A case study on Artificial intelligence based cleaner production evaluation system for surface treatment facilities

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Abstract

The metal finishing industry is water intensive. Surveys of South African metal finishing companies indicate that water consumption is as high as 400 L/m^2 of metal surface treated, whilst best available practice can achieve less than 10 L/m^2. The industry uses hazardous chemicals such as chrome VI, cadmium, nickel and cyanide. If consumption of these chemicals can be optimized, quantities of heavy metals released into the environment will be reduced. In some cases where cleaner production techniques were applied by local companies, heavy metals have been completely eliminated from effluents discharged to municipal sewers, which represents a significant benefit to the urban environment. This benefit was accompanied by significant reduction in the use of chemicals, with a concomitant cost saving and competitive advantage to the companies concerned.

A Danish environmental aid initiative promoted cleaner production in the South African metal finishing industry. Local consultants were trained by Danish experts in this field. The general methodology was to conduct an audit of the chemical, water, human resource and environment aspects of the company and compare it to best available practice. Once the review was completed, a detailed feasibility was carried out on systems and equipment required to reduce chemical consumption, water consumption, human resources and environmental impact. Applied to a number of South African companies, these methods have typically achieved reductions of the order of 90% in water use and 50% to 60% in the use of chemicals.

There were difficulties in applying the Danish methodology to South African metal finishing companies, as it makes use of quantitative indices derived from the process operations. The companies are often small and technically unsophisticated, and do not have ready access to the process data that is needed. An alternate system is required to simplify the evaluation and optimization process. This paper proposes a case study on a fuzzy logic operator based evaluation system that outputs the cleaner production status of the company. The model is compared to an established cleaner production tool.

Key words: Cleaner Production, Artificial Intelligence, Metal Finishing

1. Introduction

Internationally, the application of cleaner production systems in metal finishing has resulted in significant reductions on the demand for natural resources. These resources include water, energy and raw materials. Cleaner production applications have also resulted in significant reductions in the release of toxic waste into the environment.

The successful application of cleaner production usually starts with a cleaner production audit. This audit depends significantly on the availability of the necessary skills, the availability of precise data and can be described as time intensive. These factors result in significant financial outlays by companies seeking cleaner production evaluations.

The metal finishing community in Durban, South Africa has benefited from two significant efforts to reduce the impact of metal finishing waste on the environment. The first mission was conducted by Barclay[1]from 1998 to 2001 and the second by DANIDA[2]from 2000 to 2003.

Barclay recorded a total cost saving of over two million Rands. Water savings were more than a quarter of a million Rands and process chemical savings were one point one million Rands. Senior students were employed to conduct cleaner production assessments over a period of six weeks.

The second effort by DANIDA resulted in similar reductions on raw material demands. The overall impact was measured by noting an 86% reduction of metal load to the Umbilo municipal treatment facility.[3]This facility receives waste from a large percentage of electroplaters in the greater Durban area.

From the final report by Barclay[1] and Koefoed,[4]it was stated that success for both these cleaner production initiative was limited by the availability of data. Thus the application of cleaner production could have enjoyed greater success, had the barrier of rigid data requirements been overcome.

Applications of effective pollution prevention strategies in plants have been considered an urgent and continuous effort for Cleaner Production (CP).[5,6] An alternate cleaner production evaluation system must be designed to meet the needs of the diverse plating industry. A key requirement for application of cleaner production evaluation systems is reductions in rigid data requirements. To alleviate the data-scarce and lack-of-skill related problems in environmental performance evaluation for cleaner production, a system that requires minimum data for decision analysis would be ideal. The approach should be general and thus suitable for any type of environmental cleanness problems in the electroplating industry. The model should still be specific enough to outline potential savings. These savings needs to be strongly justified so as to persuade the company to change to environmentally friendly options.

A detailed environmental evaluation always requires the company under consideration to make available the required data. This data must be accurate and in the required format. 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 conduct an adequate evaluation. 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 a wide range of applications. In this study, a fuzzy-logic-based approach is introduced to represent and manipulate expert knowledge and to provide satisfactory evaluation results.

2. Evaluation of current audit systems

Various cleaner production evaluation systems were reviewed to determine the most comprehensive system. These included:

The study by the Queensland Department of Environment involved some thirty companies with regular sharing of information[7] The sharing of information assisted the companies to improve. An assessment guide consisting of some 12 tables requiring detailed qualitative inputs from companies.

The government of western Australia[8] has embarked on various cleaner production projects including the metal finishing industry. Detailed studies of electroplating facilities implied evaluations of consumption of water and chemical consumption. The final output from the audits is a qualitative document on areas of improvement. This document does not calculate the specifics for plating efficiencies or water savings.

Viguri [9] conducted a waste minimization audit on chrome platers in Spain by using basic chemical auditing such as material and energy balances. Viguri noted the difficulty in obtaining detailed data required to conduct the study.

China International Training Center for Sustainable Development conducted cleaner production audits[10] with UNEP support. The system entailed identifying and targeting 21 areas for improvement at a metal plating facility. The success of the project was significant. The time and level of technical expertise required was also significant in that the consulting cost was 60% of the budget. The results covered selected sections of the plant.

Barclay,[1] conducted waste minimization studies at 29 metal finishing companies in Durban, South Africa. Senior chemical engineering students carried out these audits over a period of six weeks. Among the key barriers identified by Barclay and her team, was the lack of available data by companies and the lack of available time by senior plant personnel.

Cushnee[11] performed perhaps the most comprehensive study of surface finishers. This study on behalf of the National Metal finishing Resource Center (NMFCE) with US EPA funding, surveyed 134 metal finishing companies and attempted to establish some benchmarking. The questionnaire required inputs on water, sludge, chemicals and energy. The first phase of the questionnaire consisted of eight pages and twelve questions with approximately 50 input data requirements. Phase 2 required very detailed inputs such as surface areas and bath chemistries and consisted of some seven pages with more than 200 data requirements.

