Unpredictability of Demineralized Water Production due to the Random Nature of Key Simulator Variables

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Abstract—Every Power Station in Eskom – South Africa, uses demineralized (demin) water to keep their boiler's functioning and generators producing electricity. There is a constant demand of demin water that needs to be met by the demin plant. The demin water production process has many inputs and dynamic variables and many of these variables have fluctuating trends. Sometimes these fluctuations can directly impact the availability of demin water to the power station. The focus of this article is to investigate the random nature of some of these variables and show how this (mostly overlooked) randomness can affect your demin water production and ultimately the availability of demin water to the boilers. This investigation was done, by using a system dynamics model built with iSee Stella that has been implemented at the stations to project the station's demin water availability for the next week. Three parameters were investigated: The first being water quality, second the demin water consumption rate outliers and lastly the impact of unforeseen maintenance activities on one vessel. The results show that water quality has a large influence on demin water availability but the occurrence of poor water quality is less prevalent, while the outliers in demin water consumption are dominant and also have a significant impact on water availability. Thus cannot be arbitrarily averaged out for the projection period. The effect of maintenance is dependent on the current state of the system, whether the maintenance is planned or unplanned and its duration: 10 hour unplanned maintenance interruption could lead to a 180% fall in tank levels. The System Dynamics Simulator was successful in showing the impact of the normally neglected and "minority" operational fluctuations on a demin plant; these effects need to be taken into account if possible.

Keywords: *Demineralised water, Randomness, Coal Fired Power Station, outlier, System Dynamics Simulation*

I. Introduction

A. *What is demineralised water and how is it produced?*

Demineralized (demin) water is water that is free of dissolved minerals and contains only pure water ions (H+ and OH-). Demineralization can be done through the process of Ion Exchange. Most of the Eskom coal fired stations are equipped with ion exchange vessels, as this was the cheapest and most reliable demineralization technology at the time of their construction (ENViCare).

Resin beads are small spheres which are manufactured to have a fixed ion (positive-Anion) and (Negative-Cation) which then attracts the negative or positive ion counterpart. Therefore they rely on the resin being able to replace the mineral ion with a hydrogen(+) or hydroxide(-) ion. As these replacements take place, the resin has less exchangeable ions and when most of the resin inside a bed has exhausted their ions, the water being produced will start leaking some of the mineral ions. When this leakage takes place, it means that the vessel cannot produce any more demin water, since its ability to remove ions has been exhausted. The advantage of the resin lies in its ability to be regenerated. The resin can then be regenerated with acid or caustic, depending on the type of resin. This regeneration removes the mineral ions from the resin and replaces it with hydrogen (H^+) or hydroxide (OH^-) components. After regeneration, the vessel can be put back into service to demineralize the filtered water again (ROHM & HAAS, 2008).

B. *Factors influencing demin water*

In this paper three factors that influence the production of demin water is investigated by using a system dynamics model build for a specific water treatment plant in Eskom. The three factors are: water quality outliers, higher consumption distributions and unplanned maintenance.

C. *Research Questions*

The following points list the main research questions that will be investigated:

- Can a System Dynamics model built in iSee Stella be used to evaluate the unpredictability of the demin plant?
- How does raw water quality affect demin water availablity?
- How does the outliers in demin water consumption affect demin water availability?
- What is the possible effects of having a component failure on demin water availablity?

II. Background and Literature

All the variables mentioned above fluctuate on a regular basis. Process control has been put in place to minimize these fluctuations, but outliers still occur. The effect of water quality outliers is the first operation variable that will be analyzed.

A. *Raw water quality*

Demin water operation has two main phases: production and regeneration. The production side depends highly on the quality of the filtered water. The more mineral ions that exist in the demin water, the faster the resin reaches its adsorption capacity. This would result in the end of the production period. On the regeneration side, the strength of the acid, temperature of the water and the amount and type of ions inside the resin all play a major role on the time it will take to complete the regeneration.

Ion exchange's main focus is to replace existing ions in the raw water with acceptable ions for the designed system. In the water-steam cycle, it is required to have completely ion free water, which means that the ions in the raw water are replaced with hydrogen and hydroxide. It is then clear that the more ions in the raw water, the less demin water can be produced due to the higher concentration of ions (salts).

In this case the more ions that are in the water, the bigger the loading would be on the vessels. This would mean that the same vessel would produce a smaller amount of water before having to undergo regeneration. In the simulation that was built for Eskom's Duvha Power Station, this is defined as "Throughput Limits". This variable represents the maximum amount of water that can be produced before the vessel has to undergo regeneration.

The mathematical relationship between ions in the water, defined as mg of ions per litre of water, and throughput limit, defined as liters of water, is inverse proportional. This means the more ions in the water (lesser water quality), the less the throughput would be. To quantify the effect of raw water quality on the demin tank levels, it is assumed that the percentage change in raw water ions would have an inverse proportional effect on the throughputs of all the vessels.

There are many components to raw water quality like Sodium, Magnesium, Calcium, Sulfate etc. concentrations, Alkalinity or pH, but data was available for the sodium concentration in parts per billion (PPB) for the water after the cation vessel. The following graph shows the change in water quality over a few months.

