Model development for optimum acid usage and production efficiencies*

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ABSTRACT

The efficiency of the acid cleaning process is critical in ensuring optimum quality at an electroplating facility. This efficiency depends on various variables including the operating temperature, acid/inhibitor concentration, rate of contamination etc. Dumping of acid solutions is a frequent occurrence at electroplating facilities. In most instances the remaining usable lifespan of the acid is unknown. It would be ideal to predict the actual rate of cleaning and contamination of the acid solution. This would be useful in predicting acid dosing, acid lifespan and acid efficiency. A major consideration to this problem is the uncertainties associated with the variables for the acid usage. These include changes in operations, changes in temperature, concentration changes, contaminant changes etc. In this study a model is developed that predicts the acid consumption whilst allowing for all operational uncertainties. A comparison is presented on the results of this model and existing plant data. This model finds further application in predicting the production rate of metal through an electroplating facility. A Mathlab Case study on this application is presented.

Keywords: *Acid efficiency, Cleaner production, electroplating, waste reduction*

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1 Introduction

This paper aims at describing the process of compiling an acid model for the electroplating process. The purpose of this acid model was twofold, firstly the acid model was required to predict optimum operation of the acid tank and secondly the model developed was used to determine the plant production in terms of surface area of metal plated.

The purpose of this study was to determine the surface area, in square meters, of a production facility based on basic operator inputs. This surface area would then be used to determine the precise operations of a plant so as to determine the cleaner production status of the company. For the purpose of model verification 25 companies were audited using traditional cleaner production auditing systems. For these audits the it took a few hours to determine the surface in meters squared. It was noted that traditional auditing systems required the production in meters squared and none of the companies kept recodes of production in meters squared.

The acid model inputs were related to the operations of the acid tank and included; dosing and dosing times, barrel/day, temperatures, drip times etc.

The model was developed based on data obtained from a factorial experimental design. The key principal of the design being, replication of typical operational practice at an electroplating plant. The acid reactions together with the factorial model was used to develop an acid model that could successfully predict the acid consumption based on operational practices at an electroplating facility.

This model was then used to reverse-calculate the surface area passing through the electroplating facility. This was achieved by using the weekly acid dosage obtained from the operator as a weekly acid consumption. The database of values was used to determine the accuracy of the model.

Due to the nature of the process there is a large variation in the operations variables. Hence, the validity of the acid model is reinforced by the application of the Monte Carlo Technique. These variable changes are integrated into the surface area prediction by application of the Monte Carlo technique. Mathlab was used to simulate the Monte Carlo based model.

2 Background

Preparation of the metal surface for electroplating consists of two processes. The first is the removal of oil (known as degreasing) and the second is the acid cleaning process. The aim of this paper is to discuss the investigation into the acid cleaning process. This process is normally referred to as pickling. Pickling is the term applied to the method of cleaning metallic surfaces by immersion in acid[1].

The surface needs to be acid cleaned due to the formation of "rust" or iron oxide on the surface of the metal. If this rust is not properly removed the integrity of the plating is compromised. This usually implies that there is poor adhesion of the plated metal onto its substrate.

The formation of rust occurs due to the various machining processes that the metal has undergone. This is typical of all surfaces to be plated as they have been manufactured into high value products by heating/cooling and cutting processes. When steel or iron is heated and allowed to cool, unless this cooling takes place in an atmosphere free from oxygen, a scale layer of oxide is formed.[1]

With abundant oxygen supply and heat, the oxide layer is in the form of Fe_2O_3 or Fe_3O_4. and sometimes a little FeO. [2] Prior to being plated the metal is subject to corrosion. Corrosion results due to the presence of water, air, moisture and perhaps some acids. Thus a piece of steel shows various compounds of iron oxides in the form of rust. Hoerle[3] investigated some of the oxides of iron and its corrosion properties, see Table 1

Table 1: Some of the oxides of iron and its properties.[3]

Composition	**Name**	**Crystal System**
Fe_3O_4	Magnetite	Cubic(Spinel)
γ-Fe_2O_3	Maghemite	Cubic(spinel)
α-FeOOH	Goethite	Orthorhombic
γ-FeOOH	Lepidocrocite	Orthorhombic
β-FeOOH	Akaganeite	Tetragonal
γ-Fe-OH-OH	Reduced lepidocrocite	Orthorhombic
$Fe(OH)_2$	Ferrous hydroxide	Hexagonal

There have been various studies on the rust formation.[4,5] These studies have lead to the development of detailed models. These studies have indicated that the prediction of the type and form of iron oxide to be cleaned of the surface is complex and cannot be easily predicted.