Detail production and mass consumptions were required from the companies. A summary of the typical consumptions was then established and comparative statistics were distributed. No best available practice benchmarking or flexibility on different plating systems were integrated into the system. The companies, after an intensive data chasing exercise had a set of survey ideals to work towards and not optimum individual calculations. The data requirements for the system required management level inputs and data gathering systems. It is estimated that each company required more than two weeks to complete the information sheets. The final outputs were general and not individualistic. The companies received a 145-page document on best available practice, based on the investigation.

Dahl[12] introduced the Scandinavian system of cleaner production auditing in South Africa in the year 2000. Three workshop sessions were held on technical training combined with practical plant assessments. Trainees require 10 working days of training before an initial assessment. A total of 25 initial trainees on the system found that it required data inputs that were detailed.[13]

The system is spreadsheet based with different category inputs. The audit consists of an initial seven-page information sheet to companies requiring detailed chemical and water consumptions. A reasonable chemical engineering background is required to complete the audit. It was found to take up to one month to complete individual company audits[13].

The most significant problem with the Flemming system being the data requirements[13]. The success of the system was limited by intensive data requirements.[13] The companies, in most instances found it almost impossible to complete the data required.

The greatest difficulty was the determination of the production by measuring the surface area plated. Most companies charge for work on a mass basis and surface areas are rarely measured. Evaluators spent hours with the companies to determine the surface area. It was not usual that two different reviewers found different surface areas. The quantification of the surface area and exact chemical savings was conducted using mathematical models. This study focuses on generating key indicators for areas of application of cleaner production.

The Flemming model has been applied to a major part of the metal finishers in Denmark and other DANIDA sponsored projects throughout Europe. From all the models that were reviewed for this study, Flemming's model was found to be the most effective. The Fleming structure was found to contain the most detailed knowledge for cleaner production auditing for metal finishing.

3. Sensitivity of existing model to rigid data

The Flemming's model was found to have a suitable structure for fuzzy application. The level of sensitivity of the Flemming model to input data changes are evaluated to determine the potential fuzzy application.

For the development of a comprehensive alternate system, two parallel approaches were followed. The first was to identify the sections of the review system that could be conducted using fuzzy or imprecise inputs and the second was to develop mathematical models for the sections that required fuzzy models that could not be applied. The latter is addressed by using operator inputs into mathematical models and is not the focus of this paper.

The evaluation of the sensitivity of the applicable Flemming's categories to imprecise inputs would initially be evaluated. Flemming's model consists of various detailed excel tables, as an illustrated example, the rinse tables, would be detailed together with the model sensitivity to input variable changes. The other Flemming tables are based on the exact same methodology and only the key outputs are illustrated.

3.1. The rinse tables

The cleaner production evaluation of the rinse systems aims at conducting a detailed analysis of the usage and management of water for the purpose of rinsing. The rinse system includes the rinse tanks, water inlet points, water flow rate, drip times, orientation and tank agitation.

The auditor is required to insert a range of inputs into the rinse tables. These inputs are based on measurements and observations made by the auditor on the facility under consideration. Table 1 details a listing of the typical inputs required for the rinse tables together with a brief description of each input.

Table 1: Inputs required for Flemming's rinse tables.

Input No.	**Input**	**Input options**	**Abbreviation**
1	**Tank Number**	**1…n (where n= total number of tanks)**	T_n
2	Rise system	1 = running rinse 2 = static rinse (drag-out rinse) 3 = Spray rinse 4 =static + running rinse 5 =static +2-running rinse 6 =static +3-running rinse 11 = 2-step counter current rinse 12 = 3-step counter current rinse 13 = 4-step counter current rinse 14 = static + 2-step counter current rinse 15 = static + 3-step counter current rinse	Rin_{sys}
3	Input water type	T-water = tap water I-water = ion-exchanged water C-water = chemical treated water R-water = reuse water from another rinse tank DI-water = de-ionised water	I_W
4	Tank volume	10 Liters 12000 liters	T_{Vol}
5	Dripping	1 = 20-sec 2 = 15-19 sec 3 = 10-14 sec 4 = 5-9 sec 5 = 0-4 sec	DT
6	Hanging	1 = All water run off immediately 2= All water run off after some time 3 = Moderate run off 4 = Slow run off 5 = Slow run off + water pockets	HG
7	Agitation	1 = agitation and motion 2 = agitation and motion 3 = heavy motion, no agitation 4 = some motion, no agitation 5 = no motion, no agitation	AG
8	Inlet/outlet	1 = Inlet (top) reverse outlet (bottom) 2 = Inlet (top) reverse outlet (dived)	IN

		3 = Inlet reverse outlet, bottom 4 = Inlet reverse outlet, top 5 = Inlet near outlet, top	
9	Back-mix	1 = No back-flow 2 = Minimum back-flow 3 = Moderate back-flow 4 = Some back-flow 5 = Heavy back-flow	BM
10	Flow-control	1 = Complete flow-control 2 = Some flow adjustment 3 = Coarse flow-control 4 = Very little flow-control 5 = Totally open valve	FC
11	Water consumption	1-1000l/hr	W_c
12	Dilution factor	100-1.000: After degreasing and pickling 500-2.000: Before electroplating metal finishing baths 200-2.000: After miscellaneous chemical baths 5.000-10.000: Final rinsing after decorative chromium 1.000-5.000: Final rinsing after other galvanic baths	D_f
13	Dragout	25-50: Vertical hanging, good dripping 160 Vertical hanging, bad dripping 50-100: Horizontal hanging, good dripping 200-400: Horizontal hanging, bad dripping 300-1.000: Cup-shaped items, bad dripping 100-200: Typical “normal average” 200-300: Barrels	D_o
14	Surface area	1-1000000 m^2/yr	S_a
15	Hours per year	1-8760 hours/ year	H_y

From Table1 it can be seen that the reviewer has to be able to extract the relevant input on the choices available for the observed inputs. These inputs include:

- Tank Number
- Rinse system
- Input water type
- Hanging
- Agitation
- Inlet/outlet
- Back mixing
- Flow control

The auditor has to then determine/ calculate the other inputs. These inputs include:

- Drip times have to be measured using a stopwatch
- Tank volumes have to be measured and calculated
- Dilution factors or "F" values have to be extracted from Flemming's tables based on the process tank located before the rinse tank under consideration.
- Drag-out has to be either physically measured or the reviewer has to estimate a value based on the inputs listed by Flemming
- Surface area is the biggest challenge and needs to be determined by the consultant together with the company representative
- Hours per year is determined by multiplying the weekly hours by the number of weeks worked

3.2 Rinse table calculations

In order to determine the state of the rinsing system, the abbreviations from Table 1 are used to conduct the following calculations:

Drip times, hanging times, agitation, inlet/outlet, back mixing, flow control is entered for each rinse tank. The calculations for state of the rinsing system are conducted using the data inputs in table 1. The actual calculations are:

The rinse system (R_{in}) is entered, if the rinse system score is >10 then the following calculations are conducted,

S_{RS}^{n1} = Intermediate calculation

$$S_{RS}^{1} = 100*\{(DT-1)*0.2+(HG-1)*0.1+(AG-1)*0.1+(IN-1)*0.1 + (BM-1)*0.25+(FC-1)*.25\}/4 \quad \text{......} 1a$$

If R_{in} <10 then

$$S_{RS}^{1} = 100*\{(DT-1)*10/75+(HG-1)*10/75+(AG-1)*10/75+ (IN-1)*10/75+(BM-1)*25/75+(FC-1)*25/75\}/4 \quad \text{......} 1b$$

The result of the above is used together with the water consumption for each tank (W_c) which is calculated as:

$$S_{RS}^{2} = S_{RS}^{1} * W_c \quad \text{......} 2$$

This is summed over all the tanks to a total for the "LM" factor.

$$LM = \sum_{1}^{n} S_{RS}^{1} * W_c \quad \text{......} 3$$

Where n = number of rinse tanks

The water consumption for all rinse tanks are summed:

$$S_{RS}^{3} = \sum_{1}^{n} W_c ....4$$

The state of the rinsing system is (S_{RS}^{F}) calculated as:

$$S_{RS}^{F} = \frac{LM}{S_{RS}^{3}} ....5$$

Determining the actual water savings rating (W_{SR})

The inputs include the actual water consumption, operational hours per year and the production in meters squared/year.

Present water consumption (P_{WC}) is calculated as:

$$P_{WC} = (W_C * H_Y)/S_a ....6$$

This is summed for all the rinse tanks

$$P_{WC}^{T} = \sum_{1}^{n} (W_C * H_Y)/S_a ....7$$

$$P_{WC}^{F} = (P_{WC} * S_a)/1000 ....8$$

The PARCOM rating (P_R) is calculated as:

$$P_R^{1} = (D_f)^{1/3} * D_0 ....9$$

$$P_R^{F} = P_R^{1} * S_a ....10$$

$$W_{SR} = (100 * \frac{P_{WC}}{P_R^{\ F}})/P_{WC} ....11$$

Thus the actual water savings is rated on a scale of 1-100. The inputs are entered into a spreadsheet format, see Figure1A&B. There are various such sections in the Flemming model and the aim is to determine the impact of data variation on the specific model output. For the purpose of this investigation a typical company was randomly selected from the database of companies investigated. From the data extracted from this company, the initial rinse table indicated a 46.6 % potential for improvement. The table is illustrated in Figure 1A&B.

Figure 1A: Company results for rinse tables

Rinse	Process bath	Raw water	Tank	Rinse system data score (1=OK, 5=unsatisfactory)						Total,%	Waterflow, l/h		Water consumption: l/m2		Savings
system	before rinse		litre	Drip-ping	Hang-ing	Agita-tion	Inlet-outlet	Back-mix	Flow-control	Max100	Actual	Goal	Calcu-lated	goal	m3/yr
11		T	570	1	1	1	1	1	1	0	500	72.7355	18.3	2.7	2461.0
2		T	570	1	1	1	1	1	1	0		81.9182	0.0	3.0	0.0
12		T	750	1	1	1	1	1	1	0	300	81.9182	11.0	3.0	1256.2
11		T	570	1	1	1	1	1	1	0	400	81.9182	14.6	3.0	1832.2
1		T	750	4	3	3	4	1	2	52	300	81.9182	11.0	3.0	1256.2
1		T	1000	4	3	3	4	1	2	52	150	103.21	5.5	3.8	269.5
2		T	750	4	3	3	4	1	2	52	270	81.9182	9.9	3.0	1083.4
													0.0	0.0	0.0
													0.0	0.0	0.0
											1920	585.537	70.3	21.4	8158.4

Figure 1B: Company results for rinse tables-continued

Support table							
F-value	h/yr	m2/yr	Drag-out, l/m2	L * M	Helping Score	PARCOM Water Consumption, m3/yr	Present Water Consumption, m3/yr
700	5760	157,283	0.3	18,125.00	36	418.96	2,880.00
1000	5760	157,283	0.3	0.00	52	471.85	0.00
1000	5760	157,283	0.3	13,500.00	45	471.85	1,728.00
1000	5760	157,283	0.3	20,500.00	51	471.85	2,304.00
1000	5760	157,283	0.3	15,500.00	52	471.85	1,728.00
2000	5760	157,283	0.3	7,750.00	52	594.49	864.00
1000	5760	157,283	0.3	13,950.00	52	471.85	1,555.20
				0.00	-25	0.00	0.00
				0.00	-25	0.00	0.00
				89,325.00		3,372.69	11,059.20

Possibilities for optimisation, total		46.52
Possibilities for relative savings		69.50
Possibilities for absolute savings		7686.51

From Figure 1 A&B it can be seen that the reviewer scoring is for individual rinse tanks whilst the final outputs rate the entire rinse system. It is noted that the output for "Possibilities for optimization, total" is 46.52 for the company under consideration. This output is used as an indication of areas to address for potential cleaner production improvements. The ranges for these outputs are listed in Table 2. From Table 2 it can be seen that the ranges are large, typically in the order of 20. Thus it can be seen that the outputs are imprecise/fuzzy. A detailed analysis of the exact effects of input variation on outputs would indicate the potential to use fuzzy inputs.