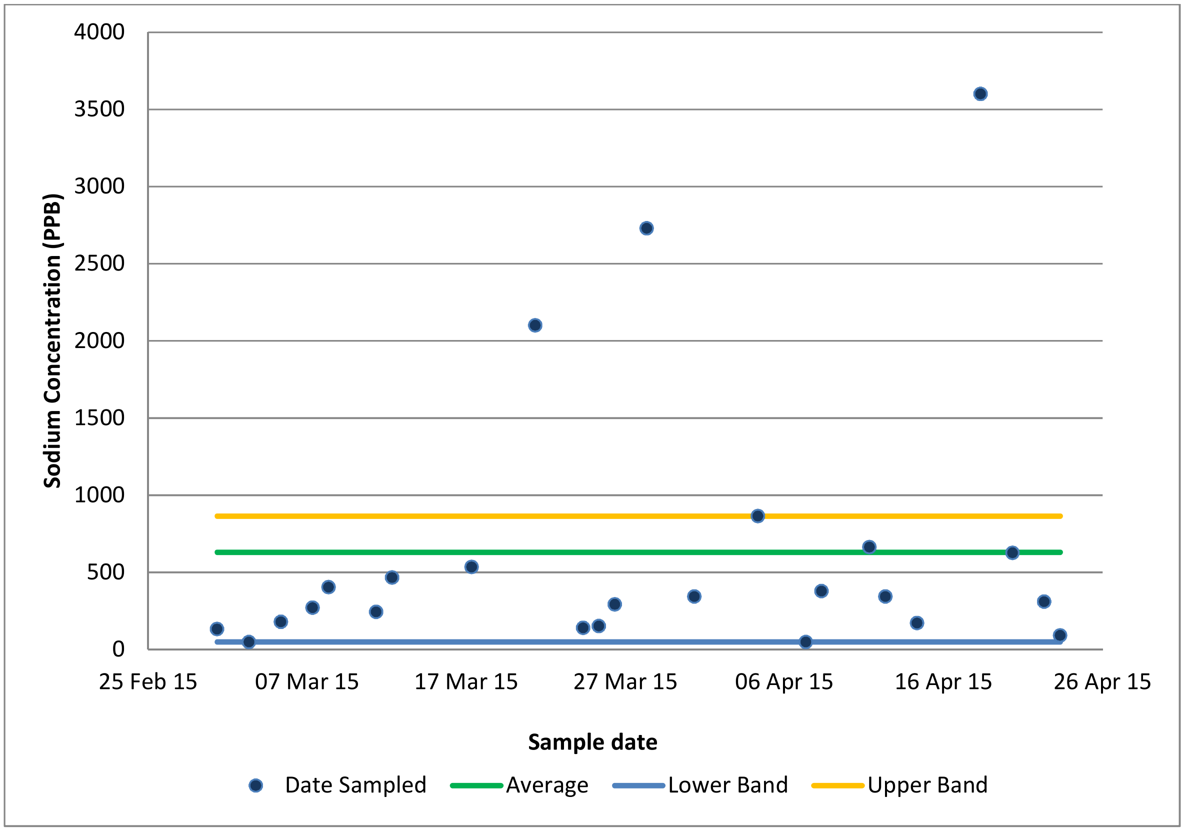

Figure 1: Sodium Concentration changes (Data from Duvha Power Station)

From this graph it is clear the concentration varies greatly. There are three major outliers of which the largest was on the 18th of April 2015 at a value of 3600 PPB. The average is 630 PPB while the standard deviation without the outliers is 204 PPB. Therefore it is seen that the normal variation on the sodium concentration is about 32%. The vessels are run in such a way that it will still produce 7000 m^3 during the normal fluctuations of the quality. The 3600 PPB is however 3 times higher than the Upper Band in Figure 1, which means that the raw water quality reduced by 75% at that time. If it is assumed that the water quality was experiencing a outlier of high ion concentration due to some variation in feed for about 7 hours, it would significantly influence your production. This would mean that for the same amount of water to be treated, it would require 3 times more resin than normal rates during these 7 hours. This aspect will be investigated and assessed in the Results and Discussions section.

B. *Outliers in Demin Water Consumption*

Demin water is produced so that the six units at the power station can be in operation. The units all require "make-up demin water". The amount of demin water required changes frequently due to the large system and many inputs to the units. A common occurrence is high consumption when a unit that was off-line and is returned to service, this is defined as a "Light-Up". This outlier high consumption has a major effect on the availability of demin water. The demin water that is produced is stored in Demin Storage Tanks (DST) and the amount of water contained in these tanks, gives an indication of demin water availability. The higher distribution of demin water consumption is also investigated in the paper and it was seen that using just an average value for consumption could lead to deceptive results.

Demin water consumption would theoretically be based on the amount of electricity that the station is producing. The more electricity a unit would produce, the more demin water it would consume to make up the water lost through the steam leaks and blowdowns of a unit. In real time, it does not have such a direct relationship due to aspects like light ups. A unit can only be put back online, when a light up has been completed. During all this time, no electricity is being produced while demin water consumption is at its highest. Demin water consumption therefore depends on a few aspects. The daily demin water consumption for unit 1 at Duvha Power Station for the 2014 calendar year can be seen below:

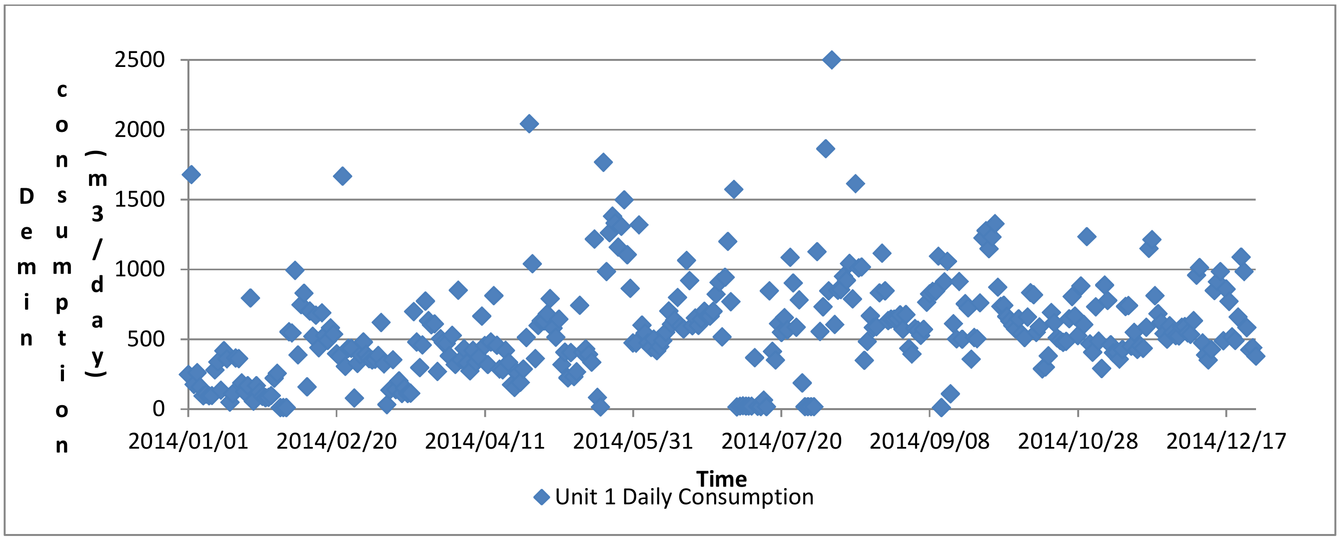

Figure 2: Demin Water Consumption for unit 1

In Figure 2 is can be seen that the data is highly variable. During May 2014 it can be seen that the average consumption was higher than the rest of the months, but overall there seems to be fluctuating times when the consumption was much higher than normal. Design consumption on a unit should be around 12.5 m^3/hr, which is about 300 m^3/day. The average is 575 m^3/day while the standard deviation is 361 m^3/day. The values above 936 m^3/day (average + 1 Standard deviation) were then removed and the following set of points were obtained.