Hoerle[3] identified Fe_2O_3 as the major oxide formed on post-machined components. Based on this reaction 3 would be used as a basis for the reaction calculations for the purpose of this study. Complex models for the types of rust formed would be considered to be beyond the scope of this study. Reaction 3, as for all chemical reactions, is dependent on various variables. The variables would determine the efficiency of the rust removal before electroplating. These variables are considered for further investigation and form the bases of the acid model developed in this thesis.

The reactions for iron and sulfuric acid can be summarized as[6,7]:

$$Fe + H_2SO_4 \Rightarrow FeSO_4 + H_2 \quad (1)$$

$$FeO + H_2SO_4 \Rightarrow FeSO_4 + H_2O \quad (2)$$

$$Fe_2O_3 + 3H_2SO_4 \Rightarrow Fe_2(SO_4)_3 + 3H_2O \quad (3)$$

$$Fe_3O_2 + 4H_2SO_4 \Rightarrow Fe_2(SO_4)_3 + FeSO_4 + 4H_2O \quad (4)$$

2.1 Rust removal by sulfuric Acid

In the typical surface finishing company rust removal is achieved by using either sulfuric or hydrochloric acid. From the database of 25 companies reviewed for the purpose of this study, 15 used sulfuric acid for metal pickling. Hence for the purpose of model development, the pickling model would be developed around the use of sulfuric acid.

3. The variables affecting the rate of cleaning

The investigation into the factors affecting the rate at which the acid is able to remove the rust and surface clean the metal indicated that it is dependent on various variables. The variables that can be considered to effect the chemical reaction are temperature, concentration of the different components, time and inhibitor concentration. The following variables were considered for the acid reaction.

3.1 Iron content

Iron is considered to be a contaminant in the pickling process. The amount of iron in solution is critical to the solution effectiveness. Current practice at electroplating facilities dictate that acids with high iron content be dumped. In experiments conducted by Marcus e*t al*[7,8,9] it was found that initial reaction rate increases with small iron contamination. These experiments also indicated lower reaction efficiencies as the iron content increased. Markus[9] carried out experiments with an iron content of 0.1 to 0.3 mol/l which reinforced this theory.

The fresh acid concentration at plating facilities acids start with zero iron content and is usually dumped when the iron reaches 100 g/l. Large amounts of metal sludge forms at the bottom of the tank as the iron content increases. Hence the iron content is a critical factor and was considered as a variable for experimentation.

3.2 Acid concentration

The chemical concentration is critical to any reaction. The acid concentration is also a consideration as experiments conducted by Quraishi[10] indicate that the acid concentration does have a significant effect on the pickling reaction. Markus[9] also indicates that the acid concentration does have a significant effect on the ferrous reaction. Since is common practice at plating facilities to increase or use higher acid concentrations for "dirtier parts", the concentration of the acid was considered to be a variable for experimentation.

3.3 Temperature

In any reaction the temperature is usually a key variable and according to Quraishi *et al* [10,11,,12] experiments with sulfuric acid and iron are highly dependent on the reaction temperature. This was reconfirmed by Markus and Rubisov as results from trials at elevated temperature, 75 to 95 deg, indicated that together with acid concentration, temperature had a significant effect on the reaction. This was especially true at elevated temperatures. Since most acid cleaning solutions are operated at elevated temperatures and concentration, it was appropriate to use temperature as a variable in experiments.

The above variables were used together with time and inhibitor concentration for the purpose of experimentation.

4 Experimental

4.1 The experimental method

It would be simple to predict the rate of reaction of an acid on a metal piece if the variables discussed above remained constant. Electroplating companies operate at various concentrations of acids and at various temperatures ranging from ambient to 80 deg C. The instantaneous concentration of iron in solution changes with every piece pickled. The acid concentration changes as the reaction proceeds. Topping up of chemicals usually occurs once per week. The impact of dragout losses and topping up after dragout is a significant factor to consider in the acid reaction as it impacts on the acid concentration.

This study aims at predicting the operation of the acid tank at any electroplating facility. Since these facilities operate within a large range of variables, the model must have the ability to accommodate all these variables with there relative impacts.

Considering all the above, it was only possible to develop a model that allows for the combine effect of the variables under consideration i.e. their interaction is important. Hence the fractional factorial method was employed. It would have been ideal to have conducted a detailed study into the reactions but due to various limitations the factorial method was chosen as the most appropriate method to ensure a quick and reasonable precise model.

Appendix 1 contains the factorial design that was used to determine the acid model. The variables are acid concentration (variable 1), temperature (variable 2), contaminant (variable 3), inhibitor concentration (variable 4) and time (variable 5)

Each variable has to be given a maximum and a minimum limit as per Table 5.2. This is determined from the data obtained from the companies via the review process[13]. The range that was used for the above reactions were as listed in Table 5.2.