Table 2: Scoring ranges of output: "Possibilities for optimization, total"

Output range	Implied saving potential
0-20	Very low potential for saving
21-40	Medium potential for saving
41-60	Medium to high potential for saving
61-100	Very high potential for saving

In order to determine the sensitivity of the rinse system to input variation the system has to be looked at holistically. As can be seen in Table 2 the range for the output ratings are fairly wide. It would be ideal to investigate the impact of the variation in inputs to the output. This is done by assuming that the inputs are imprecise ie randomly changing the input variables. The output rating is then compared to the Flemming rinse table output.

This implies that the reviewer's inputs for the seven rinse tanks under consideration have to be varied randomly, remembering that each tank has fifteen inputs. This makes the task complex and hence the entire rinse system was programmed in MatLab, and the Monte Carlo technique applied to changing the inputs.

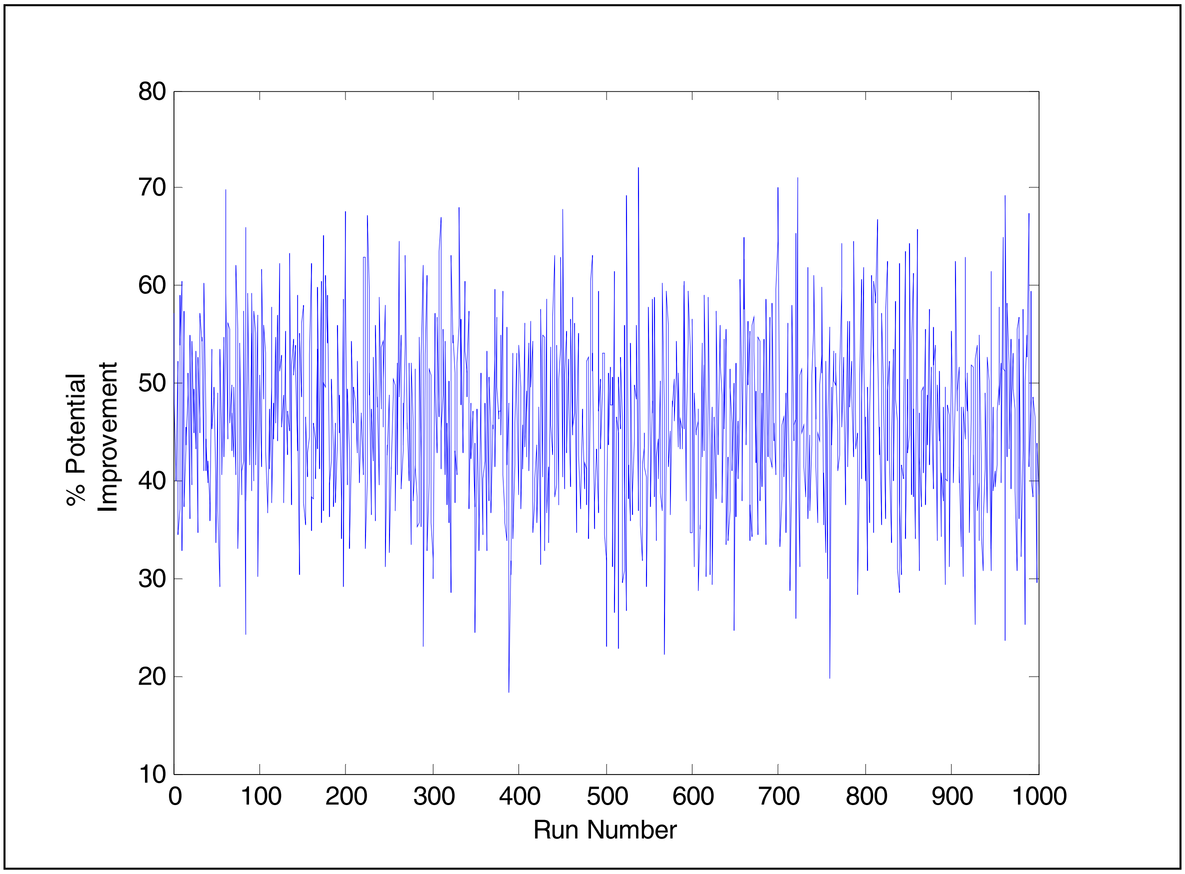
The input values in Table 1 were varied to determine the impact of the changes. Initially only five of the input values were increased/decreased. This was done randomly for any specified number of values in Table 1. This process was repeated 1000 times and the output compared to the initial output of 46.6%. This process was repeated for up to 90 random input changes (15 inputs for six tanks). The average outputs for a total Monte Carlo of 1000 runs are noted in Table 3. The values were initially increased/decreased by less than 10% or in the second runs, between 10 and 20%.

Table 3: Monte Carlo results for input changes for rinse tables

No. of inputs changed	Mean Output for input change of <10%	Standard Deviation	Mean Output for input change of >10%>20%	Standard Deviation
0	46.6	-	-	-
5	45.86	1.07	45.88	2.19
10	45.92	1.6	45.89	3.01
20	45.76	2.18	45.74	4.24
30	45.95	2.65	45.81	5.41
40	45.73	3.18	45.79	6.4
50	45.92	3.52	46.1	7.1
60	46.03	3.84	46.17	7.43
70	45.91	4.12	46.06	8.34
80	45.94	4.4	45.53	9.09
90	45.68	4.52	45.61	9.48

From Table 3 it can be seen that there is no significant change to the output rating of 46.6%. What is clear however is the increase in standard deviation of the output as the number of inputs changed is increased from 5 to 90. The percentage change in inputs has a significant impact on the outputs i.e. for five random input changes of 10 % from the original value the standard deviation was 1.07, which is doubled to 2.19, when the input is changed, by 20% of its original value. Figure 2 illustrates the Math lab output for a the run where 60 random inputs were changed by +/- 1 .

