questions needs to be generated for this purpose.

4. Fuzzy Alternates

The alternates need to be presented in a user friendly and easily identifiable format for the operator. This implies determining the appropriate questions and options for the operator under each of the alternates.

4.1 Dripping

Dripping is understood to be the length of time where the items are placed above the process bath before being moved to the next bath. If the time of dripping is too short, the liquid will not drip off completely before the item is moved on to the next tank.

A score for dripping is, therefore determined by the length of time for which the items are dripping above the bath, before being send on to the next bath.

The scores in Table 1 below are acceptable for racked goods but for barrel goods a more individual assessment can be necessary.

Table 1: Scoring by dripping (Racks or jigs)

Fuzzy association	Operator options
0.2	Jigs hangs for 0-4 seconds above tank before moving to next tank
0.4	Jigs hangs for 5-9 seconds above tank before moving to next tank
0.6	Jigs hangs for 10-14 seconds above tank before moving to next tank
0.8	Jigs hangs for 15-19 seconds above tank before moving to next tank
1	Jigs hangs for >20 seconds above tank before moving to next tank

4.2 Hanging

By hanging (suspension) we understand the physical way in, which the items are placed on the rack or jig. By tilting the items in order to avoid as much entrapments as possible, drag-out volume is minimised. For example, a cup-shaped item must always is racked upside-down; hollow tubes should be racked horizontal with a slight slope.

The score for hanging therefore depends on the efficiency of the liquid to drip off the item, before the items are lead to the next process. For barrel items the score should always be 1.

Table 2: Scoring by hanging (Racks or jigs)

Fuzzy association	Operator options
0.2	Pieces are hung so that there is no cup shaped sections entraining liquid. All flat sheets are hung with one corner facing down. Most liquid drains off in less than 3 seconds.
0.4	Pieces are hung so that there is some entrapment of liquid by cup shaped sections. All sheets are hung with one of the shortest end facing downwards. Most liquid drains off in less than 8 seconds.
0.6	Pieces are hung so that there is a large entrapment of liquid by cup shaped sections. All sheets are hung with one the shortest end facing downwards. Most liquid drains off in less than 12 seconds.
0.8	Pieces are hung so that cup shaped sections entraining liquid. All flat sheets are hung with the longer side facing down. Most liquid drains off once the jig is tilted and takes less than 15 seconds.
1	Pieces are hung so that cup shaped sections entraining liquid. All flat sheets are hung with the longer side facing down. Most liquid drains off in once the jig is tilted and takes greater than 15 seconds.

4.3 Agitation

By agitation we understand the physical motion of the liquid. If the liquid is not in motion or being agitated the replacement of the liquid film on the item surface will be very slow, and there is a risk to drag-out the chemicals before they have been exchanged from the surface layer. By heavy agitation and liquid motion the liquid film physically is replaced much faster. The agitation and liquid motion thus have high influence on the speed of the replacement of the liquid film.

Table 3: Scoring of Agitation (Liquid Motion)

Fuzzy association	Operator options
0.2	There is no agitation or liquid motion on any tanks.
0.4	There exists visible agitation or jig motion on some tanks. Either by air or jig motion.
0.6	There exists visible agitation or jig motion on all tanks. Either by air or jig motion.
0.8	There exists visible agitation and liquid motion on all process tanks. Either by air or jig motion.
1	There exists heavy agitation and liquid motion on all process tanks. Either by air or jig motion.

4.4 Inlet/Outlet

By inlet/outlet we understand the way in which the rinse water is physically let in and out of each rinse tank. The inlet/outlet has major influence on the physical passage of water in the rinse tank and on the utilisation as well. If the inlet and outlet physically are placed side by side there can be high water consumption but a very low rinsing efficiency.

Table 4: Scoring of Inlet/Outlet

Fuzzy association	**Operator options**
0.2	Rinse tank inlet is located at the top of the tank and the outlet is located next to it on the top of the tank.
0.4	Rinse tank inlet is located at the top of the tank and the outlet is located on the top of the tank, on the opposite end.
0.6	Rinse tank inlet is located at the top of the tank and the outlet is located on the bottom of the tank, on the opposite end.
0.8	Rinse tank inlet is located at the bottom of the tank and the outlet is located at the top of the tank on the opposite end. Tank is not agitated.
1	Rinse tank inlet is located at the bottom of the tank and the outlet is located at the top of the tank on the opposite end. Tank is agitated.

4.5 Back-Mixing

When two or more rinsing tanks are connected (e.g. counter current rinse), it is important that the water will run from the tank with clean water to the tank with more dirty water. This is normally controlled by a simple gravity flow where there is a difference in water height. Under normal conditions the flow direction is correct, but if a big rack or even worse a big barrel is submersed in the dirty water, the water level in the dirty tank may increase above the water level of the clean water tank. In this case the water will flow in the wrong direction, and the clean water tank will get polluted with dirty water. In this case there is a very low efficiency of the rinsing process compared to normal conditions for this kind of rinse systems. The wrong construction should be repaired to improve rinsing quality and reduce water consumption.