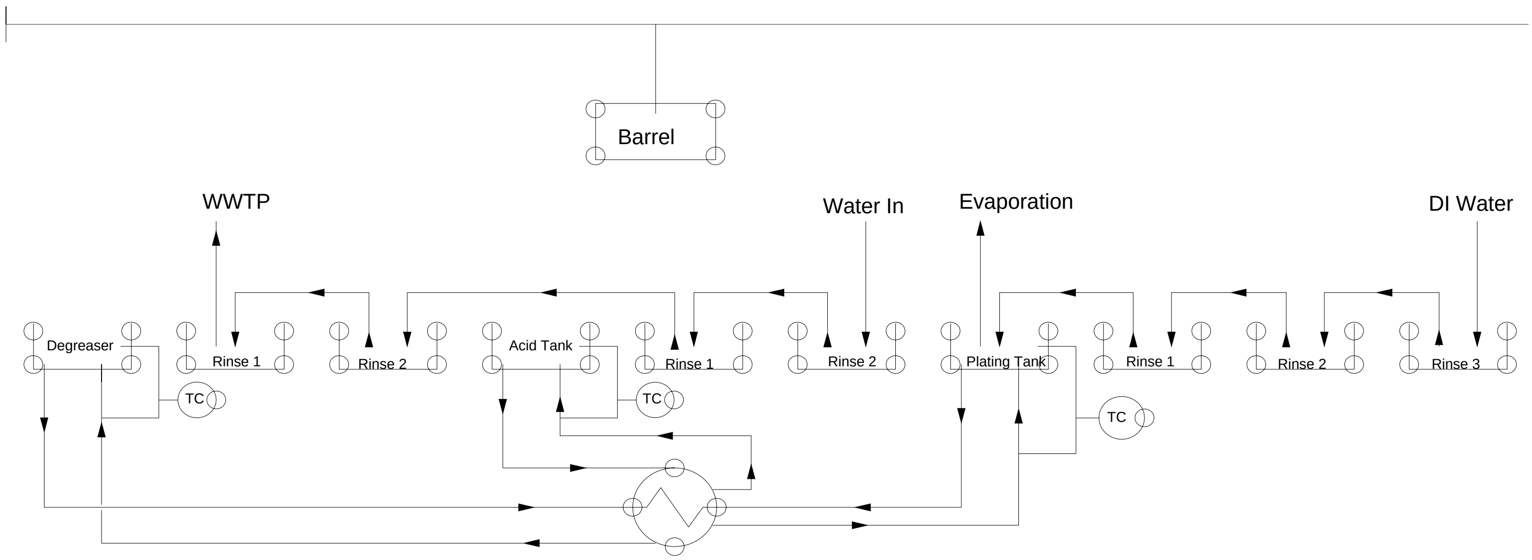
Table 2: Trial data values for factorial experiments

Variable	Minimum Value (-1)	Maximum Value(+1)
Acid	60 g/l	120 g/l
Temperature	25 ^oC	45 ^oC
Contaminant	0	1 g/l
Inhibitor	0	5 g/l
Time	3 hrs	6 hrs

The acid experiments were conducted on a lab scale pilot plant as illustrated in Figure 1 and 2. The plant consists of a degreaser system and an acid system. The plates to be acid cleaned were precision cut to ensure size consistency. They were then individually weighed before each trial using a four-digit laboratory balance. The plates were pre-cleaned using the degreaser, rinsed, dried and then reweighed.

The experiments were carried out in the lab with a temperature control bath. The metal pieces were cut to size (75mm by 50 mm). The solutions were prepared and placed in tanks for the specified times. The amount of iron reacted was determined by the difference of the metal piece before and after the experiment. A four decimal place mass balance was used to determine these weights. All pieces, once reacted were dried to ensure no liquid remained on the metal as this would impact on the mass of metal reacted.

Figure 1: P &ID of pilot plant



Diagrammatic Representation of the Plating Line

Figure 2: Photo of pilot plant

Experiments were conducted over a period of three weeks with repeatability's conducted with fresh solutions. The trials were conducted three times to ensure accuracy.

5 Experimental Results

The results from the trials indicate the rate of metal loss. This is a direct indication of the mass of metal reacted. Table 5.3 lists the results for the various trials.

