A simulation-based prediction model for coal fired power station condenser maintenance

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Abstract

Title: A simulation-based prediction model for coal fired power station condenser maintenance

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Faculty: Engineering

Degree: Master of Engineering in Mechanical Engineering

South African coal-fired power stations (CFPSs) are faced with special challenges. These include ageing infrastructure, increased maintenance requirements and reduced funds. A unique solution is therefore required whereby station performance can be maintained or even enhanced at minimum cost.

A simulation-based model could help improve the effectiveness of operations and minimise downtime. In this study such a model was developed for a South African-based CFPS. The model was built using a semi-empirical thermohydraulic model. The results of the simulation were verified against measured station data and were accurate to within 5 %.

This calibrated simulation model for the fully integrated CFPS operation was then used to investigate condenser maintenance. The practical question that had to be answered was when is the best time to clean and maintain the condensers as they have a significant impact on performance of the CFPS.

The monetary effect of early, late or non-maintenance was quantified. The model showed that the resulting loss in profit due to maintenance schedules followed an exponential trend and is therefore extremely time-sensitive.

A loss in profit of R600 000 for a 60 MW unit occurred if the condenser was maintained 30 days too early or too late and R2.5 million if maintained 60 days too early or late. When extrapolated to all South African power stations, this value increases to R250 million if all stations are maintained 30 days too early or too late and R1 billion if maintained 60 days too early or too late.

The application of the simulation-based approach showed that a verified semi-empirical model provides significant insights into CFPS performance. The approach provides a credible platform for decision making, process predictions, scenario investigations, and optimising operations. Effective condenser maintenance scheduling provided significant value to station personnel. Although this study focussed on a condenser-specific application, a similar approach can be applied to other components of the station using the same model.

The work will be presented at the ICUE conference in Cape Town in November 2019.

An article on the work was also prepared for the journal, Applied Thermal Engineering. The article is given after the Abstract. It is suggested that the reviewer read the article first as it is a concise summary of the Dissertation. It will make reading the rest of the Dissertation easier.

Keywords: Coal fired power station, maintenance scheduling, predictive maintenance, condenser, energy prediction

Journal Article

A simulation-based prediction model for coal-fired power plant condenser maintenance

Abstract

Many coal-fired power plants (CFPPs) face special challenges such as ageing infrastructure, neglected equipment maintenance, and reduced funds. A unique management solution is required whereby plant performance can be maintained or even enhanced.

Management methods which incorporate simulation-based approaches boast several benefits associated with integrated systems modelling. Other emerging solutions have highlighted the cost-savings potential of predictive maintenance scheduling where the health and risk of each component on a plant is considered. It is then possible to determine which components need to undergo maintenance at prescribed performance levels. A significant need exists to apply these methods to the struggling CFPP industry in South Africa.

To this end, a novel integrated simulation model was constructed of a South African CFPP. The model is based on semi-empirical thermohydraulic principles.

The condenser was found to have the largest effect on maximum generation capacity although its maintenance is often neglected. The model provides new insight into the cost implications associated with delayed or premature maintenance by accounting for different fouling rates inside the condenser tubes.

The results of the simulation were verified against measured plant data and was within 5 % accuracy. The model was then utilised to determine the most efficient predictive maintenance schedule of a 60 MW unit. Results showed that, when applying the new predictive maintenance schedule, considerable savings can be realised (between R500 000 and R2 000 000 per year[1]). When extrapolated to the entire South African power utility fleet, this value increases to over R900 million per annum, depending on the applied schedule.

Keywords

Coal fired power plant, maintenance scheduling, predictive maintenance, condenser, energy prediction

[1] US$ 1 = R 15.18 (04 October 2019)

1. Introduction

Numerous countries are highly dependent on coal-fired power plants (CFPPs). In South Africa (SA), for instance, CFPPs make up 92 % of the power-generating fleet [1]. Of the country's 15 plants, only two new plants have been commissioned in the past 10 years, with an average fleet age of 30 years [2]. The U.S. and EU28 countries are experiencing similar trends with the average age of CFPPs at 39.6 and 32.8 years, respectively [3].

In order to reach the Paris Agreement climate goals [4], it is estimated that the most cost-effective premature infrastructure retirements will be in the electricity and industry sectors [3]. Ageing infrastructure, coupled with a world-wide transition to net-zero emissions by mid-century [5], emphasises the need for proper maintenance of existing CFPPs.

To meet increasing energy demands, SA power utility Eskom often delays maintenance on older plants. This leads to a decline in fleet performance, and negatively impacts the ability of the fleet to meet demand [6]–[8]. Consequently, a lack of maintenance in older CFPPs has become an ever-increasing concern [7], [8]. Eskom's annual budget allocated towards maintenance decreased from 30 % in 2006 to 9 % in 2012 [9]. Figure 1 illustrates SA's diminishing power supply since the South African energy crisis in 2008 [10].

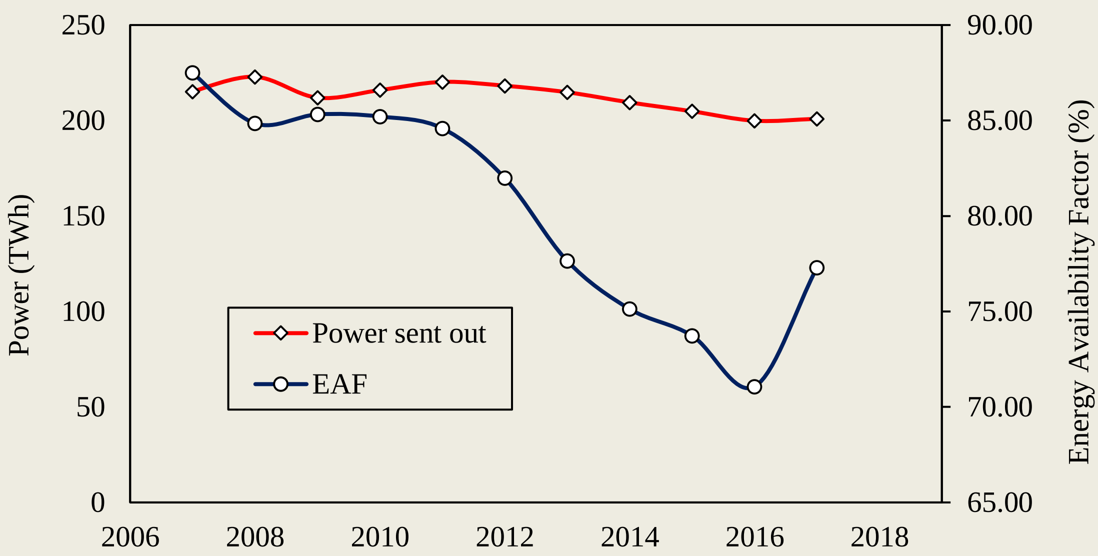


Figure 1: South Africa's energy availability since the energy crisis in 2008, adapted from [10].

Time-based prescriptive maintenance can no longer be used due to the age of components on plants. Power utilities started transitioning to predictive maintenance techniques [10], [11]. These techniques consider the health and risk of each component on a plant and determine which components need to undergo maintenance at prescribed limits or performance levels [12].

A CFPP consists of various components. Each component influences the overall efficiency and maximum generation capacity of the plant. The condenser has the largest effect on maximum generation ability [13]–[16]. However, condenser maintenance is typically neglected as the effects of fouling inside the equipment [17] are not easily visible.

Condensers tend to foul on the cooling water side inside the tubes due to the deposit of impurities, biomass and sludges. Fouling greatly reduces heat transfer contact area and consequently the heat transfer coefficient because of reduced thermal conductivity and unfavourable flow dynamics [17]. Fouling can occur at different rates depending on cooling water quality. In plants with untreated cooling water significant fouling can occur in as short as 4 – 6 months [18]. Costs arising from additional fuel requirements and production losses associated with condenser fouling are reported in the range of R5.88 million to R32.34 million per annum per plant [19].

Numerous cleaning methods have been investigated [20], [21]. The time needed for condenser maintenance is often only limited by crew size and work space. The efficiency, generation and costs benefits often result in a short payback period and improved performance for the remainder of the maintenance cycle [22]. Additionally, by incorporating the revenue losses associated with each cleaning, the optimal number of cleanings required throughout the operational year can be determined [19].

Studies support the potential value of effective condenser maintenance [19], [20], [23], [24]. The trend shows a need for condition-based predictive maintenance (CBPM) methodologies [25]–[29] to improve equipment performance. CBPM techniques have performance and economic benefits as the technique allows for early diagnosis of potential failures, as well as the ability to plan effective maintenance actions [30].

To support the need for CBPM techniques, 11 studies were found to be highly relevant to this study [12], [16], [24], [31]–[38] . These studies were evaluated according to six desirable criteria deemed necessary for predictive maintenance scheduling of a CFPP condenser. The criteria were determined based on the requirements of the methodology discussed later. The studies are compared in Table 1 using a matrix to highlight the need for this study.

It is common for CBPM techniques to be executed on isolated equipment making the integrated effects of systems challenging to predict. Also, ageing power plants present unique challenges where original design conditions do not apply. Consequently, existing models need to be adapted to represent real-life plant conditions. Simulation-based methodologies provide an opportunity to overcome these shortcomings.

Table 1: Table matrix indicating desired elements from previous studies.

Source	Simulated	Integrated	Verified	Plant Performance	Maintenance Model	Cost Implication	Comments
[12]				✓	✓	✓	Condition-based maintenance model
[16]		✓		✓		✓	Plant efficiency improvement with condenser performance
[24]		✓		✓	✓	✓	Dissertation on condenser backpressure effect
[31]				✓	✓		Combined cycle reliability and modelling
[32]		✓			✓	✓	Developed maintenance scheduling model
[33]		✓			✓	✓	Detects critical components for maintenance
[34]		✓		✓		✓	Effect of condenser performance
[35]	✓	✓	✓	✓			Simulation for online fouling monitoring
[36]	✓	✓			✓	✓	Condenser fouling monitoring and maintenance model
[37]	✓		✓		✓	✓	Specifically investigated steam piping
[38]			✓	✓	✓	✓	Focus on coal mills

Simulation software allows multiple solutions to be investigated at minimal cost, without physical changes to the CFPPs. This avoids downtime, minimises risk, and provides multiple solutions for unique situations [39]–[41]. Simulations can also be used for energy- and exergy-based calculations and comparisons [42], as well as computational flow dynamic (CFD) investigations [43].

Semi-empirical simulation approaches boast various benefits, such as quick turnaround times, and allowing for the simulation of actual operating conditions (part loads) instead of the usual design conditions [44], [45]. Semi-empirical simulations are used as operational tools i.e. not as design tools like that of general simulation programs.

Energy management methods using simulations are predominantly focussed on buildings -and commercial applications [44], [46], [47]. As mentioned previously, there are several benefits related to integrated systems modelling using energy-based simulations. There is also a significant need for new approaches to apply these novel simulations to the CFPP industry.

The objectives of this study therefore include the following:

- Develop and verify an integrated simulation-based model.
- Determined whether a semi-empirical model can be representative of actual plant conditions of unique/ageing plants which are not operating at the expected design specifications.
- Provide a predictive maintenance model specifically based on the condenser.
- Test and validate the results provided by the predictive maintenance model.
- Evaluate the usefulness of the developed simulation-based approach for future work.

The model is developed using data from a CFPP located in South Africa. This station has been operating for over 60 years and consists of six serviceable 60 MW turbine units and six serviceable boilers from a total of seven installed turbines and boilers. Only a single generating unit was selected for the study since the other five are similar. Each unit also operates independently from the others.

2. Methodology

2.1. Overview

Figure 2 gives a high-level overview of the process followed to develop the solution.

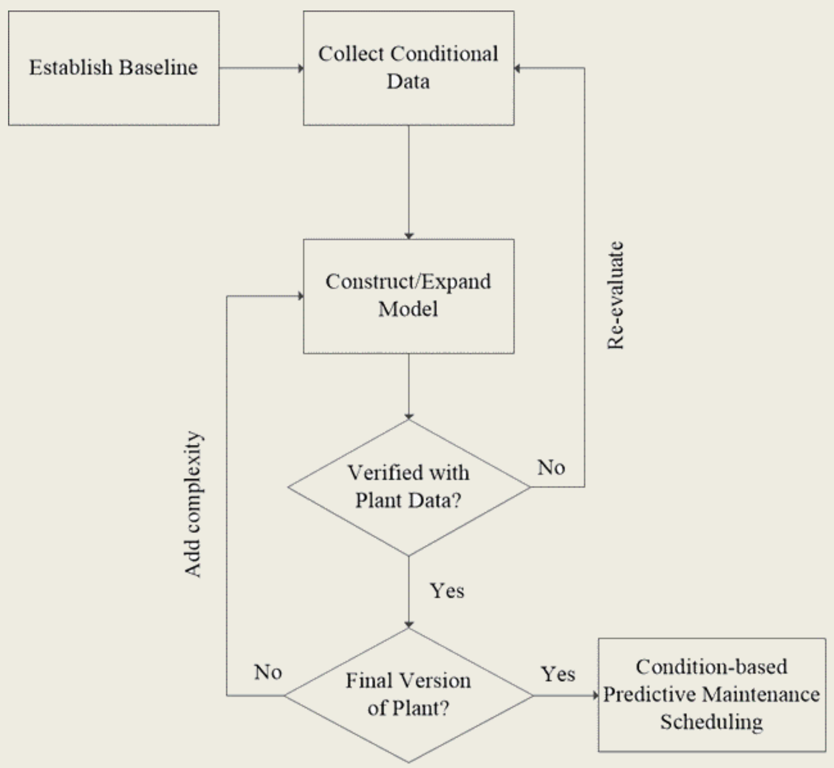


Figure 2: Overview of the model development process.

The method entails an iterative process, beginning with a simplified representation or component of the plant and expanding upon the complexity. The model is calibrated as it develops after each addition of a component or expansion of the plant. Ultimately, an entire power station can be modelled using a small number of components. When the final representation of the plant has been modelled and verified, the model is used for CBPM scheduling.

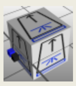
2.2. Simulation Model/Software

Simulation software has become an invaluable tool in the operation of modern companies, assisting with decision making, predictions, "what-if" scenario investigations, and process optimisation.

Process Toolbox (PTB) was used during the course of this study. The mathematical calculations in PTB are based on a semi-empirical thermohydraulic model. This requires prior knowledge of the system's parameters and significant data or specifications of the plant.

The software is component-based, with each component a simplified representation of a CFPP component or equipment (e.g. condenser or boiler). The various components communicate through links or connections, and the user indicates which are located upstream or downstream. Each component is classified under one of four larger categories, namely water, steam, general and air (compressed or atmospheric). Examples of key components are described in Table 2.

Table 2: Examples of simulation components and descriptions.

Category	**Description**	**Image**	**Detail**
Steam	Steam turbine		Converts potential and thermal energy to electric energy.
Water	Cooling tower		Water to air heat exchanger.
Air	Air fan		Adds potential energy to condensate, increases pressure.
General	Air coal burner		Adds energy to air flow in the form of heat input.

Each component requires certain critical parameters be specified (such as desired mass flow rates and temperatures). The simulation software then iteratively solves for energy, mass and momentum (1-dimensional CFD) across the integrated model, striving towards a solution matching the user-specified “inputs”.

2.3. Condenser Calibration

When modelling the condenser, or cooling circuit, heat transfer between the steam-side and the water-side is simulated to ensure that the steam fully condenses within the condenser and that the correct back pressure is achieved. The calibration method is summarised in Table 3.

Table 3: Condenser calibration method.

Step	Description
1.	Separate into water-side and steam-side.
2.	Use steam boundaries and mass flow for inlet and outlet conditions of steam-side.
3.	Use water boundaries and mass flow for inlet and outlet conditions of water-side.
4.	Adjust heat transfer coefficient to reach desired inlet and outlet conditions.
6.	Remove mass flows and add cooling tower and pumps.
7.	Adjust overall heat transfer (UA) of cooling tower to achieve desired inlet and outlet conditions.

The condenser is a critical component of the study and care should be taken towards ensuring correct calibration and verification.

Figure 3 shows the convergence of the simulation towards steady state conditions after approximately 20 hours.

Although steady state is quickly achieved on the water side, the steam side requires more time to stabilise due to the large effect of the upstream turbine and boiler conditions such as temperatures, pressures and mass flows. Steady state conditions are reached after approximately 20 hours.

Figure 3 also reports the condenser inlet quality. The quality is defined as the mass ratio of liquid water present where $x = 1$ is a fully saturated steam flow and $x = 0$ a fully saturated water flow. The quality at the inlet reaches a steady state quality of 0.9 after approximately 20 hours.

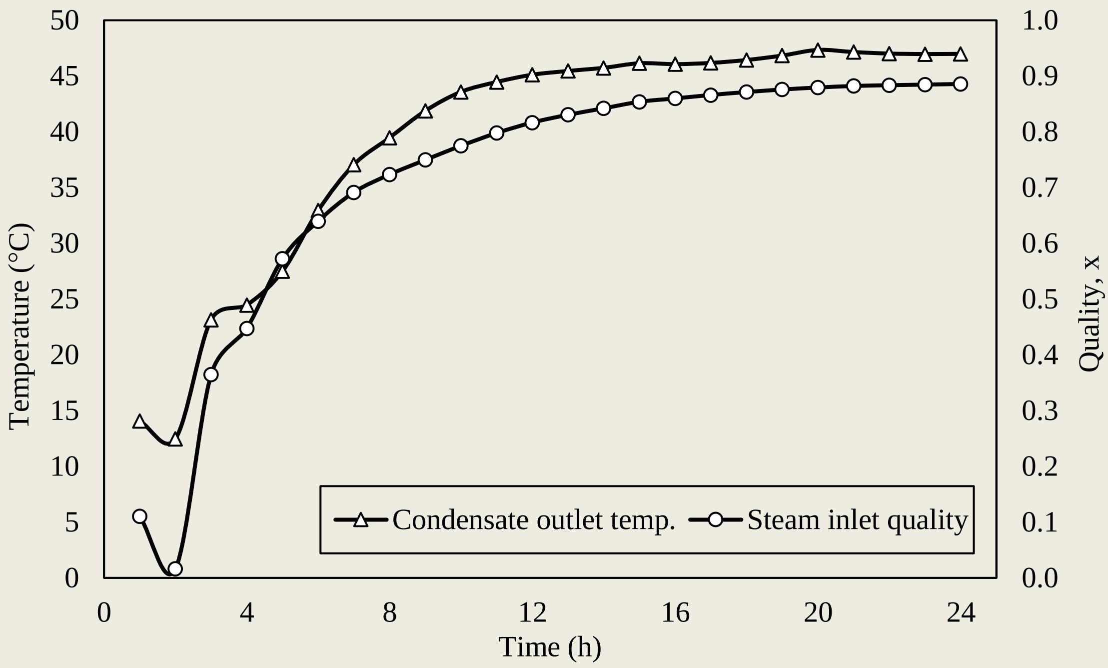


Figure 3: Convergence of condenser conditions.

2.4. Predictive Maintenance

Fouling of the condenser is a slow process which is either ignored or its effects only realised at a critical stage resulting in unplanned shutdowns. This leads to reactive maintenance. The effects of condenser degradation on the entire plant are quantified by two key performance indicators (KPIs), namely plant efficiency and plant output (measured in MW). By applying an integrated simulation, a predictive maintenance model can be developed to support critical financial decision making by balancing time, cost and equipment availability.

This also reduces the operating costs of the equipment and overall expenditure of the plant. This is achieved by prescribing suggested maintenance intervals, or certain setpoints such as condenser pressure or temperature, for each individual power-generating unit. Each unit is individually investigated and characterised according to its past performance and fouling rate.

From literature [16], [17], it was found that with increased fouling condenser back pressure would increase and, as a result, increase the condenser outlet temperature. Therefore, it is assumed that the condenser outlet temperature is directly related to the amount of fouling within the condenser. To simulate the effect of condenser fouling on unit performance a multi-step approach was undertaken. It is known that condenser fouling increases the back pressure of the condenser due to reduced heat transfer rates. To simulate the effect, the condenser pressure is increased in increments. A minimum of 4 increments is required to yield results that accurately represent plant performance.

The two main indicators of performance, generation and efficiency, were linked to fouling by plotting the two indicators as a function of condenser outlet temperature. An empirical exponential fouling rate was introduced into the model, described by Equation (1).

$$T_c = \left(\frac{day}{B}\right)^n + T_{clean} \tag{1}$$

where T_c is the condensate temperature, day is the amount of days between cleaning, B and n are unitless coefficients, and T_{clean} is the temperature directly after cleaning of the condenser.

Knowledge of the correlation between plant performance and condenser fouling allows for the development of a condenser maintenance schedule. The generation and efficiency curves give a direct correlation to the condenser outlet temperature/backpressure and, subsequently, the plant performance on any given day. This can be converted into a currency value or daily operating cost of the plant.

An iterative predication model then simulates several periods between cleaning scenarios. Each iteration calculates an individual day's performance, cost and profit. Once cleaning days are reached the unit is switched off for x days for the clean -and outlet temperature, backpressure, generation, and efficiency to return to normal clean conditions. This takes place between set boundaries described by the user. The user inputs required for the calculation are summarised in the following section.

It is important to note that the simulation model needs to be calibrated to the unique operating conditions of any generating unit under investigation.

3. Results and Discussion

3.1. Case Study Background

The simulation model and newly developed maintenance prediction tool were applied to a CFPP case study located in South Africa, referred to as Station A. Station A has been operating for over 60 years, and consists of six serviceable 60 MW turbine units and six serviceable boilers from a total of seven installed turbines and boilers. Only a single generating unit was selected for the study. The model was modified and calibrated to Station A's operating conditions. The constructed model is illustrated in Figure 4. The user inputs required for the calculations are summarised in Table 4.

Table 4: Maintenance prediction model inputs.

Description	**Unit**
Last clean	Date
Days between cleans	days
Clean condensate temperature	°C
Type of fouling	Linear/Exp
Exponential coefficients	
B	-
n	-
Cost per kWh sold	R/kWh
Condenser repair price	R/unit
Coal price	R/ton

The model was calibrated to measured values. All parameters were calibrated to within 5 % of actual data. The results are summarised in Table 5.

Table 5: Overall -and condenser calibration results of Station A.

OVERALL				
	Unit	Simulation	Actual	Error (%)
Gross power	MW	60.11	60.20	0.15
Net power	MW	57.90	58.00	0.16
Auxiliary power	MW	2.20	2.20	0.00
Coal usage	ton/hr	36.37	36.00	1.02
Heat input	MW	247.50	247.50	0.00
Thermal efficiency	%	23.39	23.43	0.16
Power produced per day	MWh	1389.65	1391.88	0.16
CONDENSER				
	Unit	Simulation	Actual	Error (%)
Steam inlet	°C	49.46	51.00	3.06
Quality at inlet	-	0.89	-	-
Condensate outlet	°C	47.17	48.00	1.75
Cold water inlet	°C	23.50	23.00	2.16
Cold water outlet	°C	35.47	34.00	4.23
Pressure	kPa abs	12.04	12.20	1.32

From this calibration procedure, it was observed that the simulation model does not require all the parameters in order to fairly represent the power station (within an accuracy margin of 5 %). A noted advantage of a semi-empirical simulation is that the model is not too sensitive to low quality data or data unavailability. Data collection is therefore made simpler. However, this increases model calibration complexity and time, i.e. if more data is available the calibration time is shorter due to less trial-and-error. For example, only inlet pressures and temperatures were required to calibrate the feedwater heaters during this case study.

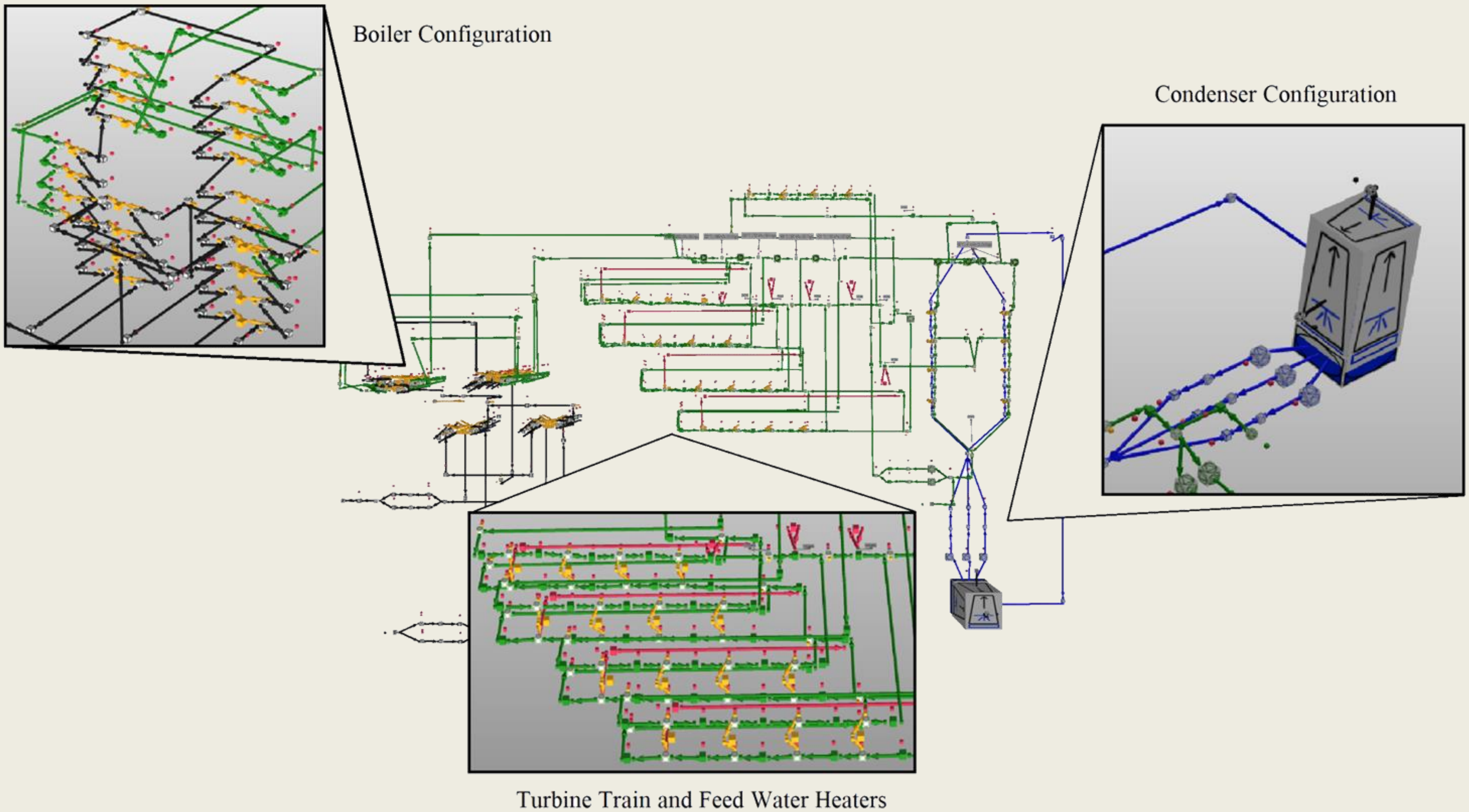


Figure 4: Model layout representing the plant's physical components and connections (top view), with detailed representations of the various components and configurations.

3.2. Generation and Efficiency

The fouling in the condenser was simulated, and the output is shown in Figure 5. It shows the plant performance curves against increasing condenser outlet temperature, which is a direct result of fouling. The correlations derived from the curve are used in the prediction model for determining the performance of the generating unit as a function of the corresponding condenser outlet temperature. From this the performance can be estimated for any given day assuming the condenser follows the previous temperature curve.

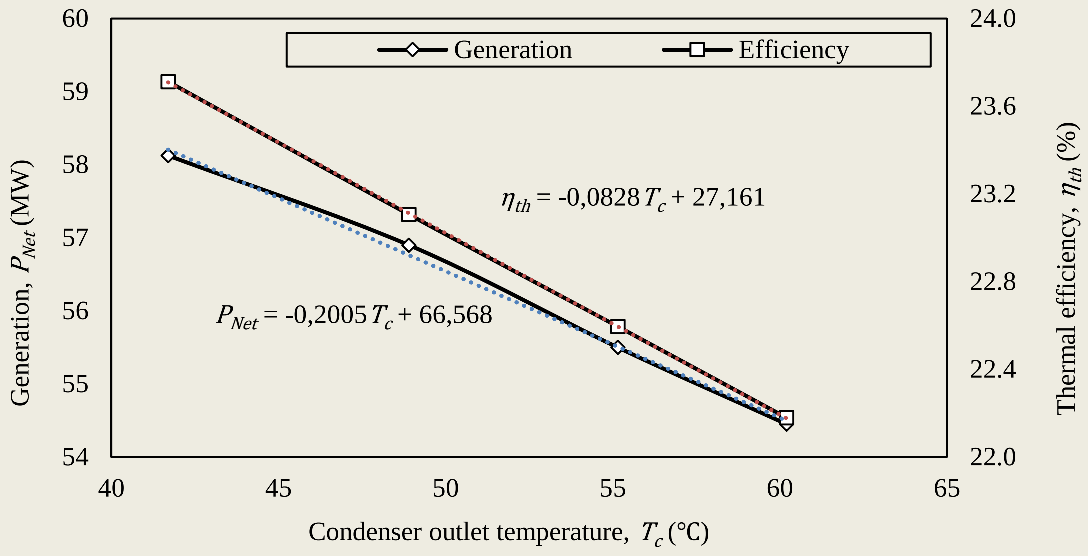


Figure 5: Plant generation capacity and efficiency as a function of condenser outlet temperature.