Figure 2: Math lab results for 60 input changes of +/-1, for the rinse system



It can be seen that variable changes on average result in a negligible mean output change for the rinse system. The result indicates that the maximum standard deviation is less than 10 % of the range i.e. 2/3 of the outputs is 10% or less imprecise. From Table 2 it can be seen that the output bands are wide (20%) and a net increase or decrease of 10% would usually not impact on the output rating. At worst it would result in the company moving one rating up or down. Thus it can be concluded that for the rinse tables, the output would not be significantly compromised if the inputs were not precise.

The same methods were used to determine the plant wide sensitivity to variable changes. Similar results were obtained and it can thus be concluded that the model can potentially be dependent on non-rigid data.

4. Fuzzy logic based model

The plant wide evaluation tool deals with various areas of the plating plant under consideration. To assist the evaluation process, a proper plant classification will be undertaken. The following electroplating plant sections, together with their justification, are used.

Consumption: Process chemical. 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.

Consumption: Water. The actual water flows in all the rinse steps must be evaluated. This will be critical for identifying the best opportunities for water use and reuse.

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

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

Chemicals for wastewater treatment plant. The efficiency of chemical treatment of wastewater in a WWTP is directly related to waste reduction and thus should also be evaluated.

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

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

Health and safety and environment. This is to evaluate the employee's health and safety. The impact of the types of chemicals and working environment must be investigated.

4.1. Application of Multi Objective Decision-Making to rinse system

For the application of the multi objective decision making the first step would be to declare the operator inputs for the different operator questions. These choices of potential operator answers are referred to as the alternates available. The alternates need to be presented in a user friendly and easily identifiable format for the operator to make his selection. A detailed list of these questions and alternates for the rinse system is described.

4.1.1 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 sent on to the next bath.

Operator alternates for dripping time:

- Jig drip time is between 0-4 Seconds
- Jig drip time is between 5-9 Seconds
- Jig drip time is between 10-14 Seconds
- Jig drip time is between 15-19 Seconds
- Jig drip time is >20 Seconds

The scores above are acceptable for racked goods.

4.1.2. Hanging

By hanging (suspension) it is understood to be the physical orientation 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 is always 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.

Operator alternates for parts hanging:

- No cup-shaped parts entraining liquid, flat sheets hung with one corner facing down, draining time less than 3 seconds.
- Some liquid entrapment by cup-shaped parts, flat sheets hung with the shortest end facing down, 3~8 seconds of draining time
- Large liquid entrapment by cup-shaped parts, sheets hung with the shortest end facing down, 8~12 seconds of draining time
- Large liquid entrapment by cup-shaped parts, sheets hung with a longer side facing down, 12~15 seconds of draining time
- Large liquid entrapment by cup-shaped parts, sheets hung with a longer side facing down, draining time greater than 15 seconds

4.1.3. Agitation

By agitation it is understood to be 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 aggressive agitation and liquid motion the liquid film is physically replaced much faster. The agitation and liquid motion thus have high influence on the speed of the replacement of the liquid film.

Operator alternates for Agitation:

- No agitation or liquid motion in any tanks
- Visible agitation or jig motion on some cleaning tanks
- Visible agitation or jig motion on all cleaning tanks
- Visible agitation and liquid motion on all process tanks
- Aggressive agitation and liquid motion on all process tanks

4.1.4. Water Inlet/Outlet

Water inlet/outlet is understood to be 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. This is mainly due to concentration pockets caused by insufficient mixing. If the inlet and outlet are physically placed side by side there can be high water consumption but a very low rinsing efficiency.

Operator alternates for Process Inlet/Outlet:

- Inlet located at the top of the tank and outlet next to it on the top of the tank
- Inlet located at the top of the tank and the outlet on the top of the tank but on the opposite end

- Inlet located at the top of the tank and the outlet on the bottom of the tank but on the opposite end
- 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
- 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

4.1.5. Back-Mixing

When two or more rinsing tanks are connected (e.g. counter current rinse), it is important that the water run from the tank with a lower chemical concentration to a tank with a higher chemical concentration. 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 construction should be corrected to improve rinsing quality and reduce water consumption.

Operator alternates for Back Mixing:

- Rinse tanks linked across the bottom or top, allowing continuous flow of water
- Small pipes linking rinse tanks, resulting in continuous back mixing; high spills between rinse tanks during jig submersion
- Rinse tanks linked across the bottom or top, allowing moderate water flow, or very small water overflows to the next rinse tank during jig submersion
- Rinse tanks linked across the bottom or top, allowing very little water flow, or some water overflows to the next rinse tank during jig submersion
- No back mixing, tanks not linked

4.1.6. Flow-control

Controlling the inlet flow of water to a rinse tank is probably the most important factor influencing the water consumption. To control the flow a valve is needed for adjustment and a flow meter to monitor the flow - but more importantly the exact water flow rate is required. 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 totally open water-valve, 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 it is seen that the operations staff increase the water flow by further opening the water-valve because it was found that the rinse water was too dirty. This is an important task to set up correct instructions and ensure that these instructions are followed.

Operator alternates for Flow Control:

- Rinse water supplied by non-restricted pipe, separate inlet for each rinse tank
- Rinse water supplied by a valve on the end of a pipe with some control
- Static tanks dumped regularly or with moderate flow control but without rinse recovery system, and no rinse water redirecting

- Static tanks dumped regularly or with moderate flow control but without rinse recovery system, and rinse water redirectable
- Continuous flow control via predetermined rinse water requirements, all water recovered via low flow rinse back into plating tank

5. Rinse management application

The alternates listed above are used to establish the fuzzy model. These alternates are considered for development of the fuzzy rinse management model. The set of alternates are defined as A:

$$A = \{a_1, a_2, \ldots, a_6\} = \{DT, HG, AG, IN, BM, FC\} \quad \ldots 12$$

Where:

DT: Drip time that parts stay above a tank before moving to the next tank
HG: Orientation of the parts hanging on a jig
AG: Agitation of the solution in a tank by air or jig movement
IN: Water flows through a rinse tank
BM: Back mixing of rinse due to connections of the rinse tanks
FC: Flows control of rinse water to a rinse tank