Table 3: Table of results for the factorial acid experiments

Company	Production Sq meters	Mass acid Dumped	Dragout g/m2	Dragout consump-tion	Reaction consump-tion	Acid Tank Conc g/l	Load Surface area	Acid Depletion Grams/ load	Acid Consumption		% error
									database	model	
A	54001	640.0	0.4	861.0	2178.0	160.0	0.5	24.9	7103.0	7359.0	-3.6
B	2200	268.0	0.3	26.0	5.8	80.0	0.1	0.8	275.0	274.0	0.4
C	25344	4050	0.3	61.2	1686.0	100.0	0.5	25.4	6400.0	5797.0	9.4
D	1100000	2624.0	0.3	587.0	13578.0	160.0	3.0	146.9	35340.0	31955.0	9.6
E	20496	4320.0	0.3	307.0	743.0	100.0	0.2	10.1	6160.0	5371.0	12.8
F	6522	1800	0.3	756.0	3956.0	120.0	0.2	127.0	6840.0	6653.0	2.7
G	4000	768.0	0.3	768.0	113.0	80.0	0.1	2.0	960.0	881.0	8.2
H	30000	500.0	0.4	1199.0	1394.0	100.0	0.2	1.9	3302.0	3094.0	6.3
I	157283	4800.0	0.3	2422.0	379.0	100.0	0.5	9.7	11280.0	10403.0	7.8
J	33689	180.0	0.2	672.0	571.0	100.0	0.2	5.2	1400.0	1424.0	-1.7
K	12219	320.0	0.4	243.0	214.0	100.0	0.2	6.3	800.0	778.0	2.8
L	950	38.4	0.4	23.0	106.0	120.0	0.2	20.7	150.0	167.0	-11.3
M	20323	600.0	0.3	367.0	6317.0	120.0	0.2	143.8	7103.0	7280.0	-2.5
N	6806	400.0	0.3	244.0	247.0	120.0	0.2	5.6	800.0	891.0	-11.4
O	11222	168.0	0.4	11.0	177.0	80.0	0.2	1.5	395.0	356.0	9.9

The trials were conducted and results selected in accordance with statistical control. The results were used to develop the mathematical model representing the acid process

5.1 Usage of results

In order to ensure the integrity of the results, all trials were statistically verified using statistical control. The statistical control chart was adopted to determine the accuracy of the experimental results. The data points that fell within the statistical control limits were used for the model.

The results were used in the factorial method and manipulated to determine the relationship between the rate of metal depletion and the various variables, see Appendix C for detailed factorial calculations.

The factorial methodology is able to convert the impact of different variable changes into a representative equation. The factorial equation representing the variable change for acid depletion is:

$$M_D = 153.2 + 12.57 C^A_{H2SO4} - 46.07 C^A_{Fe} + 26.72 T^A - 75.42 IN^A + 35.08 t^A$$
$$+ (18.7\ C^A_{H2SO4} * C^A_{Fe}) + (49.78\ C^A_{H2SO4} T^A) + (27.003 * C^A_{Fe} * T^A)$$
$$- (12 * \mathrm{IN}^A * t^A) - (0.947 * C^A_{H2SO4} * \mathrm{IN}^A) + (44.61 * C^A_{Fe} * \mathrm{IN}^A)$$
$$- (17.2 * T^A * t^A) - (8.1 * T^A * \mathrm{IN}^A) - (18.3 * C^A_{H2SO4} * \mathrm{t}^{\mathrm{A}})$$
$$- (48.72 * \mathrm{t}^{\mathrm{A}} * C^A_{Fe}) + (34.84 * C^A_{H2SO4} * C^A_{Fe} * T^A_{Fe} * \mathrm{IN}^A * t^A) \quad (5)$$

Where:

C^A_{H2SO4} =Concentration of acid

C^A_E =Concentration of Iron

T^A_E =Temperature of bath

IN^A =Inhibitor concentration

t^A =Time

It can be seen that the equation is subject to all the variables discussed previously including their interactive effects. The equation outputs the metal mass depleted under the specified conditions. It is a statistical model and hence errors were expected. The results of the model have to be compared to the actual experimental results in order to compare the accuracy of the model developed. This is done by reverse calculating the model outputs based on experimental conditions. Table 4 and Figure 3 contains a comparison of results for each trial undertaken and results from the developed model.