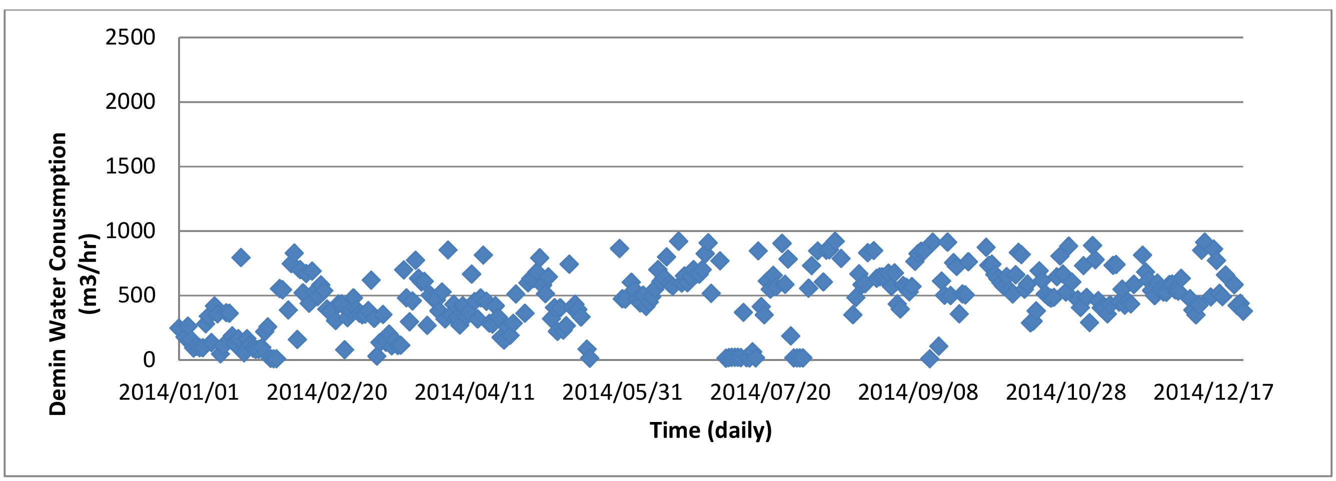

Figure 3: Demin water consumption for unit 1 after removing higher values

The average for this distribution is 473 m^3/hr while the standard deviation is 238 m^3/hr. It was then investigated if a normal distribution could fit this data. So the distribution curve was drawn and the following was found:

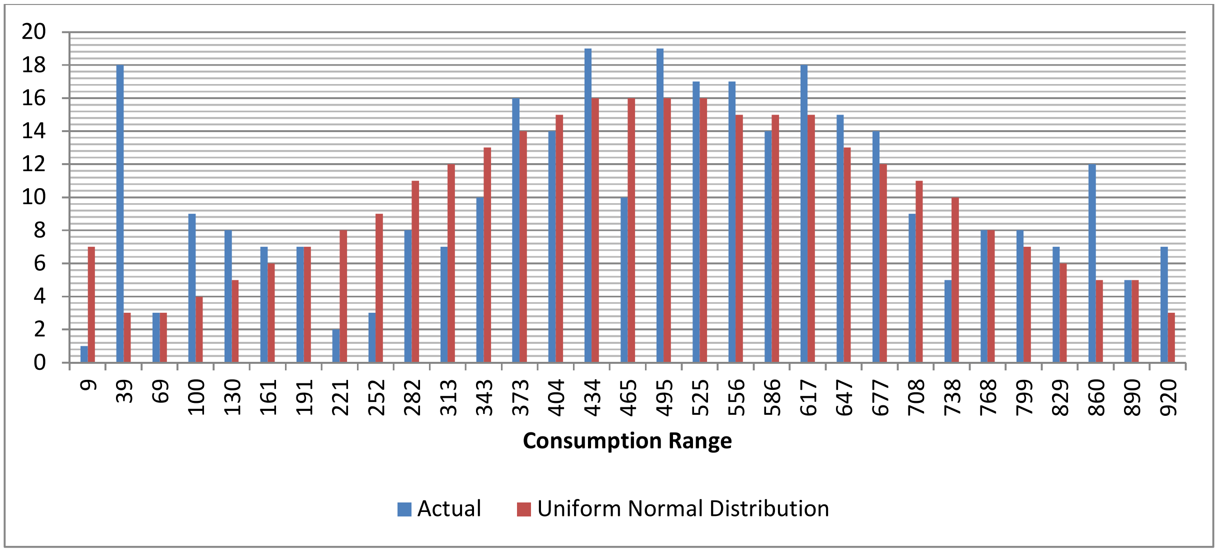

Figure 4: Distribution data

From this graph it can be seen that the actual distribution is not a uniform normal distribution. This would mean that exact data would not be able to be drawn from the data themselves, but that there seems to be two distributions of data. The data was then split into higher consumption data and "average"/lower consumption data. It was then established how often those values larger than 936 m^3/day appear. The outliers were then counted and in the period of 356 days, there were outliers/higher consumption on 48 days which means about 13.48% of the time, there were outliers. The outliers had an average of about 1 246 m^3/day and a standard deviation of 318 m^3/day. These larger values would have a direct effect on the availability of demin water.

Duvha should produce around 200 m^3/hr of demin water per train. If the operation methodology is followed so that they are having one train producing water, one train being on regeneration and one train online always, then the total amount that can be produced in one day is 4 800 m^3/day. The average consumption in those high outliers was 1 246 m^3/day for unit 1. If all six units were experiencing a similar outlier, that would mean 7 476 m^3/day, but you can only produce 4 800 m^3/day, so the deficit will come from the demin tanks. It is even more shocking comparing the design value of 300 m^3/day with the 1 246 m^3/day when outliers are experienced. This is more than 4 times the design consumption. If the frequency of outliers increase, it is easy to see how the station would experience problems with demin water availability. In the results section, the effect of these outliers and their standard deviation is investigated.

C. Unpredictable component failure

Although there can be many unforeseen events, one of those events are component failures. A component like a pump failure would result in one vessel being out of service and although this seems insignificant when you have three available trains and the maintenance takes 10 hours to complete, the question is how the same failure would affect the system when the consumption is fluctuating towards higher consumption values. These outliers, randomness and predictableness' effects on the water quality were investigated in this article.

There are many components that are subject to wear and tear on the demin plant: pumps, flow distributors, pipes, valves and the vessels themselves (not exhaustive list). All these components are subject to temperature changes as well as friction from the water flow. Valves can experience very high differential pressures and pumps would lose their integrity over time. All these effects take a long time to have a fatal effect on the component when operated within its specified conditions of service.

It has however happened that these conditions were not met and it could have a significant reduction on the component life span. Acids and caustic are used on the plant and if the wrong concentrations or temperatures are used, it could damage the valves and vessels themselves. The integrity of every component is also not measured hourly and this leads to an uncertainty to when precisely it reaches component failure. (Everett *et al.*, 2012)

Different components have different failure rates and different replacement/repair times and due to the conditions being irregular it makes it almost impossible to know exactly when a component will fail. When a component like a vessel obtains a leak or rupture, it would take significant time to repair the component and having one component out of service, would most likely lead to the whole train being out of service. If the repair takes a week, this would mean that the train would be out of service for at least a week considering that the resin may need to be removed to perform the repairs.

In the results section, the effect of a random component failure on the sustainability of the demin water supply is investigated. Typical failure rates for centrifugal pumps in a process are 17.5 failures per 10^6 hours. The definition of Failure rate is the probability that a component will fail per unit of time at time t, given that it has survived until time t (Miguel *et al.*, 2010). This could be written into a formula and would appear as:

$$Failure\ Rate = \frac{\#\ of\ failure}{Hours\ of\ operation}$$

This would mean that a failure would definitely take place at the reciprocal of failure rate. This is then 57 143 hours or roughly 6.5 years. This time could be increased when maintenance is done correctly, but Duvha has been in operation since 1984, which is about 32 years. In this time the pumps would have been replaced, but it clearly shows that due to the age of the station, components have experienced severe degradation and component failures could take place at any time.

