Chapter 17

Fuzzy Logic Application, Control and Monitoring of Critical Machine Parameters in a Processing Company

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Additional information is available at the end of the chapter

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Abstract

The processing company under study found out that the boiler was the key machine and needs artificial intelligence monitoring and control. It was simulated under Matlab software and oil level, and pressure and temperature were to be modelled and controlled using the programmable logic controller (PLC) with a fuzzy logic controller as the main brain of control. The company is for processing of fruits to produce juice.

Keywords: fuzzy logic, control, critical machinery, monitoring, processing

1. Introduction

Beverage industry denotes the industry accountable for the manufacture of drinks through the usage of highly automated systems, which are responsible for the production of beverages within a short period of time [1–3]. Beverage industry is greatly affected with profitability problems. The ever-increasing costs of new equipment and spares, perennial foreign currency shortages and the need for improved competitiveness bring about the need for more effective maintenance systems [4–6]. This results in maximum utilization of plant-installed capacity through improved reliability, uptime, quality and asset life—all achieved at optimal levels of costs versus benefits. Emphasis should be on ensuring that the correct maintenance is being done (doing the right job) rather than merely ensuring that maintenance is being done correctly (doing the job right). At the processing company, process losses have traditionally been 1.5% of total losses but increased to 10% in 2011. This has raised concern and hence the need to find new emerging maintenance management philosophies, such as improving maintenance cost effectiveness as one sure way of increasing the overall profitability [7].

1.1. Background

Currently, the plant uses run-to-failure maintenance as a strategy to take care of its machines. This approach is reported to be creating a high risk to workers, production and property. This is seen by the high rate of unscheduled events associated with breakdowns, emergency equipment, long working hours and high maintenance costs. This has lowered down the image of the company in terms of competition when compared the benchmarks with other beverage companies in developing nations. The progression towards a global economy has increased the base of competition for almost all companies. By competition, it is suggested that every organization out there is always targeting to keep a certain score. The record on a scorecard may be a ratio of more sales, increased revenue or a mounting customer base. Despite the benchmark used for the measurements, for a business to remain competitive, there is a basic company demand to improve at maintaining and taking care of machinery as well as meeting customers' requirements. The competitiveness of production corporations relies on the availability and productivity of their manufacturing equipment, which is possible if all manufacturing losses are recognized and eliminated so that the products can be sold on a marker at a minimum cost.

1.2. Fuzzy logic

The rules can process simple arithmetic and logical operations with the help of Locator Identifier Separation Protocol (LISP), but a process control algorithm that is based on fuzzy logic is called fuzzy control [8]. The oldest and most common maintenance and repair strategy are "fix it when it breaks". The appeal of this approach is that no analysis or planning is required [9]. Early detection of faults in a machinery is a key parameter in control and maintenance to avoid failure of equipment [10].

2. Critical machinery

The criticality index is regularly used to decide the extent of the nature of assessment on a given machine by checking the machine's objective [11], excess (that is on the off chance that if the machine falls flat, is there a standby machine which can assume control), repairing expenses, idle sways, well-being, security and environmental concerns and other considerable features. The criticality record puts all machines into one of three classifications as follows:

Critical equipment: This is the fundamental machinery at the processing company. With basic equipment which is the core focus of the procedure, it is understood to require adequate online state checking to ceaselessly capture much information from the mechanism as could be expected paying little heed to expenditure and is frequently indicated by the plant protection. Estimations, for example, differential development, velocity, spiral relocation and shaft pivotal, dislodging and packaging vibration, temperatures, weights and loads, are taken where conceivable. Such qualities are regularly sustained into a hardware administration programming system, which is fit for slanting the recorded information and giving the administrators data, for example, executing information and even anticipating failures and giving conclusions of breakdowns beforehand.

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Vital equipment: These are units that are essential to the procedure; however, in the event that there is a breakdown, the procedure still proceeds. Excess units (if accessible) would be in this domain. Analysing and regulation of these units are additionally crucial to keep up option strategies given that critical machinery falls flat.

Balance of industrial equipment or the general purpose: These are the components that complement the whole plant and are ordinarily assessed, utilizing a handheld information gatherer, as said beforehand, to occasionally build an idea of the strength of the machine.

2.1. Types of failure caused by not maintaining machinery

Breakdowns might be characterized by their seriousness in any of these four classes and are contingent upon the characterized breakdown impacts below:

1. Insignificant breakdown: Any breakdown that does not debase the general routine and adequacy of the framework past worthy breaking points [12].
2. Key breakdown: Any breakdown that will corrupt the framework implementation and viability past worthy points of confinement, however, they can be controlled [13].
3. Critical breakdown: Any breakdown that will corrupt the framework past adequate points of confinement and could make a security danger if a prompt restorative move is not made [14].
4. Catastrophic breakdown: Any breakdown that could bring about critical framework harm, for example, to block useful achievement, and bring about death and staff wounds [15].

2.2. Types of condition monitoring techniques

In line with the research area of interest, condition monitoring will be looked at since it is a branch of Condition Based Maintenance (CBM).

2.2.1. Noise and vibration

All machines vibrate, and when they are in good condition, their frequency spectrum has a characteristic form; any departure from this form indicates that something is wrong—fatigue, or wear, or ageing of something of some component. Parameters that are useful include amplitude, frequency and phase angle [16].

2.2.2. Amplitude

This gives an indication of the stress under which a piece of rotating machinery is working, in particular, it can give a measure of the eccentricity (out-of-roundness) of a rotor [17].

2.2.3. Frequency

Through the frequency spectrum, you can detect a fault in rotating machinery. Vibrations fall into two main classes:

Synchronous: Frequencies are in multiples or sub-multiples of the frequency of rotation, that is, they are harmonics or sub-harmonics of that frequency.

Asynchronous: These are not related to the rotation frequency; they can be the natural frequencies of various parts of the system, which can be identified [17].

2.2.4. Phase angle

It locates the high point in a rotor that is not perfectly circular and thus gauges its out-of-balance characteristics. Machines must be continuously monitored to denote their state. The following machines can do these:

1. Clearance recorder: recording the actual movements of the shaft which generate the vibrations.
2. Speed recorder: mounted externally to a machine, and it gives a strong signal at medium frequencies, depending on the temperature and the general environment.
3. Accelerometer: also installed to a machine, and it gives a strong signal at high frequencies [17].

2.2.5. Temperature

Temperature recording is a relatively simple matter at the industrial level. Change of temperature in rotating machinery is often a sign of deterioration and is therefore something to which close attention should be given. This is currently practised in thermography [18].

2.2.6. Tribology

An examination of the particles suspended in oil can give very valuable information. The amount of suspended material is an indicator of the state of deterioration of the machine; the composition can identify the source of the wear and thus the component that is failing. The necessary analysis can be done in the laboratory with the electron microscope. Basically, the monitoring techniques that were listed in **Table 1** are almost the major ones currently used.

Type	Method
Visual	Eye
Temperature	Thermometer, thermocouple
Lubricant monitoring	Filtering, spectroscopy
Vibration	Signal frequency analysis
Crack	Di-penetrant analysis, radiography
Corrosion monitoring	Eye, corrosometer

Table 1. Summary of condition monitoring techniques.

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3. Problem behind the processing company (PC)

The reactive nature of the corrective maintenance strategy at the company has resulted in loss of trivial production time. Downtime due to breakdown is greatly affecting the production targets and delivery of juice products to customers which had resulted in loss of goodwill and trust from consumers. The processing company (PC) uses a number of raw materials for the production of the fruit juice concentrates: mangoes, guavas, oranges, tomatoes, lemons, grape fruits, granadilla and other continuous inputs such as municipality and borehole water, diesel, electricity and labour. The company has got equipment in place which were mainly supplied by a company in Italy. The mission of the production department is to safely produce quality products and maintain equipment at a lowest possible cost to meet sales and marketing demands.

3.1. Failure in equipment

Using records from previous seasons, equipment with high failure rates and high downtimes is identified. For easy interpretation and identification of this equipment, the information is sorted using Microsoft Excel and graphs are drawn. From the bar graph showing the relative contributions of equipment to the total downtime, equipment that contributed the most to the total downtime is identified. Breakdown of any of these equipment results in stoppage of the production; therefore, the production loss that is represented by a breakdown of each of these machines is equivalent to the production of the diffuser line, which is 60% of total production (300 TCH of 500 TCH). The following graph in **Figure 1** shows the downtimes caused by the breakdown of each item during the last juice extraction season, and **Figure 1** shows how extraction takes place.

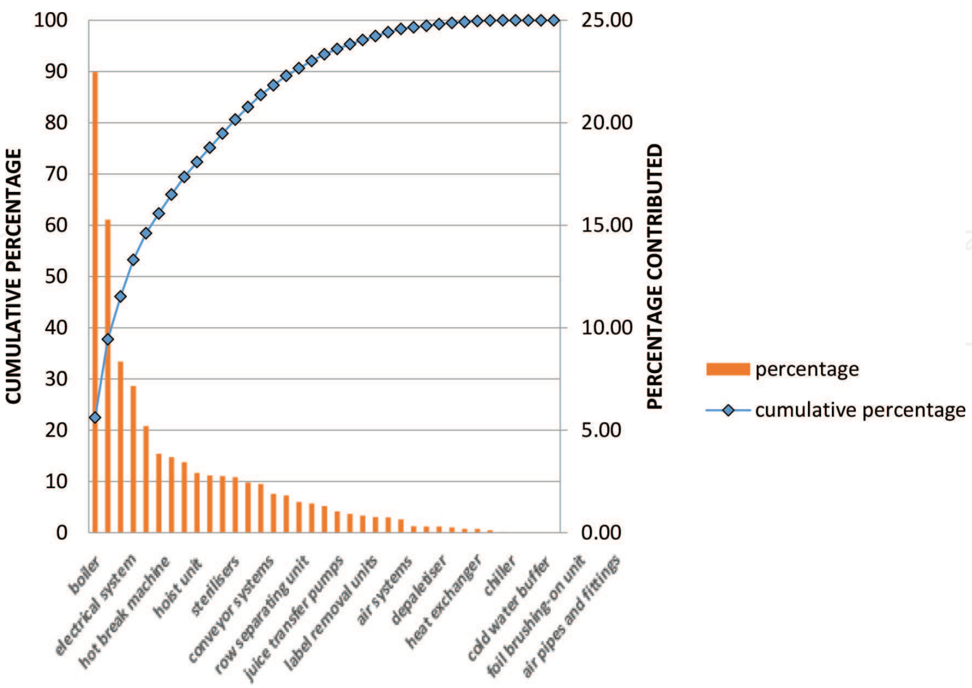

Figure 1. Unit and cumulative downtime of equipment.