The prediction model's inputs for Station A are entered in the format shown in Table 6.

3.3. Predictive model results

The prediction model iteratively runs through numerous combinations of cleaning schedules in a user-specified range. In this case, the predictive maintenance schedule was modelled from 105 days to 285 days between cleans. For each schedule the average daily profit is retained, and this is plotted on a graph yielding the results shown in Figure 6. A polynomial curve is fitted to the data which estimates the average expected daily profit depending on the maintenance schedule.

The station is of considerable age and regularly experiences unplanned outages. Consequently, random breakdowns were incorporated to further improve the accuracy of the prediction model, also shown in Figure 6. The average number of breakdowns per year and average time to rectify were determined from historical data.

The curves in Figure 6 also indicate that unplanned outages have a small effect on the maintenance schedule. However, a large loss in revenue is still experienced due to the outage. For the purposes of maintenance scheduling, it is assumed that unplanned outages can be ignored to reduce calculation times.

Table 6: Input data used to approximate condenser fouling.

Description	Unit	Value
Last clean	Date	2018/11/05
Clean condensate temperature, T_{clean}	°C	43
Type of fouling	-	Exp
Exponential coefficients		
B	-	80
n	-	2.8
Average breakdowns per year	y^{-1}	5
Average time to rectify	days	2
Condenser repair price	R/unit	-R170 000.00
Time to clean condenser	days	5
Cost per kWh sold	R/kWh	R0.86
Coal price	R/ton	R0.00[2]

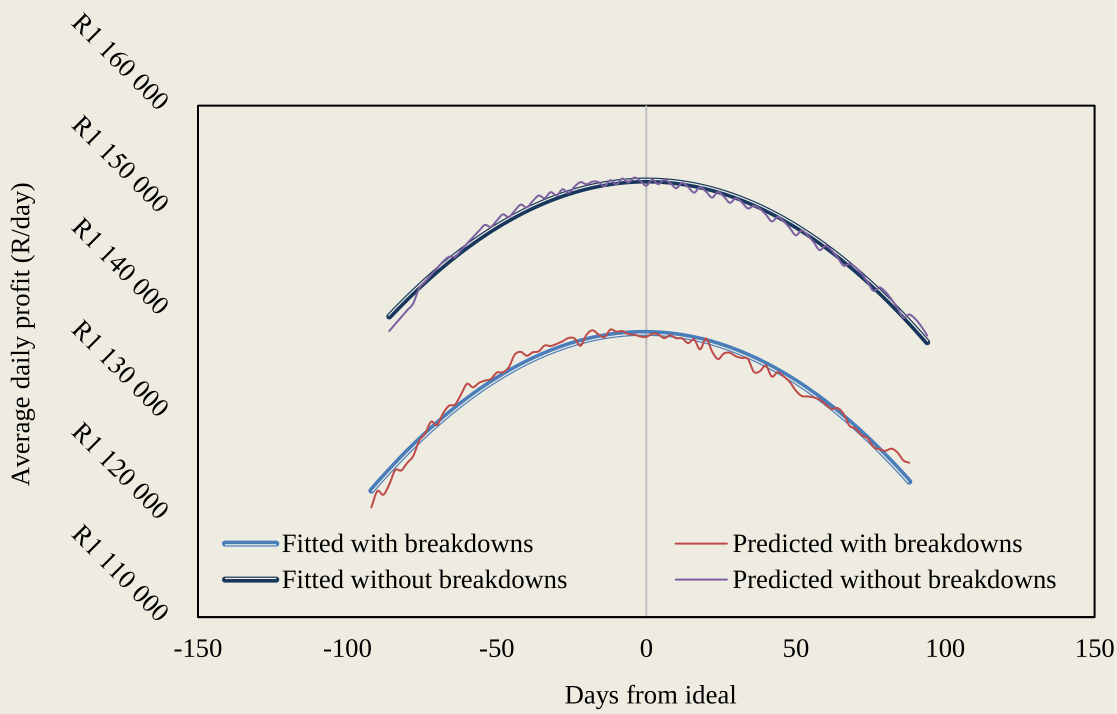


Figure 6: Time-predictive maintenance curves, with and without breakdowns.

[2] Due to a contractual agreement with the local municipality, the company does not pay for coal reserves and therefore Station A's expenditure only consists of fixed costs such as salaries, utilities, maintenance etc. This will affect the outcome of the prediction model and is a critical component of the cost prediction as it varies with station performance.

From the results obtained in Figure 6, the maintenance prediction results are summarised in Table **7**.

Table 7: Maintenance prediction model results.

Result	Unit	Value
Best average profit	R/day	R1 152 678.76
Days between full clean	days	191
Suggested maintenance date	Date	2019/05/15
Suggested condensate outlet temperature	℃	56.4

As an indication of the effect of early or late maintenance, Figure 7 was compiled by comparing the maximum achievable average daily profit to the average daily profit from conducting maintenance earlier or later than ideal. The curve plotted is described as the average loss in profit per year as compared to the ideal maintenance schedule.

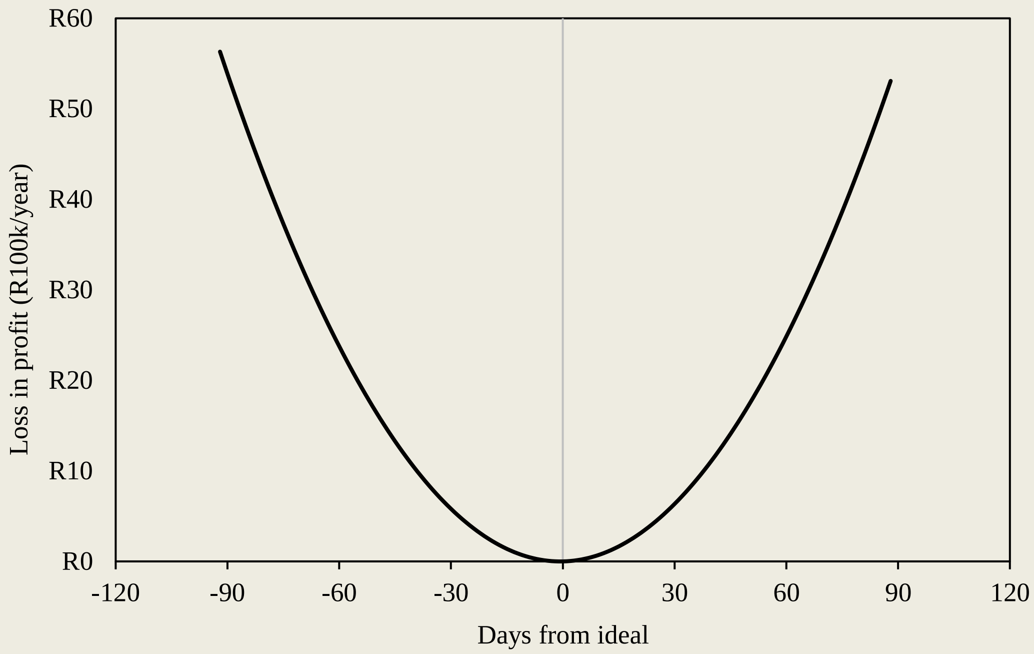


Figure 7: Loss-in-profit curve.

The generating unit could be analysed immediately after its condenser clean on 2018/11/05 and therefore a good baseline could be developed with a suggested condenser maintenance date of 2019/05/15.

3.4. Potential of Extended Applications

Due to South Africa's large reliance on CFPPs it is of intertest to investigate the effect on non-maintenance or late maintenance on their CFPP fleet. Therefore, using the prediction model and simulation results obtained from the 60 MW unit, the approach was extrapolated to a 350 MW unit. The corresponding inputs are shown in Table 8.

Table 8: Extrapolated model (350 MW) inputs.

Description	Unit	Value
Last clean	Date	2018/11/05
Clean condensate temperature, T_c	℃	41
Rated generation	MW	350
Clean efficiency	%	32
Type of fouling	Linear/Exp	Exp
Linear fouling rate	℃/day	0.07
Exponential coefficients		
B	-	80
n	-	2.8
Average breakdowns per year	y^{-1}	5
Average time to rectify	days	2
Condenser repair price	R/unit	-R17 000 000.00
Time to clean condenser	days	5
Cost per kWh sold	R/kWh	R0.86
Coal price	R/ton	R420.00

The extrapolated inputs are similar to that of the 60 MW unit with the major exceptions being the inclusion of coal cost, higher efficiency and higher generation. The assumption was made that the condenser fouls in a similar fashion as that of the 60 MW unit. This assumption assumes similar water quality and condenser design specifications. The Loss-in-profit curve for the 350 MW unit is shown in Figure 8, and indicates a substantial increase in possible savings. The results are summarised in Table 9.

Table 9: Extrapolated model outputs.

Result	Unit	Value
Best average profit	R/day	R5 067 368.18
Days between full clean	days	207
Suggested maintenance date	Date	2019/05/31
Suggested condensate outlet temperature	℃	55.3

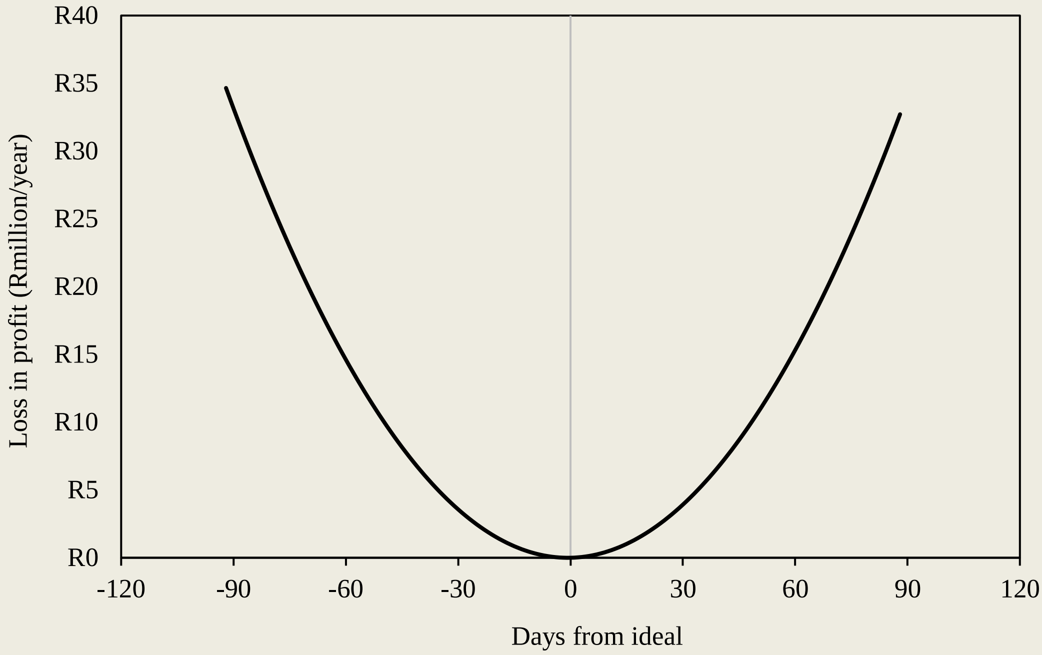


Figure 8: Loss-in-profit curve extrapolated for a 350 MW unit.

Extrapolating even further, the effect of maintenance on condensers over the entire CFPP Eskom fleet, producing an average of 23 GW, is also considered. The results are shown in Table 10 where the summation of average loss in profit per year for all Eskom CFPP units are compared to late maintenance in terms of days from ideal schedule.

Table 10: Extrapolated loss-in-profit over entire Eskom fleet.

Days from ideal	**Loss per annum** R [million]
Single 350 MW unit	
30 days	R3.6
60 days	R14.6
Eskom CFPPs (average 23 GW)	
30 days	R234.6
60 days	R960.7

The values reported here, though extrapolated, strongly support the value of utilising integrated simulation software for modelling plant performance. A single opportunity presented here predicts savings of over R950 million per year for the entire Eskom fleet. This is still less than 10 % of the projected Eskom maintenance costs for the financial year ending 2019 [48].

Overall, the application of the developed simulation-based approach indicated that a verified semi-empirical model can provide significant insights into CFPP performance. This provides a credible platform for decision-making, process predictions, scenario investigations, and optimising operations. In this study significant value was produced by investigating condenser maintenance scheduling. Although this study focussed on the specific application, a similar approach can be applied to other components of the plant using the same model.

4. Conclusion

A CFPP was modelled using a unique simulation-based approach to help identify savings opportunities at a SA-based plant. The model is based on semi-empirical thermohydraulic principles. The model was calibrated and found to be within 5 % of measured data. Using the model, an opportunity was identified whereby condenser maintenance scheduling could be improved. Consequently, plant performance is improved, and profit loss is minimised. The simulation inputs should account for the unique operating conditions of each station such as water quality. Correct application of the model suggested maintenance of the condenser every 6 months.

The results from the 60 MW study were extrapolated to a larger 350 MW unit (comparable to a larger Eskom plant) where it was predicted that a unit loss of approximately R3.6 million per year could result from 30 days premature or delayed maintenance. This amount increases to R14.6 million per year for 60 days premature or delayed maintenance. Extrapolating for a larger fleet, averaging at 23 GW, similarly led to estimates of R236.6 million and R959.4 million losses for 30- and 60-days incorrect maintenance, respectively. The results highlight the importance of optimised maintenance scheduling in CFPPs and indicate the immense potential of advancing similar studies.

5. Acknowledgements

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List of abbreviations

Abbreviation	*Description*
BFP	Boiler Feed Pump
CBM	Condition Base Maintenance
CBPM	Condition Based Predictive Maintenance
CFPS	Coal-Fired Power Station
DA	Deaerator
EAF	Energy Availability Factor
FWH	Feedwater Heater
HP	High Pressure
HT	Heat Transfer
IP	Intermediate Pressure
KMP	Key Measurement Points
KPI	Key Performance Indicators
LP	Low Pressure
OEM	Original Equipment Manufacturer
PI	Proportional Integral
PTB	Process Toolbox
SCADA	Supervisory Control and Data Acquisition
T-S	Temperature - Entropy
VBA	Visual Basic for Applications

Nomenclature

Symbol	***Description***	***Unit of measure***
A_s	Contact surface area	m^2
a	Regression slope	
B	Adjustable constant for fitting the curve to the data,	
b	Regression intercept	
c	Regression slope	
C_{coal}	Average cost of coal	R/ton
C_{energy}	Average selling price of energy produced	c/kWh
day	Day from last clean	
d	Regression intercept/Amount of days before or after maintenance	
h	Heat transfer coefficient	W/m^2K
$\dot{m}_{coal}$	Average coal usage	ton/hr
n	Adjustable exponential constant	
η_{th}	Thermal efficiency	%
P_{gen}	Average power produced	kW
P_{loss}	Loss in profit	Rands
P_{Net}	Net generation	MW
Q	Heat transfer rate	W

Chapter 1: Introduction

A Coal-Fired Power Station

The background and state of art around coal-fired power station condenser maintenance and simulation is given in this chapter.

1. Introduction

1.1. Preamble

The introduction provides background on the significant challenges faced by South African power generation in its current form. This chapter further describes the operation of a typical coal fired power station (CFPS). A specific research problem regarding condenser maintenance was highlighted by one South African CFPS. Therefore, a more in-depth discussion is given on the condenser.

Condenser performance and its effect on station performance were investigated and substantiated from literature. Literature reveals the importance of condenser maintenance and several techniques are discussed. It also showed that modern technology supports full-station simulation software as a tool to achieve optimum maintenance. From literature it is clear that condition-based maintenance (CBM) is the most applicable to the problem addressed in this study.

The need for the study is then discussed based on the needs of the CFPS and the knowledge gained from the literature reviews. The final section of this chapter briefly discusses the structure of the study. This chapter only contains critical information. Supplementary descriptions of CFPS components and literature reviews are summarised in Appendices.

An article on the work was also prepared for the journal, Applied Thermal Engineering. The article is given after the Abstract. It is suggested that the reviewer read the article first as it is a concise summary of the Dissertation. It will make reading the rest of the Dissertation easier.

1.2. Background

1.2.1. State of energy production in South Africa

South Africa's energy generation is dominated by Eskom (Pty) Ltd, which produces close to 92 % of the country's electricity requirements [1]. Eskom is a parastatal company and operates a fleet of power-producing stations. The majority of these stations are CFPSs which make up 86 % of their total generation capacity as can be seen in *Figure 1-1* [2], [3]. CFPS make up 92 % of Eskom's fleet when considering only base load operations. Therefore, Eskom has a substantial reliance on CFPS for their continued and uninterrupted power supply [4].

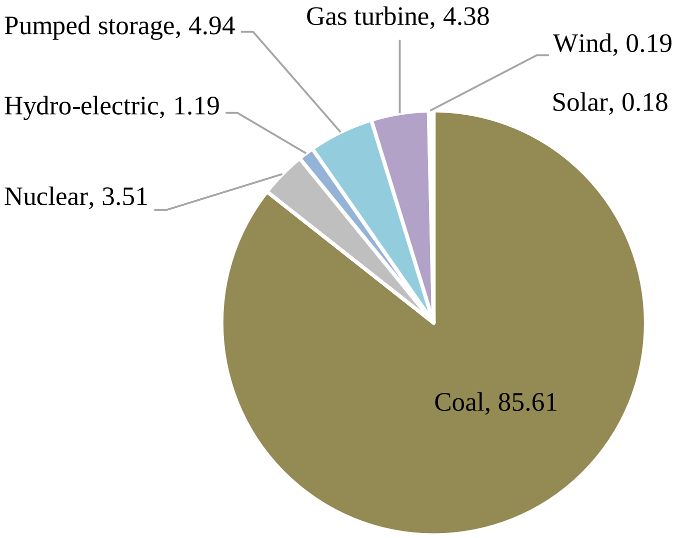

Figure 1-1: Eskom generation breakdown by percentage [5] [3]

In total, Eskom has 15 CFPS, however, only two new stations have been built in the last 10 years with an average fleet age of 40 years [6] [4]. The U.S. and EU28 countries are experiencing similar trends with the average age of their CFPSs at 39.6 and 32.8 years, respectively [7]. Emphasis was thus placed on the two new power stations (with a combined capacity of 9 564 MW, that can provide up to 30 % of the national baseload) to be completed on time and within budget [5]. These stations are, however, yet to be completed and operate at full load. The slow completion

[3] Calculated from Eskom generation map "*www.eskom.co.za/Whatweredoing/ElectricityGeneration/PowerStations/Documents/EskomGenerationDivMapREV81.pdf*"

[4] Age calculated from Eskom heritage website "*www.eskom.co.za/sites/heritage*"

of the new generating units forces Eskom to rely more on older units and subsequently increases maintenance costs [8] [5].

Figure 1-2 indicates the Energy Availability Factor (EAF) of Eskom from 2007 to 2018, which decreased from an acceptable 88 % [9] to the lowest point of 71 % in 2016. EAF indicates the availability of energy to the country at any one time. For example, if the country's generation capacity is 50 GW, with an EAF of 80 %, only an average of 40 GW is available for distribution. EAF is therefore a measure of the fleets' performance concerning maintenance and the effectiveness of the maintenance conducted [10]. Typically, the higher the EAF, the less unplanned outages and maintenance shutdowns are experienced in a year [11].

It can also be seen from *Figure 1-2* that the decrease in EAF is not due to an increase in demand or power sent out since there is a steady decrease in the total power sent out from CFPSs from 2007 to 2018. It peaks at 223 TWh in 2008 and reaches an absolute minimum of 200 TWh in 2016. *Figure 1-2* does, however, indicate reduced output due to reduced availability as the EAF as well as power sent out graphs follow similar trends.

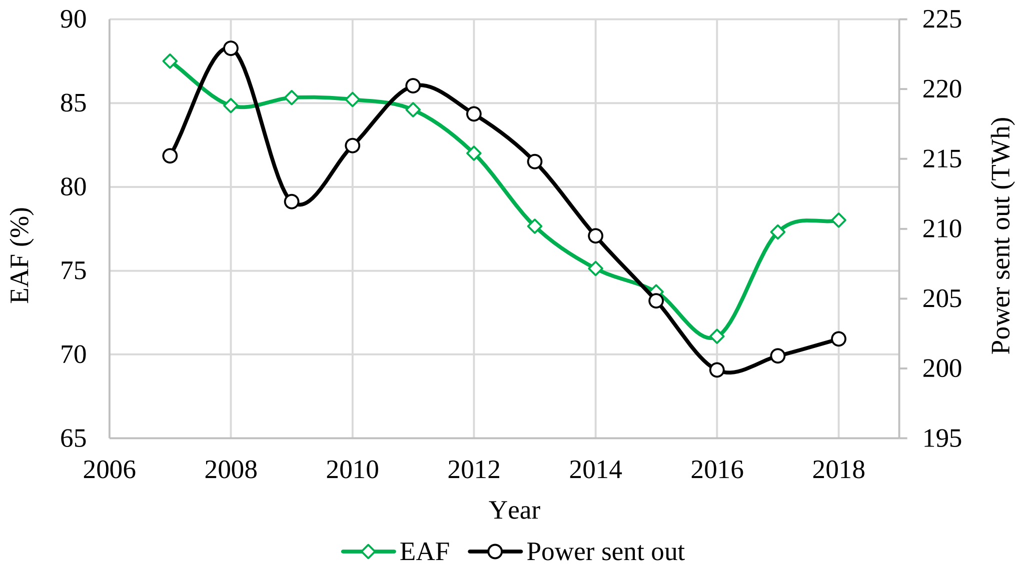

Figure 1-2: Eskom availability and primary energy trend

During the same period, when station availability decreased, electricity prices increased, as shown in *Figure 1-3*. The energy selling price increased from 16.05 c/kWh in 2004 to 85.06 c/kWh in 2018 and a subsequent increase in revenue is thus seen in *Figure 1-4*.

[5] Determined from investigating Eskom Integrated Reports 2015 – 2018 "*www.eskom.co.za/OurCompany/Investors/IntegratedReports/Pages/Annual_Statements.aspx*"

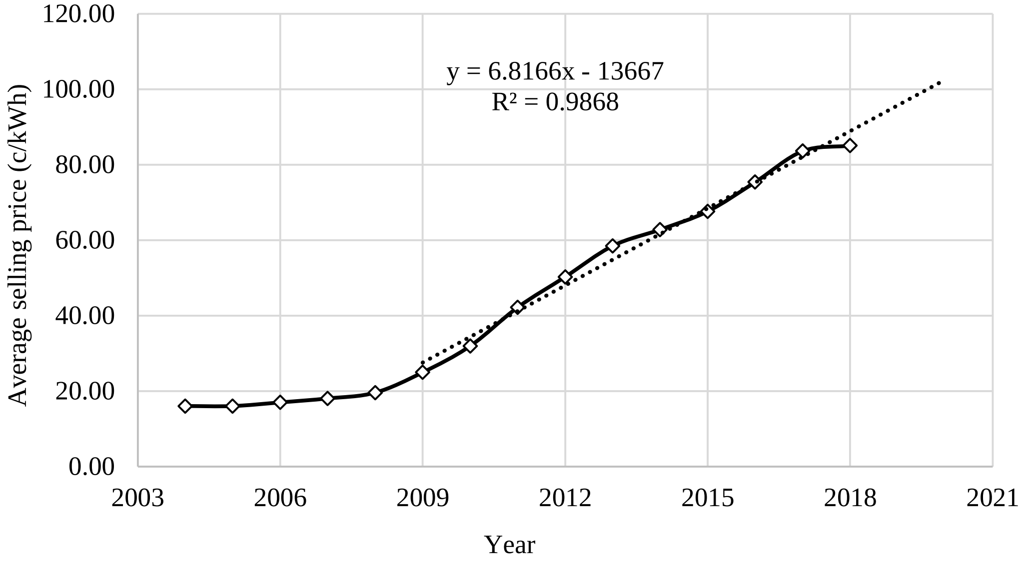

Figure 1-3: Eskom cost to generate electricity trend

Revenue was estimated using published Eskom selling prices and total GWh's sold to customers. Coal cost was estimated using coal prices [7] and a global efficiency for all Eskom CFPSs of 30 %.

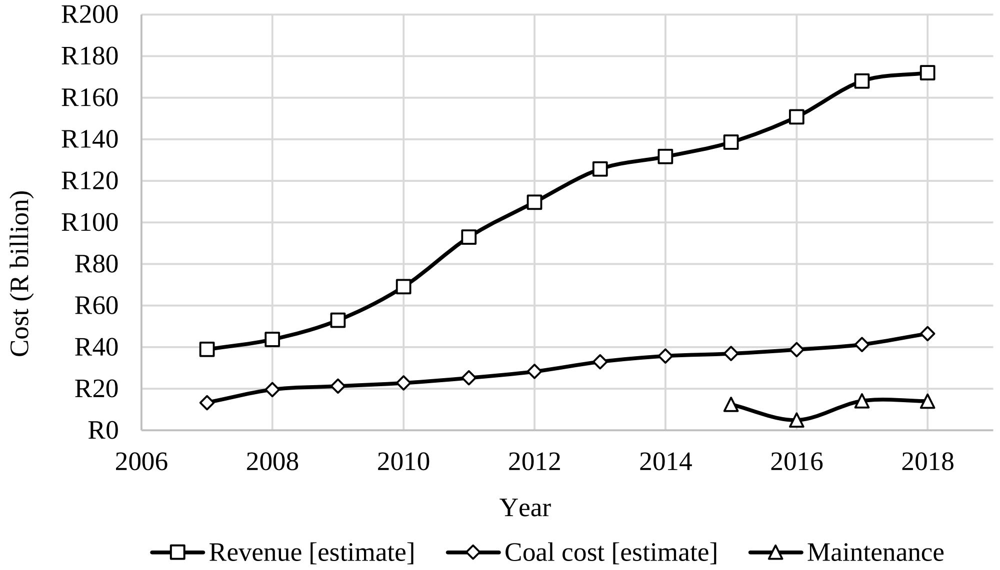

Figure 1-4: Eskom revenue, coal cost and maintenance trend [12] [6] [7]

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[6] Eskom Integrated Report 2015-2018 "*www.eskom.co.za/OurCompany/Investors/IntegratedReports/Pages/Annual_Statements.aspx*"

[7] Eskom Historical average prices and increase "*www.eskom.co.za/CustomerCare/TariffsAndCharges/Documents/Historical average prices and increase_v20160707.xlsx.*"

The baseload operations are under pressure since maintenance of the ageing fleet has become a major issue for Eskom due to the increasing cost of maintenance. However, this expenditure is seen to be plateauing (*Figure 1-4*)[8]. Within this background, time-based prescriptive maintenance is no longer an option due to the age of components on the station. Therefore, Eskom has moved away from time-based maintenance operations to predictive maintenance techniques[9]. These predictive maintenance techniques investigate the health and risk of each component on the station and determine which components need to undergo maintenance at prescribed limits or performance [13], [14].

However, in order to implement predictive maintenance techniques, station personnel must have access to good quality data for decision making [15]. Sadly, these high-quality data sources are not readily available on older power stations, especially to continually and cost-effectively assess operations. This poor data quality can contribute to lower station availability that negatively impacts power generation in South Africa.

1.2.2. Basic CFPS operation

To further understand the problem, it is important to discuss the basic workings of a coal fired power station. In its simplest form, a power station can be described as turning heat energy into kinetic energy and finally into electrical energy. Power utilities then distribute the electrical energy to users over the entire country [16] at an overall cycle efficiency of 30-36 % [17].

A CFPS can be broken up into five fundamental thermodynamic components further discussed in APPENDIX A: Basic CFPS components:

- Boiler
- Turbines
- Cooling circuit
- Feedwater heaters
- Pumps

Several other components form part of the station. However, the focus of the study is on the fundamental thermodynamic process. These other components do not have a significant effect on the efficiency and generation of the station.

[8] Eskom Integrated Report 2016 "*www.eskom.co.za/OurCompany/Investors/IntegratedReports/Pages/Annual_Statements.aspx*"
[9] Eskom Integrated Report 2015 "*www.eskom.co.za/OurCompany/Investors/IntegratedReports/Pages/Annual_Statements.aspx*"

Condenser and cooling circuit

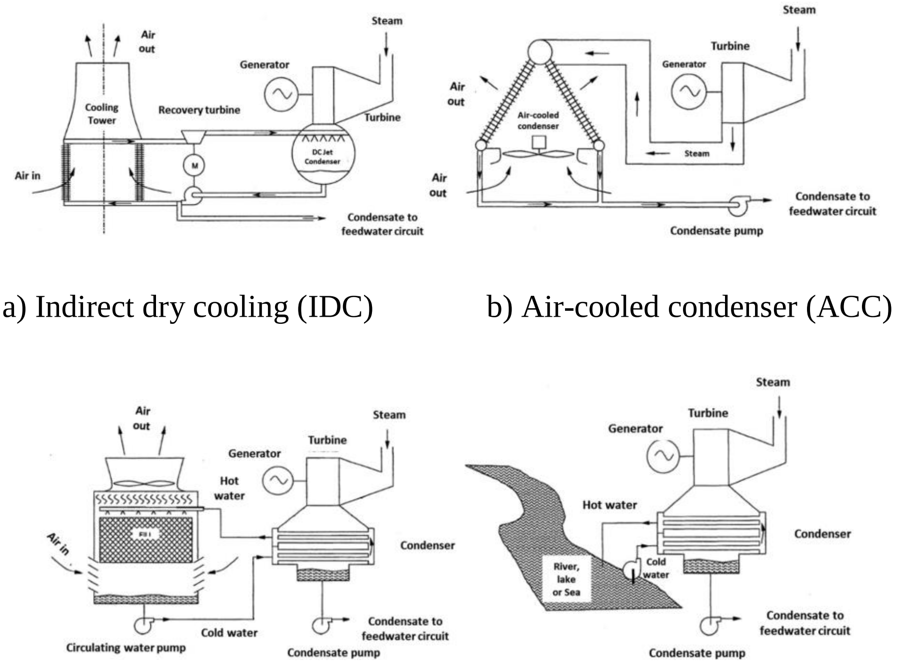
The focus of the study is mainly on the condenser and cooling circuit. This section describes the operation of the condenser and its cooling circuit.