When maintenance is done on a component it would not just be the time taken to repair the component that will be lost to the train, it needs to take the following aspects into consideration as well:

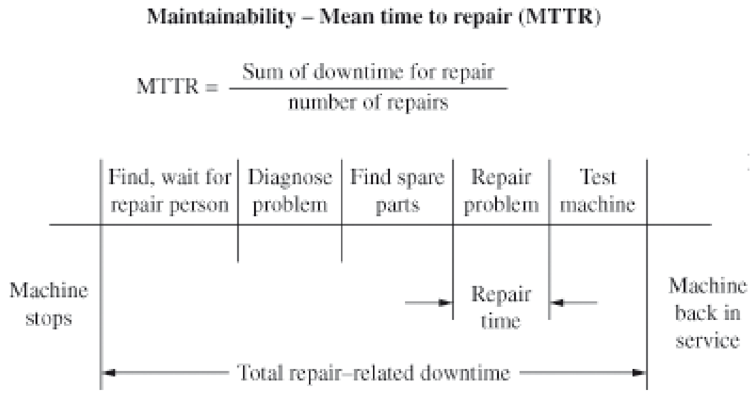

Figure 5: MTTR (Joseph *et al.*, 2010)

To get an estimate the downtime for a pump repair could be around 10 hours (Vicente, ABB Argentina). The probability of failure would increase as the component ages and this is where the uncertainty comes into play. A station that is 32 years old has many components which are aged and the probability for failure is higher than when the station was recently commissioned. The exact time when the failure would take place, would never be known and that brings in another random component into the production of demin water. In the Results and Discussion chapter, the effect of a random unforeseen component failure on the demin water sustainability will be investigated.

D. *System Dynamics*

1) *Description of the software that was used:*

The software used in this model is iSee Stella. The following is a description of the software from the iSee website: "STELLA allows you to quickly create system diagrams that can be simulated over time. Working in a completely risk-free environment and discover hidden aspects of your system that lead to unexpected outcomes. STELLA also allows you to create a user interface on top of your system diagram that makes it easy to share your understanding of the system, run your scenarios as part of a presentation, and enable others to experiment with their own policy combinations." (iSeeSystems, 2015)

2) *Why was this software chosen:*

This tool was chosen since it is one of the leading tools in the field of System Dynamics. It is well-established software which is continuously being developed but the main reason for using this specific tool is for the creation of the interface. The interface can be customized to customer requirements and enables the user to interact with the model through this easy-to-use interface. STELLA also provides almost instant comparisons between scenarios and the effect of doing a sensitivity analysis can easily be seen.

3) *Causal Loop Diagram:*

During the construction of the model, countless hours was spent with the stations, subject matter experts and managers to obtain a better understanding of the system and what was driving this system. The basic understanding of the system was captured in the following causal loop diagram:

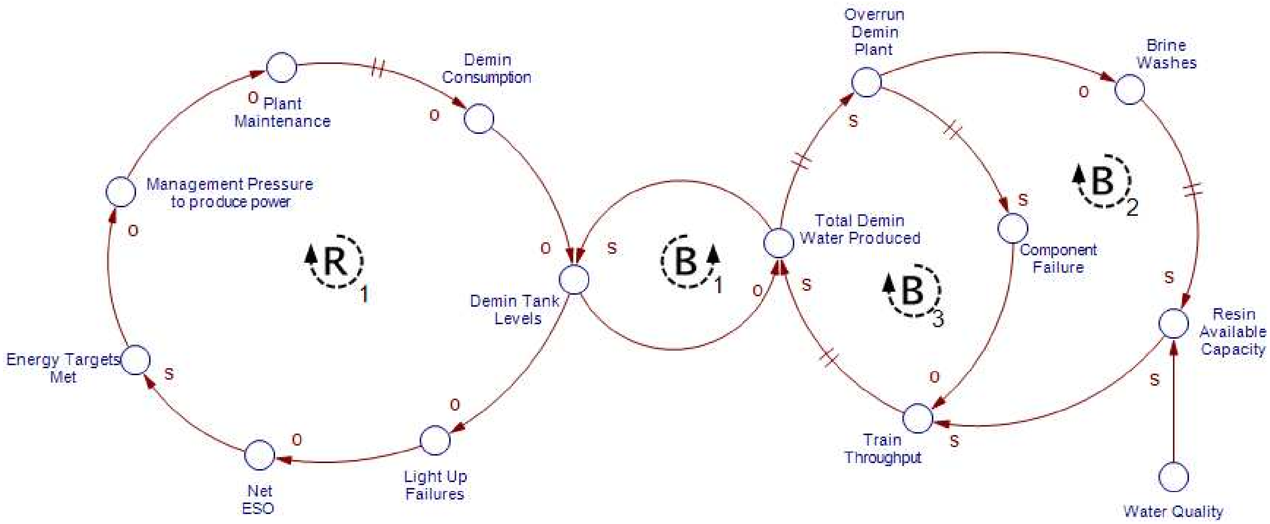

Figure 6: CLD of driving forces behind problems at the demin plant

The CLD shows the reader what are the main drivers behind the problems experiences in the station environment. Loop B_1 shows the core focus of the demin plant: Demin Tank Levels. These levels should always be kept high at about 280% out of 300%. This is done by varying the demin water production.

Loop R_1: The CLD will be explained by starting at the current main issue: Plant Maintenance. When plant maintenance is deteriorating, the demin water consumption will increase. There is a delay here, which means that the effects of poor maintenance take time to increase demin water. As demin water consumption increases (leading to many outliers in demin water consumption as discussed in this paper), the demin tank levels will decrease. When the tank levels reach dangerously low values, Light up failures will increase. When a light up fails, it means that the unit that was supposed to produce electricity will not be put in service and no electricity will be sent out. This will therefore decrease the plant's Net Energy Sent Out (ESO). Since less electricity is produced, the station's energy targets will not be met and if the energy targets are not met, senior management will experience much more stress and put more pressure on the station to produce more electricity. With the increased pressure to perform, the units cannot do all the required maintenance and demin consumption will keep on increasing! This is the first reinforcing loop and shows how this is a downward spiraling system. This downward spiral is one of the factors that lead to perpetually low demin tank levels and deteriorating demin plant conditions.

Loop B_1 and B_2: Starting at Demin Tank Levels, when these tank levels decreases, the total demin water production needs to increase to keep the tank levels high. When production increases too much, the operators and supervisors will start overrunning their demin plant, just to keep up with the consumption of demin water. This means that they will be running out of the design specifications or limits of the system, just to meet the demin water consumption from the units. Overrunning the plant could easily mean that they will not be doing their brine washes (one of the system requirements). If this process is not done, it will reduce the available resin capacity over time. Initially the effects are not seen, but as the overrunning becomes a frequent activity, the capacity starts decreasing. As this capacity decreases, the amount of water that can be produced by the train diminishes. If the train produces less water, the plant would have less production. Moving back to loop B_1, this would mean that the tank levels decrease and loop R_1 would be spiraling down faster and the demin plant condition deteriorating!