3.2. Planned stoppages

The production line is stopped once every 2 weeks. The shutdown is for the whole plant, as some equipment will be due for cleaning and some equipment would be due for servicing. The shutdown starts at 0000 h and servicing starts at 1000 h. The time from 0000 to 1000 h is used to stop the processes, empty some vessels and allow some equipment to cool. This time is also used to plan some of the jobs, perform pre-task risk assessments, order and transport spares from the stores department and also to service some equipment. Full-fledged servicing kicks off at 1000 h and continues up to 1600 h. At 1600 h, the start-up process begins with steam being released into the vessels to warm them. Production is started around 1700 h when vessels are ready to receive juice, and hot imbibition water is available. The processes are then started, and the levels gradually increased. Full production levels are achieved by 1800 h. The total downtime for this planned stoppage is thus 18 h. A crushing season starts early April and ends in mid-December. On average, it has 36 weeks. The average number of hours for planned stoppages annually is thus:

$$\text{Total annual planned downtime} = \text{Number of stoppages} \times \text{Downtime per stoppage} \quad (1)$$

$$\text{Total annual planned downtime} = \frac{36}{2} \times 18 = 324\ \text{h}. \quad (2)$$

Figure 2 shows a comparison of planned stoppages and unplanned stoppages. This is a problem in this company with more stoppages. This has justified the need for my research, as shown in **Figure 2**.

Figure 2 is very critical as most of the time, the plant is always shutdown, which results in a great deficiency and loss of goodwill from the customers as the plant is failing to meet the targets.

3.3. Plant performance

From operating history, the availability performance for each item was evaluated, and the results are shown in **Figure 3**. All availability performance scores were above 90 so for clarity

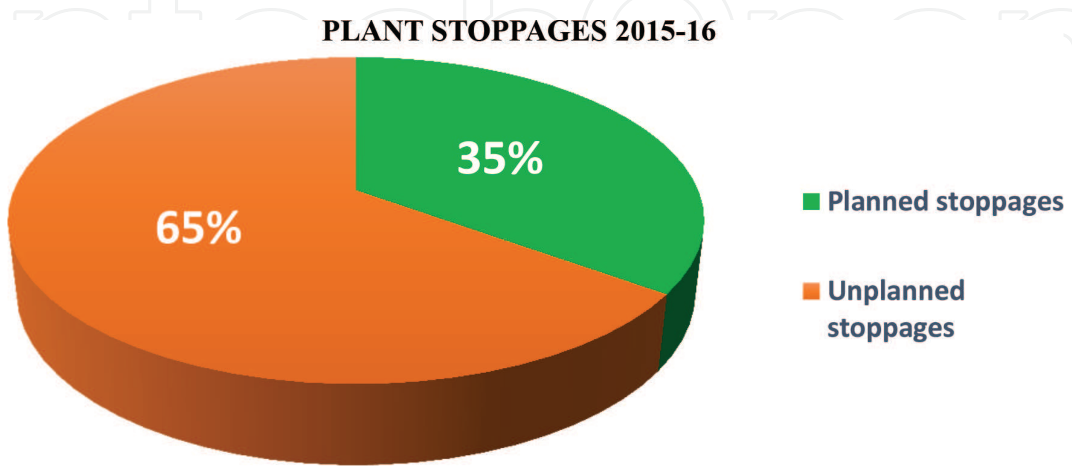

Figure 2. A pie chart for planned and unplanned stoppages.

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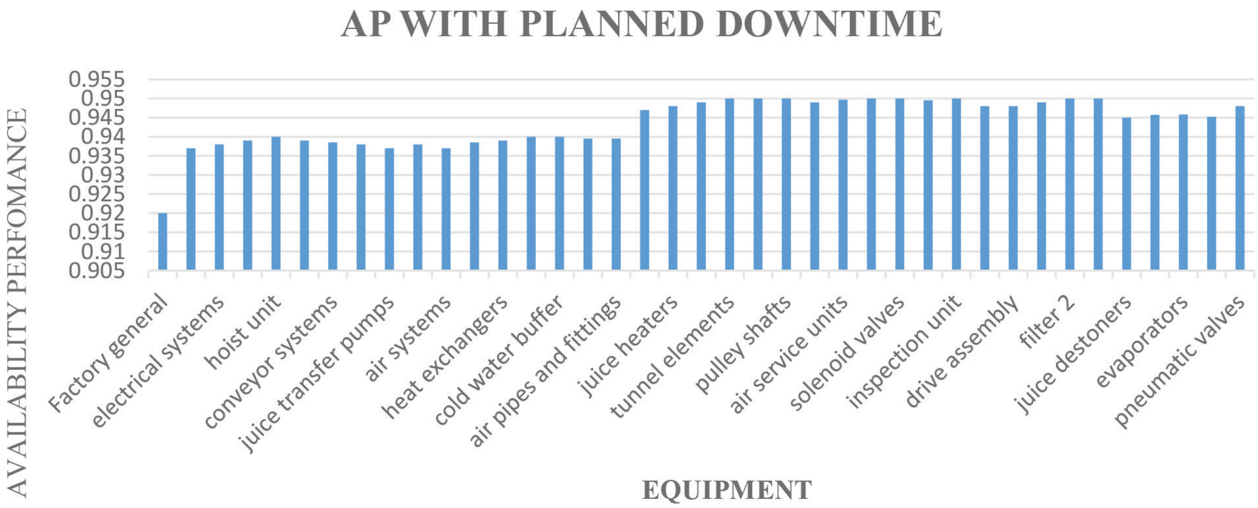

Figure 3. Equipment availability performance including planned downtime.

in comparing, the axis for availability performances was broken such that it starts at 90–100. The main contributor to downtime is planned downtime. This affects the availability of all equipment in the production line, but it is not all equipment that requires servicing every fortnight. Some of the equipment that requires servicing does not need 18 h. In view of this, maintenance schedules currently in use were analysed in order to identify equipment that really requires servicing fortnightly and has the least maintainability. **Figure 3** shows the availability performance of the plant with planned downtime.

3.4. Equipment criticality analysis

This section now seeks to identify the equipment that is critical to mainly to production, health, safety, environment and operational costs. This classification of equipment according to risk level is done so as to prioritize equipment in terms of maintenance, work orders, costs and inspection. The criticality of equipment was analysed based on two sides: the effect of failure and its consequence. Equipment history data and interviews were the methodology, which was used to find out which equipment has major effect on production. This was used to give scores to various equipment using the risk analysis matrix balanced score card by Nowlan and Heap, which is shown in Appendix.

3.4.1. Risk analysis matrix balanced score card: Appendix

As shown in Appendix, there are two categories of scores (Priority and Equipment Score), which are used to calculate the Criticality Score. The Priority Score is obtained from multiplying the results of the three factors (Factor E, Factor F and Factor G). The Equipment Score is obtained from multiplying the results of the four factors (Factor A, Factor B, Factor C and Factor D). This is summarized below.

Criticality score (The Criticality Score is obtained by multiplying the Equipment Score by the Priority Score **= ES * PS**).

Equipment score (The equipment score (ES) is obtained by multiplying the results for the four factors **= Factor A * Factor B * Factor C * Factor D**). The factors A–D are shown in Appendices 1–4.

Priority score (The priority score is obtained by multiplying the results for the three factors **(= Factor E * Factor F * Factor G**) as shown in **Table 2** and **Figure 4**.

NB: The general details on the factors used are presented in Appendices 1–4. From Table 2, it is clear that criticality equipment ranking for PC is as follows: boiler, juice transfer pumps, plant conveyor systems, sterilizers and hot break machines, and the boiler is critically affected most as shown in **Figure 5**.

The graph above shows the Key Performance Indicators (KPI) trend in the year 2010–2015. From the graph, the plant availability trend is showing an increment over the years, and the performance rate seems to be showing the same trend; thus, it seems plant availability is proportional to performance rate. Planned downtime trend has shown to be decreasing with the unplanned downtime showing an increase over the years, meaning that the maintenance effort is opposing the world-class standard as it is showing an increase in reactive domination. OEE is showing a haphazard trend as it seems to be aligning with the performance rate. OEE depends mainly on the performance rate.

Equipment	Factor A	Factor B	Factor C	Factor D	ES	Factor E	Factor F	Factor G	PS	CS
Boiler	4	4	3	4	**192**	4	4	4	64	**12,288**
Pumps and piping	4	4	3	3	**144**	4	3	4	48	**6912**
Plant conveyor Systems	4	4	3	4	**192**	4	2	4	32	**6144**
Sterilizers	4	4	3	2	**96**	2	4	3	24	**2304**
Hot break machine	4	4	3	2	**96**	2	3	3	18	**1728**
Evaporators	2	3	3	2	**36**	3	4	2	24	**864**
Heat exchangers	2	4	3	2	**48**	2	3	2	12	**576**
Super pulp creamers	4	4	3	2	**96**	2	2	1	4	**384**
Chillers	3	2	3	1	**18**	2	4	1	8	**144**
Aseptic filling machine	4	4	1	1	**16**	1	3	2	6	**96**
Sorting plant	4	3	1	2	**24**	1	1	2	2	**48**
Compressors	3	3	2	1	**18**	1	2	1	2	**36**
Washing line	2	2	2	1	**8**	1	2	1	2	**16**
Drier	1	1	1	1	**1**	1	1	1	1	**1**
CIP Plant	1	1	1	1	**1**	1	1	1	1	**1**

Table 2. Selection of critical machines.

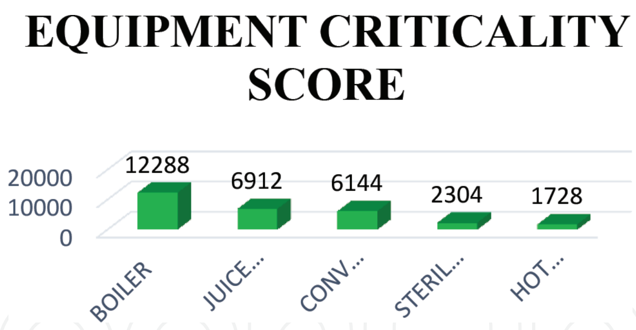

Figure 4. Critical equipment scores.