The condenser's purpose is to return low-pressure steam from the Low Pressure (LP) turbine exhaust into condensate or liquid so that the condensate can be pumped up to a higher pressure and returned to the cycle.

The condenser ejects a large portion (60.86 %) of the energy in the system, produced from combustion, to the atmosphere. It is, therefore, a critical part of the cycle [18]. The efficiency and effectiveness of the condenser, therefore, have a large effect on the cycle's maximum generation and efficiency.

The cooling occurs through a shell-and-tube heat exchanger where steam is on the shell-side and cooling water on the tube-side. As the steam travels through the condenser, it cools along the saturation line until condensate occurs. The heat removed from the steam is absorbed by the cooling water (CW). Large cooling towers supply the cooling water which ejects the heat contained in the CW to atmosphere via sprays.

Some typical layouts of cooling circuits are shown in *Figure 1-5*. However, the most popular in South Africa is wet cooling in areas where excess water is available and dry-cooling for drier regions. Dry-cooling has the advantage of keeping water in a closed-loop and thus reducing water usage. However, natural convection is not an option, and therefore large fans must be installed, reducing station efficiency slightly and increasing maintenance costs.



a) Indirect dry cooling (IDC) b) Air-cooled condenser (ACC)

c) Wet cooling tower (WCC) d) Once through cooling (OTC)

Figure 1-5: Different types of condensers [19]

Condensers operate at different conditions depending on the power station; typically, condensers operate in the region shown in *Table 1-1* [19], [20], [21].

Table 1-1: Typical condenser design conditions

Type	**Upper**	**Lower**
Steam	25 – 46 ℃	Typically, 2 ℃ less than the inlet
Cooling water	18 – 25 ℃	30 - 40 ℃
Efficiency	10 kPa	4 kPa

Full cycle

The combination of the critical components results in a closed steam cycle that generates electricity from the combustion of bituminous coal [17]. There are more efficient cycles that use combined cycles, low-pressure systems and heat recovery systems. However, for this study, only the conventional configuration will be considered as all of Eskom’s power stations follow a standard Rankine cycle[10]. *Figure 1-6* shows a functioning power station with all the key components and placement.

[10] Eskom heritage website “*www.eskom.co.za/sites/heritage*”

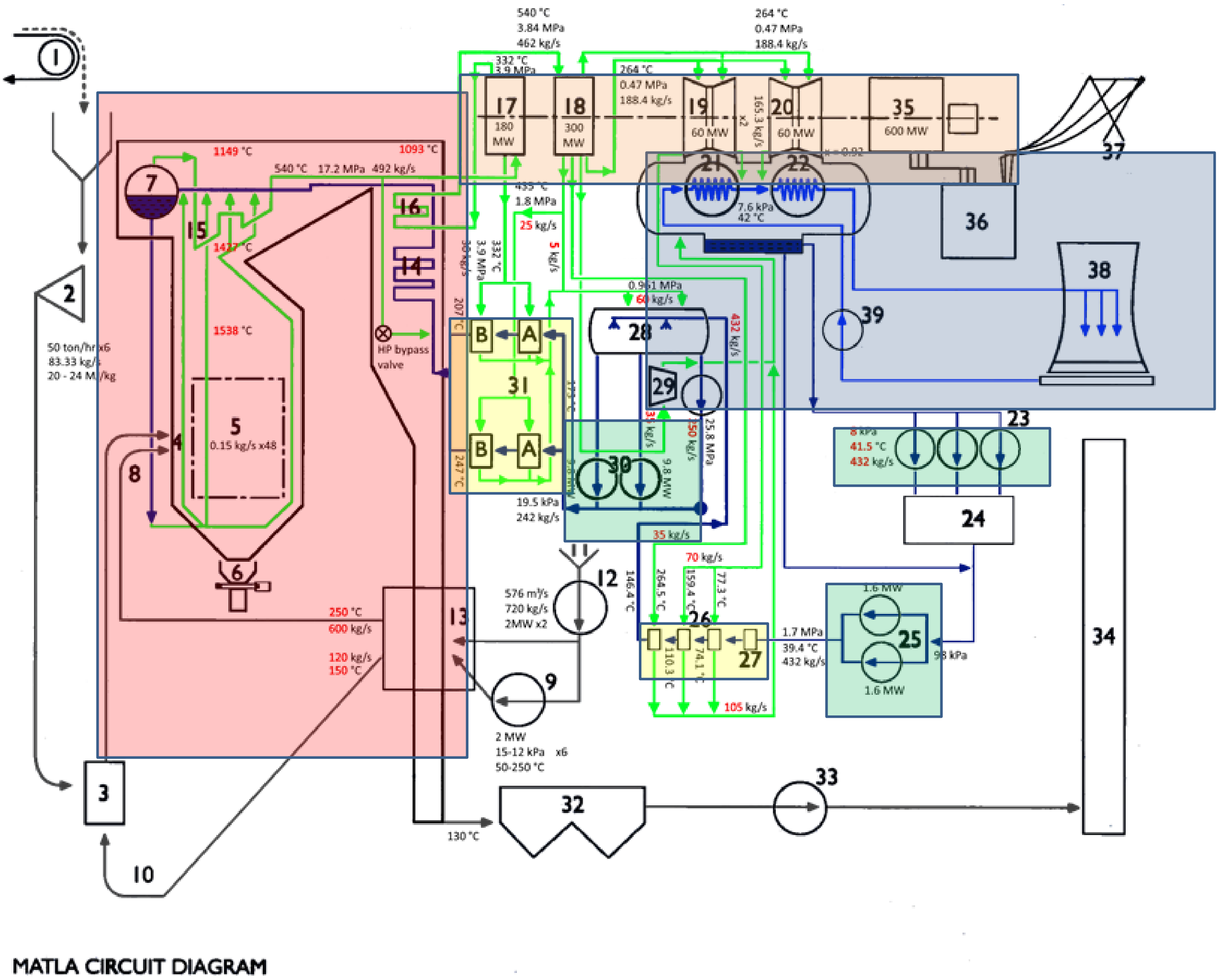


Figure 1-6: Typical coal fired power station layout and cycle [11]

1.2.3. Component-based sensitivity

The essential operation discussed in the previous section show the integrated workings of a CFPS. Each component thus affects the overall efficiency and maximum generation of the entire station. *Table 1-2* summarises the effect of the significant components.

[11] Eskom heritage website "*http://www.eskom.co.za/sites/heritage/Pages/MATLAPOWERSTATION.aspx*"

Table 1-2: Summary of sensitivity of each significant component [17]

Item	Equipment	Exergy in (MW)	Exergy out (MW)	Exergy destruction (MW)	Exergy efficiency	Exergy loss
1	Boiler	1009.59	578.81	430.78	57.33 %	91.76 %
2	HP turbine [12]	318.34	312.91	5.43	98.29 %	1.16 %
3	IP turbine [13]	260.47	256.46	4.01	98.46 %	0.85 %
4	LP turbine [14]	145.76	141.35	4.41	96.97 %	0.94 %
5	Condenser	34.72	19.82	14.9	57.09 %	3.17 %
6	Condensate pump	2.19	1.43	0.76	65.30 %	0.16 %
7	GSC [15]	1.5	1.47	0.03	98.00 %	0.01 %
8	DC [16]	1.84	1.76	0.08	95.65 %	0.02 %
9	LP FWH1 [17]	4.12	3.55	0.57	86.17 %	0.12 %
10	LP FWH2	7.33	6.71	0.62	91.54 %	0.13 %
11	LP FWH 3	10.39	9.97	0.42	95.96 %	0.09 %
12	DEA [18]	22.73	21.1	1.63	92.83 %	0.35 %
13	BFP [19]	27.94	25.54	2.4	91.41 %	0.51 %
14	HP FWH5 [20]	47.29	45.24	2.05	95.67 %	0.44 %
15	HP FWH6	66.03	64.66	1.37	97.93 %	0.29 %
	Total cycle			**469.46**		**100.00 %**

It is essential to note the ranking of the items. The boiler has the most considerable direct effect on efficiency due to the 91.76 % of exergy loss. The condenser has the most considerable effect on maximum generation due to its heat rejection to the atmosphere. The condenser is the least efficient in terms of exergy conservation with a 57.09 % exergy efficiency. The next is the boiler which operates at 57.33 % exergy efficiency [17].

Typically, the focus of station performance improvement is placed on the boiler and turbines since they have the most immediate effect on the station's performance [17]. Condenser

[12] High Pressure turbine

[13] Intermediate Pressure turbine

[14] Low Pressure turbine

[15] Gland Steam Cooler

[16] Drain cooler

[17] Low Pressure Feedwater Heater

[18] Deaerator

[19] Boiler Feed Pump

[20] High Pressure Feedwater Heater

maintenance is often neglected since its effect is not immediately visible (slow degradation) [22]. However, it still has a significant influence on station performance.

Table 1-2, however, shows the importance of condenser maintenance, due to its low exergy efficiency (57.09 %), which is the focus of this study. In the next section, a critical review of existing condenser-related research is conducted to determine the need for this study.

1.3. Condensers in CFPS operations

1.3.1. State of the art

Table 1-3 summarises the state of art for station performance and maintenance techniques. Each study was investigated according to six key criteria:

1. **Simulated**: Did the study simulate the station or condenser using simulation software? This is needed due to the simulation-based approach of the study.
2. **Integrated**: Did the study simulate the entire integrated CFPS? This is needed because this dissertation focused on the entire integrated effect of individual station components.
3. **Verified**: Did the study verify the simulation with station data? This is important because verification confirms an accurate simulation model.
4. **Station performance**: Did the study discuss station performance improvements or degradation? This is important because the focus is on the entire station performance and not on individual components.
5. **Maintenance model**: Did the study develop a maintenance model? This is important because it is the solution to the problem.
6. **Cost implication**: Did the study determine the cost implication of station performance? This is important because cost avoidance and cost implications is extremely important to industry.

Table 1-3: State of the art for condenser maintenance and station simulation [21]

ARTICLE	SIMULATED	INTEGRATED	VERIFIED	STATION PERFORMANCE	MAINTENANCE MODEL	COST IMPLICATION	COMMENTS
[13]	[pink]	[green]	[pink]	[pink]	[green]	[green]	- Condition base maintenance model
[18]	[pink]	[green]	[pink]	[green]	[pink]	[green]	- Station efficiency improvement with condenser performance
[23]	[pink]	[green]	[pink]	[pink]	[green]	[green]	- Developed maintenance scheduling model
[24]	[pink]	[green]	[pink]	[pink]	[green]	[green]	- Detects critical components for maintenance
[25]	[pink]	[green]	[pink]	[green]	[pink]	[green]	- Effect of condenser performance
[26]	[green]	[green]	[green]	[green]	[pink]	[pink]	- Simulation for online fouling monitoring
[27]	[pink]	[green]	[pink]	[green]	[green]	[green]	- Masters on Grootvlei condenser backpressure effect
[28]	[green]	[green]	[pink]	[pink]	[green]	[green]	- Condenser fouling monitoring and maintenance model
[29]	[green]	[pink]	[green]	[pink]	[green]	[green]	- Specifically investigated steam piping
[30]	[pink]	[pink]	[green]	[green]	[green]	[green]	- Focus on coal mills
[31]	[pink]	[pink]	[pink]	[green]	[green]	[pink]	- Combined cycle reliability and modelling

The state of art provides an overview of the available solutions. *Table 1-3* shows shortcomings in all the studies since they fail to satisfy all six criteria. Studies [13, 19-22] address only three of the six issues while references [23] and [24] still need to address two issues. The reason for this lack in the prior studies might be focus on individual components and lack of available data for verification. Therefore, a need exists to develop a fully integrated simulation model that allows maintenance plan development and maximises station profitability by also investigating the cost implications.

The next chapters discuss the state of the art in further detail by separating the table into three sections:

1. Condenser maintenance
2. Current condenser maintenance procedures
3. Current CFPS simulation software

21	**Legend**
[green]	Study considered criteria
[pink]	Study did not consider criteria

1.3.2. Condenser maintenance

Condenser design is such that the cooling water is an open cycle using non-ideal cooling water in terms of impurities and chemical composition. Therefore, condensers tend to foul on the cooling water side inside the tubes due to scaling, impurities, biomass and sludge [32]. See APPENDIX B: Condenser fouling for more detail.

The effects of fouling can occur at different rates depending on cooling water quality. In a station with untreated cooling water, significant fouling can occur in a period of 4 – 6 months [27]. At this point, the station equipment limitations cannot keep up with the reduction in performance of the condenser to maintain generation targets. As a result, there is a reduction in efficiency as the station does not operate at design conditions [18].

Several studies have investigated the effect of condenser maintenance on the performance and efficiency of a power station [18], [22], [25], [27], [33]. *Table 1-4* shows detailed findings. The main findings were the following:

- Condenser fouling can result in a maximum energy loss of 60.86 % to the environment.
- Inefficiencies as a result of condenser fouling can cost in the range of 0.4 - 2.2 million (USD 2009) per station per unit.
- Condenser backpressure can be responsible for up to 17 % of the total efficiency losses.
- The condenser backpressure loss can contribute more than 2 % to the thermal efficiency loss of the power station.
- The cost-benefit analysis indicated that the total cost associated with cleaning the condenser would be made up within six months.
- Old fouled tubes can result in a 4.1 % power drop after one year of operation, while new tubes maintained reasonable heat transfer coefficient for up to six months. A 1.5 % power drop after one year of operation for new tubes were seen.
- Thermal efficiency can be increased from 38.83 % to 39.45 % by reducing the condenser pressure to 65.21 mbar (6.521 kPa). This can save approximately 2.54 lakh rupees per day (R54 000 [22] – 2019) per 600 MW unit.

A new conditioned condenser increases efficiency and improves generation. The cost benefits result in a short payback period and improved performance for the remainder of the maintenance cycle [33]. However, the downtime required to conduct condenser maintenance is the most

[22] Converted on 2019/11/13

significant limiting factor[23]. Pressure from management to minimise downtime can result in improvement opportunities being overlooked. Effective condenser maintenance procedures are, however, an essential part of station operation.

Table 1-4: Summary of condenser performance studies

Study	**Title**	**Findings**
[22]	The Influence of Fouling Build-up in Condenser Tubes on Power Generated by a Condensing Turbine.	Old fouled tubes: 4.1 % power drop after one year of operation. New tubes: Maintained a reasonable heat transfer coefficient for six months. New tubes: 1.5 % power drop after one year of operation.
[25]	Experimental study on performance of a steam condenser in 600 MW Singareni thermal power station.	600 MW power station in India. Reduced back-pressure of the condenser and investigated the economic savings. Thermal efficiency increased from 38.83 % to 39.45 % by reducing the condenser pressure to 65.21 mbar (6.521 kPa). Saved approximately 2.54 lakh rupees per day (R53 000 [24]). The trend shows a need for CBM methodologies to improve condenser performance.
[18]	Improvement Power Station Efficiency with Condenser Pressure.	Condenser resulted in a maximum energy loss of 60.86 % to the environment. 86.271 % exergy loss in the boiler 13.22 % exergy loss in the condenser Thermal efficiency: 38.39 % Exergy efficiency: 45.85 %
[27]	The effect of condenser backpressure on station thermal efficiency: Grootvlei Power Station as a case study.	Condenser backpressure was responsible for approximately 17 % of the total efficiency losses. The condenser backpressure loss was contributing more than 2 % to the thermal efficiency loss. The cost-benefit analysis indicated that the cost of cleaning the condenser on Unit 3 would be made up within six months.
[33]	Economic impact of condenser fouling in existing thermoelectric power stations.	Analysed 550 MW coal fired power station. Fouling costs are in the range of 0.4-2.2 million (USD 2009). Including the cost of revenue losses due to fouling and condenser maintenance determines the optimal number of cleanings per year.

[23] Personal communication with station personnel.

[24] Converted on 2019/11/13

1.3.3. Current condenser maintenance procedures

There are two main methods of maintenance, namely; corrective and preventative maintenance. Several techniques fall under each method as can be seen in *Figure 1-7*. Corrective maintenance has been the driving method in the past; however, with technology improvements and the adoption of industry 4.0, preventive maintenance has become the newly preferred method.

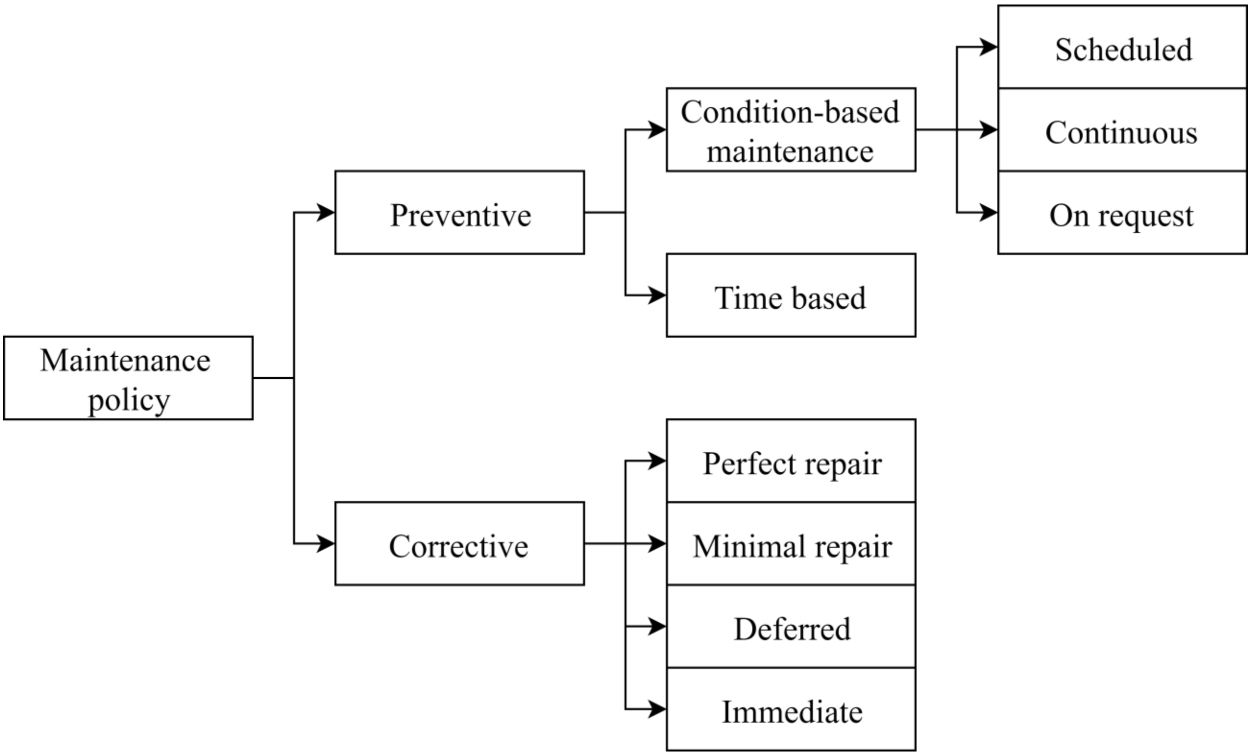


Figure 1-7: Overview of different maintenance techniques

The simplest form of preventative maintenance is time-based maintenance, where the Original Equipment Manufacturer (OEM) provides maintenance schedules to prevent equipment breakdowns [13]. The schedules are typically calculated using life of component testing which provides a component failure rate over time. The most common failure rate is the bathtub curve seen in *Figure 1-8* [34].

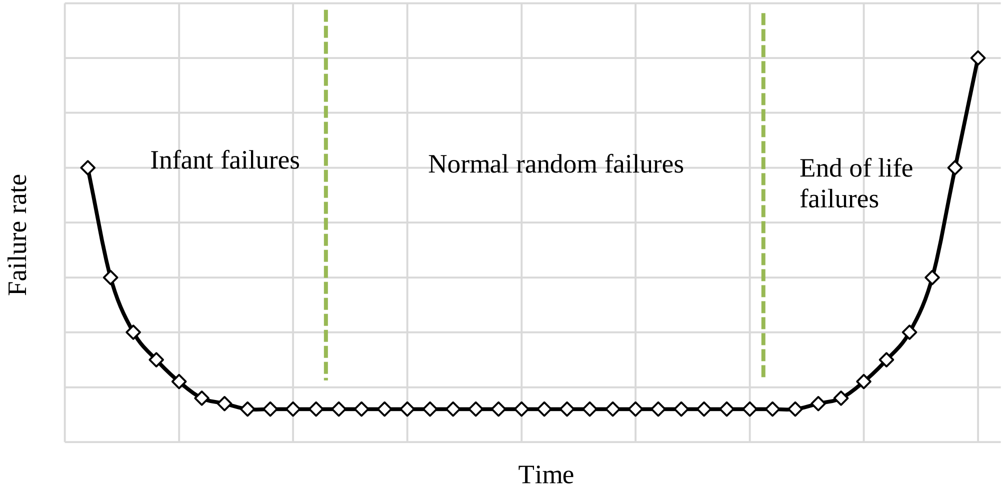


Figure 1-8: Component failure rate (bathtub curve)

Figure 1-8 indicates a high early failure rate of installed or maintained items which is known as infant failures. These failures typically result from poor installation, design defects and manufacturer defects [35]. The failure rate then stabilises at a constant failure rate and only increases exponentially as the end of life of the component is reached [36]. This failure rate analysis is known as the Weibull analysis. The Weibull curve is beneficial since it can be fitted to the data to provide an estimate of the failure rate without additional extensive component testing [37].

The limitations with Weibull-analysis is that equipment might be replaced or repaired prematurely resulting in unnecessary costs. Therefore, modern industries are moving towards condition-based maintenance (CBM).

CBM techniques have performance, and economic benefits since components are replaced or maintained only when necessary or have reached a set performance limit.

For this Dissertation, a comprehensive study was conducted to better understand the use of CBM techniques in industry. Detailed findings are shown in APPENDIX C: Maintenance study summaries. The main findings were the following:

- 920 MW CFPS, only generating 400 MW due to poor maintenance
    - Low vacuum pressure of the condenser due to dirty/plugged tubes, air ingress and tube leaks was found to be a contributing factor to low efficiency
- Condition monitoring improved generation losses by up to 84 %
- Focus was on condition-based maintenance and reliability centred maintenance

- Developed an integrated cost model regarding condenser degradation
- Used cost model and found optimised maintenance schedule of bi-annual maintenance (four months separation)
- Found probability of failure in a 50-year service life for steam pipes
- The best net profit value (NPV) for steam pipe replacement was found to be approximately 40-years

From the studies, it is clear that station, specifically condenser maintenance, has a large effect on the overall station performance with knock-on effects. The condenser is not a localised component and therefore requires an integrated approach to maintain a station cost-effectively. A key challenge is thus to collect and analyse large amounts of data-based observations to support the CBM techniques [15], [30]. This challenge is, however, hampered by a lack of data availability and becomes exacerbated on older facilities.

Fortunately, the engineering and maintenance environment has access to useful tools such as full station simulation software to assist in designing an effective maintenance plan. These tools' usefulness increases when access to verified data is limited. Hence, this study's purpose is to evaluate how new simulation-based approaches can be used to support CBM requirements and techniques.

1.3.4. Current CFPS simulation software

Simulation software has become an intricate part of the engineering environment including in the operational arena. The benefits of simulation software are listed below: [38], [39]

1. Understand the problem

A good understanding of the problem or process is required to simulate it. Modelling and simulation therefore develop an in-depth understanding.

2. Multiple solutions

Multiple solutions can be tested for the best outcome without the need for expensive "real-life" tests.

3. What-if scenarios

Several questions can be asked and simulated regarding station operations. Without simulation it would require real-time station changes and accompanying risks.

Simulation software also helps with decision making, process predictions, scenario investigations and optimising of operations. In this literature study, several power station simulation packages are investigated and compared with specific emphasis on packages available to Eskom.

Six functional evaluation questions were asked to investigate and compare the available power station simulation software. The questions are the following:

1. **Training:** Is the software used to train personnel? This determines if the software is training focussed and not operational focussed.
2. **Digital twin:** Does the software provide an accurate digital copy of the actual process? This indicates if the software is used to copy an existing system and not necessarily to improve any aspect of it.
3. **Scenario investigation:** Does the software provide the functionality to simulate possible scenarios? This indicates if the software operational orientated and allows multiple solutions and scenarios for a specific problem.
4. **Optimisation:** Can the software help to improve efficiency of the process? This indicates if the software is operational orientated assisting in improving systems.
5. **Real-time monitoring:** Does the software provide a platform for real-time systems monitoring? This indicates if the program is supervisory control and data acquisition (SCADA) orientated.
6. **Dynamic analysis:** Can the software perform a dynamic evaluation of the simulation? Power Stations operate at varying conditions and dynamic analysis improves the possibilities of the software.

Several simulation packages were evaluated based on the above criteria. *Table 1-5* summarises the results.

Table 1-5: Power station simulation software summary

Nr.	Software	Use case					
		Training	Digital twin	Scenario investigation	Optimisation	Real-time monitoring	Dynamic analysis
1.	FlowNex[25]		✓	✓	✓		✓
2.	Thermoflex[26]		✓	✓	✓		✓
3.	Ovation[27]	✓	✓	✓	✓		
4.	SimSci[28]	✓	✓	✓	✓	✓	
5.	SimExec[29]	✓	✓	✓	✓		✓
6.	EES[30]			✓			
7.	Excel (IF97)[31]			✓			
8.	IPSEpro[32]		✓	✓	✓		
9.	3KEYMASTER[33]	✓	✓	✓	✓	✓	
10.	PREDIX[34]	✓	✓	✓	✓	✓	
11.	ETAPRO[35]		✓	✓	✓	✓	
12.	PTB[36]	✓	✓	✓	✓	✓	✓

The list of software packages mentioned in *Table 1-5* was narrowed down by their ability to simulate the station and provide scenario investigation.

Though all the software packages in *Table 1-5* are capable of providing reliable and accurate simulation data, the in-house software Process Toolbox (PTB) comply with all the desired criteria (Acquisition of software licenses was also not required). For this research the station was therefore modelled using the PTB software package.

The software is a semi-empirical thermohydraulic model which requires prior knowledge of the system's parameters and significant data or specifications of the station. However, after

[25] https://www.flownex.com/about-us/about-flownex

[26] https://www.thermoflow.com/combinedcycle_TFX.html

[27] http://www.emerson.com/en-us/automation/control-and-safety-systems/distributed-control-systems-dcs/ovation-distributed-control-system/power-station-simulator

[28] https://sw.aveva.com/engineer-procure-construct

[29] https://www.gses.com/simulation-technology/#THERMAL-jade

[30] http://www.fchart.com/ees/

[31] http://www.fluidika.com/home/ws_excel

[32] http://www.ipsepro.com/CMS/index.php/ipsepro/model-libraries/advanced-power-station-library

[33] https://www.ws-corp.com/default.asp?PageID=66&PageNavigation=Simulation-Platform

[34] https://www.ge.com/digital/predix-platform-foundation-digital-industrial-applications

[35] https://www.gpstrategies.com/solution/performance-condition-monitoring-etapro/

[36] PTB: See journal article "*A simulation-based prediction model for coal-fired power station condenser maintenance*"

modelling the station accurately, detailed scenarios and investigations have a quick turnaround time [38].

The software was used to develop a predictive condenser maintenance model. It is based on simulations which were used to show the effect of changing station performance conditions due to condenser fouling.

1.4. Problem statement and objectives

South African coal fired power stations are in a unique environment with unique challenges which include but are not limited to: increased maintenance requirements due to station age as well as reduced funds. The unique challenges, therefore, require unique solutions. Station performance can, however, be maintained or increased through efficient maintenance techniques. These techniques should also allow the utility to utilise the available funds in the most effective way possible.

The aim of this study is to develop a simulation-based maintenance model to improve the effectiveness of condenser maintenance and minimise station downtime. This can be broken down into the following specific objectives:

- Develop and verify an integrated simulation-based model
- Utilise a semi-empirical approach to calibrate the model for a specific ageing power station
- Develop a predictive condenser maintenance model based on the simulation
- Test the results
- Evaluate the usefulness of the developed simulation-based approach for future work

The findings from this study will provide insight into the use of simulation-based approaches for actively operating power stations. It will also provide an understanding of how semi-empirical models can be used to represent actual station conditions where the station is not operating at the expected design specifications. Recommendations for further applications on CFPS and other steam-related processes will also be discussed based on the findings.

1.5. Conclusion

In this chapter the background to and objectives of the study were discussed. It was found that South Africa has a reliance on CFPSs and that the current condition of Eskom's fleet is alarmingly old. The importance of maintenance on South Africa's ageing fleet was also discussed and maintenance techniques were investigated.

Based on the identified problems in the maintenance of Eskom's fleet a proposed solution was identified. The solution will be beneficial to the South African power generation community since it provides improved effectiveness of maintenance which is a continuous issue for Eskom.