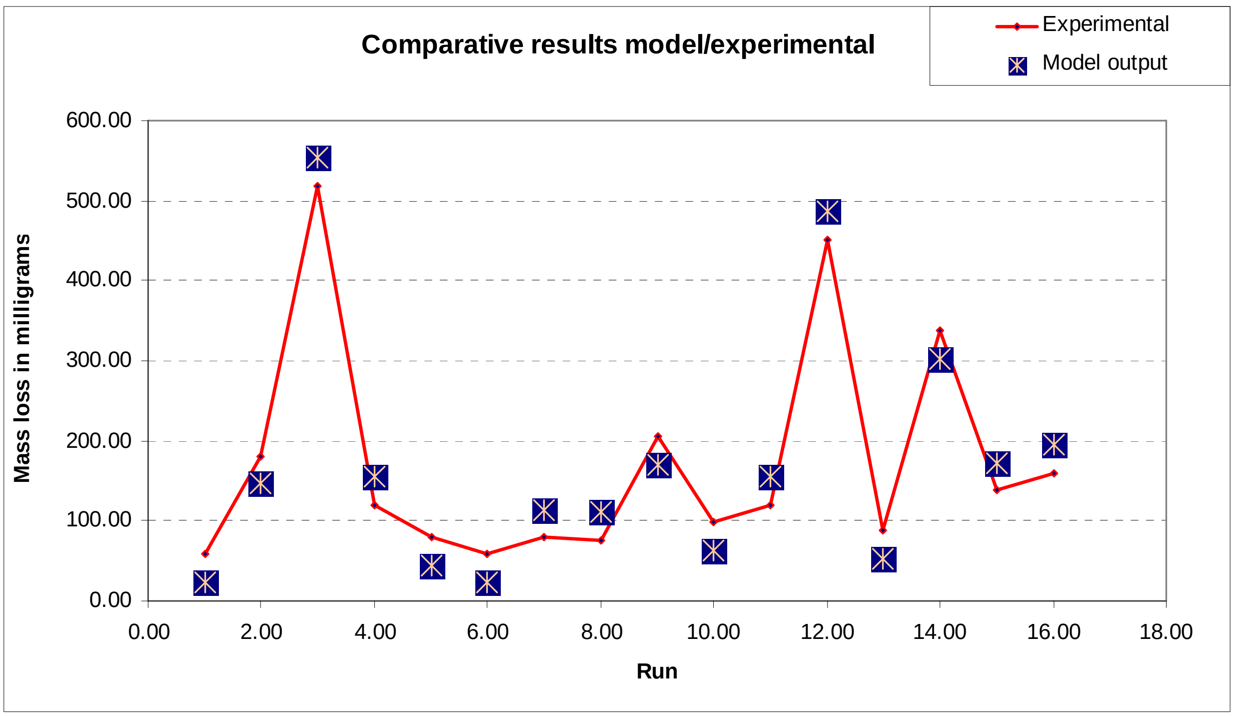
Table 4: Comparative values of factorial output and actual experimental results.

Run No.	Experimental results	Model Output	Deviation
1	57.90	22.69	-35.21
2	181.00	146.04	-34.96
3	518.00	552.96	34.96
4	120.00	155.21	35.21
5	79.25	44.04	-35.21
6	58.45	23.49	-34.96
7	78.80	113.76	34.96
8	75.80	111.01	35.21
9	204.90	169.69	-35.21
10	97.75	62.79	-34.96
11	120.00	154.96	34.96
12	452.00	487.21	35.21
13	87.10	51.89	-35.21

14	337.95	302.99	-34.96
15	137.45	172.41	34.96
16	159.60	194.81	35.21
		Standard deviation	35.04

From Table 4 it is clearly seen that the outputs from the model and the experimental results correlate. The results from Table 5.4 is graphically represented in Figure 5.1.

Figure 5.3: Comparison between model output and experimental results



From Figure 5.3 it can be seen that the model outputs are very close to the actual experimental results. It can thus be stated that the model equation is representative.

6 Model development

This equation can now be used to predict the consumption of acid at plating facilities. Using the database of companies the above model can be applied for verification.

The different reactions require different amounts of acid to remove the oxide layer. The major reactions that would be dealt with are equations 3 and 4. Hence the consumption of acid can be considered to be 3 moles for every mole of rust removed. The may contain an inhibitor, which is designed to reduce the acid reaction with the metal.

The consumption of acid can be calculated by determining the mass change in metal i.e. the metal or iron that is reacted is now in solution and hence this has consumed a specific amount of acid. For the purpose of our calculations the average molecular weight of the iron oxide to be removed, would be taken as 179.6.This is determined by reaction equations (equation 3) i.e. three moles of acid is consumed as per mole of metal reacted. Since the mass of metal reacted is known the number of moles of acid consumed is easily calculated. Once this is completed a new concentration of acid is determined and the metal in solution is the effective acid contamination. Due consideration has to be given to the variables that effect the rate of reaction of the metal and the acid. The contaminants i.e. iron are continuously increasing as the acid is used and hence results in a lower reaction rate. Due to the repetitive and evolving nature of the process it would be ideally represented in a computer model.

7 Model validation

The model developed needed to be evaluated using existing company data to determine its accuracy. Hence spreadsheets were developed to test data of individual companies against the model.

For the purpose of model verification the input variables needed to be obtained. The variables required were tank size, concentration temperature, time etc. This was obtained from the database of reviews. For the purpose of confirming the model the above was to be carried out using the data from the database.

7.1 Verification using database results and model

The model assumes a weekly dosing system; this is common practice at all electroplating facilities. The chemical supplier samples the acid tank once per week. The topping up of acid occurs based on this analysis.

The above data is used to determine the individual barrel consumption. The current annual surface area of the company is used as a staring point. This is divided into 48 weeks since chemical dosing at all facilities is done on a weekly basis. This surface area is used to calculate the usage of chemicals. The daily surface plated can be calculated and an individual barrel/jig surface estimated. This can then be used to calculate the consumption of acid for this surface area.