Table 5: Scoring of Back-mixing

Fuzzy association	Operator options
0.2	Rinse tanks are linked across the bottom and /or top allowing continuous flow of water.
0.4	Small pipes link rinse tanks resulting in continuous back mixing. Spills between rinse tanks are high during jig submersion.
0.6	Rinse tanks are linked across the bottom and /or top allowing moderate flow of water during jig submersion or Rinse tank overflows very small amounts of water to the next rinse tank during jig submersion.
0.8	Rinse tanks are linked across the bottom and /or top allowing very little flow of water during jig submersion or Rinse tank overflows some water to the next rinse tank during jig submersion.
1	No back mixing. Tanks are not linked.

4.6 Flow-control

Controlling the inlet flow of water to a rinse tank is maybe the most important factor influencing the water consumption. To control the flow you need a valve for adjustment and a flow meter to monitor the flow - but you also need to know how much water is needed. The demand of water is determined by the defined water quality (F = dilution factor) and the drag-out from the previous process tank.

The typical situation is a water-valve totally open, and nobody has considered if less water would be sufficient. Some companies implement some kind of water restrictors and this is highly recommended, but it is still very important that the restrictors are allowed to control the water flow. Too often we see the operation staff increasing the water flow by further opening the water-valve because they found the rinse water too dirty. This is an important part of the management task to set up correct instructions and ensure that these instructions are followed.

Table 6: Scoring of Flow-control

Fuzzy association	Operator options
0.2	Rinse water supplied by non-restricted pipe. Each rinse tank has a separate inlet.
0.4	Rinse water supplied by valve on the end of a pipe with some control.
0.6	Static tanks, dumped regularly or moderate flow control with no rinse recovery system. No redirecting of rinse water occurs.
0.8	Static tanks, dumped regularly or moderate flow control with no rinse recovery system. Redirecting of rinse water occurs.
1	Flow control to rinse tank via predetermined rinse water requirements. Flow is continuously controlled and stops when no tank operations occur. All water is recovered via low flow rinse back into plating tank.

The overall shape and functioning of the each actual rinsing process of the line is scored as a weighted average, as the 6 parameters do no have equal impact. The score of the actual rinsing system will uncover if you can save rinse water by improving the existing system. The assessment is exclusively based on the functioning of the existing rinsing system.

5. Plant wide Application of Multi-objective decision-making

The inputs from Table 1-6 are then used in equation 1. The output is a rating of the rinse system of the company under review. The output is on a scale of 0-100. Where 0 would indicate no scope for improvement whilst 100 would indicate a very poorly operated plant.

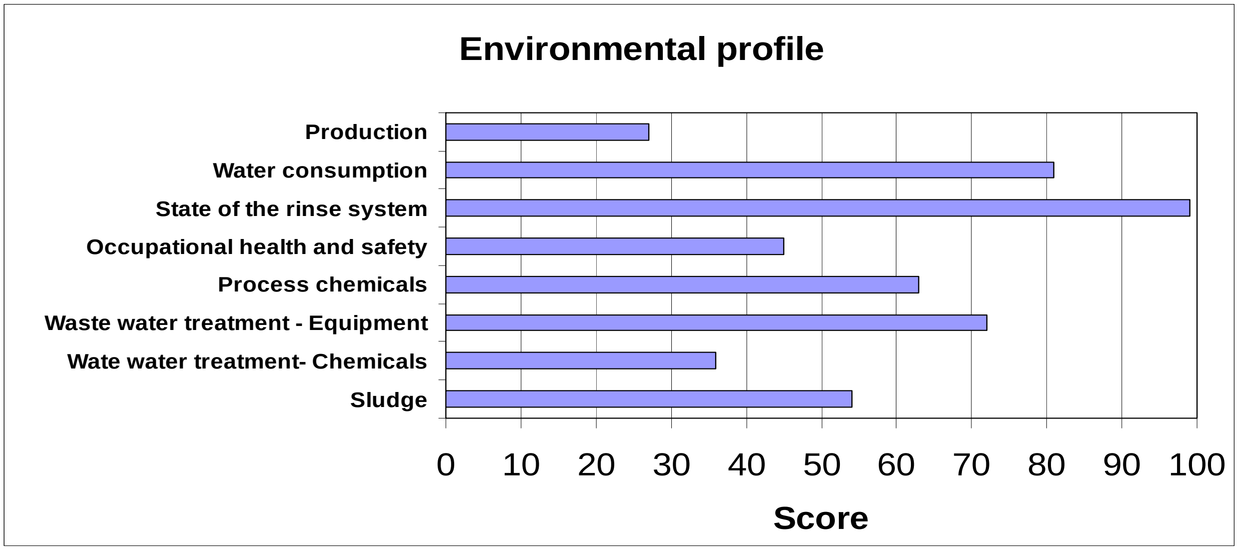
The above methodology can then be applied to the rest of the plant under the categories:

- Sludge
- Waste water treatment plant chemicals
- Waste water treatment plant equipment
- Chemical
- Occupational health and safety
- State of the rinsing system
- Water consumption
- Production

The appropriate fuzzy questions are developed to accommodate operator inputs under these categories. The preferences are appropriately inputed in accordance with each category. A comprehensive plant wide system is developed that outputs an environmental status of the company.

The outputs from each section are summarized on a scale of zero to 100. Where a zero would indicate no room for improvement and a 100 would indicate major potential savings with system improvements.

Figure 2: Graph of plant environmental profile



6. Conclusion

Fuzzy logic can be used to determine a detailed plant environmental status. This system can be further integrated with plant models to develop a comprehensive status of a surface finishing facility. The system when compared to similar review system[4] produces comparable results.

7. References

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