1.6. Outline of document

Chapter 1: Introduction – The reasons for this study were given in this chapter. The present South African power generation scenario is reviewed to develop the study's problem statement. The main objective of the study to test how a simulation-based approach can be used to improve an actively operating power station. Condition-based maintenance of condensers was identified as a relevant area to implement this test.

Chapter 2: Development of model – This chapter describes the process followed for a generic solution to cost-effective condenser maintenance. The output from this chapter is a simulation model (integrated, calibrated and verified) and a condenser maintenance prediction model.

Chapter 3: Model application and results (Case Study) – Chapter 3 applies the developed model to a real-life CFPS case study (60 MW generating unit). Extrapolating the method to all Eskom power stations provides insight into the effect of condenser maintenance on a national scale.

Chapter 4: Conclusions and recommendations – Conclusions and recommendations are given in the last chapter.

Chapter 2: Development of model

Natural Convection Cooling Tower

The methodology to achieve the following are discussed: develop and test a simulation-based maintenance model to improve condenser efficiency with minimum downtime of a CFPS.

2. Development of model

2.1. Preamble

Chapter 2 describes the process followed to develop a solution to the problem defined in Chapter 1. *Figure 2-1* gives a high-level overview of the process. This chapter's focus is on a generic power station maintenance prediction model. Chapter 3 applies the model to a real-world case study.

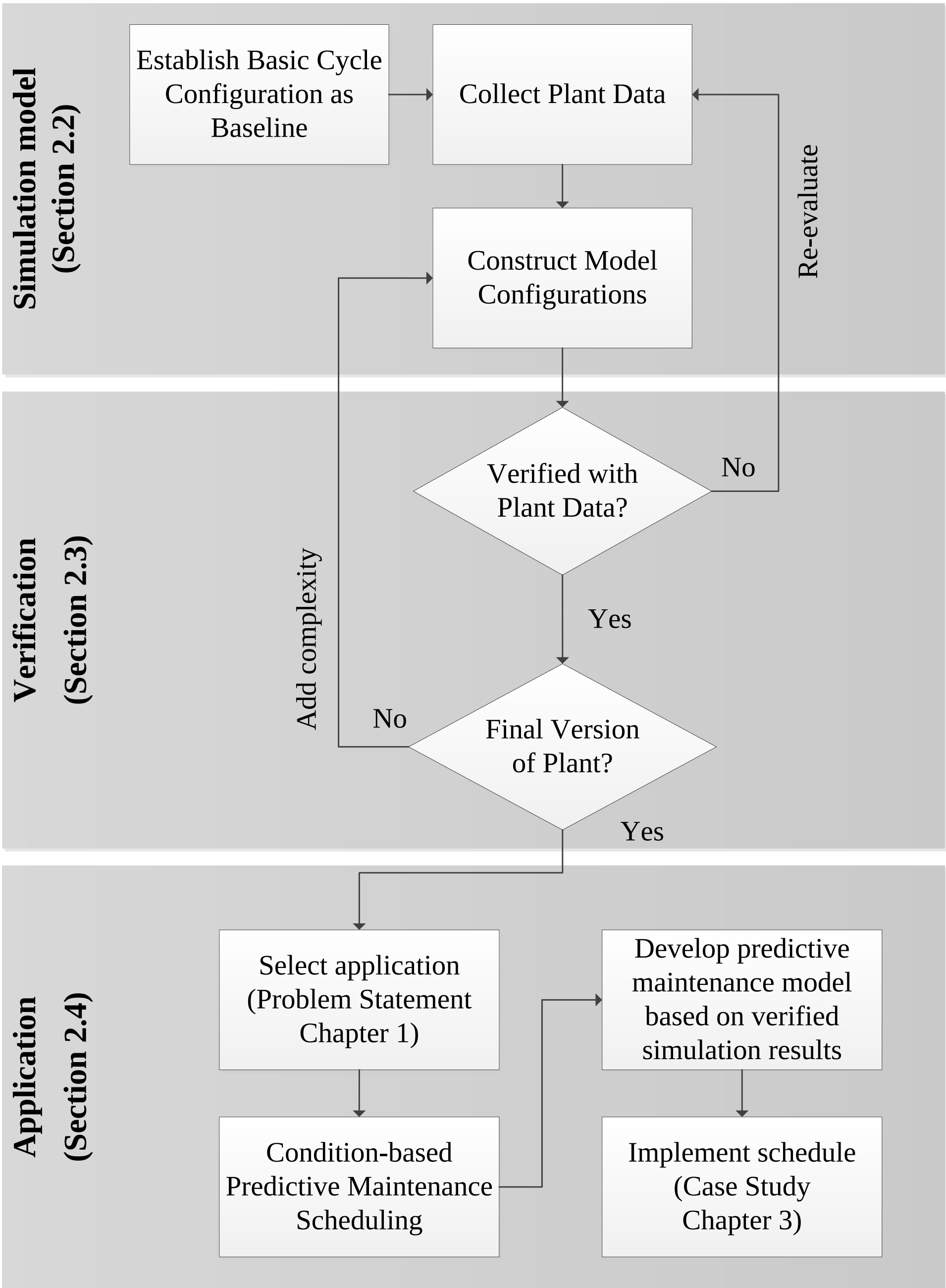


Figure 2-1: Flow diagram describing the method

The basic steps described in *Figure 2-1* include:

1. **Simulation model:** The model is constructed to follow the power station layout. The basic power cycle is first built and verified according to actual station data. Once the basic cycle is verified, more complexity is added in a recurring cycle until the simulation represents the required level of detail and accuracy. Finally, the detailed model is verified according to actual station data.
2. **Verification:** Verification occurs concurrently with the construction of the model. The final model is then an accurate digital version of the real power station.
3. **Predictive maintenance model:** A verified simulation model can be used for different applications. The specific application with this research is to develop a predictive maintenance model for the condenser section of a power station.

The basic steps are expanded to a ten-step process:

Simulation model and verification

1. Obtain data for a specific unit
2. Model the specific unit (using chosen simulation software)
3. Calibrate unit according to measured data

Predictive maintenance model

4. Introduce component-specific degradation (fouling) in simulation
5. Obtain performance parameters as a function of degradation (fouling)
6. Apply to the prediction model
7. Predict daily station performance and costs
8. Iterate for multiple estimates of days between maintenance schedules
9. Find the best average daily profit
10. Obtain cost breakdown and maintenance schedule

The chapter starts with a description of the simulation software used and provides a detailed breakdown of the simulation model and its construction. All the major components of a CFPS station are modelled. The result is an integrated station simulation model which is used to quantify the effect of individual station components on the performance of the entire station.

The simulation model is verified using original design specifications. The process of verification is done concurrently with the construction of the model.

Theoretical scenarios are discussed and simulated to evaluate the importance and value of an integrated simulation. The simulation highlights the effect of a fouled condenser on station performance and generation. From this, a predictive maintenance model is designed and implemented. The maintenance model uses the integrated simulation as it is the backbone in determining the best time to maintain/clean the condenser.

2.2. Simulation model

The model aims to simulate the entire station and not only the condenser specifically. This has several advantages namely:

- Fully integrated simulation (coal to power)
- Visualise the effect of individual station components on the entire station performance
- Visualise the effect of multiple station components on the entire station performance simultaneously

Since a CFPS is a very complicated system, the full system simulation should allow the user to fully quantify the impact of the proposed maintenance solutions not only on the condensers but on the entire plant. This in turn should allow the simulation to be more accurate to life since the different components would all influence each other in an actual CFPS.

2.2.1. Simulation method

The simulation method forms part of the 10-step process. Steps 1 – 3 describe the method as follows:

1. Obtain data for a specific unit
2. Model the specific unit using simulation software
3. Calibrate the unit according to measured date. The target accuracy is 5 % [37].

A summary of the software packages that could potentially be used is shown in *Table 2-1*.

Table 2-1: Simulation software packages

Nr.	Software
1.	FlowNex
2.	Thermoflex
3.	Ovation
4.	SimSci

Nr.	Software
5.	SimExec
6.	EES
7.	Excel (IF97)
8.	IPSEpro

Nr.	Software
9.	3KEYMASTER
10.	PREDIX
11.	ETAPRO
12.	PTB

[37] 5 % is deemed sufficient as instrumentation and measurement accuracy can deviate by as much as 5 % [39].

For this study Process Toolbox (PTB) was used as the software is available and “ticked” all the boxes. In the next chapters the focus will be on modelling the problem in PTB.

2.2.2. Overview of software components

PTB’s semi-empirical thermohydraulic platform is used to model the power station. The modelling, therefore, requires prior knowledge of the system’s parameters and significant data or specification of the station.

The software is component-based using a drag-and-drop interface. The various components communicate with each other through links or connections. The software allows the user to link upstream and downstream components, as seen in *Figure 2-2*.

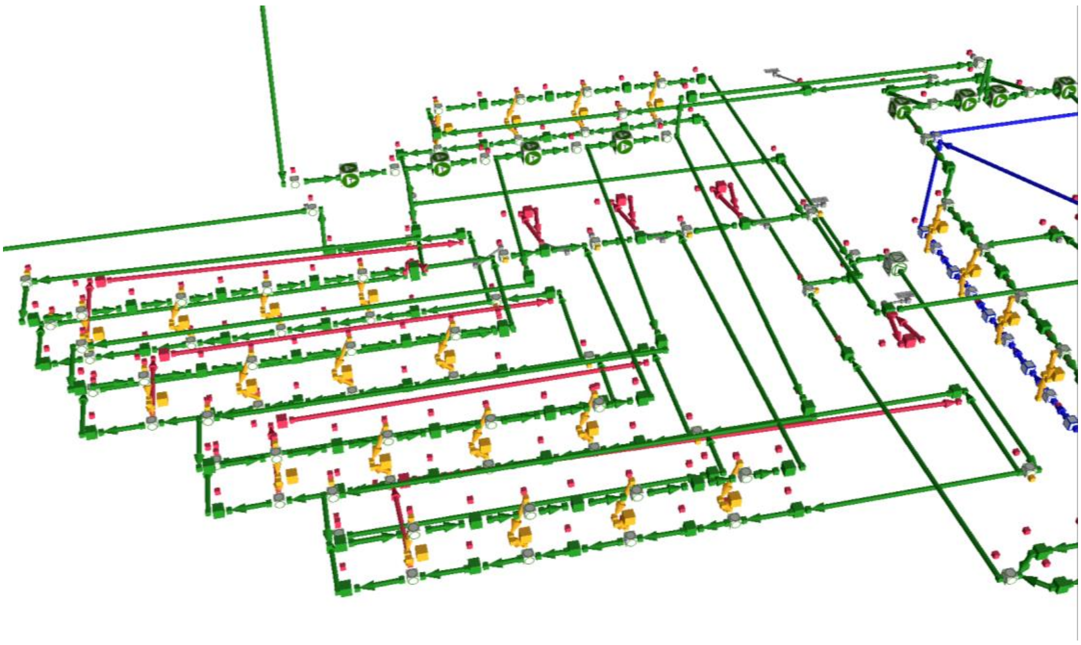


Figure 2-2: PTB interface with component connections

Each component falls under four main categories, namely; water, air, steam, and general components. APPENDIX D: PTB components breakdown shows and describes the critical simulation components used for this study. APPENDIX E: Detailed PTB inputs and outputs shows the typical input and output windows for PTB.

The combination of individual components in APPENDIX D: PTB components breakdown results in specific configurations to represent different CFPS equipment. The process is done sequentially with increasing levels of detail, starting with the basic cycle in the next section.

2.2.3. Basic cycle configuration

The method starts simple and expands on complexity calibrating the simulation as it transforms. The first step is to build the entire power station using a small number of components, keeping it simple and adding complexity later. An example of a simple power station configuration is shown in *Figure 2-3*. The following components represent the entire station:

- boiler = a single node
- turbine train = single turbine
- cooling circuit = pump and cooling tower
- pump train = single pump

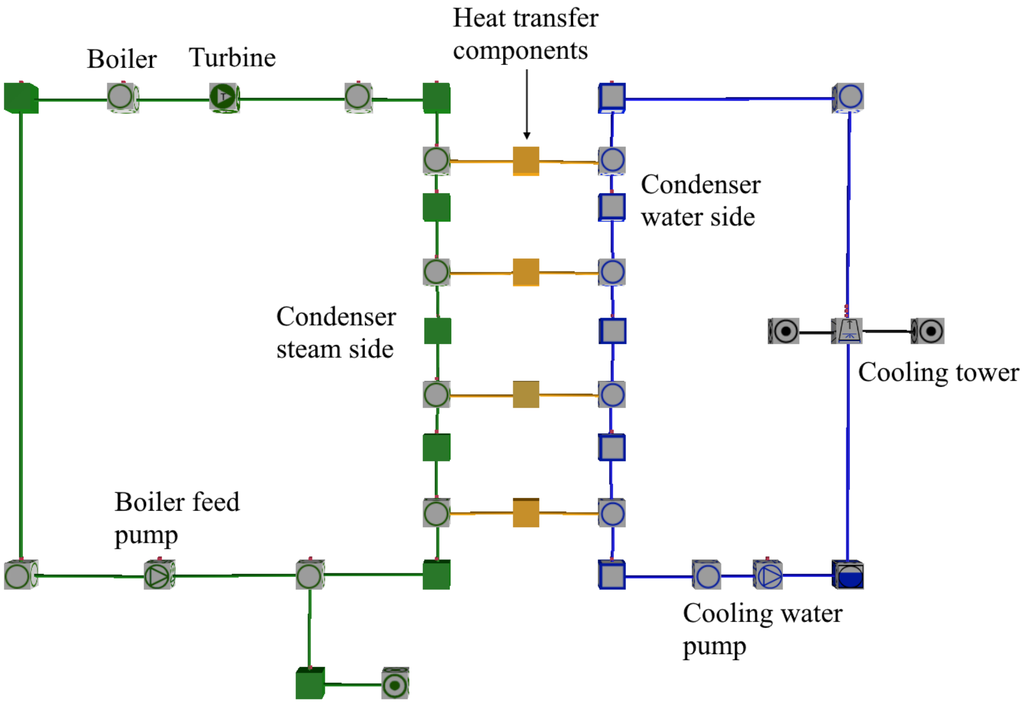


Figure 2-3: Basic steam cycle built in PTB

The simulation model illustrated in *Figure 2-3* is highly simplified and only represents a small power-generating circuit consisting of a single steam/power generation loop (green) and a single cooling loop (blue). However, when this simulation is calibrated to represent actual station data, it provides the correct key boundary conditions. The calibrated simple simulation is the starting point from which the simulation model's level of complexity is increased to provide a more useful and accurate representation of the actual station.

Complexity is increased by developing more detailed configurations of the power station components (i.e. boiler, turbine, condenser and feedwater heaters) and then adding these sequentially to the simulation.

2.2.4. Boiler configuration and calibration

Actual station data provides the overall inlet conditions and outlet conditions of the boiler in terms of flow, temperatures and pressures on both the superheated and reheated steam. Therefore, the objective is to model the entire boiler, add complexity and to maintain the boundary conditions.

The boiler consists of multiple air-to-water, air-to-steam and air-to-air heat exchangers. *Figure 2-4* shows the heat exchangers modelled using an air node, heat transfer component and steam node. The heat transfer component is used to enter the individual heat exchanger specifications.

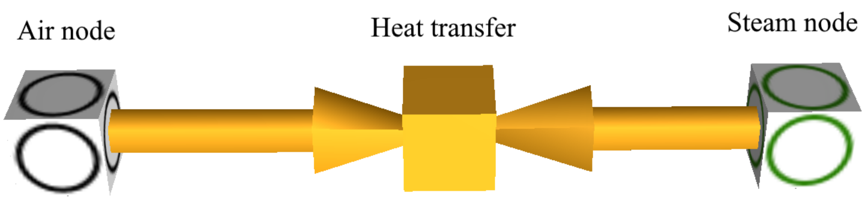


Figure 2-4: Heat exchange using PTB

The boiler construction starts by linking multiple smaller heat exchange chains, representing a fully developed heat exchanger. Multiple heat transfer components are used to provide more stability in the simulation and finer control over heat transfer and steam quality. The effect thereof reduces the change in temperature over each node.

Boilers are uniquely designed and have varying heat exchanger layouts. Actual boiler schematics are useful in indicating specific locations and flows of the heat exchangers within the boiler. *Figure 2-5* shows the PTB model using a generic boiler blueprint. The typical heat exchangers found in a boiler are economiser, boiler wall tubing, superheaters, reheater and air heater.

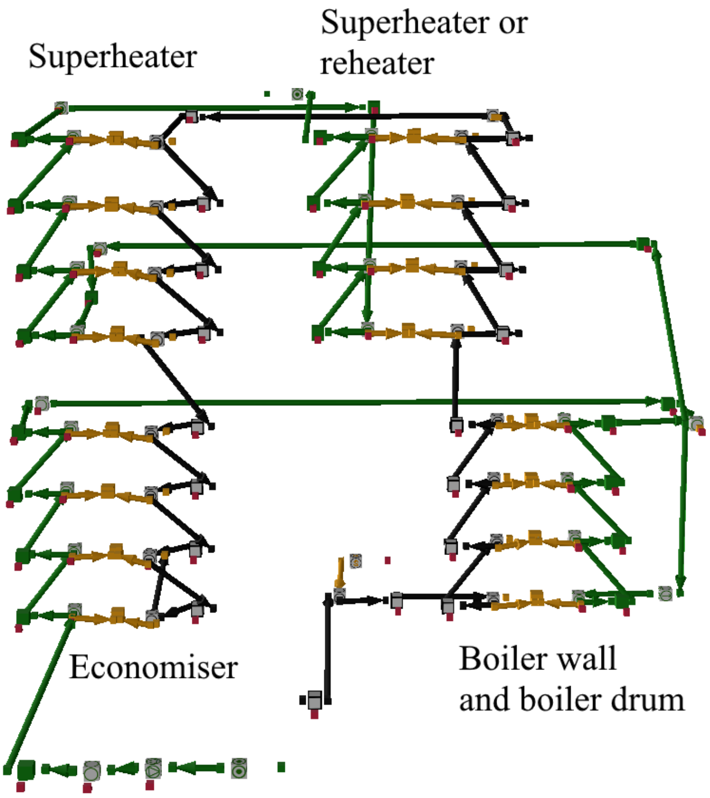


Figure 2-5: Boiler completed with heat exchangers

The air side of the boiler requires the addition of the fans and combustion chamber, namely; forced draft (FD), induced draft (ID), primary air (PA) and air coal burner. Adding the fans arrangement and air coal burner the boiler is completed, but not calibrated. At this stage, boundary conditions are added to the air, water and steam inlets using air and steam pressure boundary components, as shown in *Figure 2-6*.

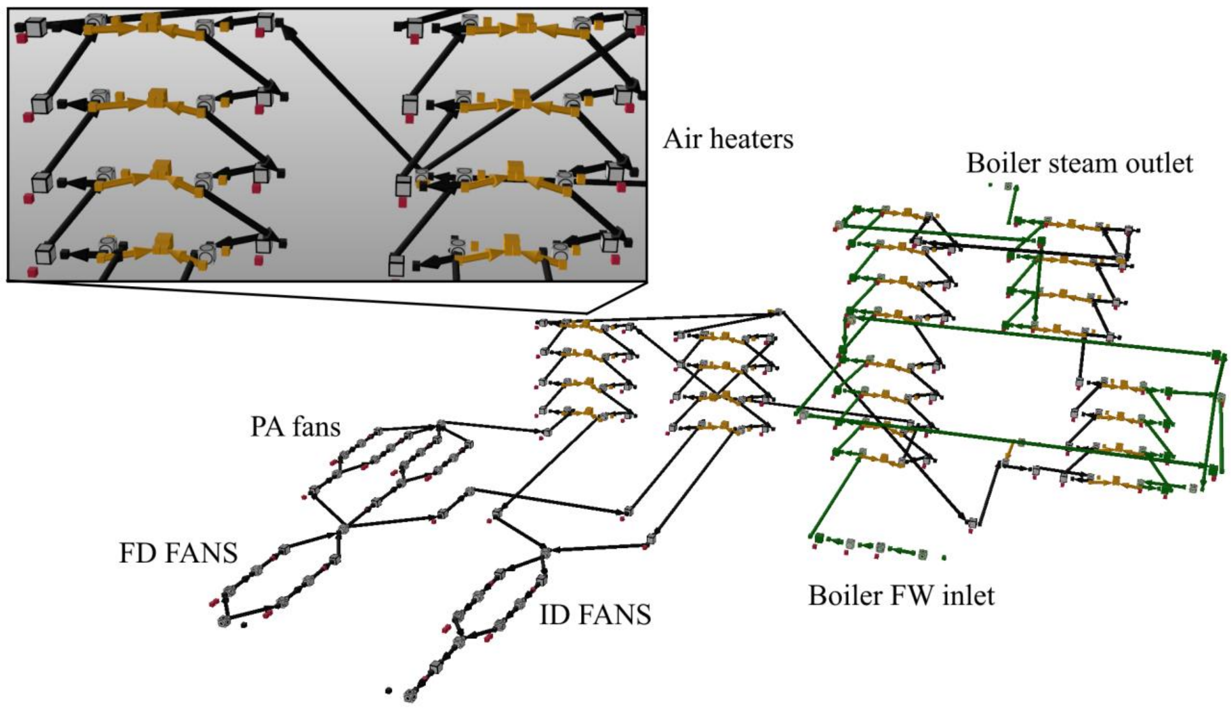


Figure 2-6: Completed boiler

Calibration of the boiler configuration to match actual station boundary conditions can take a considerable amount of time. *Table 2-2* summarises the steps in assisting with boiler calibration.

Table 2-2: Boiler calibration technique

Step	Description	Comment
1	Build individual heat exchangers	Economiser, boiler wall and drum, superheater(s) and reheater.
2	Calibrate individual heat exchangers using user-specified boundary conditions	Steam flow, steam inlet and outlet conditions, air inlet and outlet conditions
3	Add air side components to model	Specify all fans (fan curve) and air pipes
4	Calibrate airside using user-specified boundary conditions	Temperatures, pressures and flows
5	Combine heat exchangers and airside	
6	Calibrate entire boiler with steam boundaries and air boundaries	Steam boundaries are at the economiser inlet and superheater outlet (also reheater outlet if fitted) Air boundaries are at the FD fan inlet and ID fan outlet (ambient conditions)

2.2.5. Turbine configuration and calibration

The turbine train consists of multiple turbines, of which each turbine consists of multiple stages. A single turbine component represents each stage in the simulation model. Therefore, for a High Pressure (HP) turbine with a single stage and an Intermediate Pressure (IP) turbine with three stages, the model consists of three individual turbine components with steam nodes between each turbine as shown in *Figure 2-7*. Extraction of steam for reheat, steam-driven pumps and feedwater heaters occur at steam nodes between stages.

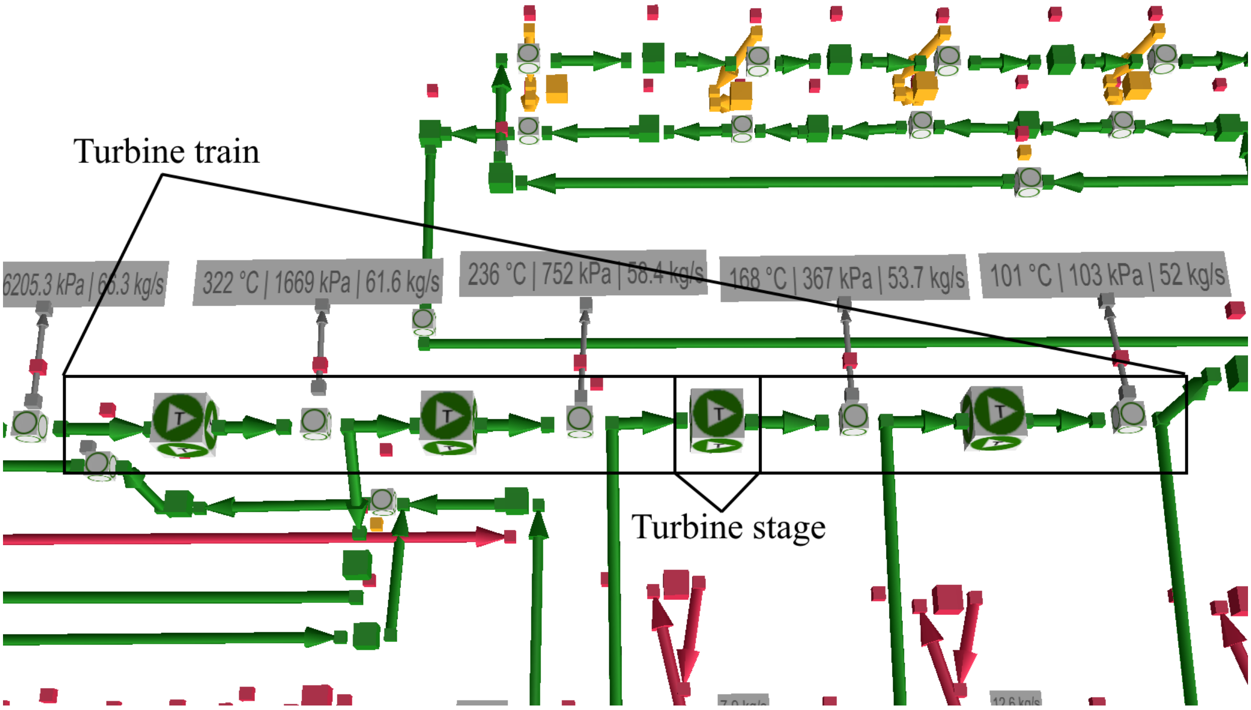


Figure 2-7: Turbine stages and train

Adding the HP, IP and Low Pressure (LP) stages in series create the full turbine train as shown in *Figure 2-7* where each node represents an extraction point in the steam cycle.

Similar to the boiler, calibration of the turbine train can be a time-consuming exercise in constructing a verified simulation. *Table 2-3* summarises the method for turbine train calibration.

Table 2-3: Turbine calibration technique

Step	Description	Comments
1	Separate each turbine into respective stages	
2	Use steam boundaries for inlet and outlet conditions of each stage	From data or by using a Mollier steam chart (Temperatures and pressures)
3	Calibrate each stage of each turbine	Focus on flow, pressures, temperatures and generation (MWs)
4	Add stages to create a single whole turbine and calibrate	Example: HP turbine has five stages, therefore five-turbine components in series
6	Add turbines in series to create turbine train and calibrate	Use the turbine flow valve to control pressures

2.2.6. Condenser configuration and calibration

Figure 2-8 is the fully modelled cooling circuit complete with a concurrent flow condensing heat exchanger found in a typical power station.

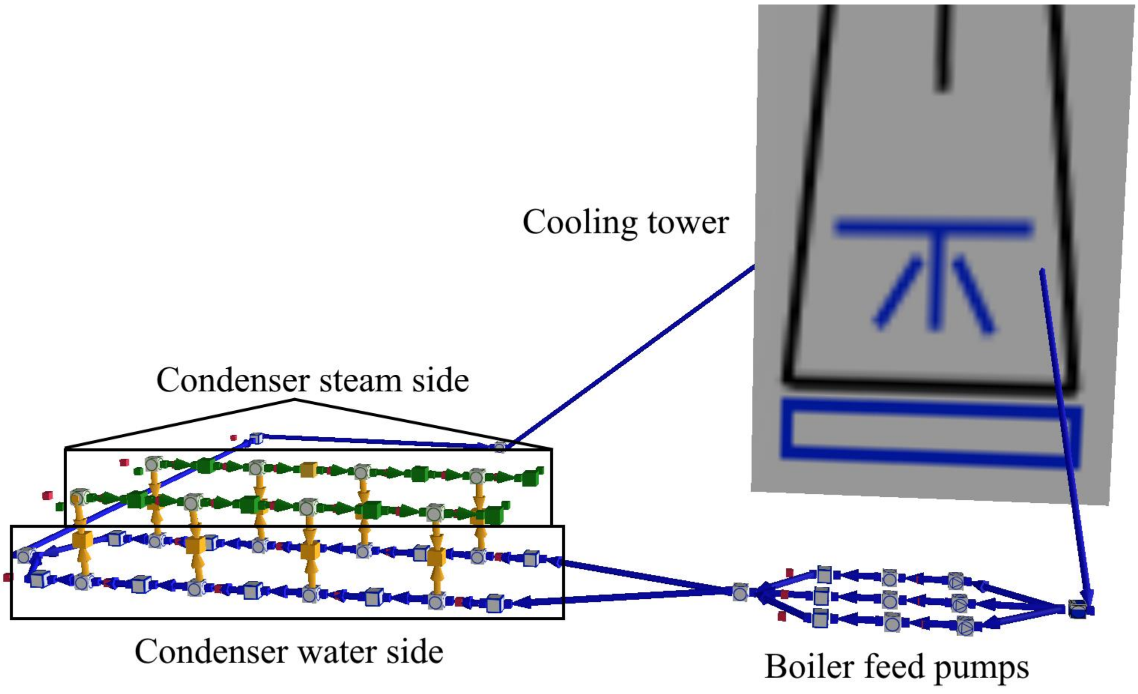


Figure 2-8: Cooling circuit

The condenser or cooling circuit consists of a steam side and water side with heat transfer between the two mediums achieved with the heat transfer component. The construction of the steam side consists of splitting the outlet node of the LP turbine into two separate steam flows. The flows consist of a steam pipe and steam node combination, as is shown in *Figure 2-8*.