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

$$O = \{o_1, o_2, \ldots, o_4\} = \{CC, P, WC, C\} \quad \ldots 13$$

where

CC: the chemical consumption
P: the production rate
WC: the water consumption
C: the cost for wastewater treatment and due to production loss

Available information. In this application, the CP evaluators obtained the level of importance of each factor to each objective. This data is compiled in the following notation suggested by Zadeh.[19]

$$o_1 = \left\{ \frac{0.8}{DT}; \frac{0.5}{HG}; \frac{0.2}{AG}; \frac{0.1}{IN}; \frac{0.1}{BM}; \frac{0.15}{FC} \right\} \quad \ldots 14$$

$$o_2 = \left\{ \frac{0.4}{DT}; \frac{0.15}{HG}; \frac{0.2}{AG}; \frac{0.15}{IN}; \frac{0.1}{BM}; \frac{0.1}{FC} \right\} \quad \ldots 15$$

$$o_3 = \left\{ \frac{0.7}{DT}; \frac{0.2}{HG}; \frac{0.1}{AG}; \frac{0.7}{IN}; \frac{0.1}{BM}; \frac{0.8}{FC} \right\} \quad \ldots 16$$

$$o_4 = \left\{ \frac{0.2}{DT}; \frac{0.2}{HG}; \frac{0.1}{AG}; \frac{0.1}{IN}; \frac{0.1}{BM}; \frac{0.15}{FC} \right\} \quad \ldots 17$$

In the above notation, the numerator and denominator of each fraction are, respectively, the fuzzy number ($\mu_{o_j}(a_i)$) as the importance to the objective and the corresponding factor (a_i). The numerator is a subjective value entered based on experience.

$B = \{b_1, b_2, \ldots, b_4\} = \{0.9, 0.75, 1, 0.65\}$……………………………………………18

The subjective values reflect the following basic analysis for rinse management: (i) the water consumption objective (o_3) as the most important ($b_3 = 1$), (ii) the chemical consumption (o_1) as very important ($b_2 = 0.9$), (iii) the production (o_2) due to rinse management considered fairly important ($b_2 = 0.75$), and (iv) the additional cost (o_4) as the least important ($b_4 = 0.65$) in evaluation.

Evaluation: The following manipulations are performed in accordance with multi objective decision theory:

$$D(a_1) = (0.1 \vee 0.8) \wedge (0.25 \vee 0.4) \wedge (0 \vee 0.7) \wedge (0.35 \vee 0.2) = 0.35 \quad \ldots\ldots..19$$
$$D(a_2) = (0.1 \vee 0.5) \wedge (0.25 \vee 0.15) \wedge (0 \vee 0.2) \wedge (0.35 \vee 0.2) = 0.2 \quad \ldots\ldots..20$$
$$D(a_3) = (0.1 \vee 0.2) \wedge (0.25 \vee 0.2) \wedge (0 \vee 0.1) \wedge (0.35 \vee 0.1) = 0.1 \quad \ldots\ldots..21$$
$$D(a_4) = (0.1 \vee 0.1) \wedge (0.25 \vee 0.15) \wedge (0 \vee 0.7) \wedge (0.35 \vee 0.1) = 0.1 \quad \ldots\ldots..22$$
$$D(a_5) = (0.1 \vee 0.1) \wedge (0.25 \vee 0.1) \wedge (0 \vee 0.1) \wedge (0.35 \vee 0.1) = 0.1 \quad \ldots\ldots..23$$
$$D(a_6) = (0.1 \vee 0.15) \wedge (0.25 \vee 0.1) \wedge (0 \vee 0.8) \wedge (0.35 \vee 0.15) = 0.15 \quad \ldots\ldots..24$$

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

This evaluation indicates that drip time (DT, or a_1) is most critical, while agitation (AG or a_3), the inlet water flow (IN, or a_4), and the back mixing between tanks (BM, or a_5) are the least important in this case.

If the values of the concerned factors are available in a plant, the rating of the given rinse management system can be evaluated using Eq. (4.13) as follows:

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

……………………………………………………………………………25

Equation 25 is the fuzzy rating that would be used to determine the status of the rinse management system. Similar ratings are established for the other categories detailed in section 4.2.1-4.2.6.

6. Comparison of results with Database values from Flemmings model

The fuzzy results needs to be compared to the results generated by Flemming's[20] model. The initial fuzzy allocation values can be assumed to be raw estimate values. These values are aimed at being initial estimates of the potential fuzzy allocation for the operator alternates. These values enjoy a low confidence level due to the nature in which they are obtained i.e. they are purely subjective. It would be ideal to regress these values so as to try and replicate values from the database.

These values are then used as inputs into the fuzzy model. For example, if the operator selects a low rating under Drip times, such as 0.2, then the drip times (DT) value in equation 25 is multiplied by this value. This would be done for each of the categories in the rinse section. Table 4, contains a set of input values for the six different categories in the rinse section. For the testing of equation 25 four-company case scenarios were extracted from the database.

Table 4: Comparative outputs from Flemming's and Fuzzy model –rinse system

Case No.	Drip Times	Hanging	Agitation	In-Out	Back Mixing	Flow Control	Fuzzy Evaluation	Fleming's Evaluation	Sum of square
1	0.2	0.2	0.4	0.4	0.2	0.2	25.0	6.7	336.0
2	0.8	0.4	0.6	0.4	0.4	0.4	52.0	41.7	106.7
3	0.6	0.8	0.6	0.8	0.6	0.8	71.0	65.0	36.0
4	1	0.8	1	1	1	1	96.0	96.7	0.4
									479.1

As can be seen from Table 4 the fuzzy model needs to be improved so as to generate equivalent results as compared to the Flemming model[20].