This is now inputted into the model. Assuming there are n barrels/week this calculation would be done n times to produce the acid tank condition at the end of the week. Detailed tables are attached in Appendix C.

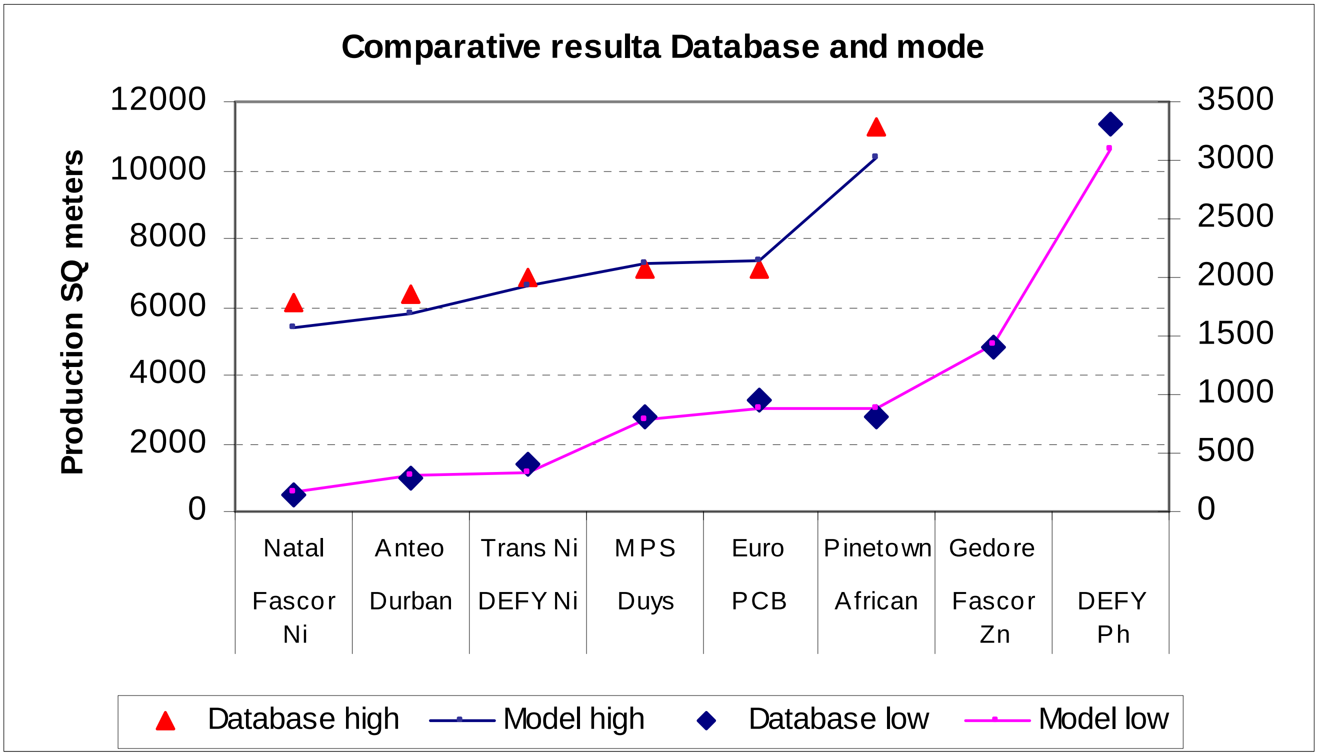
Thus the theoretical calculations for the acid system can be complete for all companies. The following table indicates the data obtained from companies during the database reviewing process as compared to the model outputs.

Table 5: Table of comparison, acid consumption

Company	Production	Mass acid	Dragout	Dragout	Reaction	Acid tank	Load	Acid depletion	Acid consumption		Percentage
	Sq meters	Dumped	g/m2	Consumption	Consumption	Conc g/l	Surface area	grams per load	Database	Model	Error
1	54001	640.0	0.4	861.0	2178.0	160.0	0.5	24.9	7103.0	7359.0	-3.6
2	2200	268.0	0.3	26.0	5.8	80.0	0.1	0.8	275.0	274.0	0.4
33	25344	4050.0	0.3	61.2	1686.0	100.0	0.5	25.4	6400.0	5797.0	9.4
4	1100000	2624.0	0.3	587.0	13578.0	160.0	3.0	146.9	35340.0	31955.0	9.6
Durban	20496	4320.0	0.3	307.0	743.0	100.0	0.2	10.1	6160.0	5371.0	12.8
6	6522	1800.0	0.3	756.0	3956.0	120.0	0.2	127.0	6840.0	6653.0	2.7
Euro	4000	768.0	0.3	768.0	113.0	80.0	0.1	2.0	960.0	881.0	8.2
Fascor Ni	30000	500.0	0.4	1199.0	1394.0	100.0	0.2	1.9	3302.0	3094.0	6.3
Fascor Zn	157283	4800.0	0.3	2422.0	379.0	100.0	0.5	9.7	11280.0	10403.0	7.8
Gedore	33689	180.0	0.2	672.0	571.0	100.0	0.2	5.2	1400.0	1424.0	-1.7
MPS	12219	320.0	0.4	243.0	214.0	100.0	0.2	6.3	800.0	778.0	2.8
Natal	950	38.4	0.4	23.0	106.0	120.0	0.2	20.7	150.0	167.0	-11.3
PCB	20323	600.0	0.3	367.0	6317.0	120.0	0.2	143.8	7103.0	7280.0	-2.5
Pinetown	6806	400.0	0.3	244.0	247.0	120.0	0.2	5.6	800.0	891.0	-11.4
Trans Ni	11222	168.0	0.4	11.0	177.0	80.0	0.2	1.5	395.0	356.0	9.9