Loop B_3 shows that the more the plant is overrun, the greater the probabilities for component failures which will also lead to reinforcing loop R_1 again. Water quality is an external variable which affects the available capacity of the resin. When the water quality deteriorates, less capacity will be available and less water will be able to be produced, similar to loop B_2 and B_3.

In summary, one of the main unseen concepts around the problems experienced at the plant is the delays that are inherent to the system. The demin plant has many delays and unfortunately when these effects start taking affect, it is already too late and the demin water tank levels cannot be sustained and can even lead to overall station's ESO being limited or reduced.

4) *Stock flow diagram:*

The model development is not the focus of this paper, but Figure 7 shows the model structure in stocks and flows. It can be seen, that if the model needs to be discussed in detail, it will require a report on its own. There is a research report written on the generalized model for Eskom SOC in South Africa.

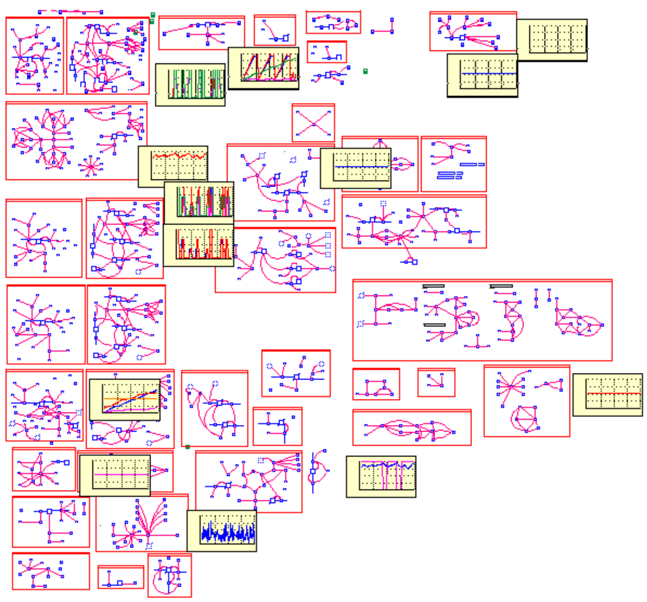

Figure 7: Overview of model structure

III. RESEARCH APPROACH

The simulator was built as part of a suite of projects where each coal fired power station's demin plant is simulated. The main purpose of the tool was to give the people working on it, the ability to project whether there will be enough demin water for the week going ahead. The project was started by doing a literature survey on the ion exchange process specifically for demin water production.
Time was spent at the power station so that the practical experience of the demin plant operation could be obtained. Data was also obtained during this time that was later used in the simulation. The simulation was then built with regular feedback to the customer and then validated. The final validation was done by using an actual week of historical data and then initializing the simulator accordingly to check if the results were in the same order.

A. Key Variables and Concepts

Demin water is produced by passing filtered water through different beds of resin. One set of cation, anion and mixed bed resin vessels are referred to as one train. There are three trains available at Duvha power station, to produce all the demin water that the whole station requires. The whole station is refers to the six units that require makeup demin water to produce electricity. The water that is produced by the demin plant is stored in the Demin Storage Tanks (DSTs) and make up water to the units are supplied from these storage tanks. The operators of the demin plant should ensure that the tank levels never drop by a third of its total capacity, which in this case is referred to as 100% of 300%. 300% signifying all three of the demin storage tanks are full of demin water and 100%, only one demin tank is full and two are empty. The complexity of the demin plant operations comes into play due to the regeneration phase of the train. The simulation is based on what the power station staff required and how they operated their plant.

B. Dynamic Hypothesis

System Dynamics can be used to simulate the demin water production process and accurately project the demin water availability on an hourly level for one week ahead.

C. Assumptions

- Water quality is not a major factor that will influence the production of demin water in this simulation and can be compensated by changing the throughput of the vessels.
- When regeneration is completed, it is assumed that the throughput is fully restored.
- The maintenance defined in the simulation is maintenance that will be done excluding maintenance that will be done simultaneously with regeneration or any other state.

D. Decision Rules

- The simulation will set the train's status to automatically go into regeneration state if the maximum throughput of the status is reached and no other state has been defined previously. The station will only be able to perform one regeneration of a certain type and no simultaneous regeneration is possible. The second train that needs to be regenerated will therefore go into awaiting regeneration.
- Train's online status will be determined by the individual priority of the train, maximum number of trains that can be online and the amount of water that can still be produced before it needs to be regenerated.
- Automatic crossfeeding is done in such a way to choose the best combination based on the throuhgputs.
- A simulation time of 169 hours has been used (week)

E. Testing

Actual data was used to test the model and the Figure 8 shows how the simulated and actual values compare. The blue line shows the simulated values generated from the simulation, while the green dots shows the actual values that could be obtained from the station's historical data. The validation shows that the simulation is able to accurately project the tank levels, if the main events that are to take place during the week are known at the start of the week, for example maintenance or brine washes.

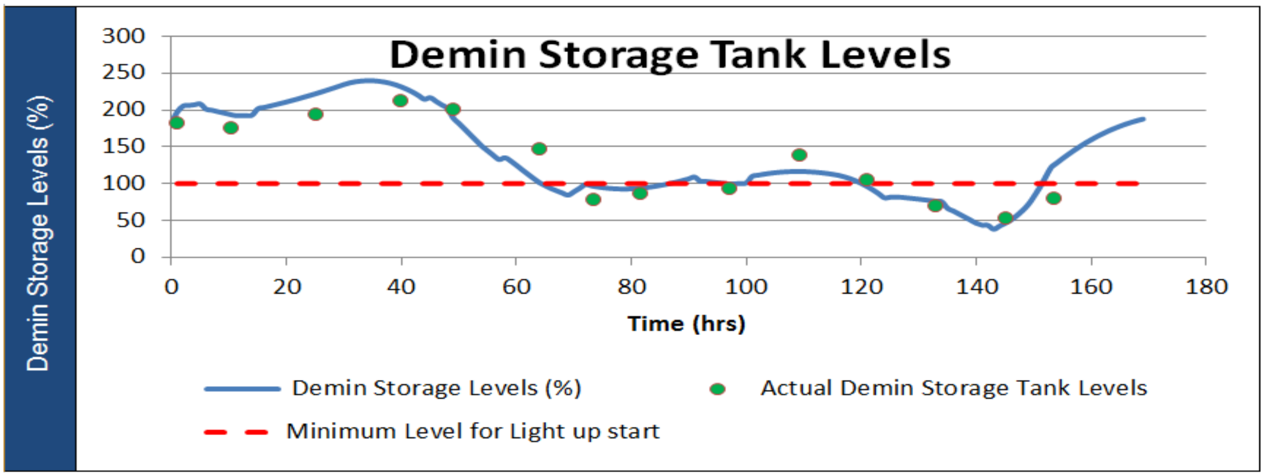

Figure 8: Validation of simulation (actual compared to simulated)

F. Model Structure

The model structure is very large but it can be broken down into the following segments:

- Vessel operation
- Regeneration
- Maintennace
- Brine washes
- Demin water consumption
- Tank levels
- Feedback loop control on train operations
- Train priorities

IV. RESULTS AND DISCUSSION

The initial simulation data was selected on an actual week of demin water production in June 2015. Data was collected from the station and mined to produce the initial conditions for the simulation for a period of a week. The following results were then based on these mined values, but changed according to each scenario as discussed below, so that a close approximation to an actual production week can be obtained.