The water side consists of an air to water cooling tower, reservoir, pumps, water nodes and piping. *Figure 2-8* shows the layout of the cooling circuit.

To accurately simulate the operation of the condenser, it is important to ensure that the steam fully condensates at the correct back pressure within the condenser. *Table 2-4* summarised the condenser calibration method.

Table 2-4: Condenser calibration technique

Step	Description	Comments
1	Separate into water side and steam side	
2	Use steam boundaries and mass flow for inlet and outlet conditions of steam side	Conditions from data
3	Use water boundaries and mass flow for inlet and outlet conditions of water side	Typically, a delta T of 10 – 15 °C
4	Adjust the heat transfer coefficient to reach desired inlet and outlet conditions	
6	Remove mass flows and add cooling tower and pumps	Ensure pumps provide the correct flow
7	Adjust universal heat transfer coefficient (UA) of cooling tower to achieve desired inlet and outlet conditions	

2.2.7. Feedwater heater configuration and calibration

The feedwater heaters (FWH) are non-contact steam-to-steam heat exchangers. The heat transfer component facilitates the transfer of heat between the two sides. *Figure 2-9* illustrates this clearly.

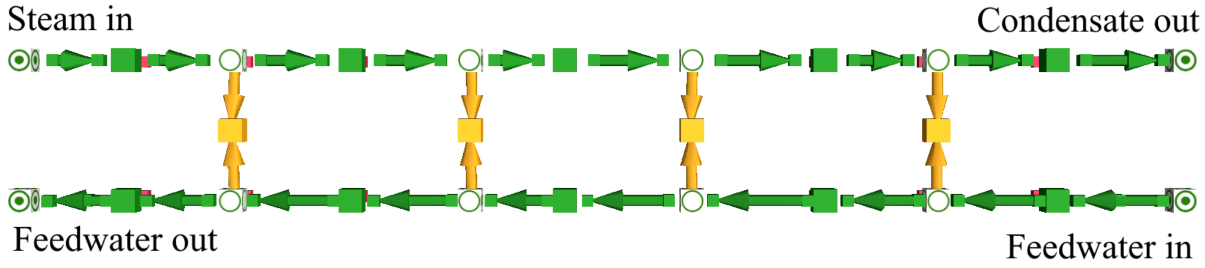


Figure 2-9: Single feedwater heater schematic

Station design dictates the location of each FWH in the system according to their respective design pressures. *Figure 2-10* shows an example of an FWH system layout in PTB.

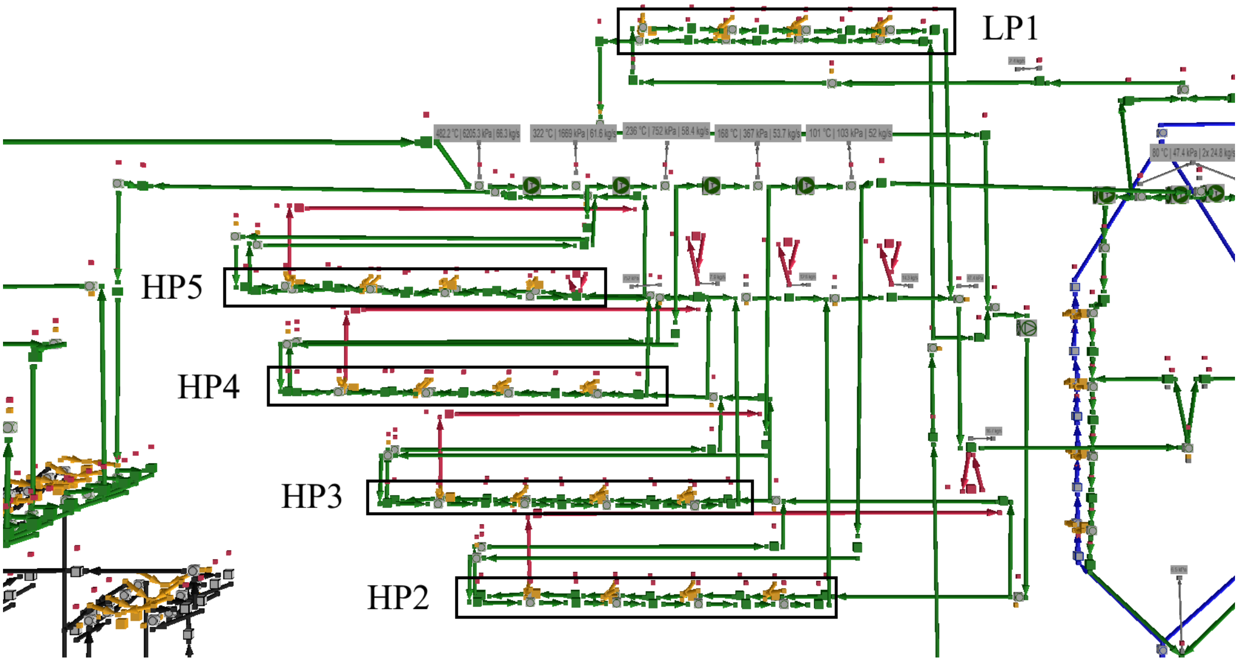


Figure 2-10: Feedwater heater system schematic

The important factors to take into consideration when calibrating the FWHs are steam (shell) pressure, steam flow, feedwater flow, inlet and outlet temperatures on both tube and shell sides. *Table 2-4* summarises the calibration techniques and steps.

Table 2-5: Feedwater heater system calibration technique

Step	**Description**	**Comments**
1	Separate all FWHs into single units	
2	Use steam boundaries and mass flow for inlet and outlet conditions of steam side	Conditions from data
3	Use steam boundaries and mass flow for inlet and outlet conditions of feedwater	Conditions from data
4	Adjust the heat transfer coefficient to reach desired inlet and outlet conditions	
6	Add all FWHs in sequence according to station layout with a single FWH inlet and FWH outlet	
7	Specify all pumps, pipes (not yet added from initial calibration) and steam extraction boundaries	Steam pipe phase specification is extremely important, ensure correct steam extraction pressures
8	Add PI controllers for flow control to each FWH	

2.2.8. Full cycle configuration and calibration

Adding the fully calibrated major components (boiler, turbine train, cooling circuit, FWHs, pumps) to the main model containing the entire station completes the full cycle configuration. The resulting simulation model, shown in *Figure 2-11*, fully integrates coal heat input to electrical output.

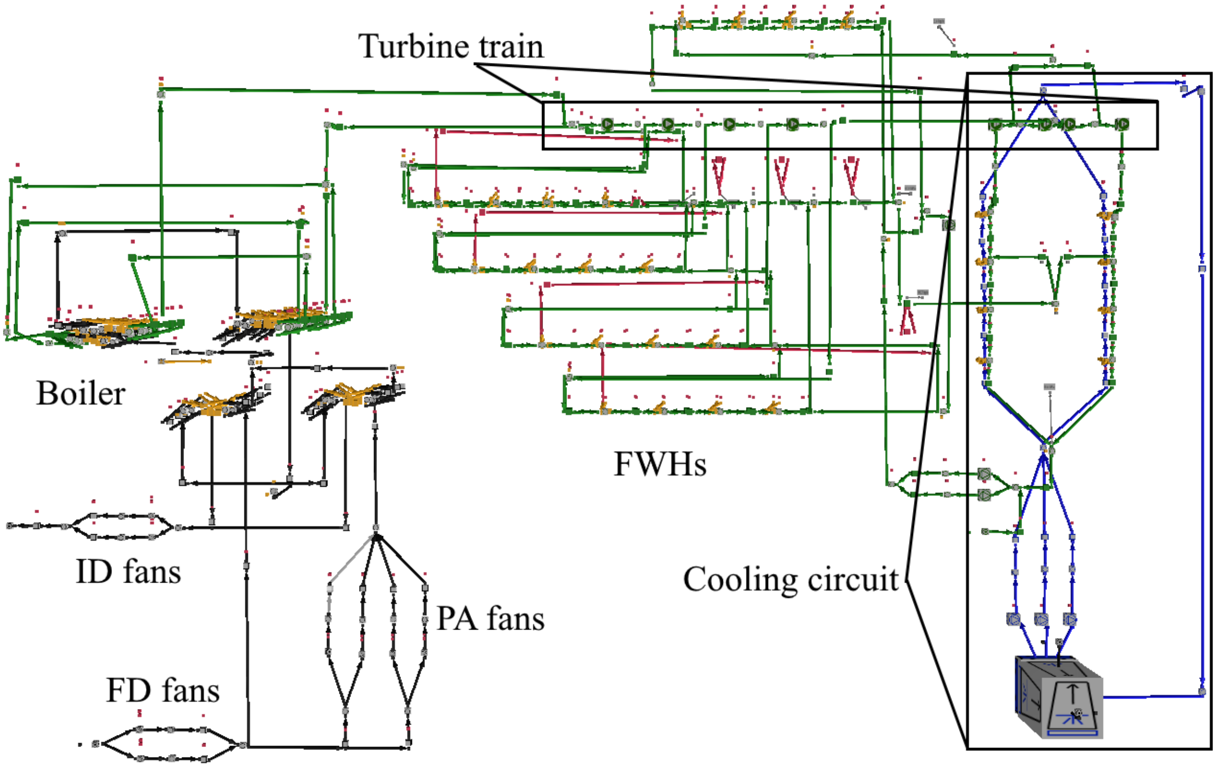


Figure 2-11: Fully integrated coal fired power station simulation model (PTB)

As with any model, full integration of all components does not always lead to a fully calibrated simulation. Therefore, *Table 2-6* summarises the strategy followed to achieve a fully integrated and calibrated simulation.

Table 2-6: Full cycle calibration technique

Step	Description	Comments
1	Add complexity to the basic cycle in stages	
2	Start with boiler	Ensure all outputs remain similar, if yes, move on. If no, there is an issue with the added component, and it should be thoroughly checked for calibration errors.
3	Add the turbine train	Ensure all outputs remain similar, if yes, move on. If no, there is an issue with the added component, and it should be thoroughly checked for calibration errors.
4	Add cooling circuit	Ensure all outputs remain similar, if yes, move on. If no, there is an issue with the added component, and it should be thoroughly checked for calibration errors.
6	Add FWHs	Ensure all outputs remain similar, if yes, move on. If no, there is an issue with the added component, and it should be thoroughly checked for calibration errors.

2.2.9. Summary of simulation model configuration

This section dealt with the simulation model of the developed solution. Certain components needed for the creation of the simulation were identified and these components were combined to develop key configurations, i.e. boiler, turbine, condenser and feedwater heaters, where each configuration required calibration. Summaries of the calibration technique for each configuration were also given. By adding the calibrated components together, this section thus provides the basis to simulate a full cycle CFPS. The next section discusses the verification process of each configuration.

2.3. Verification

2.3.1. Overview of the verification process

Verification requires confirmation that the outputs of the simulation model match that of actual station data. Therefore, this section provides a summary of the parameters verified for each configuration for which calibration was done during the construction phase. The simulation model is set up to start at initial (non-operational) conditions which reach steady-state (operational) conditions based on the model calibration characteristics. The time taken to reach steady-state is not as critical as simply reaching steady-state (operational) conditions within the specified simulation time. This is visualised and confirmed by plotting the simulation results.

The final steady-state conditions are verified with tables comparing simulated results to actual results. However, degradation and performance results are compared by plotting actual results and simulation results on the same axis. The graphs and methods shown in this chapter are generic and only indicate the typical responses when verifying a CFPS simulation model. The data is obtained from a generic PTB CFPS simulation. The case study implementation provides a real-world verification step by comparing actual results to simulation results. During the verification step simulation error is found for each major component and the entire cycle. The target error for calibration and verification is 5 %[38].

2.3.2. Boiler configuration verification

The boiler is a key part of the CFPS and simulation; therefore, correct calibration of the boiler is important. The key parameters (seen in *Table 2-7*) to verify are the temperatures, pressures and mass flows (T's, P's, $\dot{m}$) for the different heat exchangers in the boiler configuration.

Table 2-7: Suggested key measurement points for the boiler

<table>
<tr><th colspan="2">BOILER</th></tr>
<tr><th></th><th>Unit</th></tr>
<tr><td>Flow</td><td>kg/s</td></tr>
<tr><td rowspan="2">Inlet</td><td>˚C</td></tr>
<tr><td>MPa</td></tr>
<tr><td>Economiser outlet</td><td>˚C</td></tr>
<tr><td rowspan="2">Boiler drum</td><td>˚C</td></tr>
<tr><td>MPa</td></tr>
<tr><td rowspan="2">SH outlet</td><td>˚C</td></tr>
<tr><td>MPa</td></tr>
</table>

Plotting the key parameters (T's, P's & $\dot{m}$) against the time period ensures correct calibration and subsequently verifies the simulation. Time periods can be set to indicate seconds, minutes and hours.

Figure 2-12 shows the key temperatures of the boiler and indicates a steady-state simulation with all values reaching steady-state after 17 time periods, i.e. a 17-hour start-up procedure of the boiler [40].

[38] 5 % is deemed sufficient as instrumentation and measurement accuracy can deviate by as much as 5 % [39].

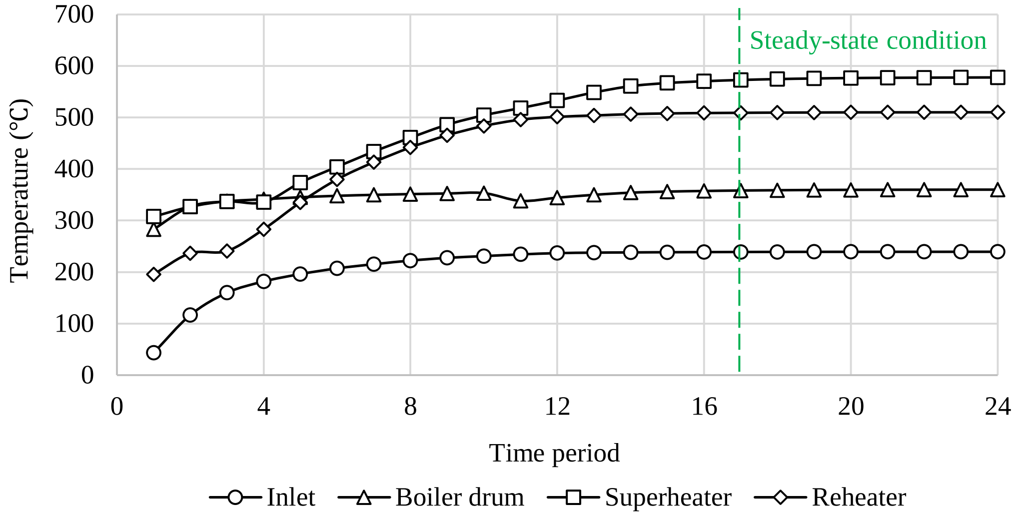


Figure 2-12: Boiler start-up and steady-state (temperatures)

Figure 2-13 shows the pressures within the boiler steam side with steady-state being reached after 12 hours from start-up and thus reaching steady operating conditions.

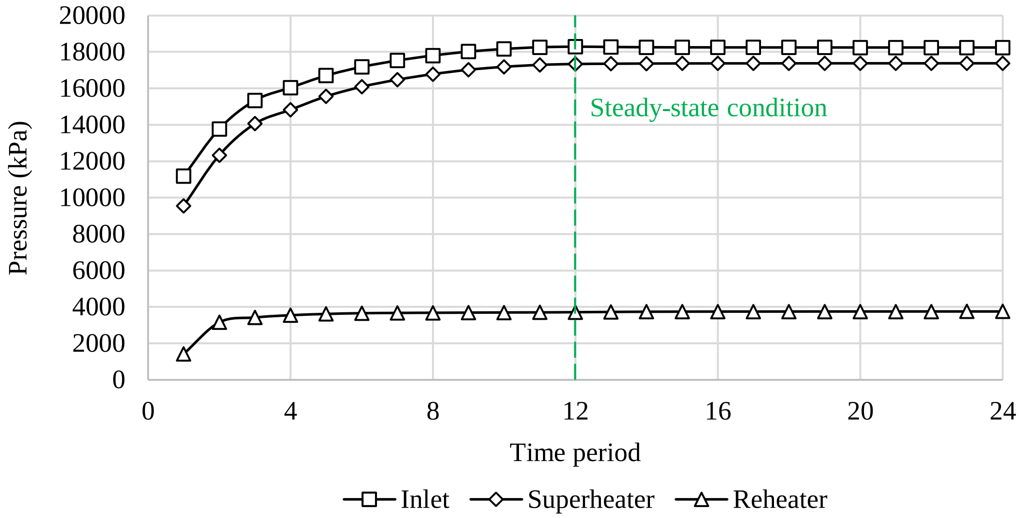


Figure 2-13: Boiler start-up and steady-state (pressures)

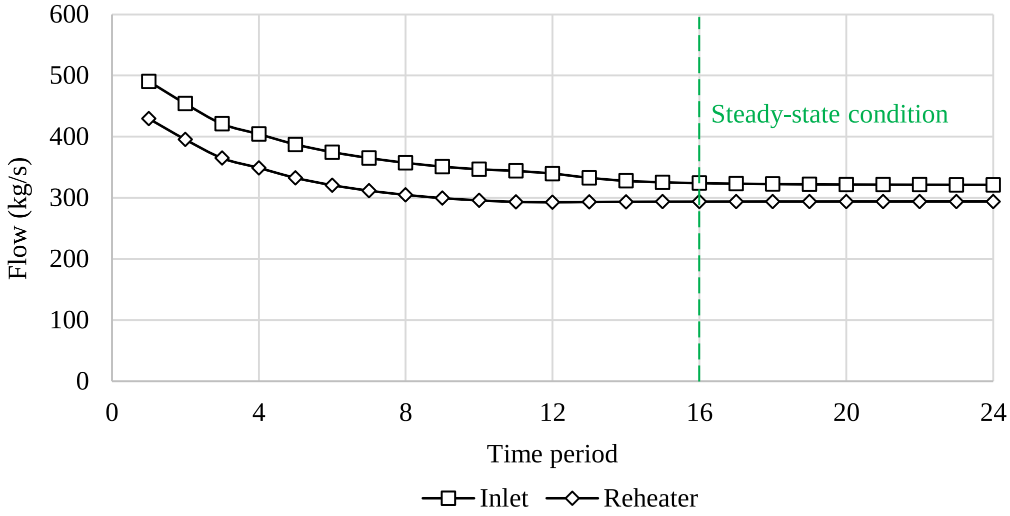


Figure 2-14: Boiler start-up and steady-state (mass flows)

The graphs (*Figure 2-12*, *Figure 2-13* and *Figure 2-14*) display the key parameters which are used to verify that the simulation model is operating correctly. If the simulated steady-state conditions correspond with actual station steady-state conditions, then the assumption can be made that the boiler simulation model has been modelled and calibrated correctly.

2.3.3. Turbine configuration verification

The turbine configuration verification is analogous to the boiler verification explained in the preceding section. The key parameters (seen in *Table 2-8*) that need to be verified are the inlet conditions (i.e. temperature, pressure, flow) and output power.

Table 2-8: Suggested key measurement points for the turbine

TURBINES	
HP STAGE 1 - 4 & LP STAGE 1 - 2	
	Unit
Power	MW
Flow	kg/s
Inlet	˚C
	kPa
Outlet	˚C
	kPa

A turbine train typically consists of three turbines and several stages. In this section, the conditions of the IP turbine and its three stages are presented to illustrate the general turbine verification process.

Figure 2-15 shows the inlet temperature conditions of each stage in the IP turbine. Similar to the boiler, temperatures stabilise after approximately 16 hours. The boiler has a direct effect on the conditions of the turbine.

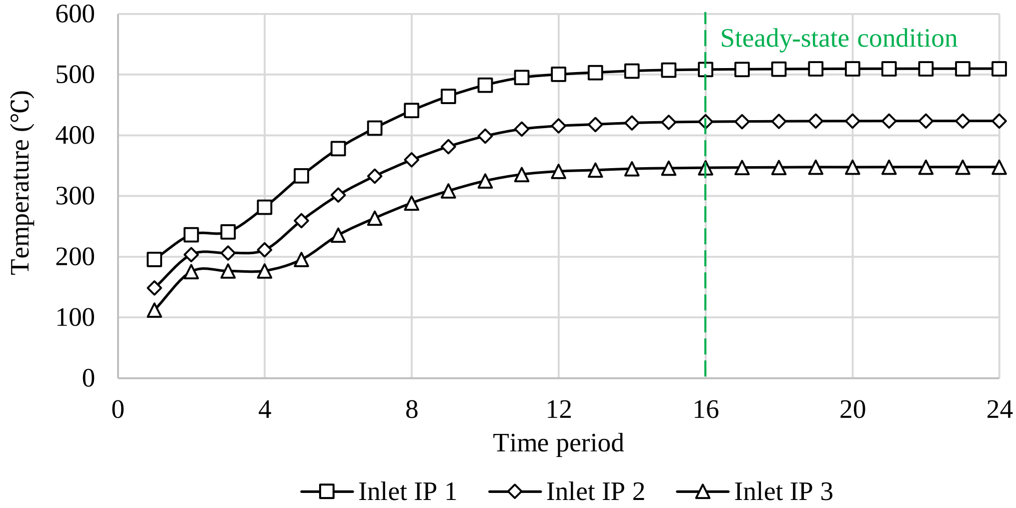


Figure 2-15: Turbine start-up and steady-state (temperatures)

The pressure reacts much faster than that of the temperature, which stabilises before 8 hours, as shown in *Figure 2-16*.

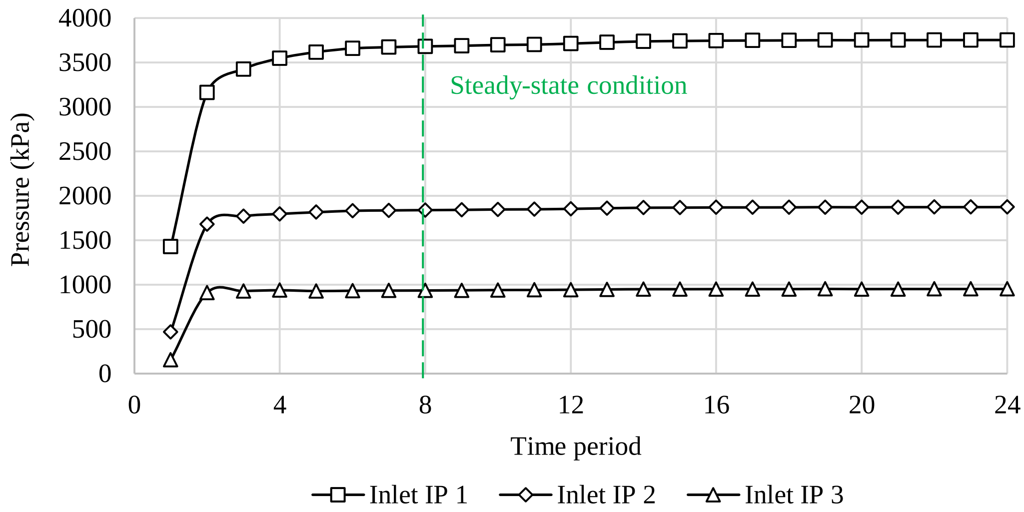


Figure 2-16: Turbine start-up and steady-state (pressures)

Figure 2-17 shows the flow through each stage. Each stage shows a similar trend with different mass flows decreasing from IP1 to IP3. The decreased flow is as a result of steam extraction for the FWH heaters. The flows stabilise after approximately 12 hours.

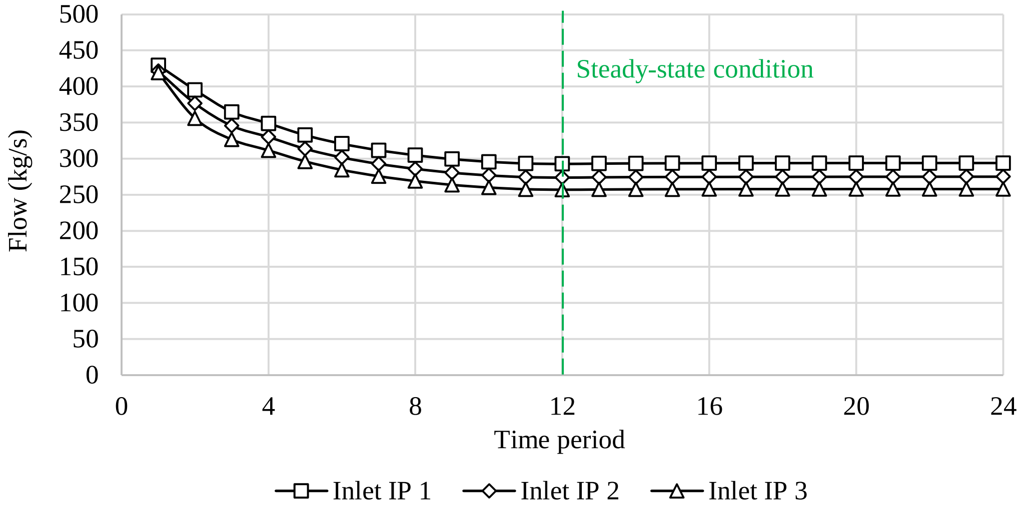


Figure 2-17: Turbine start-up and steady-state (mass flows)

Figure 2-18 plots the power of each stage as an additional verification measurement. The steady-state approach for these parameters are similar to that of temperature, mass flow and pressure as the power is simply a function of these three parameters.

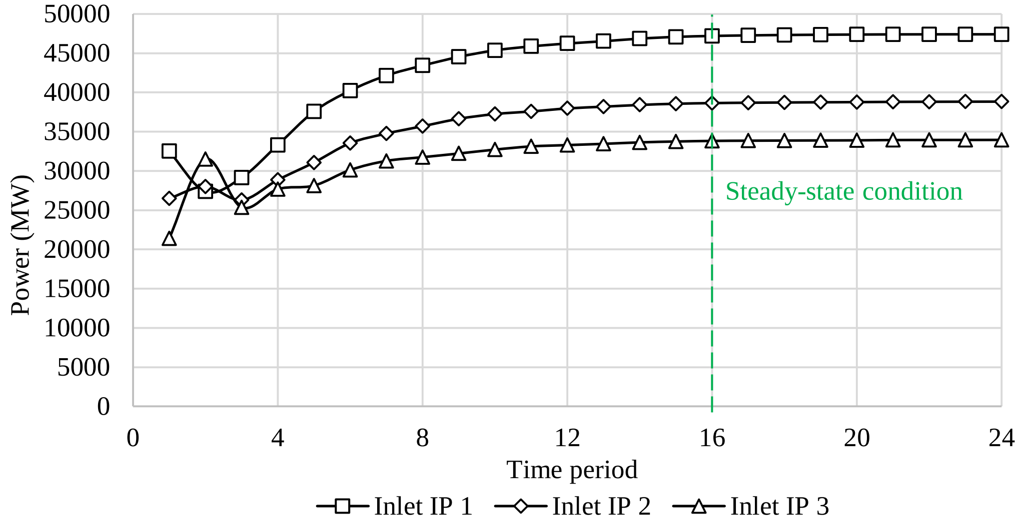


Figure 2-18: Turbine start-up and steady-state (powers)

Figure 2-15 to *Figure 2-18* display the key parameters which are used to verify whether the simulation model outputs are representative of the actual turbine operation of the facility. The remaining turbines configurations of the station (e.g. HP, LP) have identical verification processes to the IP turbine (displayed in this section).

2.3.4. Condenser configuration verification

The condenser is a critical component of this study. Therefore, the configuration requires accurate calibration and verification. Chapter 1 noted that the neglect of condenser parameters as the focus is typically on the other components which are of more interest, specifically the boiler. The key parameters (seen in *Table 2-9*) that require verification include the condenser steam- and water side temperatures as well as the inlet steam quality.

Table 2-9: Suggested key measurement points for the condenser

CONDENSER	
	Unit
Steam inlet	˚C
Quality at inlet	-
Condensate outlet	˚C
CW inlet	˚C
CW outlet	˚C
Pressure	kPa abs

Figure 2-19 shows the boundary conditions of the steam (shell side) and water (tube side) on both the inlet and outlet of each. Here it is important to ensure that the temperatures, as well as the difference in temperature between both steam and water inlets and outlets, reach steady-state. The steam ΔT is expected to be ±2 ℃ and the water ΔT in the region of ±15 ℃.

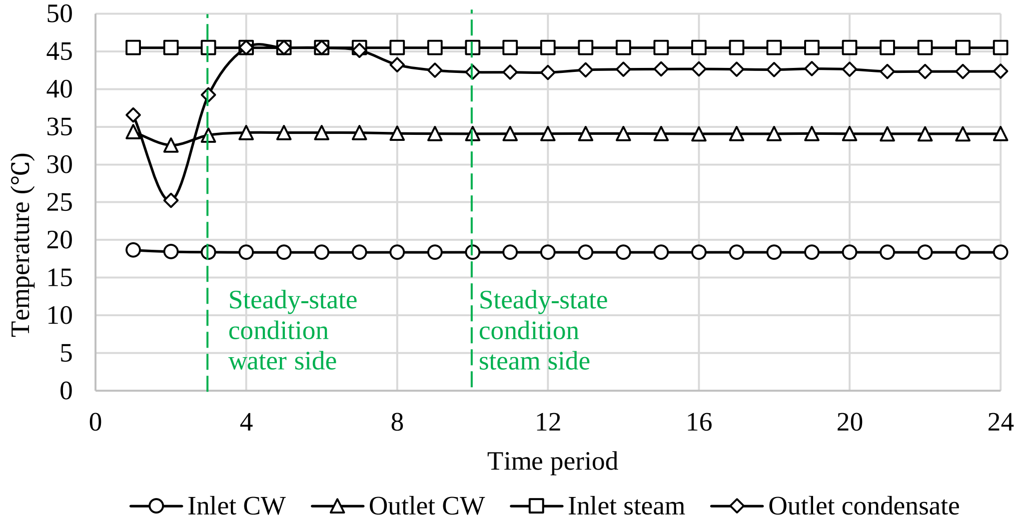


Figure 2-19: Condenser start-up and steady-state (temperatures)

Figure 2-19 indicates quick steady-state conditions as the thermal mass of the water (+- 10 000 kg/s) is large and does not fluctuate significantly. Additionally, the initial temperature is close to the steady-state temperature reaching steady-state after three hours.