This table indicates that the model is able to predict with a reasonable level of accuracy the acid consumption. The model is thus considered able to predict accurately the acid consumption at an electroplating facility given the acid system operating conditions. Figure 4 is a graphical representation of the model results and the actual database values for acid consumption. Due to the large range of values for the company acid consumption data is separated into the larger acid consumption (>3500kg) and the smaller (upper and lower trend on graph).

Figure 4: Illustration of the comparison between the database acid consumption and the model acid consumption.



The model developed so far has surface area as an input variable and is able to calculate the acid consumption. This is a stepping stone towards the actual system as in the actual system the surface area is not known and it is proposed to determine the surface area from the model above. This can be done by rearranging Equation 5.5 with surface area as the subject of the formula. The weekly acid dosed is known by the operator and hence would be ideally suited for our model system. This would fit perfectly into the operator based cleaner production evaluation.

Thus the requirement is to input the average weekly chemical consumption into the model. Since the operator conducts chemical dosing on a weekly basis, his input needs to be harnessed and used for the model. This is also in line with the aims of the holistic model i.e. the use of operator level inputs. So a modified model is developed that inputs all variables as previously done but now, instead of the surface area as an input, the weekly acid consumption is entered.

The model requires some initial surface area for each barrel/jig in order to determine the chemical consumption. This is obtained from a simple correlation from the database values. See Appendix C.

8 Mathlab Model

A major consideration for the establishment of the model is the uncertainties of the input data. Plant data would be based on operator inputs and hence are subjective. The plant status may also change within a certain limit hence this needs to be accommodated within the model.
The uncertainties are:

- Temperature
- Acid concentration
- Contaminant
- Pickling time
- Inhibitor concentration

8.1 Temperature

The temperature in the acid tank may vary due to various factors, among these factors are the environmental temperature, topping up rate, heater control, production rate and operation influences.

The tank temperature may increase or degrease based on the weather conditions, wind factors and convective losses. This means that minor changes in temperature can be encountered due to outside climate changes.

The acid tank is subjective to dragout, dragin and receives cold components from the previous tank. This would have a significant effect on the temperature of the acid tank. The acid tank may be heated after a weekend or night of non production.

The acid tank temperature is maintained by the use of electrical heaters. These heaters are controlled based on a control loop. Variations in temperature would occur depending on the ability of the control system to manage all the disturbances.

8.2 Concentration

The acid model calculates the evolution of acid tank concentration. This indicates a change in tank concentration depending on measurement and dosing. Other factors such as dragin and dragout also influence the concentration in the acid tank. The model program allows for an increase or degrease of concentration of approximately 1g/l.

8.3 Contaminant

The model indicates an evolution of contaminant in the acid tank. It is known that the contaminant builds up in the acid tank over a period of time until it is unacceptably high and has to be dumped. The initial contaminant would be taken as 1 g/l for the model prediction.

8.4 Time

Most plating plants work on a schedule system and this implies that operators/cranes would not be able to remove a jig/barrel from a plating bath at the precise allocated time. The model allows for a 1-minute delay/advance removal of the jig/barrel.

8.5 Surface area

The program assumes an initial surface area/jig and then depending on the iteration increases or decreases the surface area. The operator loading of the barrel/jig is also an important factor to consider as components vary and hence individual barrel surface areas would change. The model allows for an approximate variation of 5% for surface area.

The Mathlab program is established and run with the above variable changes. The Monte Carlo technique can be applied to the Mathlab program with the above variable changes. The random numbers are generated for each iteration, which makes the model as realistic as possible.

8.6 Random numbers

The generation of random numbers is critical to the Monte Carlo technique and the selection of the optimum random number type is essential for accuracy in modeling. The “randn” function from Mathlab generates random numbers, which are normally distributed with a mean of zero and a variance and standard deviation of one. From previous plant data it can be seen that the variables for the model is normally distributed around the set point. The variance however is different for the different variables under investigation. The variance for the temperature is two degrees whilst that for the contamination is one gram per liter. Thus the random numbers generated in Mathlab has to be adjusted accordingly. The random numbers were then used for the various substitutions.