A. Raw water quality deviation effects on demin water production

As discussed in the literature section on Raw Water Quality, it was found that the normal variation on water quality is around 34%. There is however a few outliers and the biggest outlier in that specific time frame was three times higher than the upper band of normal values. This meant that the throughput will be reached 4 times faster during the time when the water quality is experiencing this outlier.

The simulation was then adapted to increase the depletion in throughputs 4 times the normal flowrate to incorporate the effect of this reduced quality during this outlier. Two variables were added, the first being the time step when the bad quality of water enters the system and the second the duration that this bad quality lasts. When looking through the data in Figure 1, the next data point after the bad reading is 2 days later. This accounted for about 48 hours. If we assume that the bad quality water lasted for half of that time: 24 hours, it would be interesting to see how this outlier would affect the week's production. The outlier has a different effect on the net system depending on when the outlier started. This can be seen below:

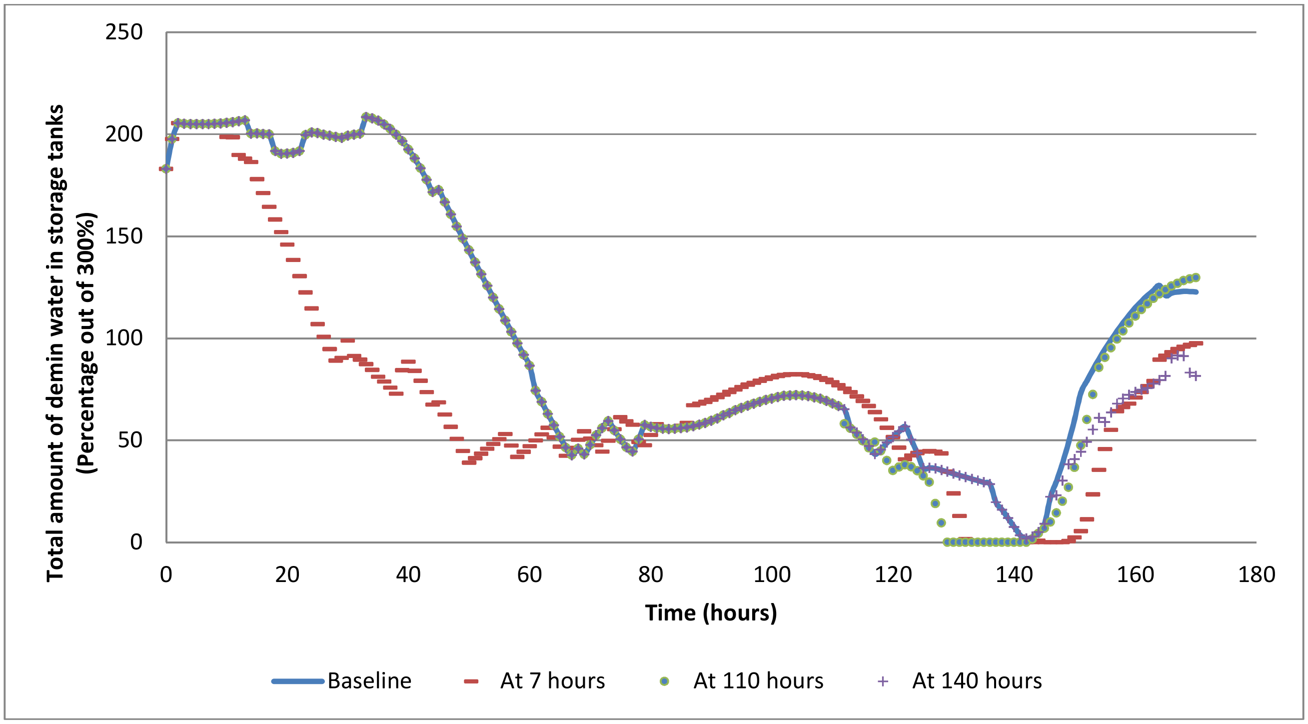

Figure 9: Effect of the water quality outlier on demin water production for 24 hours at different start times

Figure 9 reveals some of the effects about poor water quality outliers: The first scenario which is a 24 hour period of poor quality water which started at the 7th hour. Looking at the red stripes, it can be seen how drastically this water quality change affects the system just before the 20th hour and is much lower than the base. The real problem however is at the 133th hour where the water is completely depleted and remains depleted for 18 hours. This is extremely negative to the station, since they would not be able to feed demin water to the units which could easily result in units going offline and a massive financial loss to the power station since less electricity is produced, not to mention the expensive starting up of the unit/s.

The second scenario shows if the 24 hour period of poor quality water was moved to the 110th hour, shown by the green dots. As expected the production does not change until about the 115th hour. It drastically falls to zero tank level. The station remains without water for about 13 hours. This is still extremely dangerous and undesirable as explained above, but it remains without water for 5 hours less than the first scenario. The other positive remark about this scenario is that the final tank levels for this case at the end of the week matches closely with the base case scenario, which means the net result after a week on tank levels are fairly the same (assuming the 13 hours of no water can be handled correctly). The reason behind this would be that during the time when all the vessels exhaust due to overloading with poor quality water, the levels reach zero and consumption then needs to adjust to zero as well. During zero consumption the trains can regain their ability to produce water without depleting tank levels due to no consumption.

The third and final scenario shows if the outlier was moved to the 140th hour. This is shown by the purple crosses. Evaluating the entire series of points, it is easy to see that this is the best scenario yet on the overall production week. There is almost no point where water runs out, since it still follows the baseline curve until the 147th hour. The final value however is the lowest of the three scenarios at around 81% out of the 300% total. This is not ideal but it is the best case compared to the other scenarios.

The three scenarios were chosen at these specific times since they represent different phases of net accumulation. The first scenario takes place when the net accumulation is almost zero, which results in the total tank level to relatively stay the same. This revealed the worst projection. The second scenario is in a time where consumption was high and the net accumulation of demin water becoming a negative value. This was the second worst condition, but was saved due to the no water – no consumption concept explained above. Although no consumption would be devastating, this scenario does however reveal that if production can be stopped during the time when the bad water quality outlier is present, it could save much of the plant's water.

The third scenario is when the net production of demin water is positive and shows the best case. Although the final levels are lower than the base case, it is much more acceptable than having a complete loss of demin water capacity. The reason why this would be the best scenario is because of the positive net accumulation of demin water. The consumption is low enough so that the system is able to handle the multiple train regenerations.