Using the excel solver and defining the sum of squares as the main objective to minimize, the estimates of the fuzzy allocations can be improved. The solver is then run with the above ranges and the Excel output would by regression minimize the difference between the database results and the fuzzy outputs. It is noted that the operator input ratings were used for the regression. The actual outputs would not change significantly if the expert input factors were regressed. This implies that the output would remain unchanged as the operator input ratings and the expert inputs can be considered to be a ratio.

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The regression results for the alternates are summarized in Table 5.

Table 5: Summary of regressed values:

General segregation	Drip times	Hanging	Agitation	Inlet	Back mixing	Flow control
Low	0	0	0	0	0	0
	0.05	0.05	0.18	0.2	0.05	0.05
Medium	0.3	0.3	0.3	0.3	0.3	0.3
	0.51	0.5	0.5	0.6	0.56	0.6
High	0.7	0.83	0.81	0.7	0.8	0.72
	1	1	1	1	1	1

From Table 6 it can be seen that the regression has resulted in some changes to the fuzzy alternate allocations. These values are all within the initial estimated range. It can also be seen that the sum of square differences is considerably reduced. Hence the regressed fuzzy outputs are used as fuzzy allocation for the operator questions.

Table 6: Comparative results after regression.

Case No.	Drip Times	Hanging	Agitation	In-Out	Back Mixing	Flow Control	Fuzzy Evaluation	Fleming's Evaluation	Sum of square
1	0.05	0.05	0.3	0.3	0.05	0.05	11.25	6.7	21.0
2	0.7	0.3	0.5	0.3	0.3	0.3	42.0	41.7	0.11
3	0.51	0.83	0.5	0.56	0.56	0.72	65.0	65.0	0.0
4	1	0.83	1	1	1	1	96.7	96.7	0.0
									21.11

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

The above methodology can then be applied to the rest of the plant under five of the categories listed in section 4.0 in this paper. The appropriate fuzzy questions are developed to accommodate operator inputs under these categories. The preferences are appropriately inputted 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 indicates no room for improvement and 100 indicate major potential savings.

A case study was undertaken to verify the application.

7.1. Company Introduction

Saayman Danks Electroplaters is a jobbing shop plating nickel, zinc and chrome finishes for a wide range of application. The company has various clients ranging from car component manufacturers to private customers. The zinc electroplating facility was established in 1971 and is thus 33 years old. Due to space constraints very little upgrading has been conducted on the facility. The chemicals for the alkali zinc plating plant are supplied by Chemserve systems.

The plant operates 24 hours per day, six days per week. There are a total of 11 operators, working a two-shift cycle, operating the plant. This includes jiggers, plant operators and foreman.

A key factor for consideration for this case study is the fact that the owner of this facility has been involved in cleaner production initiatives over the past 10 years. He has had the privilege of being the provincial chairperson, national chairperson and South African representative on international funding agencies. It can thus be assumed that information was reasonably available at this company.

7.2. Data acquisition

The data acquisition process for the application of Flemming's model at Saayman Danks electroplaters was conducted over a two-week period. The pre-review questionnaire was completed in part by the owner and the lab manager. At the end of the first week a plant visit was conducted to facilitate the data gathering. During this time discussions were held on the requirements of the data sheets.

The owner indicated his method of determining the surface area for the purpose of the review. The owner explained the difficulty in obtaining exact data; this included obtaining figures from the accounts department on exact chemical usage. At the end of this session it was agreed that the review information would be completed the following week.

On the day of the review, more explanations were required on the data sheets as the company had only completed three tables and found it difficult to complete the rest. The initial data capturing was done on site and various measurements were conducted together with the plant foreman.

A major discrepancy arouse with the surface area value provided by the company. After discussions with the owner it was found that he had under estimated the surface area by fifty percent. Thus the surface area input was adjusted.

The plant operator using a measuring cylinder and stopwatch determined the water consumption. All the relevant inputs were gathered and the data entered into the spreadsheets. The entire day was spent on data collection and spreadsheets inputs.

8. Comparative application of models

The application of the artificial intelligence based model together with Flemming's model was applied at Saayman Danks electroplaters. For the purposes of the proposed model the questions detailed in section 4.1 together with questions on the rest of the plant were used for data gathering. The questionnaire comprised of some 40 question.

In order to ensure an independent assessment, the questionnaire was completed by an independent reviewer. The reviewer had no prior knowledge of the plating process and no experience in conducting reviews.

The company had availed their plant foreman to answer the questions, as the plant operators did not communicate in English. The foreman was also responsible for day to day running of the plant, including dosing of chemicals.

The questionnaire was conducted on site and was completed in 34 minutes. The data gathered was then plugged into the various models and the results analyzed. No further contact was made with the company for further data.

9. Results

The operator inputs for the fuzzy logic category from the questionnaire was entered into the visual basic software, that was specifically developed to determine the different ratings for the eight categories. The eight categories were described in section 4. The results are indicated on a scale of 0-100, with zero indicating an excellent facility with no room for improvement whilst 100 indicates significant room for improvements.

The comments made under each of the categories can be developed as automatic outputs, based on the operator inputs i.e. the important categories can be highlighted if a high fuzzy rating is allocated to this question.

The comparative results for the eight categories are:

9.1. Rinse Management

The evaluation results indicate a 66.9% potential as compared to Flemming's 63%. This indicates significant room for improvement with regards rinse management at Saayman Danks. From the fuzzy logic multi variable analysis, drip time was regarded as the key contributor to the rinse management rating. From the operator inputs, it can be seen that the company obtained the worst possible rating.

The other key areas that obtained the highest fuzzy ratings were the location of the inlet and outlet rinse water and agitation of the tanks.

Intermediate ratings were obtained for the hanging and inlet water flow control. It was noted that there was no back mixing present.

9.2. Sludge reduction

The evaluation results indicate a 55.25 % saving potential as compared to 60% in Flemming's waste minimization tables. This indicates that improving on the chemical losses can reduce the sludge generated at Saayman Danks. The fuzzy decision system highlights drag-out as the most significant variable to consider for sludge reduction. The company obtained the maximum penalty for having just a single rinse tank after their process tanks. From the operator feedback, it was noted that Saayman Danks scored in the intermediate range for the rest of the questions. This indicated that if the drag-out was improved then significant sludge reductions would be encountered.