3.5. Boiler analysis

When failure occurs in any manufacturing process, it is critical to identify and analyse the root causes leading to that failure. Hybrid proactive maintenance strategy is condition-based maintenance complementing preventive maintenance (PM) strategy. PM uses mean time to failure (MTTF) as its pivot in the calculation of PM intervals. This gives calculations for MTTF on unrepairable equipment and mean time before failure (MTBF) on repairable equipment based on the assumption that the failure rate of each component is constant. Failure Modes Effects and Criticality Analysis (FMECA) analysis for the boiler is discussed in detail in a later chapter. The risk priority number chart is drawn with the highest scores corresponding to the most critical boiler component. The root cause failure analysis (RFCA) for the boiler machine is presented in the form of the Ishikawa diagram which was drawn using the Edraw max software as in **Figure 6**. The Ishikawa diagram is also called a fishbone diagram. The gearbox and feed check are reportedly failing almost every week. A Mamdani fuzzy logic controller is further presented in this chapter to monitor parameters such as moisture and dust effects on the feed check valve as well as oil level and torque control on the boiler gearbox. The fuzzy logic framework was determined among other counterfeit shrewd frameworks to be best fitting to comprehend the breakdown difficulties of the heater. A gearbox is continually sticking, and it is difficult to investigate the breakdown of fuzzy logic, and the reason is an instrument that

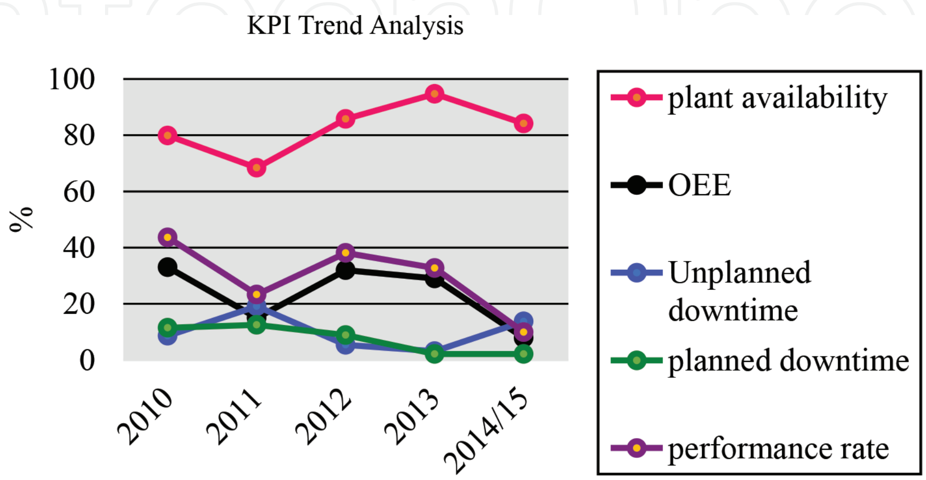

Figure 5. KPI trend analysis.

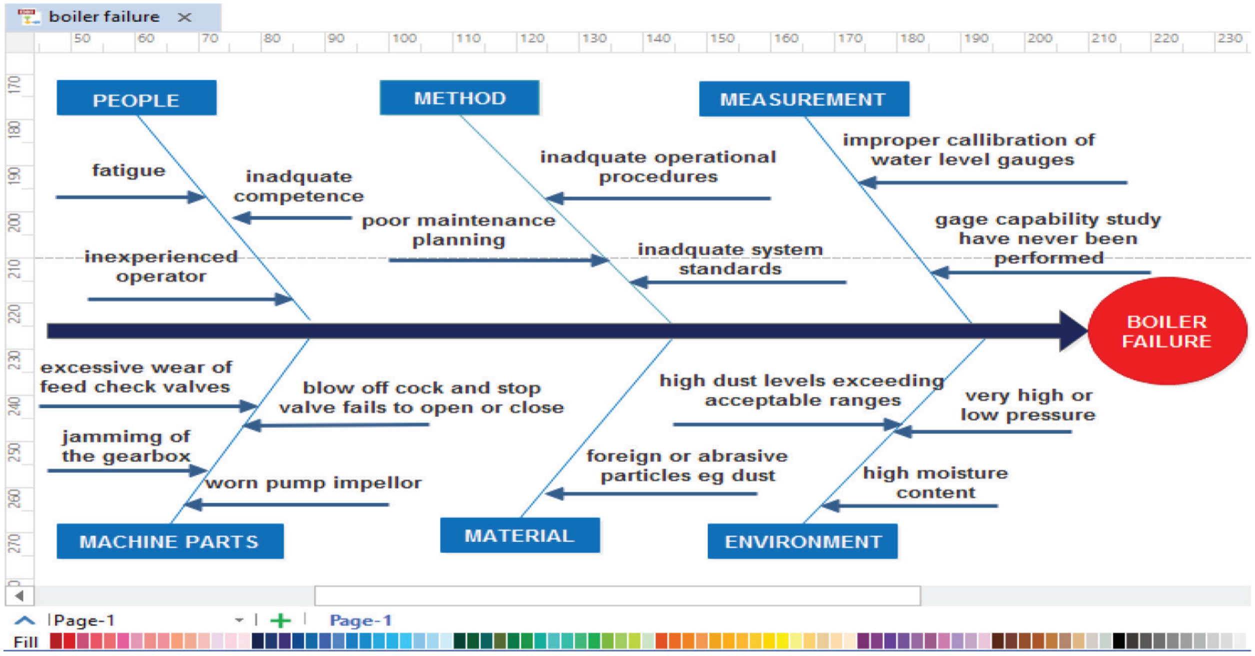

Figure 6. Ishikawa diagram for the root cause failure analysis of a steam boiler failure (Edraw Max).

was utilized for observation. On the risk priority side, it helps me knowing which segments to take and observe the most.

In general, I will do main emphasis on the raw data analysis of the overall plant performance as shown in **Figure 7**. Critical equipment has been selected using the Nowlan and Heap procedure. The critical components for the plant were found to be the boiler, juice transfer pumps, conveyor system, sterilization unit and hot break machine. This is the equipment that stands to benefit the most from a change in maintenance policy. Because of the time constraint, suitable maintenance strategies will be produced for the boiler of these critical items, which show the greatest opportunity for improvement.

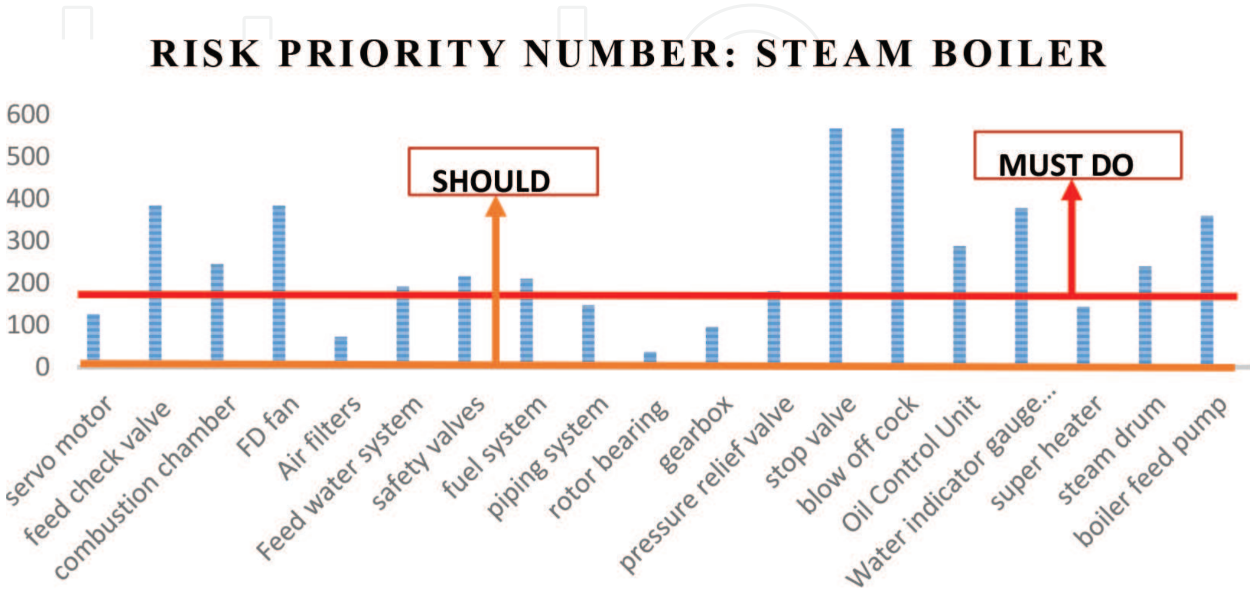

Figure 7. Risk priority number for steam boiler.

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4. Results of the boiler for case study using fuzzy logic

Analysis of the boiler is carried out in this section, and **Figure 8** shows the risk priority number for the steam boiler.

4.1. Fuzzy logic systems (using Matlab software)

The purpose of the gearbox in a boiler setup is to change the speed ratio between the motor and kicker. The gearbox is seen to be continually sticking, and it is difficult to investigate the underlying reason for the breakdowns along these lines; fuzzy rationale framework is created to screen the torque and oil level when the boiler container is stacked. The gearbox must be halted when terrible conditions exist in the evaporator as an integrated upkeep procedure to abstain from sticking, henceforth, canny fuzzy rationale control. From the interviews with the engineers and plant artisans, as well as maintenance of history log books, it was noted down that oil level and torque are the major factors which are contributing to the jamming of the gearbox whenever the boiler is being loaded. In this chapter, the oil level is being controlled and is to be modified with specific levels: high, acceptable and low. Controlled torque is to be modified with specific levels: high, normal and low. This is highlighted beneath.

4.1.1. Oil level and torque control

4.1.1.1. Effects of oil level and torque control on gearbox jamming

Moisture inside the valves may result from the compressed air passing through the valve. The effects of moisture on the valves include:

- Moisture may cause rusting in the moving parts of the valve.