The steam side requires slightly more time to stabilise due to the large effect of the upstream turbine and boiler conditions such as temperatures, pressures and mass flows. The result is a slower response reaching steady-state conditions on the steam side after 10 hours.

Figure 2-20 shows the LP turbine outlet or condenser inlet quality. Quality is the amount of liquid water found in a steam flow where x = 1 is a fully saturated steam flow and x = 0 a fully saturated water flow. Lower qualities at the turbine exhaust provide a dangerous case for the turbine as the water droplets tend to damage turbine blades and reduce service life. The quality at inlet or LP turbine outlet reaches a steady-state quality of 0.9 after approximately 12 hours.

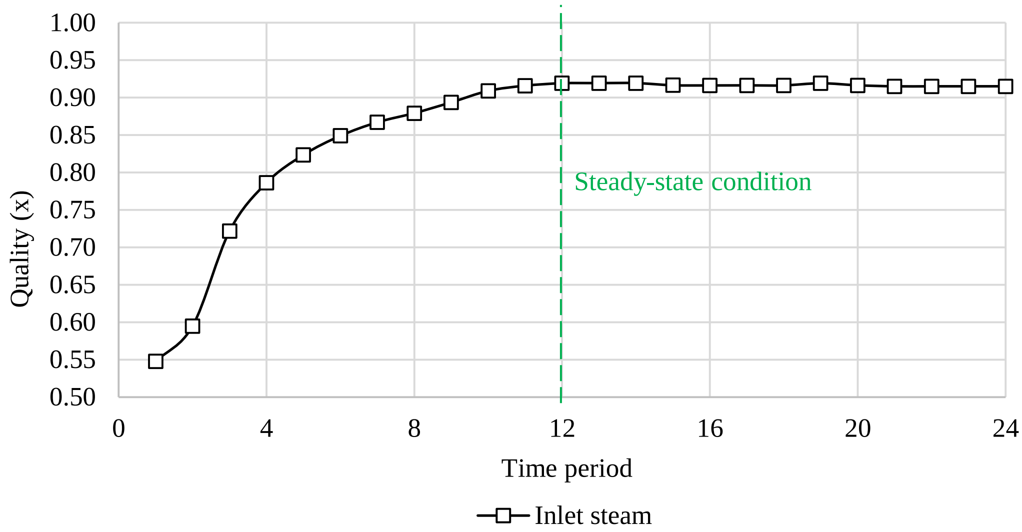


Figure 2-20: Condenser start-up and steady-state (Quality)

2.3.5. Feedwater heater configuration verification

Typically, a CFPS has a feedwater heater train consisting of four to seven FWHs or more. However, for simplicity, only one FWH is shown in this verification since the process and results are similar to the other FWHs. The key parameters (seen in *Table 2-10*) of an FWH include the temperature, pressure and flow conditions of the inlet feedwater, outlet feedwater and inlet steam.

Table 2-10: Suggested key measurement points for the feedwater heaters

FEEDWATER HEATERS	
FWH LP 1 & FWH HP 2 - 5	
	Unit
Inlet FW temp before	˚C
Inlet FW temp after	˚C
Steam flow before	kg/s

Figure 2-21 shows the key temperatures of the feedwater heater, namely the inlet feedwater temperature, outlet feedwater temperature and inlet steam temperature. From the figure, we can see that the steam temperature reaches a steady-state after approximately 12 hours with the feedwater only reaching temperature after approximately 20 hours. The discrepancy is due to the large thermal mass of the feedwater (500 kg/s from *Figure 2-23*), which requires more time to reach steady-state temperature.

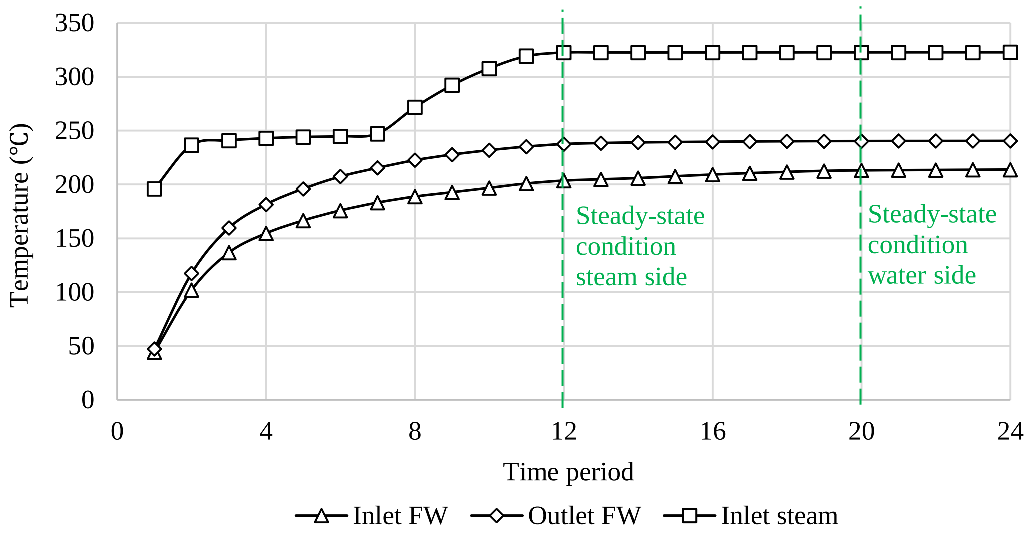


Figure 2-21: FWH start-up and steady-state (temperatures)

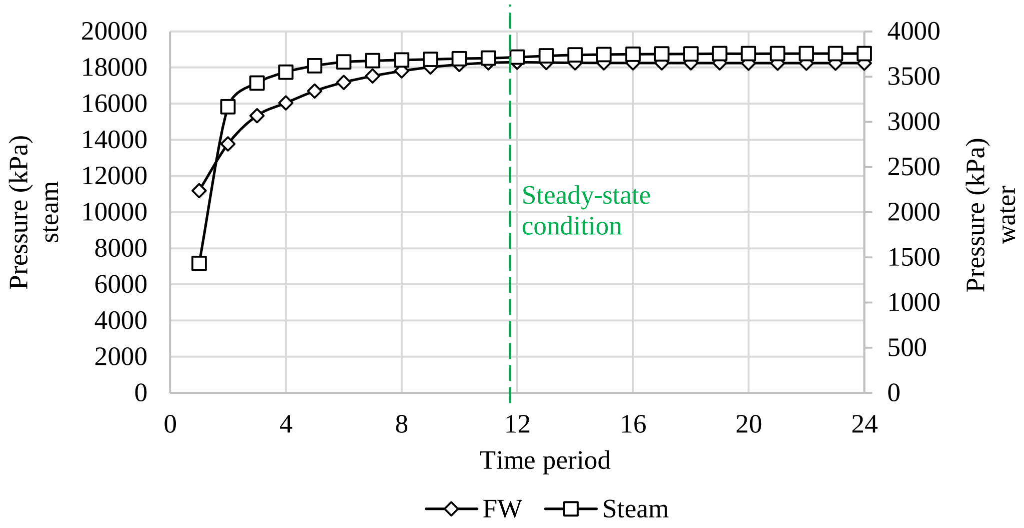


Figure 2-22: FWH 6 start-up and steady-state (pressures)

In the final step, it is important to ensure the mass flows through the FWH reach steady-state and indicate correct values. *Figure 2-23* shows that the feedwater mass flow reaches a steady-state quickly after only ten time periods or hours and the steam flow reaching a steady-state after 20 hours. Indicating the delayed response of the feedwater heater temperature from *Figure 2-21*.

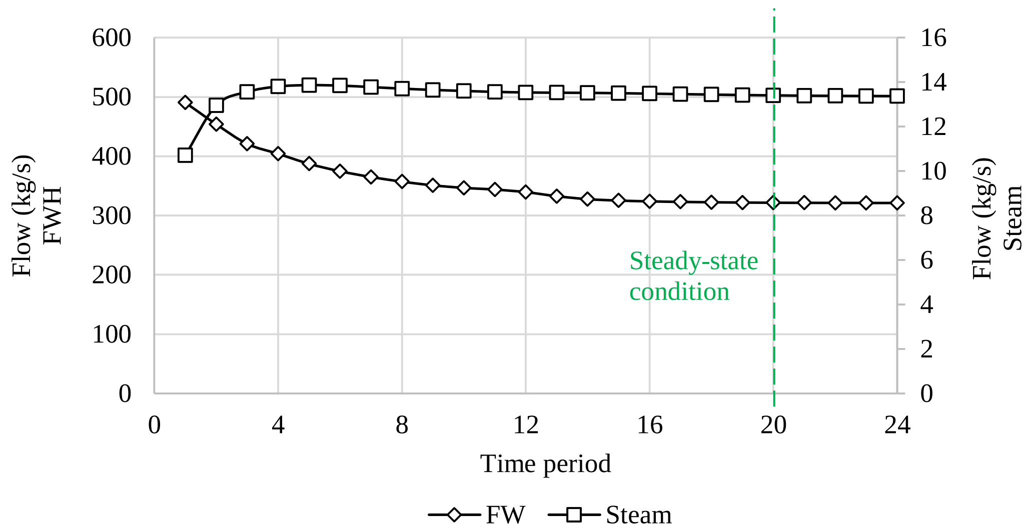


Figure 2-23: FWH 6 start-up and steady-state (mass flows)

2.3.6. Full cycle configuration verification

The final verification step is to ensure the integrated station performance parameters are within the boundaries of what the data indicates and to ensure station stability in reaching steady-state. *Table 2-11* shows the suggested key measurement points (KMPs) to compare for the full cycle verification process.

Table 2-11: Suggested key measurement points for the overall station parameters

OVERALL	
	Unit
Gross power	MW
Net power	MW
Auxiliary power	MW
Coal usage	ton/hr
Coal calorific value	GJ/ton

Figure 2-24 shows the main parameters, including the generation (gross and net) and station efficiency. The figure indicates overall station steady-state operations after approximately 16 hours. Reaching constant steady-state conditions overall configurations and key indicators, we can assume simulation stability has been. Therefore, the simulation model of the CFPS can be assumed to be calibrated correctly and verified.

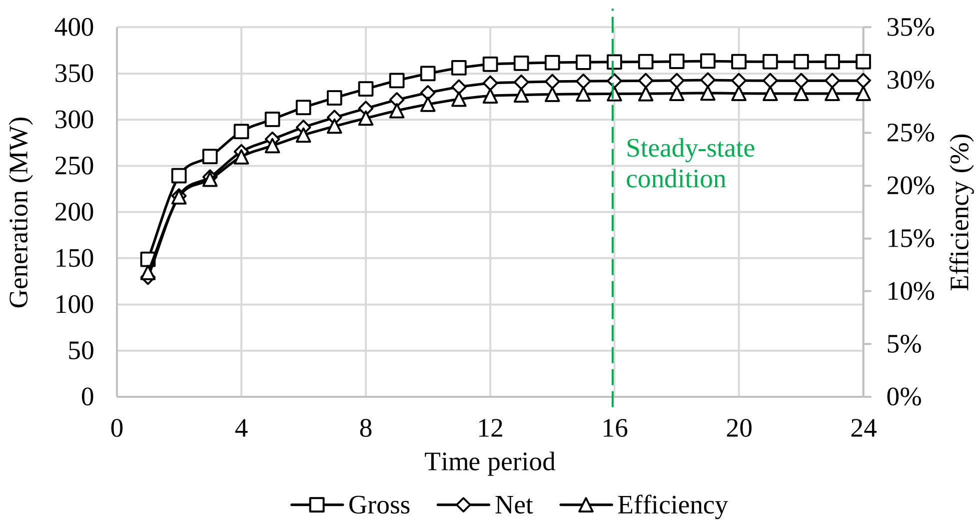


Figure 2-24: Station start-up and steady-state

2.3.7. Summary of the verification process

This section showcased the verification processes for the various parts of the simulation model. The study further identified key simulation parameters that need to be verified and explained with time-series graphs. A verified simulation model must be achieved when actual steady-state conditions can be simulated starting from ambient (or non-operational) conditions. The steps followed include:

1. Run simulation until steady-state is reached
2. Plot KMPs
3. Confirm steady-state values
4. Compare to actual steady-state conditions (error within 5 %)

The verified simulation is useful for various operational studies. However, in this study, the focus is on investigation how a verified simulation can be used to enable predictive maintenance of the condenser section. The next section presents the development of a predictive maintenance model based on simulation outputs.

2.4. Predictive maintenance model

2.4.1. Overview of predictive maintenance model development

The degradation or fouling of a condenser can have severe financial implications for a station owing to the large effect of the condenser on station performance [33]. However, fouling or degradation of the condenser is a slow process which is either ignored or the effects thereof realised at a critical stage leading to unplanned shutdowns. The effects thereof lead to reactive maintenance which results in unnecessary expenditure over the lifespan of a power station.

Improper maintenance scheduling can cause severe station performance and cost losses which requires a detailed study to determine the predictive maintenance schedule for a specific power station. In this section, the development of a predictive maintenance model is presented by:

- Specifying the requirements of a predictive maintenance model with the specific focus on condenser maintenance,
- Developing a simple method to simulate fouling in the condenser, and
- Providing the relations to convert simulation outputs to maintenance intervals, cost and revenue.

2.4.2. Operating conditions and limits

The verified integrated simulation model can be used to quantify the effect of condenser degradation on the entire station by two key performance indicators (KPIs), namely station efficiency and station output (MW).

The initial step of developing the maintenance model is to find the operating maxima, minima and limits of the station. *Table 2-11* shows the suggested critical measurement points.

Therefore, by an integrated simulation, a predictive maintenance model can be developed. The use of the predictive maintenance model can support critical financial decision making through balancing time, cost and availability. Correct maintenance also reduces the operating cost of the equipment and overall expenditure of the station. Prescribed suggested maintenance intervals (or certain setpoints such as condenser pressure or temperature) for each power generating unit achieves this goal. Where each unit is individually investigated and characterised according to its past performance and fouling rate.

Calibrating the simulation model to the unit's "optimal" current operating conditions to represent a clean, fully operational condenser and power generating unit provides the starting point. From here, fouling in the condenser is introduced to simulate the effects of degradation overtime.

2.4.3. Simulation of fouling in the condenser

An iterative approach is followed to simulate and find the effect of condenser fouling on unit performance. The back pressure of the condenser increases when the condenser fouls [27]. The increase in back pressure is as a result of reduced heat transfer due to a lower heat transfer coefficient. The investigation phase reveals the clean starting point. The effect of fouling is simulated using incremental degradation from the clean starting point.

The increment sizing is by user discretion based on the unique conditions of the CFPS under investigation. However, it is suggested to have at least four increments. The four-increment range was found to be the minimum number of increments to yield useable results for station performance determination. The scenarios will be simulated using the four increments:

1) Clean scenario (back pressure = 10 kPa)
2) Low fouling (back pressure = 14 kPa)
3) Medium fouling (back pressure = 18 kPa)
4) High fouling scenario (back pressure = 22 kPa)

The 10 kPa simulation is calibrated and verified according to station data. The three additional predicted scenarios are at higher pressures. In the initial 10 kPa simulation, the condenser subcooled[39] the steam to approximately two 2 °C below the saturation temperature. *Table 2-12* shows the target simulation calibration values through artificially introducing fouling in the condenser by reducing the heat transfer rate (h, $W/m^{2}\cdot K$) between steam and water nodes.

Table 2-12: Example of increment target values

Description	Condenser pressure	Condenser condensate outlet temperature
	(kPa)	(°C)
Original design	8	41.70
Clean present	10	42.65
Fouling stage 1	14	48.90
Fouling stage 2	18	55.15
Fouling stage 3	22	60.20

The two main indicators of performance, generation and efficiency, is considered by correlating the two indicators with condensate temperature. Increased fouling is shown by increased condensate outlet temperature, which is as a result of increased condenser back pressure). *Figure 2-25* shows an example of these correlations.

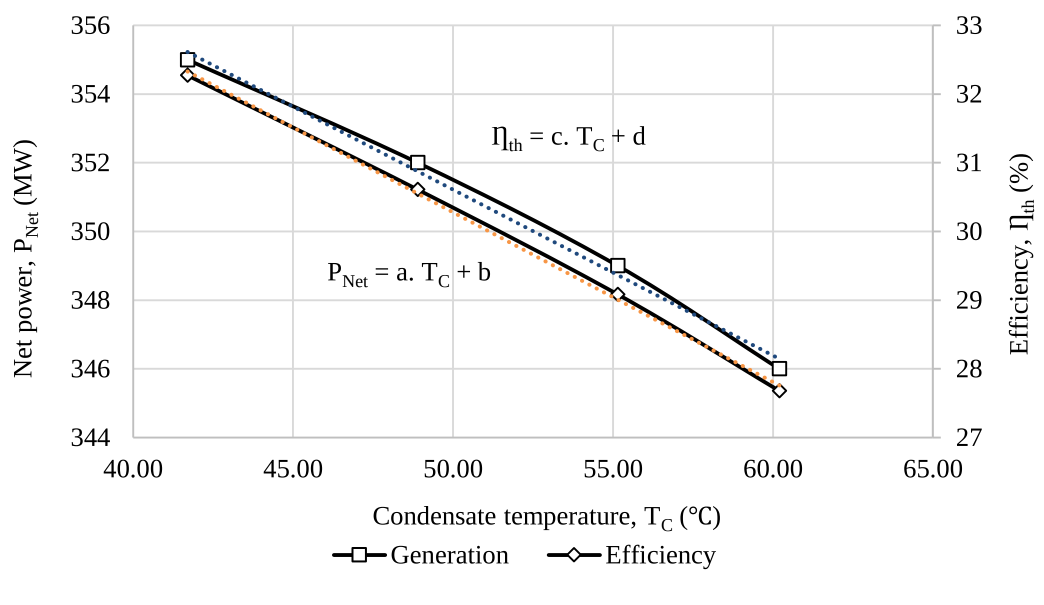


Figure 2-25: Example of station generation and efficiency as a function of condenser outlet temperature

[39] Cooling past the saturation temperature of the steam flow at a specific pressure.

Fitting regression trendlines to the data in *Figure 2-25* provides an indication of performance as the temperature increases due to fouling. *Equation 2-1* and *Equation 2-2* is an example of the typical equations expected from this exercise.

Equation 2-1: Station generation as a function of condenser outlet temperature

$$\eta_{th} = aT_C + b$$

where η_{th} is the thermal efficiency and T_C the condenser outlet temperature. Parameters *a* and *b* are the regression slope and intercept, respectively.

Equation 2-2: Station efficiency as a function of condenser outlet temperature

$$P_{Net} = cT_C + d$$

where P_{Net} is the net generation in MW. Parameters *c* and *d* are the regression slope and intercept, respectively.

2.4.4. Maintenance interval, cost and revenue prediction

Armed with knowledge regarding the degradation and reduced performance of the station as the condenser fouls, an intelligent method of maintaining the condenser can be developed using the simulation results. The generation and efficiency curves or resulting *Equation 2-1* and *Equation 2-2* provide a direct correlation to the condenser outlet temperature/backpressure and subsequently the station performance on any specific day. The results thereof converted into monetary value or daily operating cost of the station.

An iterative prediction model is used to run through several ideal days between clean scenarios. Each iteration calculates individual days performance, cost and profit. The unit is switched off for a user-specified amount of days upon reaching the suggested cleaning day. After which the outlet temperature, backpressure, generation and efficiency return to normal clean conditions. The user describes set boundaries, limits and parameters for the use of the predictive model. *Table 2-13* shows an example of the user inputs required for the calculation.

Table 2-13: Prediction model inputs: an example

Description	**Unit**	**Value**
Last clean	Date	yyyy/mm/dd
Clean condensate temperature	℃	--
Rated generation	MW	--
Clean efficiency	%	--
Type of fouling	Linear/Exp	--
Linear fouling rate	℃/day	--
Exponential coefficients	T_{cc}	--
	B	--
	n	--
Average breakdowns per year		--
Average time to rectify	days	--
Condenser cleaning price	R/unit	--
Time to clean the condenser	days	--
Cost per kWh sold	R/kWh	--
Coal price	R/ton	--

Table 2-13 requires some key station parameters, notably the temperature curve or "fouling rate" of the condenser under typical conditions. To determine the polynomial components that describe the historical temperature curve of the condenser (assuming exponential fouling). The data is plotted on a graph, as seen in *Figure 2-26* and the components adjusted until finding a reasonable fit.

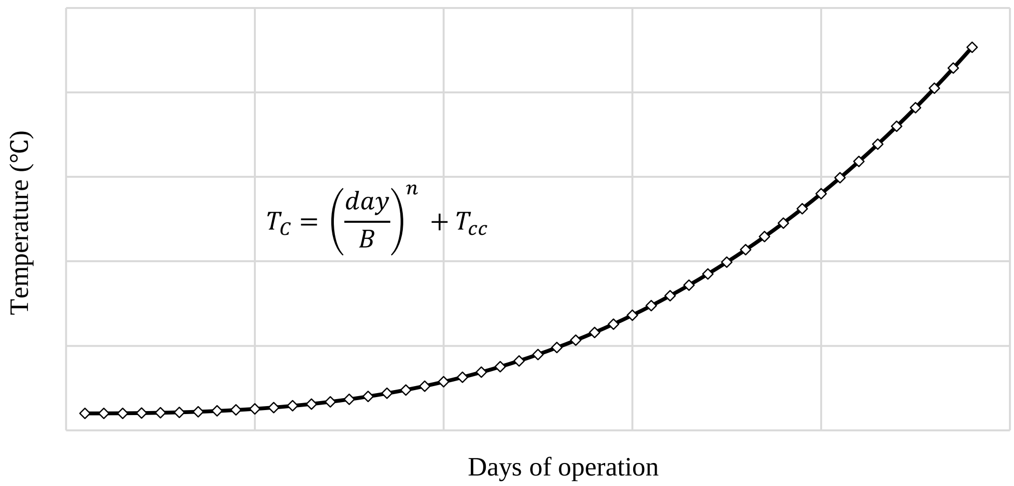


Figure 2-26: Temperature curve parameterisation: an example

From *Figure 2-26*, the coefficients of *Equation 2-3* are determined. Adding the coefficients to the prediction model assists with estimating future fouling and performance.

Equation 2-3: Temperature curve equation

$$T_C = \left(\frac{day}{B}\right)^n + T_{cc}$$

where T_C is the condenser condensate outlet temperature in ℃, day the day from last clean, B the adjustable constant for fitting the curve to the data, n the adjustable exponential constant, T_{cc} the condensate temperature after a condenser clean in ℃.

Once all inputs are known, the model runs iteratively through all combinations using Excel and the built-in Visual Basic for Applications (VBA) code (see APPENDIX G: Predictive maintenance model (Excel sheet and VBA code).

To further improve the accuracy of the prediction model, random breakdowns were incorporated. The random breakdown generator requires two key parameters from past data: the average number of breakdowns per year and the average time to rectify the breakdown. A random Excel function generates days when the unit is offline for a breakdown and remains offline for the specified days to rectify the breakdown. *Table 2-13* shows the inputs required for the breakdown.

Table 2-14 shows the predictive model results summary.

Table 2-14: Prediction model outputs: an example

Maintenance plan		
Best average profit	R/day	--
Days between full clean	days	--
Suggested maintenance date	Date	**yyyy/mm/dd**
Suggested condensate outlet temperature	℃	--

The results include:

1. A best average operating profit per day calculated using *Equation 2-4*

Equation 2-4: Average profit per day

$$Profit = Energy\ sold - Coal\ burnt$$

$$Profit = [P_{gen} \times 24h \times C_{energy}] - [C_{coal} \times \dot{m}_{coal} \times 24]$$

where P_{gen} is the average power produced in kW, C_{energy} the average selling price of energy produced in c/kWh, C_{coal} the average cost of coal in R/ton and $\dot{m}_{coal}$ the average coal usage in ton/hr.

2. The ideal amount of days between cleans of the condenser
3. The suggested day of maintenance calculated from the date of the previous clean
4. A suggested condensate outlet temperature at which losses are too great to continue

To visualise and quantify the effect of deviation from the ideal maintenance schedule, the predictive model produces a loss in profit curve, seen in *Figure 2-27*, according to *Equation 2-5*.

Equation 2-5: Average loss in profit per annum

$$Loss = (Profit_{overall\ best} - Profit_{current}) \times 365$$

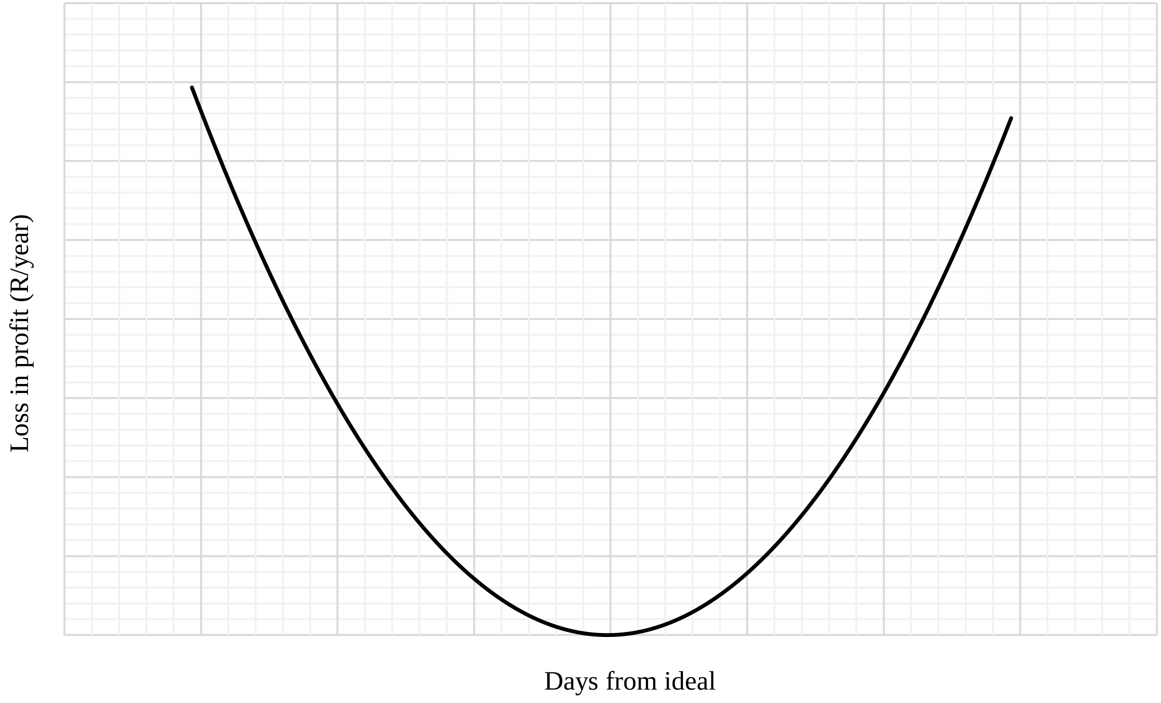


Figure 2-27: Prediction model result: an example

Figure 2-27 can assist station personnel with strategic planning by providing a suggested best time to clean. The station personnel can use their discretion to plan a cleaning date that is as close as possible to the ideal cleaning date. It is important to take note that each unit will have unique simulation results, performance degradation and maintenance schedule or prediction model. A simulation model, therefore, needs to be calibrated and verified for a specific unit to provide sensible results. In the next chapter, the approach is applied to a South African power station as a case study.

2.4.5. Summary of predictive maintenance model

The predictive model used a verified integrated simulation model as input which is used to provide unit performance characteristics as the condenser fouls. The model iteratively runs through several maintenance schedules to maximise operating profit. The outputs include a suggested maintenance schedule and condenser operating limits at which maintenance is suggested.

2.5. Conclusion

This chapter presented the steps involved in developing an integrated simulation backed maintenance model. The key points discussed included:

1. **Simulation model:** The model is constructed according to the power station layout, starting at a simple Rankine cycle. The complexity of the model is then increased systematically per major configuration to allow simulations at the required level of detail.
2. **Verification:** Verification is done concurrently with the construction of the model. The final step includes plotting the key performance indicators (KPIs) of the simulation and confirming convergence and steady-state (operation) conditions.
3. **Predictive maintenance model:** The verified simulation model is used to develop a predictive maintenance model. The model predicts degrading station performance with increased fouling in the condenser. The model suggests a maintenance schedule or maintenance at condenser condition limits. The results thereof can be used for strategic maintenance planning.