The barrels per week are generated until the iteration for acid consumptions are complete. The random numbers for this has to be the same each run. For this application random numbers are generated up front in the program and used for each iteration. The numbers generated and utilization is critical to the application accuracy.

The model is given the values required to determine an estimate surface area/barrel, this is based on database values and generates a surface/barrel based on the acid dosed per week. This initial estimate is used to generate the metal depletion, which is then used in the acid equation to generate the acid consumption/barrel. The consumption is calculated considering the number of barrels plated /week and the total acid consumed calculated. This is then compared to the actual dosed acid and the surface area adjusted until they are equal.

9 Mathlab results

Figure 5.5 is the results from the initial simulation. From the database, the actual weekly surface area for the company under consideration is 141.8. The results from Mathlab indicate that the mean surface area after 1000 runs is 135.5327 with a variance of 4.73. The model generates 135.53 this is a five percent error.

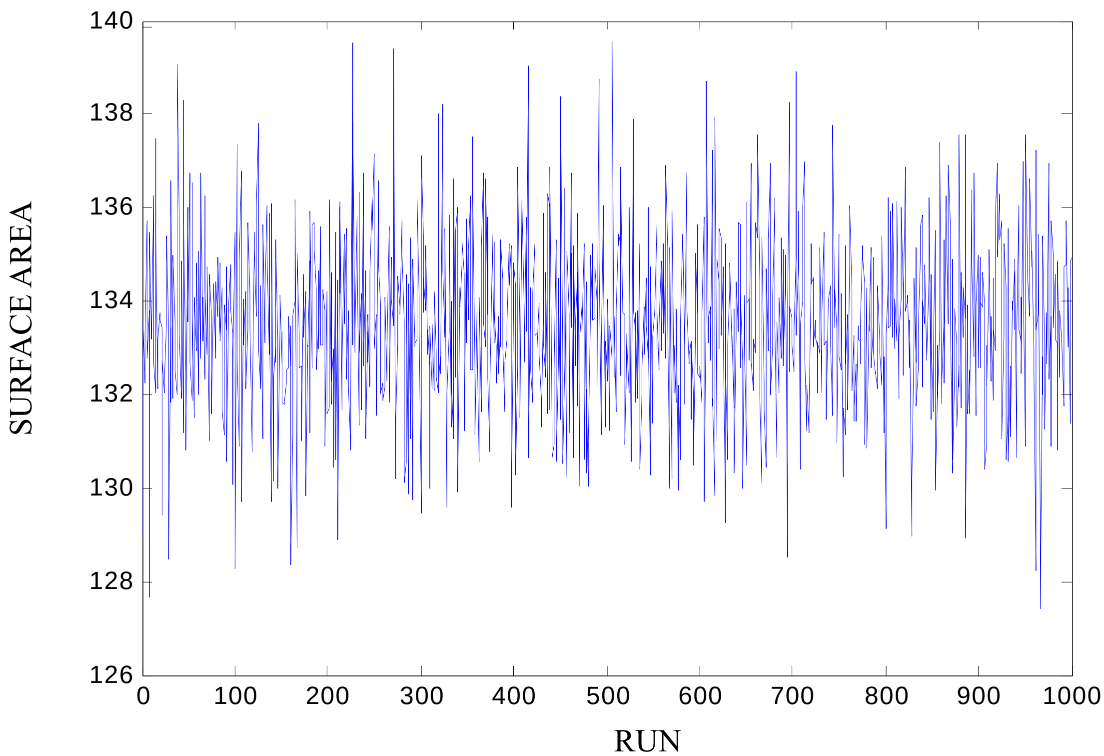


Figure 5: Mathlab Monte Carlo results for surface area

From the above it can be seen that the acid model developed is able to successfully predict the surface area plated at an electroplating facility with a high level of accuracy. The model developed only requires basic operator inputs in order to complete the calculations for surface area. The surface area predicted in this paper would be used as the production rate for the other models developed in this thesis.

Referring back to the data collection phase of this study, it was found that the surface area determined by different auditors were significantly different. The largest difference being the surface area for the second was 40% greater than the first.

With the current model it can be seen that the variance is low. The model generates an error, which is lower than the traditional models. Thus the current model can be considered to be more reliable for surface area prediction.

10 Conclusion

The paper on the acid model is critical to the development of the comprehensive cleaner production tool. The usage of the outputs from the acid model dictates the integrity of the rest of the model. It can be clearly seen from the model developed, that the acid model is accurate when tested against database values. It can be thus concluded that the acid model developed is successful in predicting the operations in the acid tank and more importantly, is able to predict the surface area passing through a production facility.

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