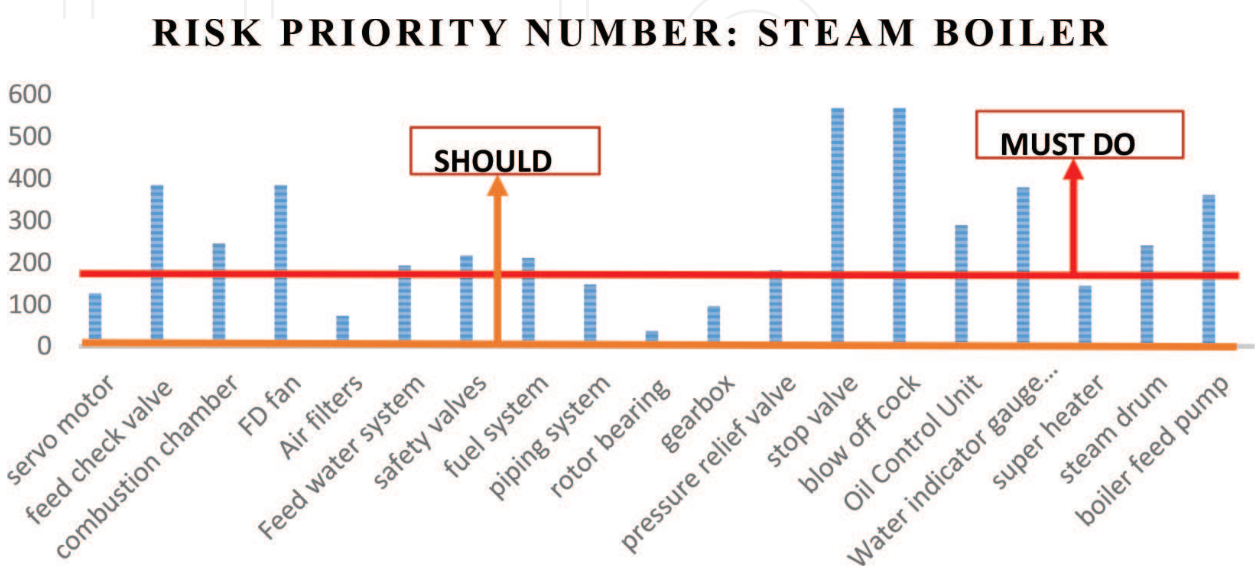

Figure 8. Risk priority number for steam boiler.

- Increased rate of wear of the valve material may also result due to moisture. Moisture washes the lubrication away, which will result in the eventual failure or malfunctioning of the valve.
- The industrial processes, which rely on the full functionality of the pneumatic control valves, may be jeopardized, and this usually results in costly breakdowns of the machine.
- Air- or gas-operated instruments may give inaccurate readings due to corrosion of the material and hence interrupting the plant processes.
- The rubber diaphragms inside the pneumatic valves can be stiffened and will eventually rupture due to the moisture flowing through them.

The following are the range of values of moisture, which are tolerated and some not tolerated inside the valve:

4.1.1.2. Oil level control

4.1.1.2.1. For a range of 0–100%

This is the aggregate scope of oil level either acknowledged or unaccepted in the gearbox.

- 0–40%

This alerts the artisans for refiling when oil is about to run out.

- 40–80%

At this level, it is acceptable, and the gearbox can continue operating.

- 80–100%

The level is fine and the gearbox has to keep running.

4.1.1.3. Torque control

4.1.1.3.1. For a range of 0–12,000 Nm

This is the total range for torque in the gearbox at any time (unaccepted or accepted).

- 0–2000 Nm

The range is very fine for starting the gearbox and is fine for running the boiler.

- 2000–8000 Nm

The torque is very fine for the gearbox to continue running.

- 8000–12,000 Nm

This range is very high, and it needs close monitoring, otherwise, stop the boiler.

4.1.1.4. Output control

4.1.1.4.1. For gearbox range of 0–100%

The gearbox has to run or stop, either of the 2, that is the meaning of 0 for stop and 100% for running that is the 0 or 1 for logic:

- 0 stop

At this range for the stop signal, the gearbox is to stop being controlled by torque and oil level

- 1 run

This involves the range 0–100%. All the conditions are being met (oil level and torque), and the gearbox can run effectively.

4.1.2. Simulation of the effects of oil level and torque on the gearbox using fuzzy logic

The rule base consists of a collection of expert rules, which are required to meet the control goals. These control rules can be developed from survey results, common sense, general principles and intuitive knowledge. The *IF − THEN or IF − AND − THEN* rules are mainly going to be used in designing the controller as shown in **Figure 9**. The situation for which the rules are projected is given by the IF part. The fuzzy system reaction in this state will be given by the THEN part. **Figure 9** below shows the fuzzy logic (Matlab software) screenshot for the two inputs (oil level and torque) and the output parameter (gearbox).

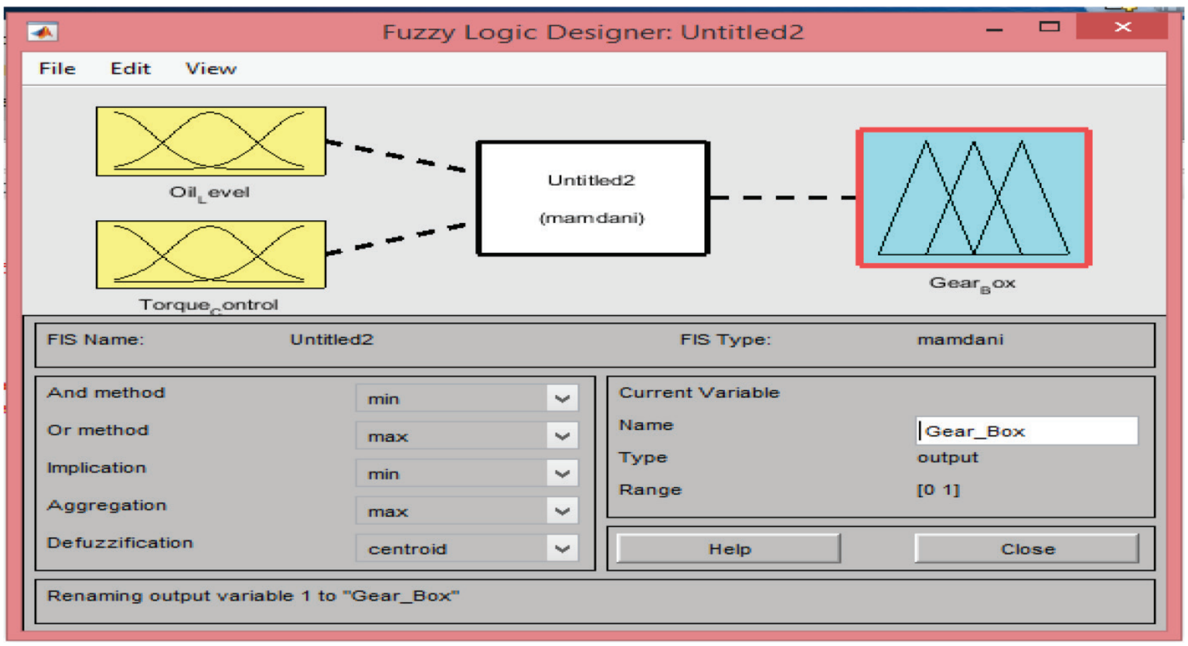

Figure 9. FIS editor for gearbox.

4.2. Control of gearbox jamming using fuzzy logic tool box

4.2.1. Membership function editor for oil level and torque monitoring

The membership function editor is the central concept of the fuzzy set, which has values ranging from 0 to 1 in the y axis. The ranges of control were done in **Tables 3–5**. Membership function editor is the stage whereby the ranges, as explained above, are inserted into the fuzzy logic Matlab software and the screenshot of the data is taken as shown in **Figure 10**. It helps to display all membership functions connected with the input and output for the entire Fuzzy Inference System (FIS). In this case, a triangular fuzzy set membership function is used for oil and torque monitoring. This is shown clearly in figures below with ranges for oil level monitoring varying from low, acceptable and high and the numerical values being added. For torque control, the corresponding numerical values range from low, normal and high. The gearbox is either run or stopped, depending on the oil level and torque conditions as in **Table 5**.

The membership functions editor for the output is shown in **Figure 11**, which is the gearbox that is plotted in the form of a triangle. Fuzzy logic is an artificial intelligence software which can store the output ranges in its memory and can learn the system to give solutions in what can be done. The Matlab software of fuzzy logic consists of the rule editor function which allows for the generation of the rules. This is done after inserting the range of values for oil level and torque monitoring and the gearbox outputs. The IF…..THEN……ELSE rules are being used for retrofitting as shown in **Figure 12**.

Input range (%)	**Fuzzy variable name**
0–40	Low
40–80	Acceptable
80–100	High

Table 3. Input 1: oil level.

Crisp input range (%)	**Fuzzy variable name**
0–2000	Low
2000–8000	Normal
8000–12,000	High

Table 4. Input 2: torque control.

Indicator	Symbol
Stop	0
Run	1

Table 5. Output 1: gearbox.

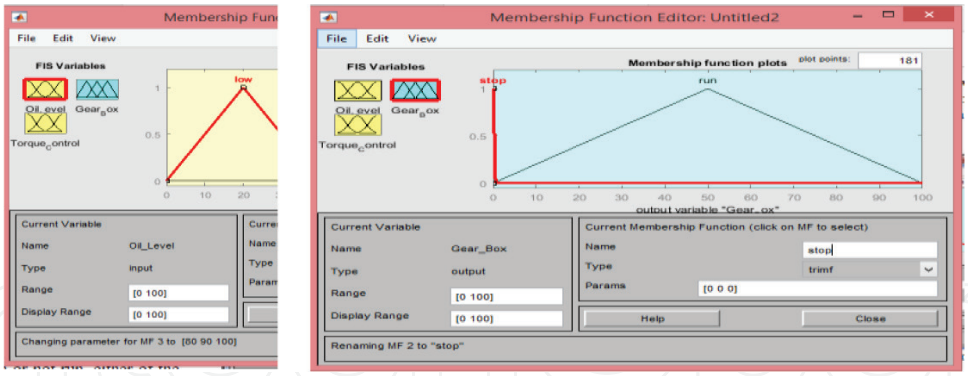

Figure 10. (a) Membership function editor for the output, gearbox and (b) membership function editor for oil level monitoring.