The key points necessary to create the simulation model are broken into a simple to follow 10-step process:

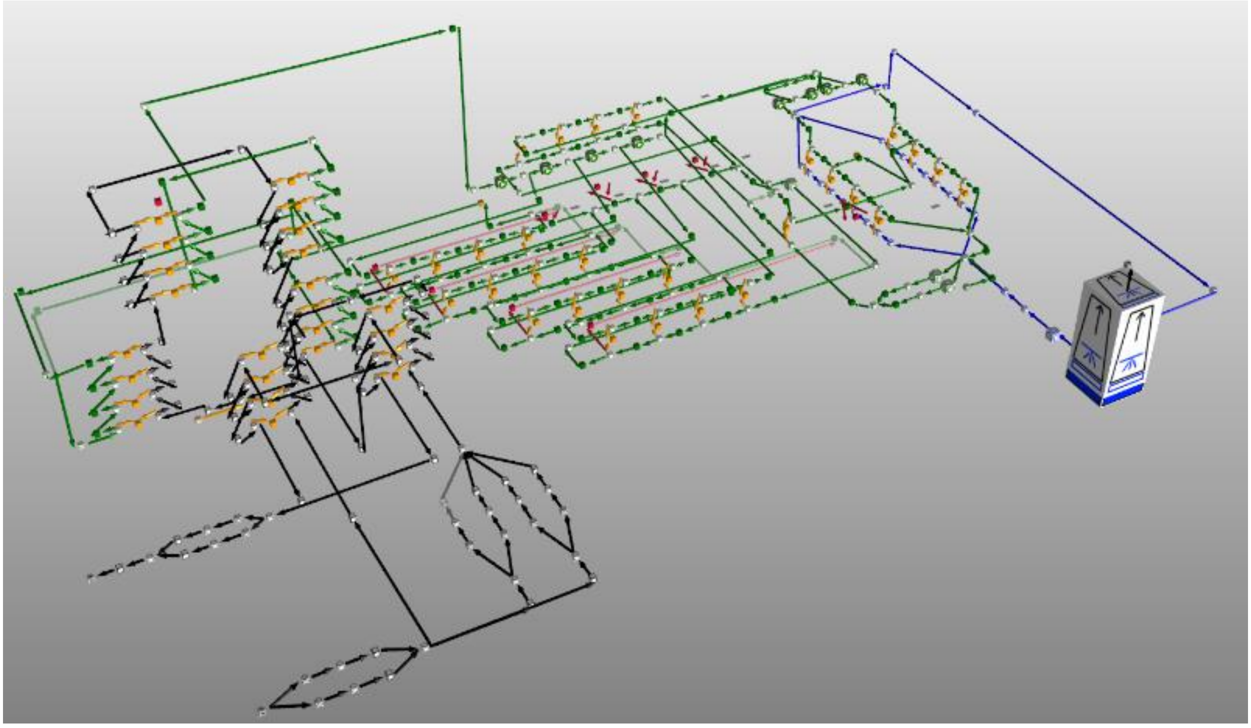
1. Obtain data for a specific unit
2. Model the specific unit (Using chosen simulation software)
3. Calibrate unit according to baseline
4. Introduce component-specific degradation (fouling) in simulation
5. Obtain performance parameters as a function of degradation (fouling)
6. Apply to the prediction model

7. Predict daily station performance and costs
8. Iterate for multiple estimates of days between maintenance schedules
9. Find the best average daily profit
10. Obtain cost breakdown and maintenance schedule

The simulation model is specifically developed for condenser performance analysis and maintenance. However, using the integrated simulation, the integrated effect of the entire power station can be investigated, and a predictive maintenance model developed for that specific component.

This chapter described the generic method which can be used to develop, calibrate and verify a simulation model for a specific power station. The next chapter applies the method to a currently operating power station (CFPS A station) and the results discussed.

Chapter 3: Model application and results



PTB CFPS simulation model

The simulation-based maintenance model was tested on a real-world case study. Results show possible avoidable losses of between R600 000 and R2.5 million per annum using this technique on a 60 MW unit.

3. Model application and results

3.1. Preamble

This chapter applies the developed ten-step simulation and maintenance prediction model to a real-world case study. The ten steps include:

1. Obtain data for a specific unit
2. Model the specific unit (using chosen simulation software)
3. Calibrate unit according to baseline
4. Introduce component-specific degradation (fouling) in simulation
5. Obtain performance parameters as a function of degradation (fouling)
6. Apply to the prediction model
7. Predict daily station performance and costs
8. Iterate for multiple estimates of days between maintenance schedules
9. Find the best average daily profit
10. Obtain cost breakdown and maintenance schedule

The case study station is a CFPS situated in South Africa. For this study the station in question is referred to as CFPS A. The case study aims to test whether the developed simulation-based methodologies can be used in practice and to evaluate its effectiveness when used in a condition-based maintenance strategy.

As the first step, a simulation model is developed and calibrated specifically for CFPS A. The simulation outputs are compared to the actual station data to verify the model and to determine its margin of accuracy. The developed fouling procedure is then conducted for the predictive maintenance model to be populated.

Once the model is verified, the condenser maintenance model is set up to predict the required maintenance intervals based on iterative simulation outputs. The model then provides an estimate for the next maintenance date and outlet temperature limit. The prediction model verification process compares the model outputs to actual station data from initial clean to the next clean. The cost of non-compliance with the predicted maintenance schedule is also quantified.

Finally, all the results and observations are consolidated to review the practicality and effectiveness of the simulation-based approach. To estimate the potential impact of the developed condition-based predictive maintenance strategy on all CFPS facilities in South Africa, extrapolating CFPS A's model achieves a countrywide estimate.

3.2. Case study application

3.2.1. Simulation model setup

The basic layout of CFPS A

CFPS A consists of two different generating stations; namely, Station A and B. Station A is an older unit with six generating units (30 MW each) and 11 chain grate boilers. Station B consists of seven generating units (60 MW each) and seven boilers. The power station is approximately 60 years old and, like similar power stations in South Africa, it is not operating at its nameplate capacity. Station A is partly to blame for the underperformance due to its long-term outage status.

The numbering of the station starts at 1 for Station A and continues through to 13 for Station B. Therefore, station B consists of units 7 – 13. Station B has six serviceable 60 MW turbine units and six serviceable boilers from a total of seven installed turbines and boilers.

The power station has a 200 MW generating target which typically results in three to four (of the six units) operating simultaneously. The study uses Unit 7 (i.e. the first of Station B's units) as the benchmark. However, due to the similarity, the process is identical for any of the seven units.

Simulation model setup for CFPS A

The method described in Section 2.2 (Chapter 2) was applied to Unit 7 of CFPS A to build the simulation model with PTB simulation software (described in Section 1.3.3) based on the station layout and available station data. The model was modified and calibrated to match CFPS A's operating conditions. Hench, it was possible to apply a semi-empirical approach to develop the simulation model with PTB simulation software. *Figure 3-1* shows the completed 3-dimensional (3D) simulation model of Unit 7 in PTB.

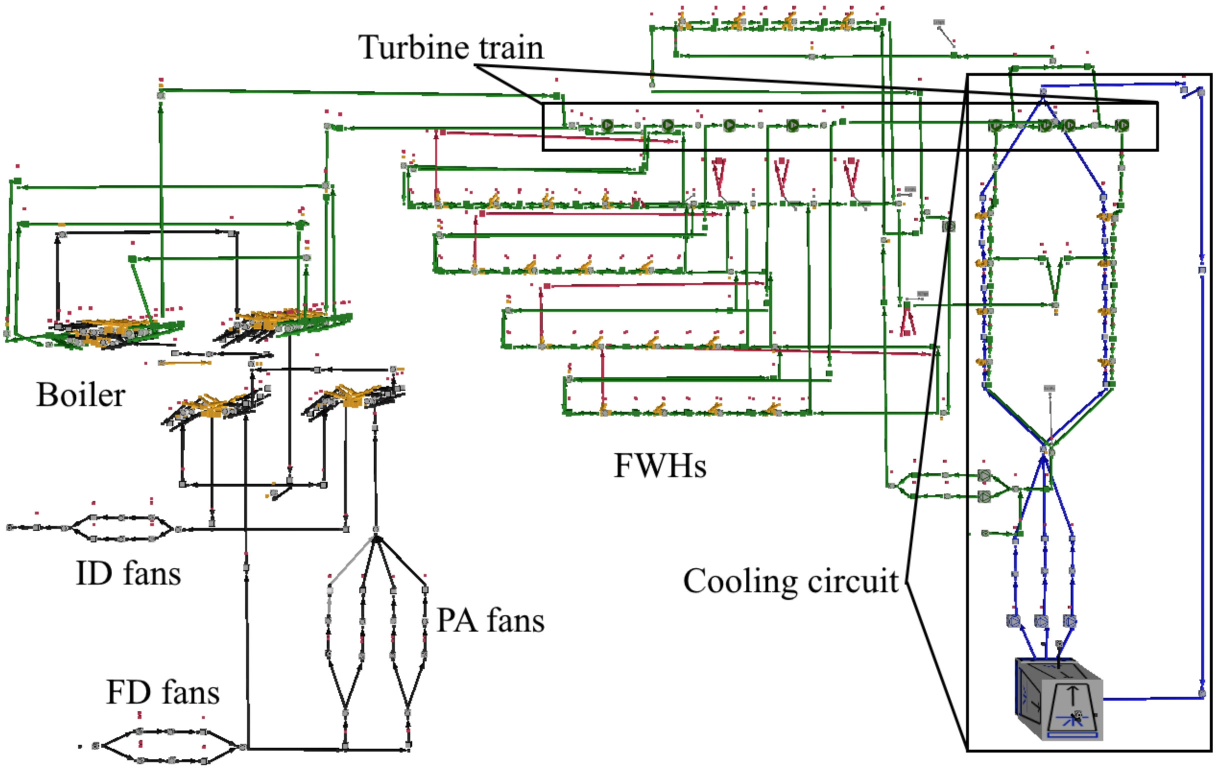


Figure 3-1: CFPS A PTB model – a top-down view

As shown in *Figure 3-1*, the simulation model includes the full closed-circuit layout of Unit 7, which follows a typical CFPS layout. However, it lacks an IP turbine and deaerator as it is an older, more simple design. The unit consists of the five main components, namely:

- The boiler (consisting of four primary air fans and pulverisers, two forced draught fans, two induced draught fans)
- Turbine train (consisting of one HP turbine with four stages, one LP turbine with two stages and two turbine rotors)
- Feedwater heater train (consisting of one LP heater and four HP heaters)
- Cooling circuit (consisting of one condenser, one pump and five shared cooling towers)
- Pumps (consisting of two condensate extraction pumps, one boiler feed pump and one cooling water pump)

The semi-empirical approach simplifies the model since it is based on actual station characteristics/data instead of being limited to only first principle design inputs.

The next step is to use measured station data to calibrate the model. Calibrating the model matches actual operating conditions with the simulation results. If reconciliation of the simulation results with actual station data is not possible, then it will indicate a shortcoming in the simulation model setup (illustrated in *Figure 3-1*). The next section discusses the final calibration and verification results from developing a simulation for CFPS A.

3.2.2. Calibration and verification of baseline

A combination of site visits using manual measuring equipment such as thermal temperature readers and data (real-time and historian averaged data) from the Supervisory Control and Data Acquisition system provides the data for the simulation. *Table 2-11* shows the key measurement points used.

For this study's application, the calibrated model should match the measured values to within 5 % of actual data. The results are shown in APPENDIX F: Baseline calibration results and summarised in *Table 3-1*. *Table 3-1* shows the calibration results for the two major components (boiler and condenser) and the overall performance parameters. Several of the measurements were either not available or were not of adequate quality, which is indicated by "not available".

The calibration procedure shows that the simulation model does not require all the parameters to compile a fair representation of the power station (within an accuracy margin of 5 %). If the accuracy margin is deemed too large or imprecise, then further detail can be added to the simulation model to better correspond with actual data.

Table 3-1: CFPS A calibration results

OVERALL				
	Unit	**Simulation**	**Actual**	**Error**
Gross power	MW	60.11	60.20	0.15 %
Net power	MW	57.90	58.00	0.16 %
Auxiliary power	MW	2.20	2.20	0.00 %
Coal usage	ton/hr	36.37	36.00	1.02 %
Heat input	MW	247.50	247.50	0.00 %
Thermal efficiency	%	23.39%	23.43%	0.16 %
Power produced per day	MWh	1389.65	1391.88	0.16 %

BOILER				
	Unit	**Simulation**	**Actual**	**Error**
Inlet	˚C	171.34	176.00	2.68 %
	MPa	6.64	6.59	0.73 %
Superheater outlet	˚C	479.96	480.00	0.01 %
	MPa	6.26	6.20	0.98 %

CONDENSER				
	Unit	**Simulation**	**Actual**	**Error**
Steam inlet	˚C	49.46	51.00	3.06 %
Quality at inlet	-	0.89	not available	not available
Condensate outlet	˚C	47.17	48.00	1.75 %
Cooling water inlet	˚C	23.50	23.00	2.16 %
Cooling water outlet	˚C	35.47	34.00	4.23 %
Pressure	kPa abs	12.04	12.20	1.32 %

The results showed that a semi-empirical simulation model is not over-dependent on the availability of data. Data collection is therefore made simpler and by developing the model to be fit for unique scenarios. However, lack of data increases model calibration complexity and time, i.e. the more data available, the quicker the calibration time due to less trial and error iterations. For example, only inlet pressures and temperatures are required to calibrate the feedwater heaters as observed from this case study.

The overall station data comparison did not exceed 1.02 % error which includes all components. The boiler and condenser errors do not exceed 2.68 % and 4.23 % respectively. Overall the calibration of the model is successful with all KMPs within 5 % error.

3.2.3. Condenser fouling

The key aspect of the study is to simulate and quantify the degradation of the condenser. Therefore, it was required to simulate fouling within the condenser. Literature showed that condenser back pressure would increase and outlet temperature would increase [22]. Therefore, the condenser’s outlet temperature is directly related to the amount of fouling within the condenser.

Section 2.4.4 describes the method used to artificially foul the condenser for CFPS A. *Figure 3-2* plots the output from this method.

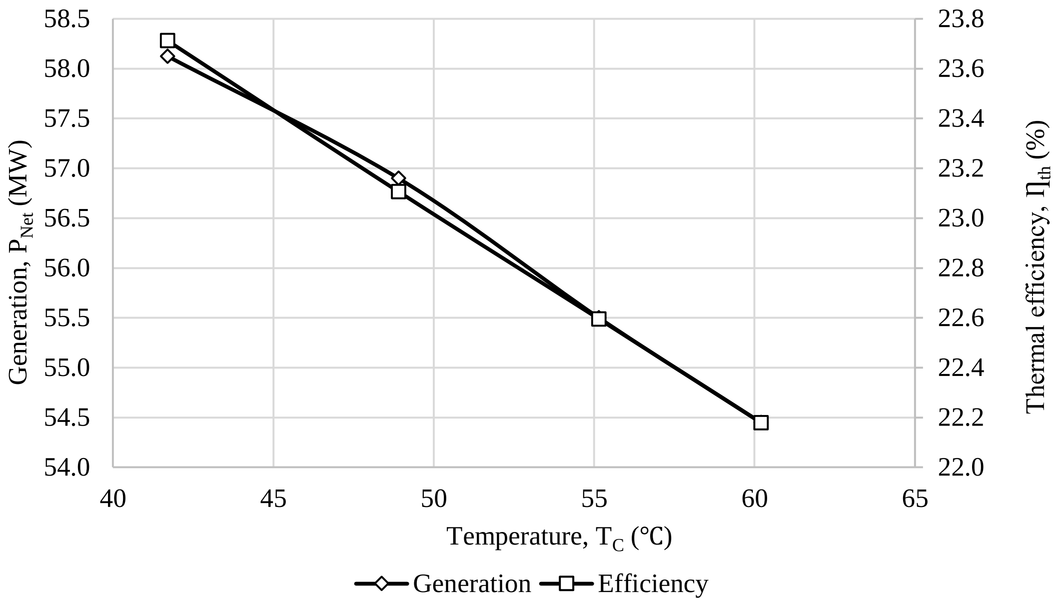


Figure 3-2: Station generation and efficiency as a function of condenser condition

Figure 3-2 plots the station performance curves against the condenser outlet temperature, which increases over time. The maximum performance is reached at a clean condenser condensate temperature of 41 ℃ with a maximum net generation of 58.13 MW and thermal efficiency of 23.71 %. Minimum performance is reached at a condensate temperature of 60 ℃ with a net generation of 54.48 MW and 22.18 % thermal efficiency. The condensate temperature range of 41 ℃ to 60 ℃ is sufficient to cover the entire operating range of the condenser.

Equation 3-1 and *Equation 3-2* describes the performance of the unit as a function of its condenser outlet temperature. The regression parameters are determined by simulating the different fouling scenarios.

Equation 3-1: Station generation as a function of condenser outlet temperature

$$\eta_{th} = -0.0828T_C + 27.161$$

where η_{th} is the thermal efficiency and T_C the condenser outlet temperature.

Equation 3-2: Station efficiency as a function of condenser outlet temperature

$$P_{Net} = -0.201T_C + 66.568$$

where P_{Net} is the net generation in MW.

Equation 3-1 and *Equation 3-2* provides the prediction of the station performance based on the verified simulation model. The next step is to use these equations in the prediction model to determine the daily performance of the unit over time.

3.3. Condenser maintenance prediction and results

3.3.1. Maintenance prediction model setup

The maintenance prediction model is the final step in determining the maintenance schedule of the equipment and determines the cost to operate and revenue of the unit on a per-day basis. The equations derived in the previous section form part of the prediction model to include the simulated parameters specific to the unit under investigation. Additional inputs are required to relate condenser performance to financial outcomes over time. *Table 3-2* shows CFPS A's inputs to the prediction model.

Table 3-2: Prediction model inputs

Description	**Unit**	**Value**
Last clean	Date	2018/11/05
Clean condensate temperature	℃	43
Type of fouling	Linear/Exp	Exp
Linear fouling rate	℃/day	NA
Exponential coefficients	T_{cc}	43
	B	80
	n	2.8
Average breakdowns per year	number/year	5
Average time to rectify	days	2
Condenser cleaning price	R/unit	-R170 000.00
Time to clean the condenser	days	5
Cost per kWh sold	R/kWh	R0.86
Coal price	R/ton	R0.00

The temperature curve parameters (T_{cc}, B, n) were determined using *Equation 2-3* and past data obtained from a data dump of Unit 7. The average number of breakdowns and time to rectify is calculated from past data. The cost and time to clean the condenser is noted from previous cleans of condensers at CFPS A. The selling price is set at the average Eskom tariff[40]. Note that CFPS

[40] Eskom Historical average prices and increase "*www.eskom.co.za/CustomerCare/TariffsAndCharges/Documents/Historical average prices and increase_v20160707.xlsx.*"

A is under an agreement where it does not pay for its coal supply. CFPS A excludes coal in the selling price of its supplied electricity. Therefore, CFPS A's expenditure only consists of fixed costs such as salaries, utilities and maintenance. The R0.00 coal cost is a unique scenario which affects the outcome of the prediction model. The model inputs are therefore unique to the power station under investigation, which emphasises the need for solutions that can be tailored to unique scenarios.

3.3.2. Predictive model results

The prediction model iteratively runs through numerous combinations of cleaning schedules in a user-specified range. In this case from 105 days to 285 days between cleans. *Figure 3-3* shows the average daily profit for each specific maintenance schedule. Fitting a polynomial curve can to the data estimates the average expected daily profit depending on the maintenance schedule. The change in average daily profit seams insignificant, however the maximum plotted loss of approximately R15 000 (R1 138 000 to R1 153 000) per day is significant when considered over a longer period such as a year.

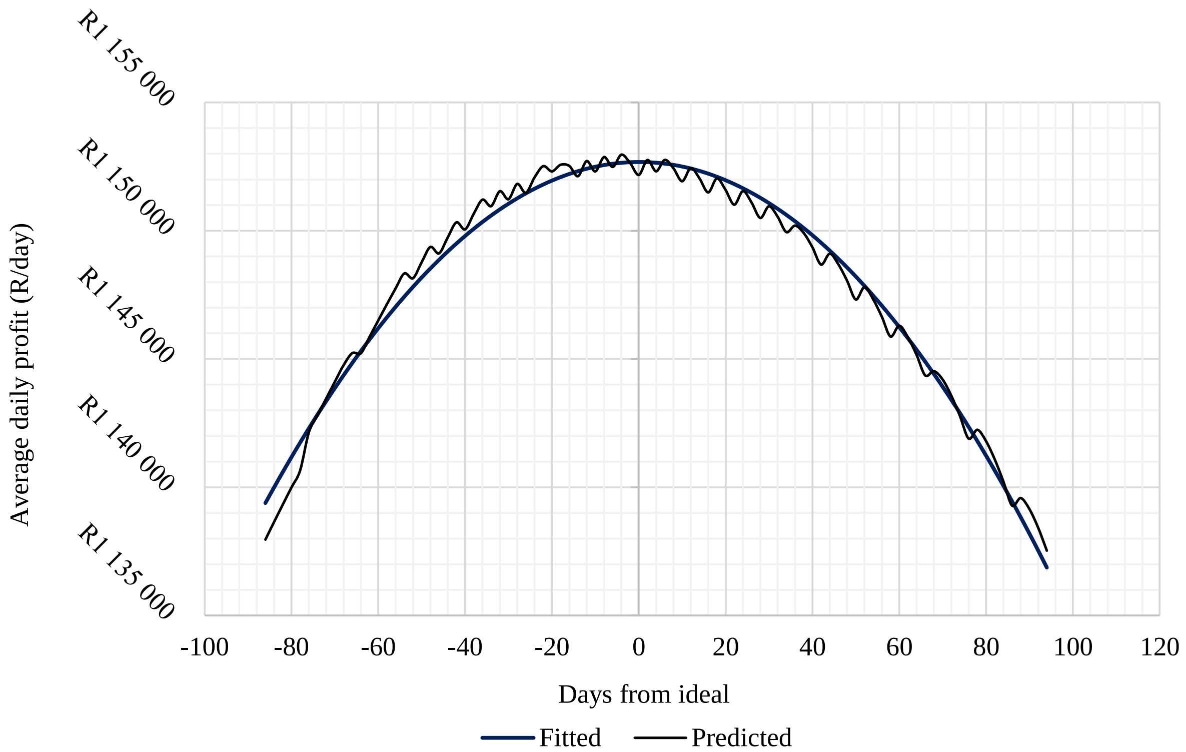


Figure 3-3: Maintenance curve (Time-based, without breakdowns)

The fit in *Figure 3-3* excludes the possibility of breakdowns. As the stations the study is applicable is of considerable age and regularly experience unplanned outages. Therefore, random breakdowns were incorporated to improve the representativeness of the prediction model further. Historical data provided the average number of breakdowns per year and the average time to rectify. Including the breakdowns and rectifying time as an input, resulting in *Figure 3-4*.

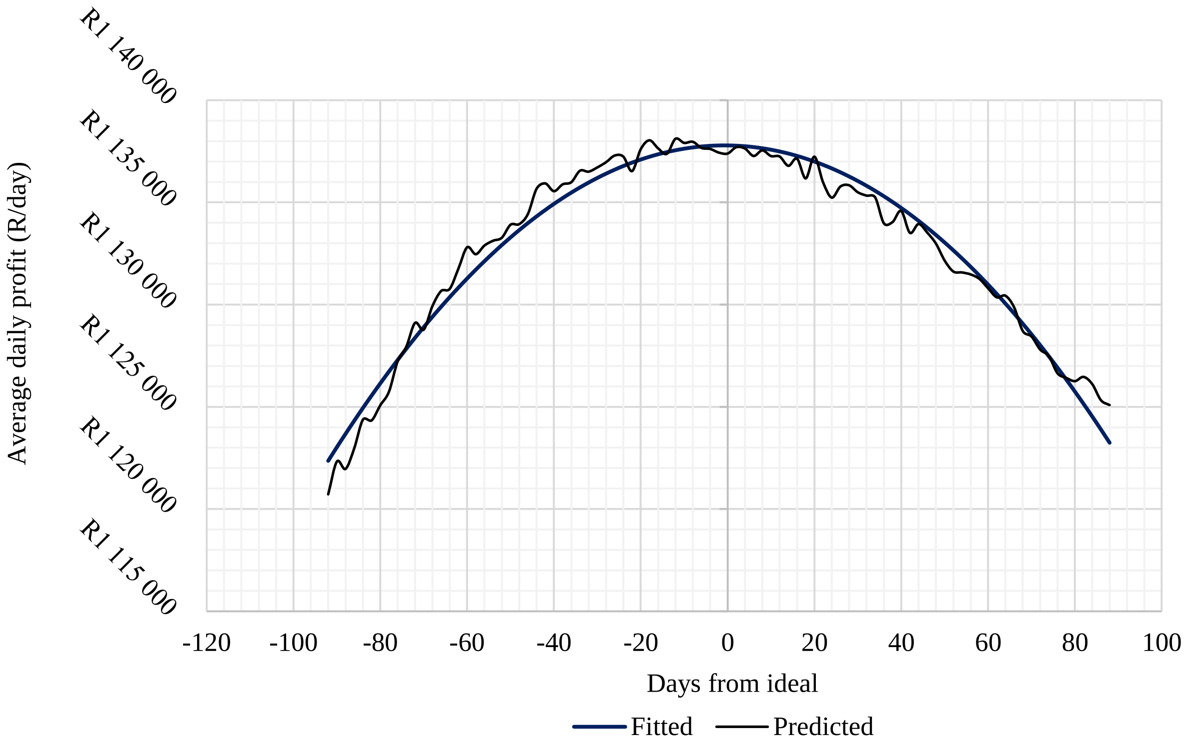


Figure 3-4: Maintenance curve (Time-based with breakdowns)

Figure 3-4 indicates that unplanned outages have a small effect on the maintenance schedule. However, there still exists a large loss in revenue due to the outage. Ignoring unplanned outages has little to no effect on the output of the model. The maximum difference of R15 000 (R1 122 000 to R1 137 000) is the same as the calculation with no unplanned outages. Therefore, unplanned outages are ignored and save calculation time.

Additionally, the average daily profit as a function of the condenser outlet temperature can be estimated since the past temperature curve is known. *Figure 3-5* is obtained from a similar function as the time-based prediction and shows the unit performance as condenser outlet temperature increases due to fouling. The condenser condensate outlet temperature is seen ranging from a minimum of 51 ℃ to a maximum of 63 ℃, which falls within a typical condensers operating range [27]. The minimum and maximum profit is the same as the curve plotted according to days from ideal.

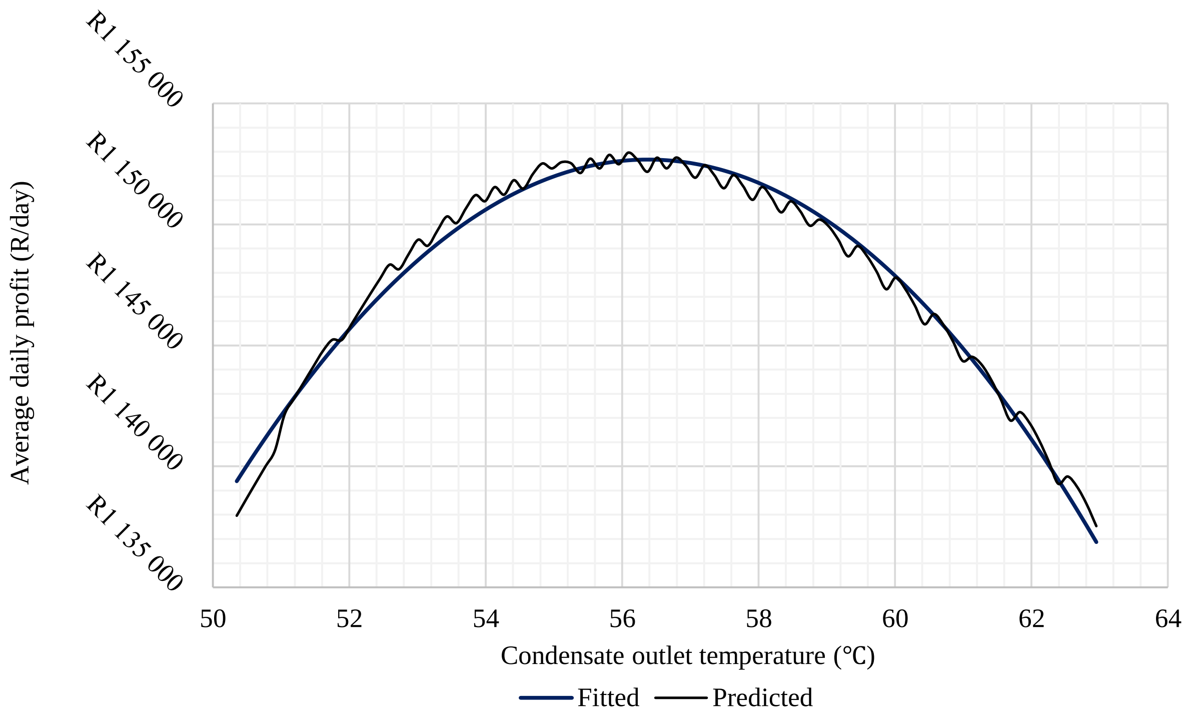


Figure 3-5: Maintenance curve (temperature-based without breakdowns)

Similar to *Figure 3-4*, *Figure 3-6* indicates that breakdowns or unplanned outages have a small effect on the maintenance schedule and prediction model. Removing the necessity to include breakdowns in the prediction model and saving calculation time. The minimum and maximum profit is the same as the curve plotted according to days from ideal.