9.3. Wastewater treatment plant chemicals

The evaluation results indicate a 33.1% potential as compared to 38% in Flemming's Wastewater chemical tables.

The potential for improvement, for chemicals used at the wastewater treatment plant can be considered to be low. The fuzzy system highlights using less excess of treatment chemicals as the major contributor to the wastewater chemical rating. Although automatic dosing occurs at Saayman Danks, the chrome is treated manually.

9.4. Wastewater treatment plant equipment

The model generated a 45.5% rating as compared to Flemmings rating of 50%.

This indicates a medium potential for improvement with regards to the operations at the wastewater treatment plant. Inputs were only received for pH adjustment. It was found that calibration was conducted once/month. This should be once every two weeks.

The fuzzy decision making system highlights the management of the treatment equipment for cyanide, chrome and metal monitoring as being most crucial for wastewater treatment. The company rated badly in the metal monitoring category, as no metal monitoring was carried out.

9.5. Chemical consumption and management

The company faired well on this category obtaining a score of 29% from the fuzzy system and a score of 27% via the Flemming system. This indicates a low potential for improvement.

The fuzzy system indicates the chemical dosing and the monitoring to be of highest importance for this category. The company scored well in this category as a dedicated chemical analyst manages the process chemicals in house. Dosing is done in accordance with in house analysis.

9.6. Occupational health and safety

Here again the fuzzy evaluations system indicated a low potential for improvements, the company scored 25% on the fuzzy system and 23% via the Flemming system. The major considerations under the occupational health and safety category are the temperature and the chemistry of the process tanks.

At Saayman Danks only the degreaser operates at a significantly high temperature. The plant is semi automatic so the scores for the other questions such as lifts etc were low and thus the overall score for this category was considered low.

9.7. Water Reuse

There was no equivalent category from the Flemming model. The fuzzy model score for this category was 49. From the fuzzy decision analysis, the redirecting of the acid and degreaser rinse together with closed circuit counter current rinsing were rated as the most important factors for water re-use. The company does redirect the acid rinse water but does not have closed circuit counter current rinses. This can potentially prove to be a significant source of water saving for the company. The exact potential water saving is quantified later in this chapter.

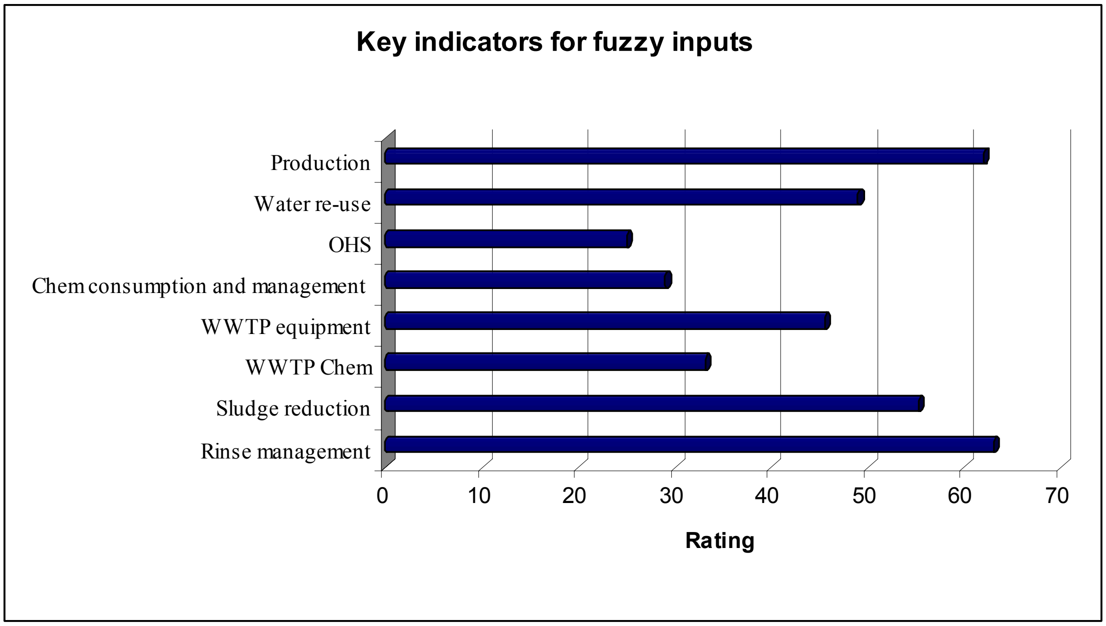
9.8. Production

Flemming's model does not contain an equivalent category so there are no comparative figures. The fuzzy model generates a score of 62%, which is indicative of a medium to high potential for improvement. The fuzzy decision analysis indicated that the determination of the plant production in surface area was the key-determining factor for this category. Saayman Danks does not measure surface area but rather measures the weight of components as a measure of production. This creates a problem in predicting the chemical and water consumption of an electroplating facility.

The determination of the plated thickness by sampling components ensures optimum operations. This is done once every month at Saayman Danks, it contributes to the score.

The other areas of improvement are the monitoring of the loading of the jigs as this is currently done infrequently. The results from the above categories is graphically represented in figure 3.

Figure 3: Model output for eight categories



10. Conclusions

From the comparative results listed it can be concluded that the artificial intelligence model outputs are similar if not equal to the Flemming model outputs. The comparative indices indicate a maximum difference in output of 4.75%. In some cases the model improves upon Flemming's model by providing further details.

The precise data requirements for determining the actual chemical consumptions have become obsolete. The data collection process has become significantly reduced. The skills level of the auditor is non existent as the expertise is captured by a structured questionnaire and the visual basic software. The added advantage of the system being the need for a low level input from the company. Traditional models requiring technical/management representatives have been reduced to operator level inputs. The areas that are highlighted can be further quantified using mathematical models.

The superiority of the proposed model is clear from the above case study. The demand for precise data becomes obsolete using the proposed model.

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