B. *High consumption distribution and it's effect on demin water availability*

As discussed in the literature section, outliers in the water consumption are quite regular at about a 13% chance to be encountered with an average value of 1 246 m^3/day compared to the normal unit consumption of 473 m^3/day and a design consumption of 300 m^3/day. If this information could be translated to a week's time period where it is a perfect sample of the whole, it would mean that out of the 169 hours there would be about 22 hours of higher consumption during which the consumption is about three times higher than normal consumption.

Although the historical data is not exactly a normal distribution, data was then approximated for the consumption based on the information above and combining it with a normal distributions to generate data. The same procedure was followed for each of the six units at Duvha power station. It was assumed that the same distribution in data variances would be seen on an hourly level. The random, inverse normal distribution and statistical parameters were used in excel to generate two sets of consumption data. All the units were summated and the following graph represents the data during the 169 hours (1 week):

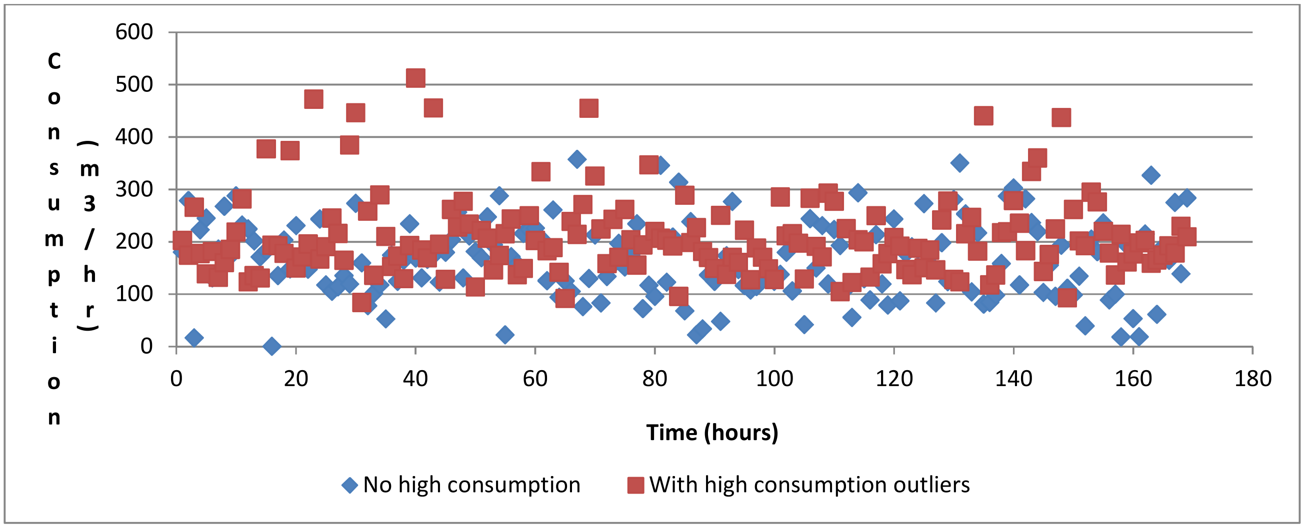

Figure 10: Data generated for weekly consumption with and without outliers.

The distribution of points for the high outliers is very similar to the original data. These two sets of consumption data was then imported into the model and the ability to choose which set to use, was built into the simulator. Three different scenarios were then used with this consumption data. These scenarios can be seen in the figure below where the effect on the demin tank levels can clearly be seen:

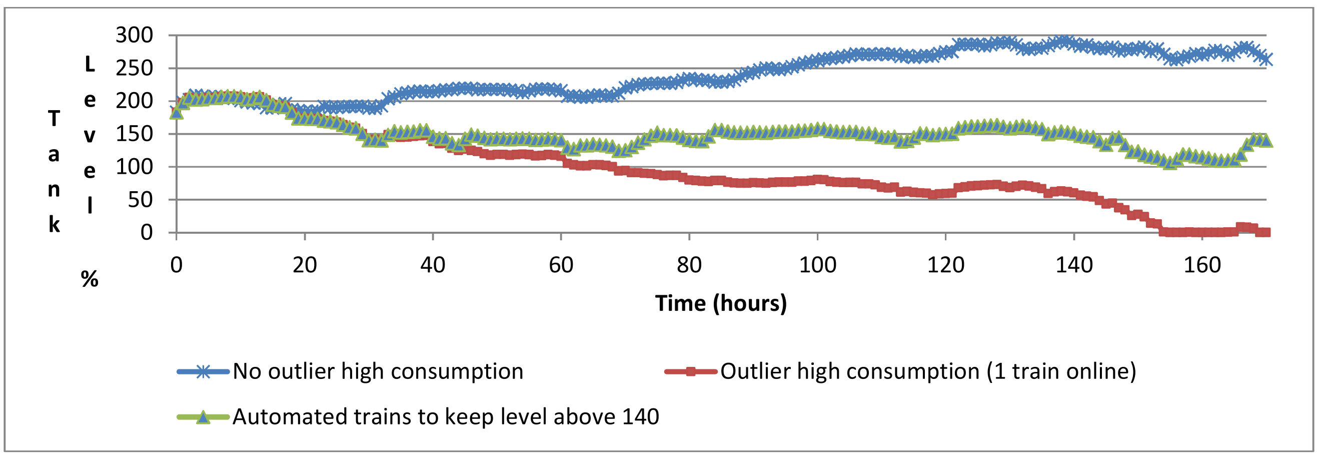

Figure 11: Effect of outlier high consumption on tank levels

One of the settings for this scenario was that the design methodology, keeping one train online, was used. In Figure 11 the blue (*) line indicates how the tank levels will change when the consumption of demin water would remain close to the average consumption of each unit and six units are online. This shows that although it takes time for all three tanks to be full (300%), it is a sustainable production. Using this same methodology but with the outliers included, the red (squares) were achieved. This scenario shows that when the outliers are included, the higher consumption depletes the tanks near the end of the run. This is mainly due to the simulator being forced to only keep one train online all the time. This also reveals that it is not possible for the demin plant to sustainably supply demin water to the station if all 6 units were online, while following the design methodology. This is the main reason why two trains are sometimes run at the same time to increase the supply of demin water and meet the demand. The third case, green (triangles), shows if the methodology was changed to put two trains online when the tank levels fall below 140%. It can be seen in this case, that it is possible to handle the outliers on consumption when two trains are online but it should be noted that the system cannot always respond as quick to higher consumptions and that that the tank levels falls to about 110% even though the set point is 140%. This means that a set point should ideally be chosen above 100% to give the system the capacity to deal with random high consumption events and not fall close to 0%.

C. *Unforseen Component Failure*

During this section, the simulator will be set to see the effect of a component failure and the consequence of having to do maintenance. The maintenance duration is defined as the total time that the component will be offline, not only the actual repair time, demonstrated by Figure 5. The simulator will be started off on the basis of the previous section and assumed that there is neither high outlier water consumption nor poor water quality during the week of operation. The results can be seen in Figure 12. The basis (blue stars) would be where there is no component failure. The second scenario (red squares) is exactly the same conditions except that there is a pump failure connected to Cation 3 at the 60^{th} hour which would take 10 hours for the whole maintenance duration and therefore the Cation 3 vessel will be unavailable during this time. The third scenario (green triangles) shows when the maintenance "slips". This means that the maintenance takes longer than initially issued. This is sometimes a common occurrence when permits are not issued beforehand due to the high safety standard Eskom tries to adhere to. If the maintenance slips by 5 hours the green triangles represents this scenario. The extra 5 hours in this case, did not make a large difference, since that specific train was not a primary production line and the second train finished regeneration, so it could take the train on maintenance's place. The fourth scenario (blue stripes) shows when the higher consumption rates are experienced simultaneously with the component failure.