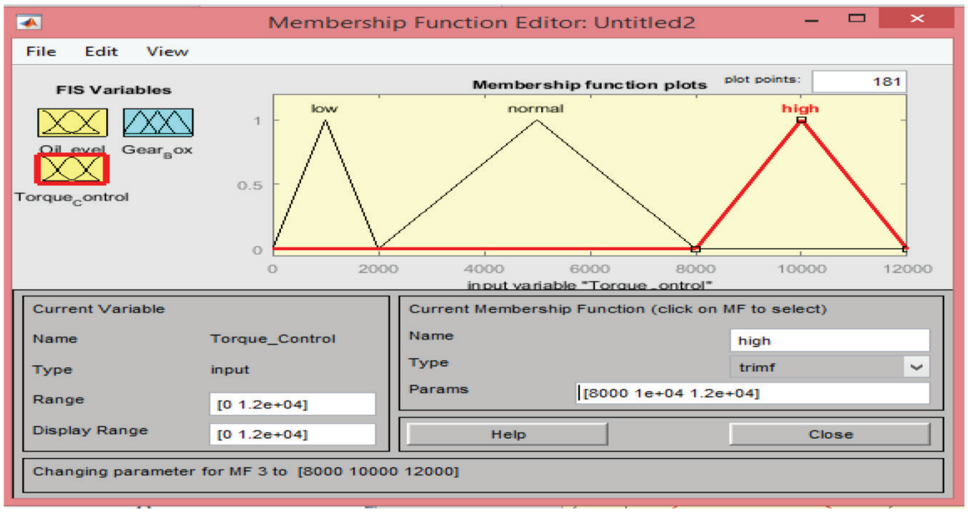

Figure 11. Membership function editor for torque control.

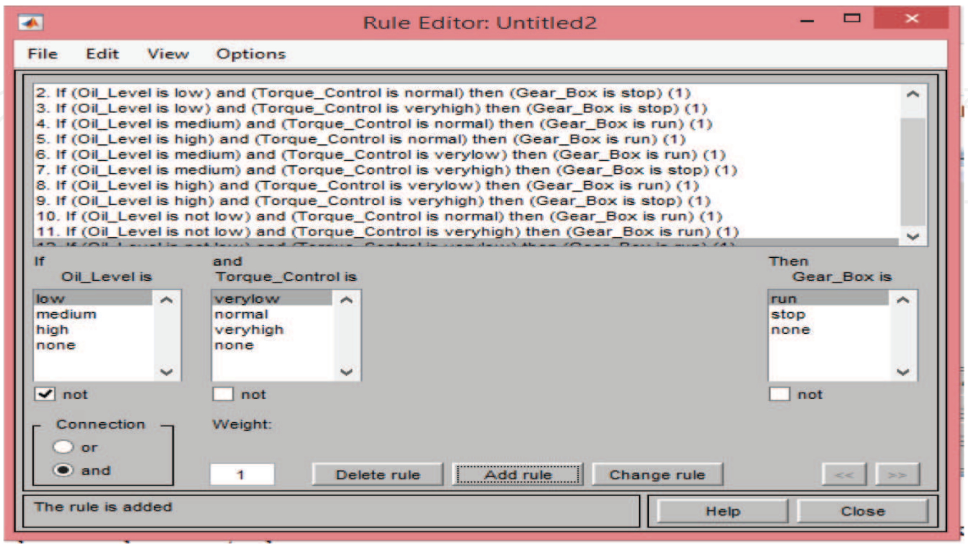

Figure 12. Rule editor for the fuzzy logic control.

After the rules are inserted, the overall results of combined effects of oil level and torque monitoring on gearbox monitoring are as discussed below. The rule viewer is an intelligent software, which is used to view the rules created using the rule editor. The rule viewer for the range values for oil level, torque and gearbox operation is discussed clearly in the figure below. However, the values obtained in the rule viewer are just optimum ranges and cannot be concluded as the best control values. Conclusions are only taken after the defuzzification process as described later in the chapter. The surface viewer shows a three-dimensional structure, which gives a conclusion to the range of values that are required to keep the gearbox functioning. This can be put in two-dimensional structure to highlight, in a simplified manner, the range of values recommended to keep the gearbox functioning as in **Figure 13**.

4.2.2. Analysis of the effects of oil level and torque on gearbox

4.2.2.1. Control of gearbox oil level

From the surface viewer of the gearbox against the oil level shown in **Figures 14** and **15**, it is seen that the gearbox is maintained and remains constant, at a 50% capacity if the oil level is 40%. If the oil level is at 40%, smooth running of the boiler is experienced. If the oil level by any means goes below 40%, stop the gearbox to avoid breakdown of the gearbox. It is seen that the fuzzy logic engine will instruct the gearbox to stop running without any human intervention so as to reduce the frequency of breakdown of the boiler machine through an effective gearbox operation. **Figure 14** shows a three-dimensional, and **Figure 15** is a two-dimensional image.

4.2.2.2. Control of gearbox torque

From the graph, **Figure 14** of gearbox operation against torque control, it is shown that the gearbox should never be operated at torque greater than 8000 Nm as shown in **Figure 16**. The gearbox is seen to run smoothly at a 50% capacity if torque ranges from 0 to 8000 Nm. From

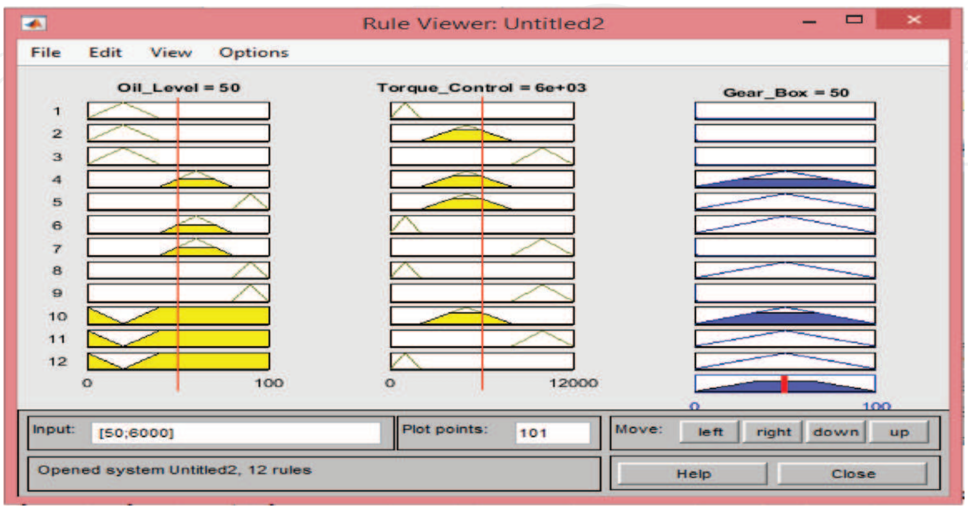

Figure 13. Rule viewer of the gearbox monitoring.

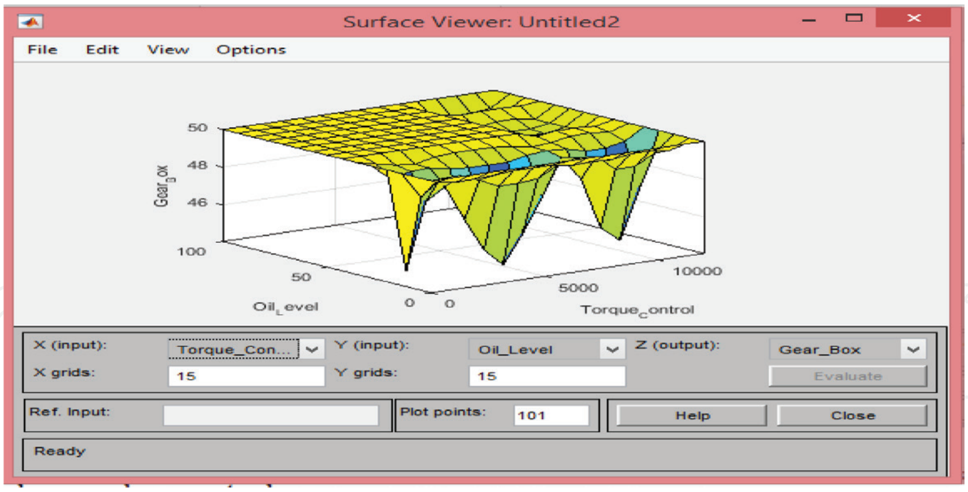

Figure 14. Surface viewer for gearbox monitoring.

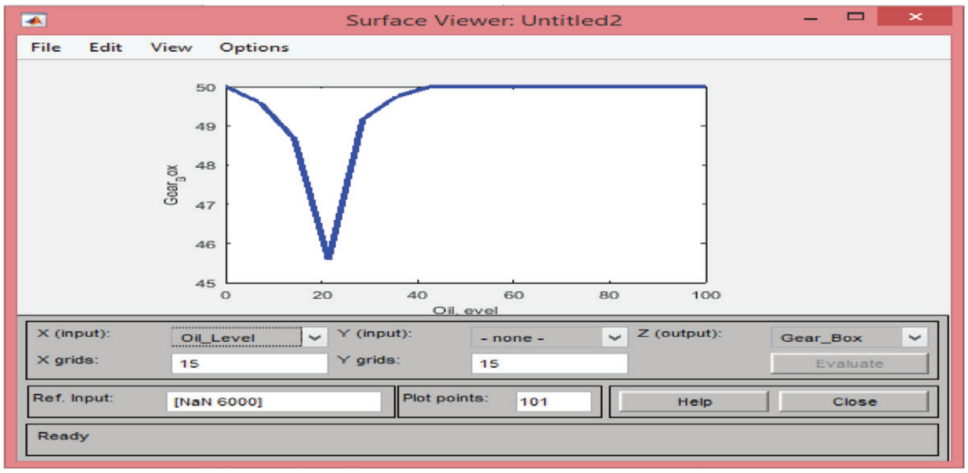

Figure 15. Surface viewer of oil level versus gearbox operation.

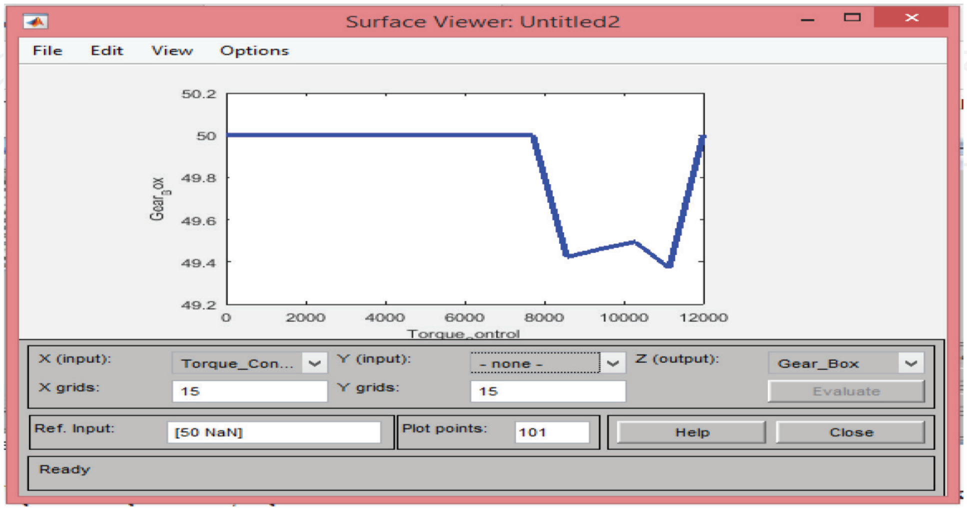

Figure 16. Surface viewer of gearbox control using torque.

this figure, it can be concluded that the required range for the gearbox to run smoothly is 0–8000 Nm of torque; otherwise, stop the gearbox and hence the boiler. Matlab software has stored this data in fuzzy logic and will automatically stop the gearbox operation and hence the boiler if the above conditions are not met.

4.2.3. Moisture and dust control on boiler feed check valves

4.2.3.1. Effects of moisture and dust levels on feed check valves

Moisture inside the valves may result from the compressed air passing through the valve. The effects of moisture on the valves include:

- Moisture may cause rusting in the moving parts of the valve.
- Increased rate of wear of the valve material may also result due to the moisture. The moisture washes the lubrication away which will result in the eventual failure or malfunctioning of the valve.
- The industrial processes which rely on the full functionality of the pneumatic control valves may be jeopardized, and this usually results in costly breakdowns of the machine.
- Air- or gas-operated instruments may give inaccurate readings due to corrosion of the material and hence, interrupting the plant processes.
- The rubber diaphragms inside the pneumatic valves can be stiffened and will eventually rupture due to the moisture flowing through them.

The following are the range of values of moisture which are tolerated and not tolerated inside the valve:

4.2.3.2. Moisture level control

4.2.3.2.1. For a range of 1–5%

This is the total range of moisture in the feed check valve at any time (either accepted or unaccepted).

- 0–1%

This defines that the amount of the moisture in the feed check valve is very minimum in such a way that it causes little or no damage to the valve.

- 1–3%

At this range, the valve works effectively but further exposure to moisture may result in a breakdown.

- 3–5%

This is the range when a maximum amount of moisture is experienced inside the valves. This range is unacceptable at all times as it leads to breakdown of the valves (rust, corrosion, wear and eventually breakdown of the boiler).

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4.2.3.3. Dust level control

4.2.3.3.1. For a range of 0–1%

This is the total range of values of dust inside the feed check valve (accepted or unaccepted).

- 0–0.02%

At this range, the valves can run effectively without any damage.

- 0.02–0.5%

This amount of dust entering the valve may cause the valve to malfunction with further exposure. However, at this range, the feed check valves are seen to be operating effectively.

- 0.5–1%

These ranges of dust are not acceptable at all. The excessive exposure of dust inside the valve may result in scoring, wear and eventually total failure of the boiler machine.

4.2.3.4. Output control

The feed check valve has to either open or close, either of the two, and that is the meaning of 0 for close and 1 for open.

- 0 close

At this range, for close signal, the valve will close if the if the dust and moisture levels inside the valves are unacceptable.

- 1 open

This involves the acceptable range. All the conditions are being met (dust and moisture level), and the valve can effectively open at any angle between 0° and 90° depending on the amount of feed water to be pumped into the boiler.

4.2.4. Simulation of the effects of dust and moisture levels on feed check valves using fuzzy logic

The moisture and dust level variations in the boiler machine can be monitored using an artificial intelligence software. The inference engine of fuzzy logic can store two input parameters (moisture and dust level) and one output parameter (feed check valve operation) as shown by the print screen below from the laptop in **Figure 17**.

Control of feed check valve operation using fuzzy logic tool box is shown in **Tables 6–8**.

4.2.5. Membership function editor for moisture and dust monitoring

This is shown clearly in **Figures 18–20** with ranges for moisture level varying from low, acceptable and high and the numerical values being added. For dust control, the corresponding numerical values range from low, normal and high. The valve either closes or opens depending on moisture and dust levels. This is done to control the feed check valves so that they won#x2019;t operate in unfavourable conditions which might result in the failure of the boiler.

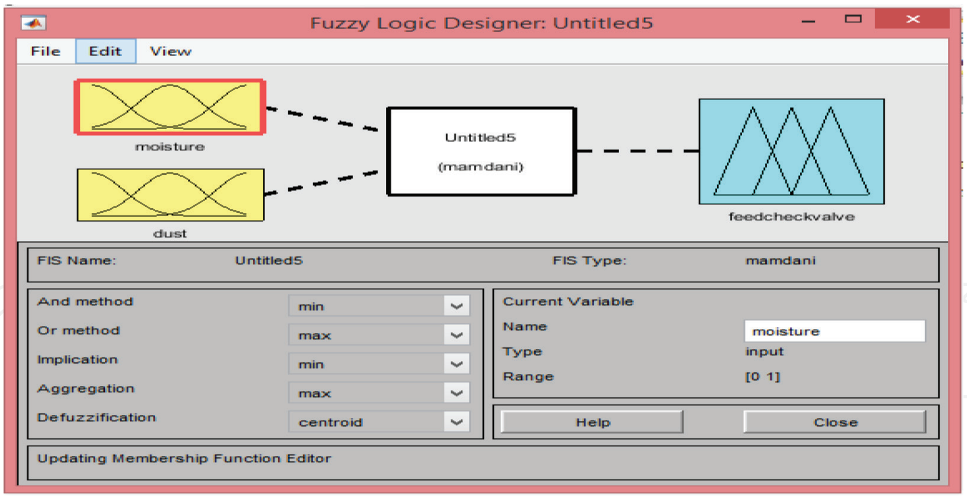

Figure 17. FIS Editor for feed check valve.

The following rules were developed in **Figure 20** and will instruct the controller what to do.

After the rules are inserted, the overall results of combined effects of moisture and dust levels on feed check valve are as discussed below. The rule viewer is an intelligent software which is used to view the rules created using the rule editor and is shown in **Figure 21**. The rule viewer for the range values for moisture level, dust and valve operation is discussed clearly

Input range (%)	Fuzzy variable name
0–1	Low
1–3	Medium
3–5	High

Table 6. Input 1: moisture level.

Input range (%)	Fuzzy variable name
0–0.02	Acceptable
0.02–0.5	Average
0.5–1	Not acceptable

Table 7. Input 2: dust level.

Output range (%)	Fuzzy variable name
0	Closed
1	Open

Table 8. Output 1: feed check valve operation.

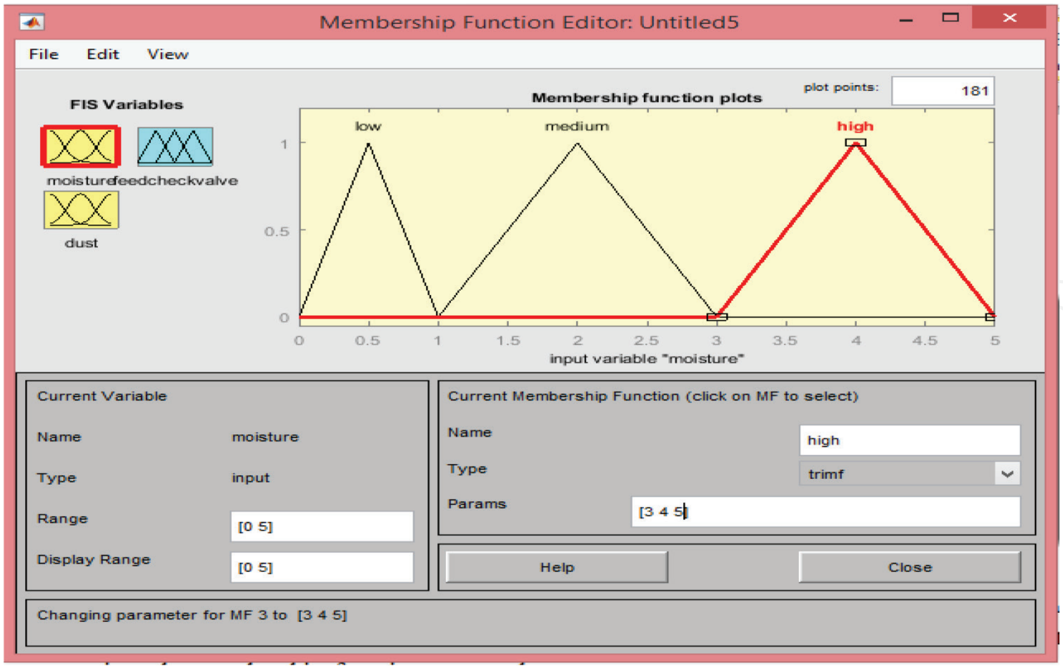

Figure 18. Membership function editor for moisture.

in **Figure 21**. The surface viewer shows a three-dimensional layout in **Figure 22**, and the blue lines indicate the values of moisture level and dust level, which may result in the failure of the valve. The required values which should be maintained are shown by the yellow surfaces. However, the values obtained from the rule viewer are just ranges and not concluded as the best control values. Conclusions are only taken after the defuzzification process.