The first scenario shows how the tank levels steadily increase until they reach around 300%. The second scenario shows that the maintenance's effect on production, as the tanks lose about 40% of their levels, while the third case which is 5 hours longer, loses about 48%. This shows that the lesser increase of 8% with 50% increase in maintenance duration would be because of the third train becoming available after it has been regenerated. The last scenario is alarming, since it shows that the tank levels fall almost 100% (one full tank lost) due to the 10 hours lost on the maintenance.

According to design, trains should easily be able to handle one train on permanent maintenance, since one train will always be on standby, but as seen in the previous result, the higher consumption rates required two trains to be online for a specific duration. The danger then comes into play when one of those trains needs to go for regeneration and the other is on maintenance. This leaves only one train to produce demin water and in the high consumption scenario, the production for one train is less than the consumption, leading to the tank levels being consumed at an alarming rate.

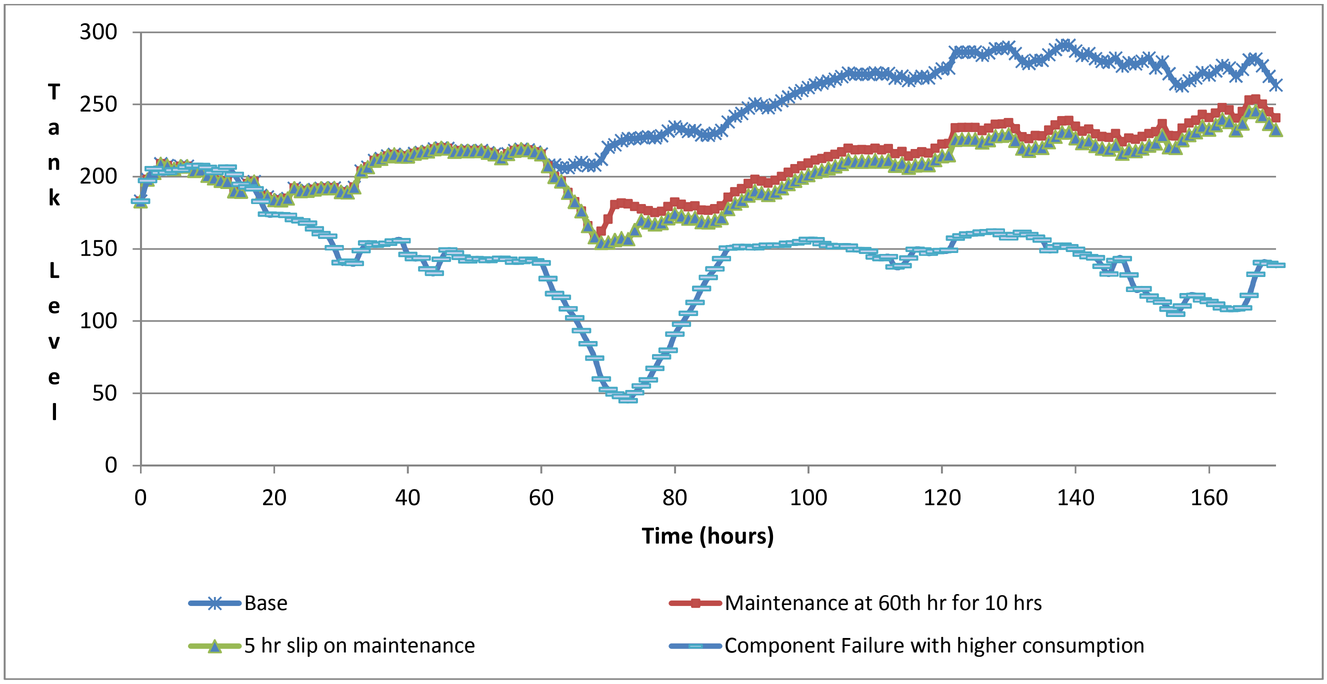

Figure 12: Effects of component failures on the sustainability of demin water

V. CONCLUSIONS AND RECOMMENDATIONS

The following are conclusions and recommendations based on the results and discussions from the simulator and knowledge gained on this project:

- Water quality experiences large fluctuations and it was seen how a misfortunately timed poor water quality outlier could lead to an 18 hour period of no demin water. This could result in a high financial loss and the operator could not have forseen the outlier. From the simulation the following recommendation would be made: if the production could be reduced or stopped during the time when the outlier is present, this would negate it's effects dramatically without losing the integrity of the plant. The station would then just increase their sampling frequency when an outlier is present and return to normal sampling rates and production when the outlier's effects have subsided.

- Changes in demin water consumption plays a major role in demin water availability. Including the outliers in the consumption of demin water could result in the difference between having three full tanks of demin water and having no demin water in a week's time lapse. Due to the higher consumption values that the demin plant would be forced to run at, at least two trains during some periods of the week just to keep up with the higher demand, even though nothing has affected the production side. The recommendation would be to keep the target value of the demin tanks at a minimum of 150%, to prevent an outlier in the consumption from depleting the tank levels.

- Unforseen component failures become much more prevelant as the station ages. This power station is currently 34 years old and pumps have a component failure rate of 1 in less than 6.5 years. The effects of having to repair a pump for 10 hours was investigated and it was seen that during a period of high consumption, the plant could lose one full tank of demin water (out of the three) due to the maintenance. A maintenance slip's effect will depend on what the state of the whole plant is and it was seen that in that specific case, the 5 hour extension on the pump maintenance had a lesser effect than the initial 10 hour maintenance. The recommendation would be to do reliability and integrity tests on the components regularly. This would give the manager a good indication of when to have spare parts ready, to reduce the maintenance time period.

In summary, three aspects of random events and outliers were investigated on the demin plant. It is clear from these conclusions that these random events could drastically alter the demin water availability. The impact ranges from having three full tanks (300%), to having no demin water in any tank (0%) when evaluating for the impact of outliers. This paper clearly illustrates that the system dynamics model can be used effectively to demonstrate the unpredictability of this complex water system.

VI. ACKNOWLEDGEMENTS

- I would like to acknowledge Stephanie Marais for initiating the project, assisting with understanding the demin plant, windtunneling the simulator and her invaluable inputs and directive.
- Sidwell Muthuvhine on the understanding and assistance behind the water quality aspects and ion exchange process.
- Themba Shabalala, André Groenewald and Cecil Mnquibisa for their support, inputs and understanding on specifically the Duvha Demin Water Plant.
- Nalini Pillay with her patience, feedback, direction and guidance which were always available.
- Reviewers: Nombuso Sibeko, Nalini Pillay.

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