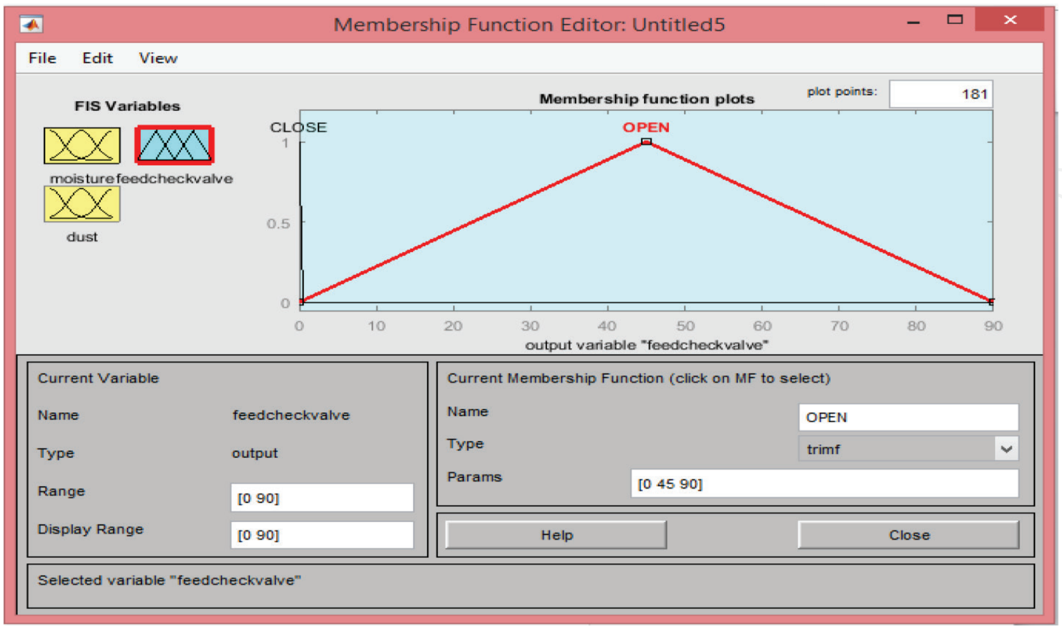

Figure 19. Membership function editor for the output and feed check valve.

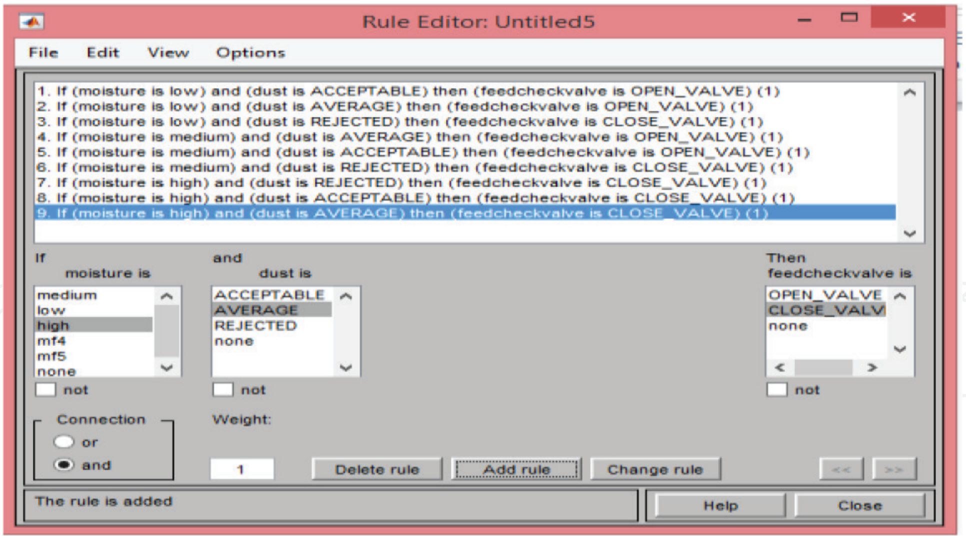

Figure 20. Rule editor for feed check valve.

4.2.6. Analysis of the effects dust and moisture on feed check valve

4.2.6.1. Control of feed check dust level

From the surface viewer of the feed check valve control against the amount of dust, it is seen that the valve remains constant at 45% corresponding to a dust range of 0–0.55%. The dust level should be maintained at this range. If the dust level is increased from 0.55 to 0.58%, there is a linear decrease in the feed check valve's opening angle from 45 to 0°. As the level of dust is further increased from 0.58 to 0.95%, the valve is kept constant at 0°. It is therefore concluded that dust level should remain between 0 and 0.55% so that the valves will run smoothly; otherwise, boiler breakdown will result. Fuzzy logic engine is an artificial intelligence system

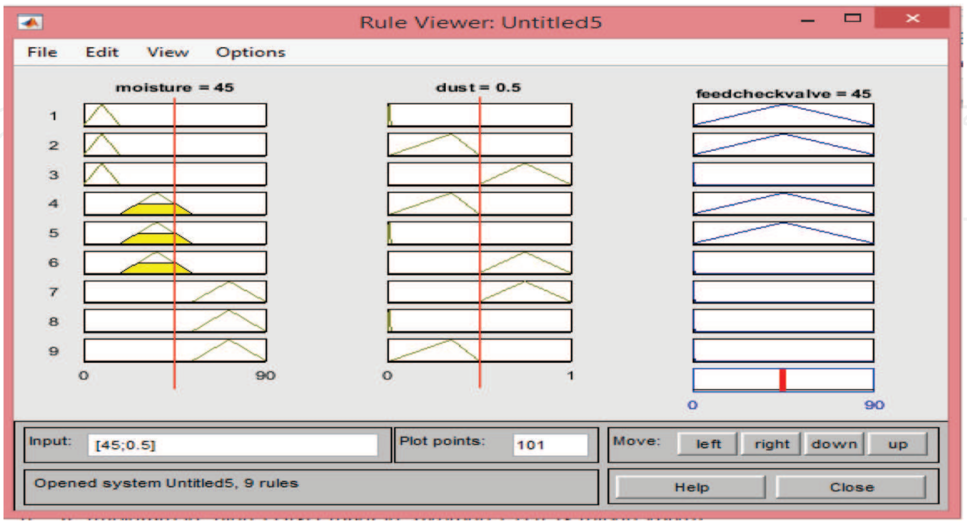

Figure 21. Rule viewer for the feed check valve monitoring.

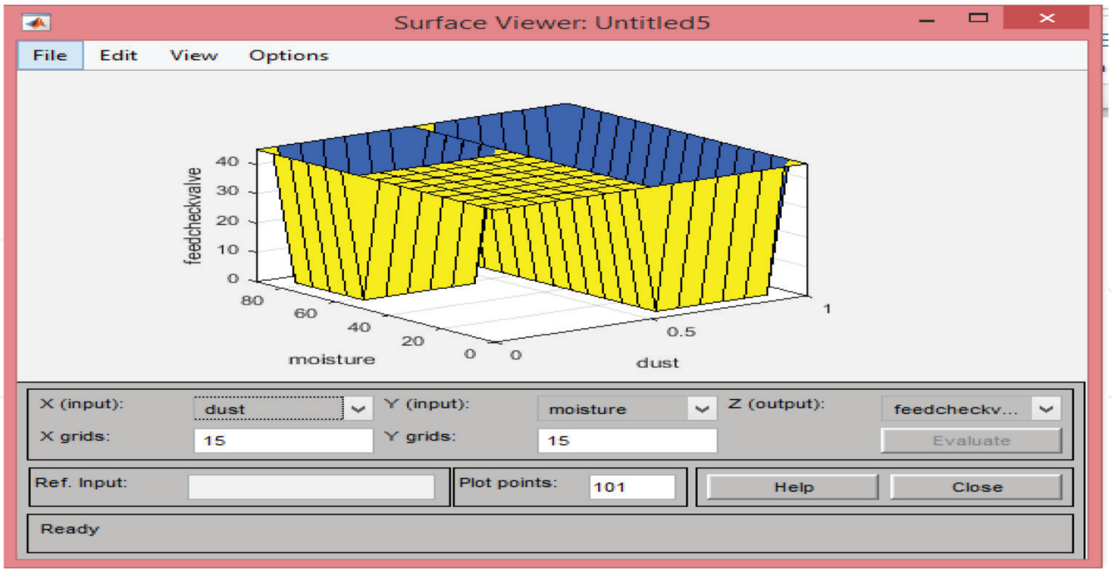

Figure 22. Surface viewer for the feed check valve monitoring.

which will instruct the valves to immediately close as soon as the dust level exceeds 0.55%, as in **Figure 23**, without any human intervention.

4.2.6.2. Control of moisture level

Figure 24 indicates that moisture level does not contribute much to the valve opening. From 0 to 85%, the feed check valves operate at a constant capacity of 45%. For smooth operation of the valves, moisture level should not exceed 85%; otherwise, fuzzy logic will set the valves to close automatically. This helps to prevent the breakdown of feed check valves.

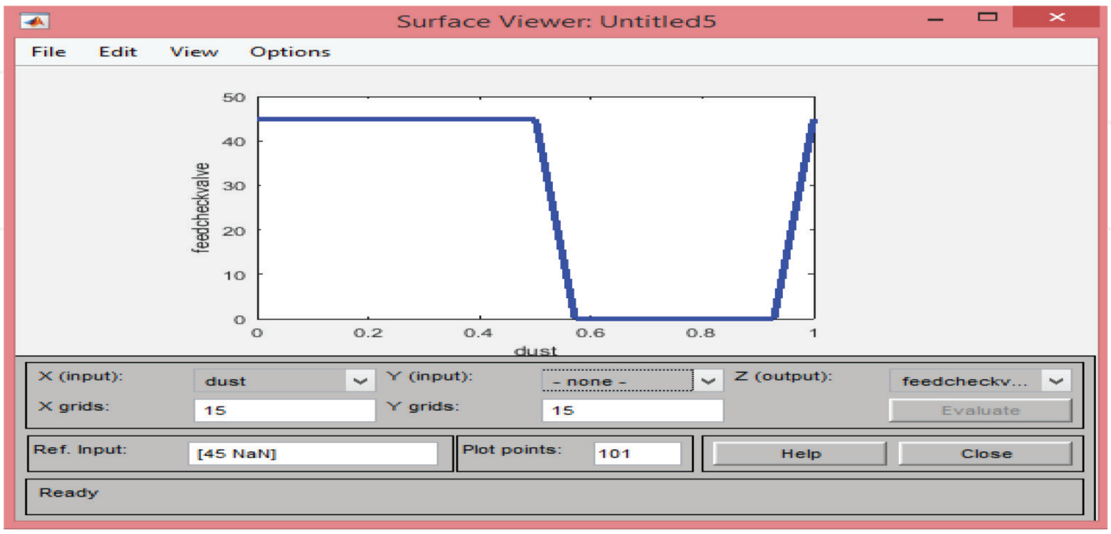

Figure 23. Surface viewer of gearbox control using dust level.

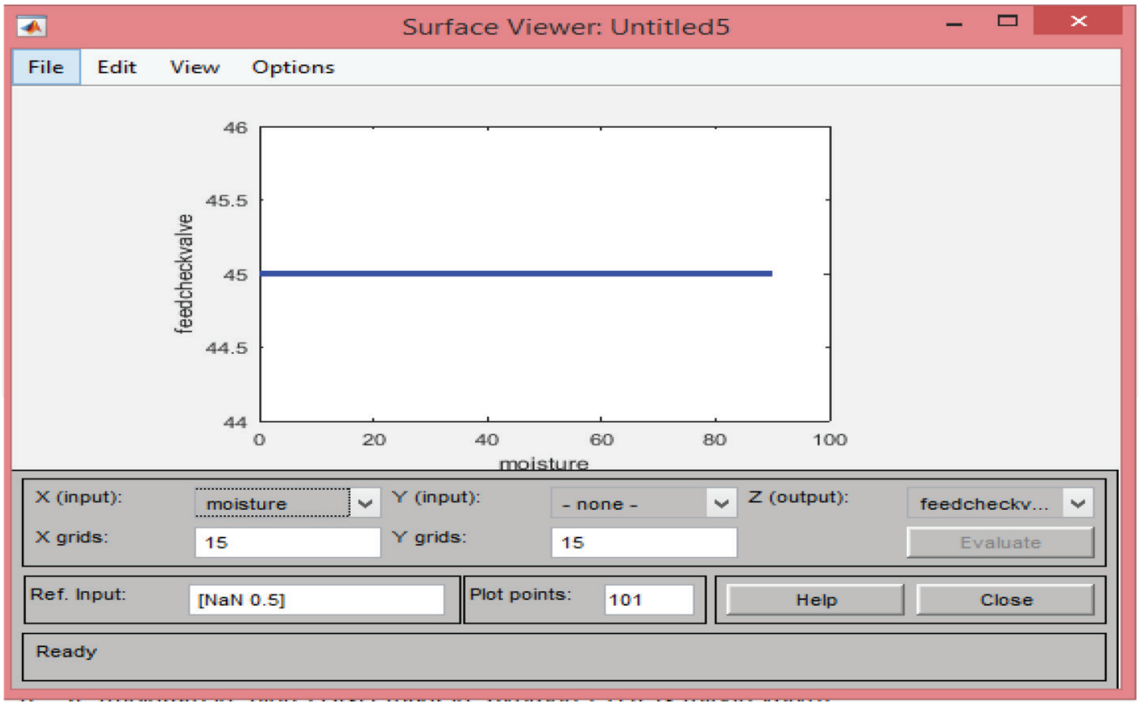

Figure 24. Surface viewer of feed check valve control using moisture.

5. Recommendations and conclusions

Improve management commitment: The success of any system depends on the commitment of the management. Design and implementation of a hybrid proactive approach require a greater initial investment for it to be successful. Since systems are people driven, it is certain to require worker participation. Management needs to look up at providing resources for in-house training for the fuzzy logic system.

Appendices for the processing company

Appendix 1: Factor A

Effect on production output (Factor A)	Factor score
No significant impact/standby equipment is available	1
Minor impact on production. Unlikely to affect other areas of the plant	2
Failure would have significant impact on output and may affect other sections	3
Major impact on the plant#x2019;s operations; failure would cause over 40% of plant production to stop	4

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Appendix 2: Factor B

Utilization (Factor B)	Factor score
Equipment is used on an occasional basis	1
Equipment is required to function independently for up to 50% of available time	2
Equipment is part of a continuous process required to function for a major proportion of the planned production time.	3
Equipment is required to function for all of the major losses	4

Appendix 3: Factor C

Quality (Factor C)	Factor score
No effect on product quality	1
Minor effect on product quality	2
Critical effect on product quality and can result in major losses	3

Appendix 4: Factor D

Effect on safety or environment (Factor D)	Factor score
Little or no risk to the safety of people, equipment or the environment	1
Minor risk to people, equipment or the environment	2
Risk to people resulting in a lost-time accident and significant damage to equipment or the environment which requires notification to relevant authorities	3
Major impact on the plant#x2019;s operations; failure would cause over 40% of plant production to stop.	4

Appendix 5: Priority score

The priority score is obtained by multiplying the results for the three factors:

$$PS = \text{Factor E} * \text{Factor F} * \text{Factor G} \tag{3}$$

Factor E

Frequency of failure (Factor E)	Factor score
Failures are rare—less than once per year	1
Occasional failure between 3 and 12 months	2
Failure likely between 1 and 3 months	3
Frequent failures at least once per month	4
Frequent failures at least once per week	5

Appendix 6: Factor F

Downtime/repair time (Factor F)	Downtime	Factor score
Minor	0–30 min	1
Significant	30–120 min	2
Major	2–8 h	3
Severe	>8 h	4

Appendix 7: Factor G

Waste (Factor G)	Quantity	F
No waste is generated under normal operating conditions	0%	1
Small amounts of waste are produced by failure	2%	2
Waste is produced during production that is significant	5%	3
Quantities of waste are significant and warrant immediate attention	10%	4

Appendix 8: Fire Tube boiler's detailed FMECA analysis

Component name	Component function	Cause(s) of failure	Effect(s) of failure	Failure mode(s)	Occurrence index (O)	Severity index (S)	Detection index (D)	Risk priority number (O)*(S)*(D)
Servo motor	To generate torque to turn fan rotor	Worn bearing, lubrication failure, burnt brushes and broken fan bolts	Excessive vibration, noise. motor overheat and sparks of fires are produced	Bearing failure, coil shorts, overheating	6	7	3	126
Feed check valve	To regulate the supply of water which is pumped into the boiler by a feed pump.	Internal valve malfunction Operator error Calibration error	Overpressure in system and leakages resulting in fire	Fails to open Remains open Crack valve	6	8	2	96
Combustion chamber	To burn fuel	Leakage through the soot blower casing seal	Combustion gases entering fire room	Too much fuel being fired, and excess air	7	7	5	245

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Component name	Component function	Cause(s) of failure	Effect(s) of failure	Failure mode(s)	Occurrence index (O)	Severity index (S)	Detection index (D)	Risk priority number (O)*(S)*(D)
Forced draft fan	To provide air into the combustion chamber	Dust, external shocks, vibration, and improper operation	Overheating, blocked fan, loss of performance (the fan does not start anymore)	Noisy operation, blocked fan blade	6	8	8	384
Air filters	To remove unwanted elements (dirt, dust, etc.)	Clogged air filter	Black smoke exiting the exhaust pipe and noisy operation	Dirty on surface Noisy operation	4	6	3	72
Feed water system	Used to control feed water into the steam drum and the feed tank	Pump blocked, Leakage in suction pipe, Non- return valve blocked in closed position	Pump runs but give no water	Pump trip	3	8	8	192
Safety valve	To prevent explosions due to excessive internal pressure of steam	Internal valve malfunction Operator error Calibration error	Steam burns: increased production time. Overpressure: protection compromised	Fails to open	6	9	4	216
Fuel system	Used to supply fuel (diesel or oil) to the boiler	Power supply switched on but no reset applied Relay RL6 faulty Detector not closing Open circuit on first detector or low pressure on the second	Gas leaks indicated and reset not operating	Relieve valve damage Faulty of the trip valve	5	6	7	210
Piping system	Conveys the hot combustion gasses away from the boiler to the outside	Failure to channel exhaust gases at all, gas flow restricted	Piping assembly collapses and falls to the bottom of the stack, leakages	Silencer mountings corroded away, corrosion	7	7	3	147

Component name	Component function	Cause(s) of failure	Effect(s) of failure	Failure mode(s)	Occurrence index (O)	Severity index (S)	Detection index (D)	Risk priority number (O)*(S)*(D)
rotor bearing	To absorb the axial thrust and support the rotor	Excessive vibrations	Bearing wear	Wear	3	6	2	36
Gearbox	To change the speed ratio between motor and kicker	Starting under load	Wear of gears	Impact wear	3	8	4	96
Pressure relief valve	To measure the pressure of the steam boiler	Internal valve malfunction Operator error and calibration error	Rapture of the boiler container or pipes	Jammed closed	5	9	4	180
Stop valve	To control the flow of steam from the boiler to the main steam pipe	Internal valve malfunction Operator error and calibration error	Overpressure: protection compromised	Leakages	7	9	9	567
Blow off cock	To empty the boiler when discharging mud, scale or sediments	Internal valve malfunction Operator error and calibration error	Overpressure in system resulting in fire, leakages	Fails to open Fails to close	7	6	8	336
Oil Control Unit	To circulate lubricant at specified flow rate and pressure	Blocked filters, worn impellor, high lubricant temperature	Delivery pressure lower than specified, flow rate lower than specified and cavitation	Blockage, wear and cavitation	6	6	8	288
Water indicator gauge glass	To indicate the water level inside the boiler	Salt deposition due to high water level in drum	Fails to react to water rise/ drop above/ below the preset value	Fails to react to water rise/ drop above/ below the preset value	6	9	7	378
Super heater	To increase temperature of saturated steam without raising its pressure	Blocked tube Starvation of tube Erosion of tube due to high excessive air	Cracking of carbon steel	Dirty on surface Noisy operation Impact wear Corrosion on surface	6	3	8	144

Component name	Component function	Cause(s) of failure	Effect(s) of failure	Failure mode(s)	Occurrence index (O)	Severity index (S)	Detection index (D)	Risk priority number (O)*(S)*(D)
Steam drum	To store steam before it is distributed to the plant	Excessive stresses produced by rolling tubes	Damage on the ligament areas	Wear	5	8	6	240
Boiler feed pump	To pump feed water into the boiler	Fatigue, corrosion, wear	Cavitation, pump overload, heavy vibration or imbalance	High-bearing temperature, broken axle, impellor	8	9	5	360

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