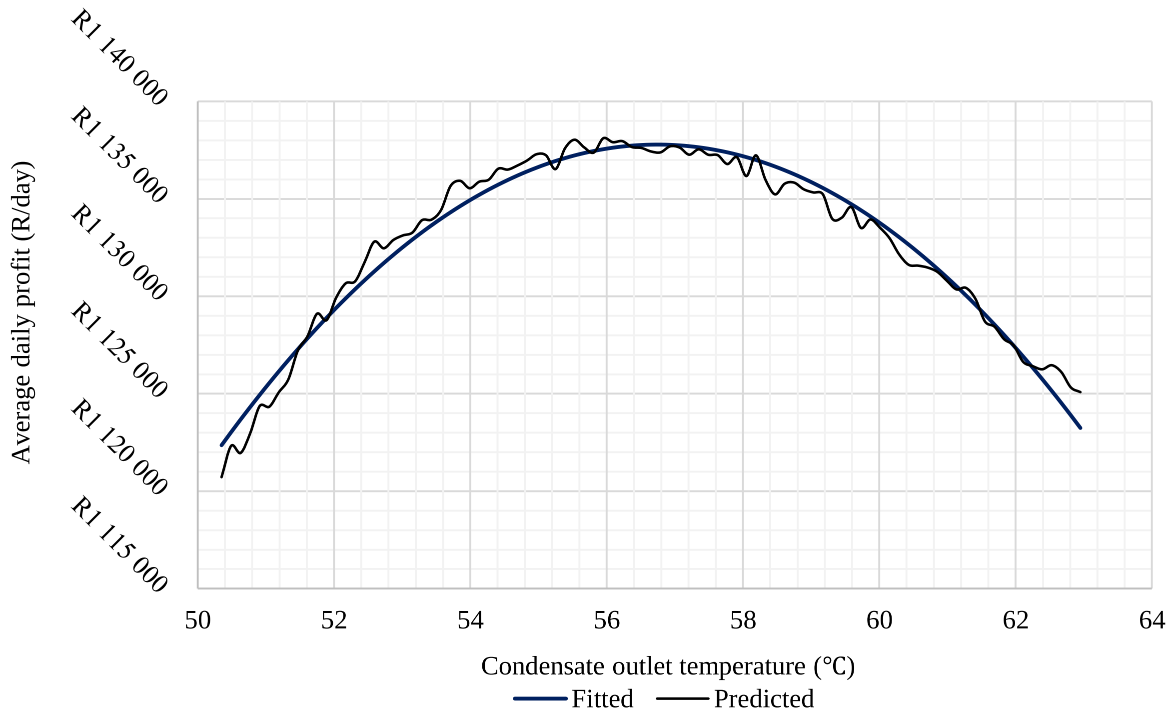


Figure 3-6: Maintenance curve (temperature-based with breakdowns)

Finally, from the results obtained in *Figure 3-3* and *Figure 3-5*, a summarised results table is generated and displayed as *Table 3-3*.

Table 3-3: Prediction model summarised outputs

Maintenance plan		
Best average profit	R/day	**R1 152 678.76**
Days between full clean	days	**191**
Suggested maintenance date	Date	**2019/05/15**
Suggested condensate outlet temperature	℃	**56.4**

Table 3-3 indicates that scheduled maintenance is on **2019/05/15** after **191** days from the previous clean on **2018/11/05** or at a condenser outlet temperature of **56.4 ℃**.

Figure 3-7 indicates the effect of early or late maintenance by comparing the maximum achievable average daily profit to the average daily profit of conducting maintenance earlier or later than ideal. The plotted curve is the average loss in profit per year as compared to the ideal maintenance schedule.

From *Figure 3-7*, it was possible to derive an average yearly loss equation depending on the time of year and condensate outlet temperature as is shown in *Equation 3-3* and *Equation 3-4*.

Equation 3-3: Expected average yearly loss in profit (time-based)

$$P_{loss} = 0.0068d^2$$

Where P_{loss} is the loss in profit in Rands (R100k) and d the amount of days before or after maintenance.

Equation 3-4: Expected average yearly loss in profit (temperature-based)

$$P_{loss} = 1.4{T_C}^2 - 156.4T_C + 4437$$

Where T_C is the condenser condensate outlet temperature.

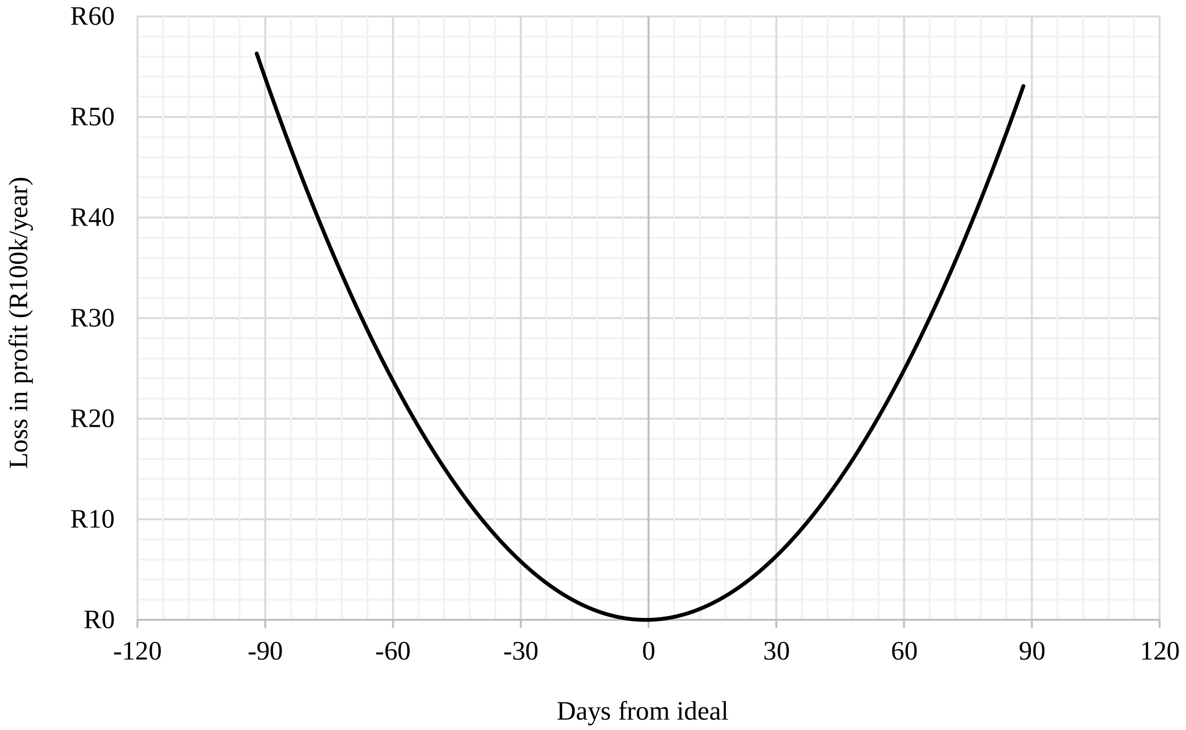


Figure 3-7: Loss in profit curve

Figure 3-7 indicates that maintaining 30 days early results in an annual loss of R581 000 and maintaining 30 days late results in an annual loss of R635 000. *Table 3-4* summarises the headline figures. Early or late maintenance has a large effect on the profit over a year, of which the effect may not be visible daily. As a result, condenser maintenance may be neglected.

Table 3-4: 60 MW unit loss in profit per annum

Days from ideal	**Loss per annum**
Single 60 MW unit	
30 days early	R581 000
30 days late	R635 000
60 days early	R2 376 000
60 days late	R2 485 000

3.3.3. Comparison with actual station maintenance

Fortunately, unit 7 could be analysed immediately after its condenser clean on **2018/11/05** and therefore a good baseline could be developed. The predictive model was applied to unit 7 which suggested a suggested condenser maintenance date of **2019/05/15**.

The station notified that unit 7 was cleaned on **2019/06/10** due to significantly reduced unit performance from condenser fouling. The clean date is 25 days from the suggested clean date, implying a yearly profit loss of R411 000 as indicated in *Figure 3-7*.

As a result, the station's maintenance schedule has been adapted to allow for two condenser cleans per unit per year. Thus, providing maintenance intervals of 182.5 days which is in line with the suggested 191 days between cleans.

3.4. Review of the simulation-based approach

The simulation-based approach proved to be effective in determining maintenance schedules for a CFPS condenser. The integrated simulation assists in determining the integrated effect of a single component in a complex system. The integration allows greater confidence in the results. The approach applies to any component of any complex system such as a CFPS.

To summarise the simulation-based predictive maintenance model follows a generic ten-step process for determining a predictive maintenance model for the condenser. The ten steps include:

1. Obtain data for a specific unit
2. Model the specific unit (using chosen simulation software)
3. Calibrate unit according to baseline
4. Introduce component-specific degradation (fouling) in simulation
5. Obtain performance parameters as a function of degradation (fouling)
6. Apply to the prediction model
7. Predict daily station performance and costs
8. Iterate for multiple estimates of days between maintenance schedules
9. Find the best average daily profit
10. Obtain cost breakdown and maintenance schedule

The integrated generic approach has some key advantages as compared to the standard hand calculations:

- Semi-empirical
    - Do not require all the data
- Quick simulation turnaround (once modelled and calibrated)
- The method is generic
    - Used for any part of the station or equipment

- Simulation and prediction model assist with:
    - financial decision making
    - operational decision making
    - improving the lifespan of the equipment

However, as with any approach, there are some disadvantages:

- Time and complexity vary depending on the number of parameters available for model calibration

3.5. Estimating the potential of extended applications

Due to South Africa's large reliance on CFPS, it is of interest to investigate the effect on non-maintenance or late maintenance on their CFPS fleet. Therefore, using the prediction model and simulation results obtained from the 60 MW Unit 7, the approach was extrapolated to a 350 MW unit. *Table 3-5* shows the extrapolated inputs and *Figure 3-8*, *Table 3-5* and *Table 3-6* shows the results.

Table 3-5: Extrapolated model inputs

Description	**Unit**	**Value**
Last clean	Date	2018/11/05
Clean condensate temperature	°C	41
Rated generation	MW	350
Clean efficiency	%	32
Type of fouling	Linear/Exp	Exp
Linear fouling rate	°C/day	0.07
Exponential coefficients	T_{cc}	41
	B	80
	n	2.8
Average breakdowns per year		5
Average time to rectify	days	2
Condenser cleaning price	R/unit	-R1 000 000.00
Time to clean the condenser	days	5
Cost per kWh sold	R/kWh	R0.86
Coal price	R/ton	R420.00

The extrapolated inputs are similar to that of Unit 7 with the major exceptions being the inclusion of coal cost, higher efficiency, higher generation and increased cost to repair the condenser. The cost to clean the condenser was directly extrapolated from CFPS A's cost to clean by $C_{350MW} = \frac{350}{60} \times C_{60MW}$ where C_{350MW} is the cost to clean a 350 MW condenser and C_{60MW} is the cost to clean a 60 MW condenser. The fouling of the condenser was assumed to be similar to CFPS A's Unit 7.

Applying the prediction model to the new extrapolated inputs, we obtain *Figure 3-8*. *Figure 3-8* indicates the loss in profit for the extrapolated 350 MW unit. The monetary effect of early or late maintenance is significantly more than CFPS A's case study. With 30 days early or late maintenance resulting in R4 million loss per year for a single generating unit.

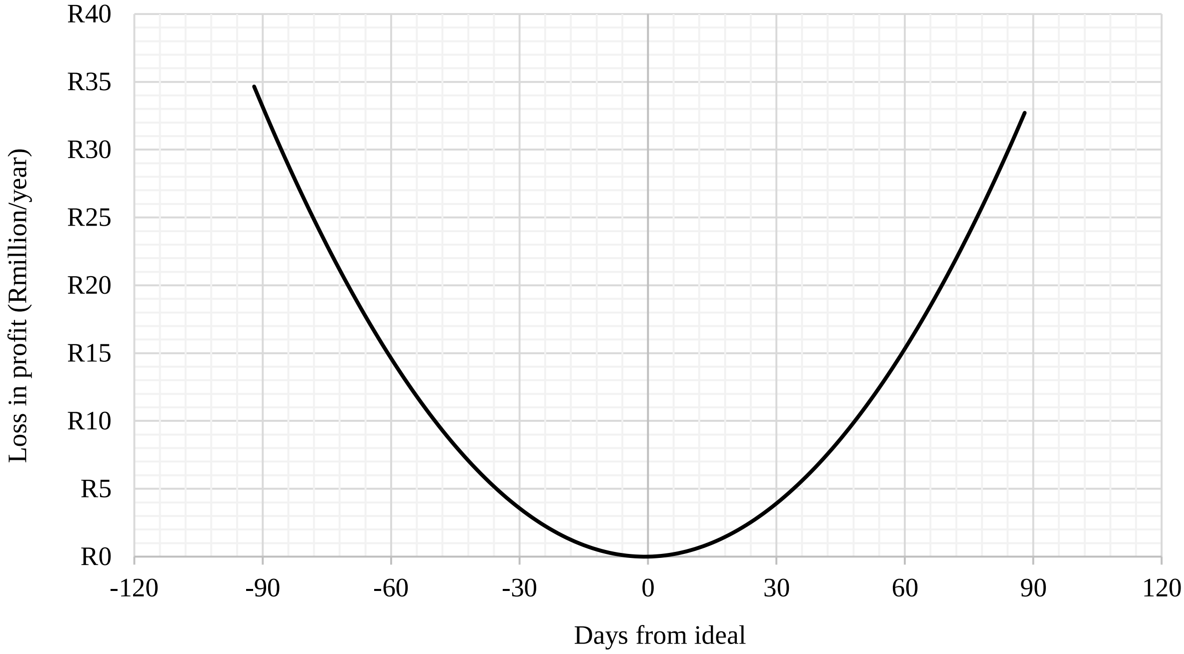


Figure 3-8: Extrapolated loss in profit curve

Finally, *Table 3-6* summarises the results of the extrapolated model showing the best daily profit of R5 million, a maintenance schedule of 7 months or at a condensate outlet temperature of 55.3 ℃. The results are very similar to that of CFPS A's case study and are as a result of the assumed similar fouling rate of the condenser.

Table 3-6: Extrapolated model outputs

Maintenance plan		
Best average profit	R/day	**R5 067 368.18**
Days between full clean	days	**207**
Suggested maintenance date	Date	**2019/05/31**
Suggested condensate outlet temperature	℃	**55.3**

The results for a large 350 MW unit can now be used to determine the effect of maintenance on condensers when extrapolated over the entire South African CFPS fleet of 34 GW. Extrapolating the method provides an estimation of how significant the consequence of late or lack of maintenance can be. Comparing the summation of average loss in profit per year for all Eskom CFPS units with late maintenance in terms of days from the ideal schedule, we obtain *Table 3-7*.

Table 3-7: Extrapolated loss in profit over entire Eskom CFPS fleet

Days from ideal	**Loss per annum**
Single 350 MW unit	
30 days early	R3.57 million
30 days late	R3.92 million
60 days early	R14.62 million
60 days late	R15.32 million
Eskom CFPS (Average 23 GW)	
30 days early	R234.6 million
30 days late	R257.6 million
60 days early	R960.7 million
60 days late	R1006.7 million

Table 3-7 may not be an accurate representation of the actual effect due to extrapolation errors. However, the effect of early or late maintenance over the entire baseload fleet is still tangible. With operational losses ranging between R240 million (one month from ideal) and R1 billion (2 months from ideal). *Table 3-7* gives an indication of the scale of importance regarding effective and planned CFPS maintenance.

3.6. Conclusion

In this chapter, a South African 60 MW CFPS unit was modelled, calibrated and verified to within 5 % of station data. The simulation was then used to derive the performance characteristics of the unit and then applied to the maintenance prediction model. The model suggested maintenance of the condenser every six months approximately, with actual maintenance schedule from the station occurring within a month of this bracket.

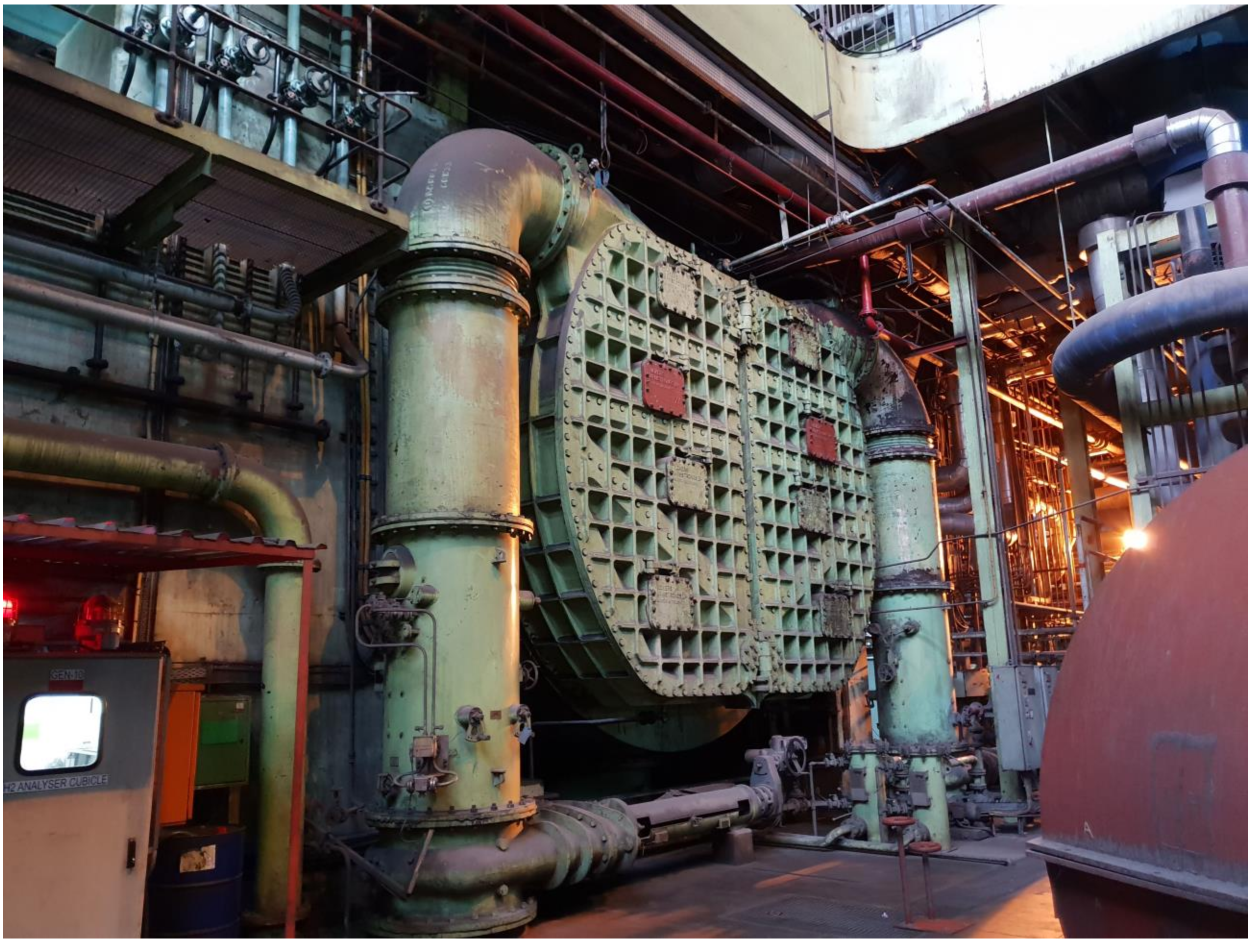
The model allowed quantification of the loss of profit when maintenance schedules deviate from the ideal scenarios. The quantification of these results based on verified simulation model is expected to assist with decision support when implementing maintenance plans. The simulation-based approach is also reviewed to comment on the usefulness of a semi-empirical simulation model in practice.

The results from the 60 MW study was applied and extrapolated to a 350 MW unit in order to estimate the losses that would occur when applied a larger power station. The extrapolated model showed unit losses reaching approximately R3.6 million a year as a result of 30 days yearly or late maintenance. This amount increases to R14.6 million for 60 days early or late maintenance.

Further, extrapolating these results showed an estimate of R236.6 million per annum loss to the entire South African CFPS fleet due to 30 days early or late maintenance and R1 billion loss due to 60 days early or late maintenance.

The results confirm the importance of planned maintenance and indicates that the overall effect is not negligible, however it is not immediately evident. The tool is therefore of use to a company such as Eskom in that the monetary effect of maintenance scheduling can be visualised in real-time.

Chapter 4: Conclusion



A CFPS condenser

The background and state of art around coal-fired power station condenser maintenance and simulation.

4. Conclusion

4.1. Preamble

This chapter provides an overview of the study focusing on the problem identified, the approach followed to solve the problem and the results from implementing the solution on a case study. Each section's key points are also discussed with the aim to confirm that the developed solution meets the expectations set in the problem statement and objectives.

4.2. Study overview

The South African power generation industry is under pressure due to steadily rising coal costs and new build projects falling behind schedule. The country's utility company, Eskom, is thus faced with a unique challenge owing to its ageing CFPS fleet which makes up the majority of their generation capacity. The increased pressure on older CFPSs necessitates increased maintenance in turn. It was therefore, determined that a process was necessary to maintain these stations as efficiently and effectively as possible. An effective maintenance plan assists with station availability, contributes to reduced operating costs and increased performance.

One of the maintenance-intensive components of a CFPS station is the condenser. Several studies were considered around station performance as a function of condenser performance. The studies showed that the condenser does indeed have a large effect on the performance of the CFPS and requires regular maintenance.

In order to investigate the maintenance techniques available, several studies concerning maintenance and the applicable techniques for CFPSs were considered. The conclusion drawn from the literature indicated a movement away from reactive maintenance to more accurate proactive maintenance. The proactive maintenance techniques included condition-based maintenance and time-based maintenance.

Typically, maintenance schedules or limits would be set by a manufacturer and were determined from extensive testing. However, the CFPS environments have significantly changed, and OEM maintenance schedules and plans from 60 years ago may not be relevant. Therefore, a representation of the current operating performance was required.

Simulation software was deemed to be the best solution to provide a representation of the current operating performance. The simulation software was required to simulate the integrated station, including all major components. Additionally, the software was required to show the integrated effect of station degradation. The chosen software, Process Toolbox, was an in-house developed software package providing in-house assistance and development support.

Using PTB, a generic CFPS model was built by starting from a simplified model and adding complexity as necessary. Each component was calibrated individually with generic values before ensuring the components reach steady-state conditions. The calibrated components were then added to the integrated model and the final calibration and verification took place. With a verified integrated CFPS model the performance analysis of the station was completed. Degradation was introduced into the condenser in the form fouling by reducing the heat transfer coefficient in the simulation. The increased fouling resulted in reduced station performance which was captured by the integrated simulation as reduced generation and efficiency.

The results thereof were used to set up a prediction model that calculates daily operating costs and profit as performance reduces. Using the reduction in performance, an iterative predictive model determines the ideal day to perform maintenance. The results are dependent on user-specified parameters unique to the CFPS under investigation.

As a case study, a 60 MW CFPS unit was modelled using the unique simulation-based approach towards energy management to help identify savings opportunities at a SA-based station. The model was calibrated and found to be within 5 % of measured data. Using the model, an opportunity was identified whereby condenser maintenance scheduling could be improved. Consequently, if implemented correctly, station performance would be improved, and profit loss would be minimised. Correct application of the model suggested maintenance of the condenser every six months, which coincided to within a month of the actual maintenance schedule used by the station.

The results from the 60 MW study were extrapolated to a larger 350 MW unit (comparable to a larger Eskom station) where it was predicted that a unit loss of approximately R3.6 million per year could result from 30 days premature or delayed maintenance. This amount increases to R14.6 million per year for 60 days premature or delayed maintenance. Extrapolating for a larger fleet, averaging at 23 GW, similarly led to estimates of R240 million and R970 million losses for 30- and 60-days incorrect maintenance, respectively.

Table 4-1 summarises the study's results and highlights the importance of optimised maintenance scheduling in CFPSs and indicate the immense potential of advancing similar studies.

Table 4-1: Summary of study results

Actual maintenance	Loss per annum
Single 60 MW case study unit (every 6 months or at a condenser outlet temperature of 56.4 °C)	
One month early	R581 000
One month late	R635 000
Two months early	R2 376 000
Two months late	R2 485 000
Single 350 MW extrapolated unit (7 months or at 55.3 °C)	
One month early	R3.57 million
One month late	R3.92 million
Two months early	R14.62 million
Two months late	R15.32 million
Extrapolated all Eskom CFPS (Average 23 GW)	
One month early	R234.6 million
One month late	R257.6 million
Two months early	R960.7 million
Two months late	R1006.7 million

4.3. Shortcomings

There are some shortcomings in the new method, some of which are discussed below:

- Since the study only considered a single case study, the accuracy of the model will be improved by including additional CFPS simulations and predictive models.
- The study only considered steady-state operating conditions and did not look at part-load operations and dynamic plat changes.
- The study did not consider an active Eskom station. Extrapolation may introduce inaccuracies which may not provide an exact representation of the Eskom CFPS fleet.
- The study did not consider simultaneous degradation of other station equipment. The degradation of other components will increase the rate at which station performance reduces. Therefore, the predictive model might provide different maintenance scheduling.

4.4. Recommendations for future work

The recommendations for future work in the field include:

- Applying the method to a larger CFPS with more accurate instrumentation and data. The increased accuracy of actual data will validate the predictive maintenance model's ability to scale. Additional extrapolation of larger units will not be required.
- Eskom is experiencing major concerns with long term pipe leaks within boilers. Therefore, a study on the effect of the pipe leaks using the integrated simulation will reveal the severity of the problem and necessity to rectify pipe leaks. Also, pipe leak priorities can be determined. This study will test the generic nature of the model.
- An investigation into variable speed drives (VSDs) for dry-cooling condensers where VSDs are not installed. Where part-load conditions on dry-cooling towers may exist, VSDs will assist in reducing the required power by the cooling fans on the dry-cooling towers.
- Using the simulation tool to simulate a maximum generation scenario whereby flow is reduced to FWHs, and maximum generation is achieved at the cost of efficiency. The proposal may assist the South African stations in meeting peak demands.
- Use the integrated simulation and predictive model for different components on the station simultaneously. The boiler, condenser, pumps and turbines are degraded simultaneously, and a schedule or condition-based limit determined from the model whereby each component will have an individual maintenance schedule or condition-based limit.
- Fully integrated simulation of all Eskom's stations, which determines a maintenance risk factor for each station. The risk factor will depend on each CFPSs availability and current operating performance. Where the worst performers will have the highest risk factor and require the most attention regarding maintenance and rehabilitation.

4.5. Concluding remarks

The study discussed the South African generation environment and developed a tool which is able to assist with the current operating challenges. Specifically focusing on effective condenser maintenance, improving operating profit through correct scheduling and minimising unplanned downtime. The tool is based on a simulation model which is adaptable to current operating conditions and provides real-time answers to maintenance specific problems. The tool is also generic and can be applied to any CFPS and any component found in a CFPS.

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A. APPENDIX A: Basic CFPS components

The five fundamental thermodynamic components are and highlighted as:

- Boiler: RED
- Turbines: ORANGE
- Cooling circuit BLUE
- Feedwater heaters:
- Pumps: GREEN

These five fundamental components operate according to the Rankine Cycle [16]. Visualising the process flow may be complex. A temperature vs entropy diagram (T-S), as seen in *Figure A-1*, assists in this regard. Temperature is plotted on the y-axis. It is the temperature at which the working fluid (steam in the case of a CFPS) operates. Entropy is plotted on the x-axis and indicates the “chaos” or energy found in the working fluid at each stage. An increase in entropy is seen where heat is generated such as in the case of the boiler. Inefficiencies in the process are indicated by increased entropy during compression (green pump) and expansion (orange turbine).

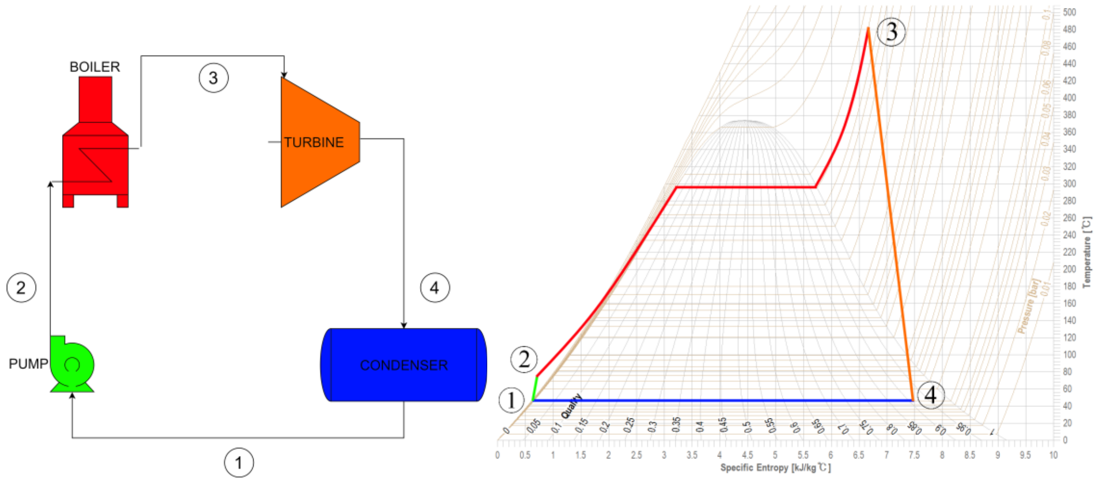


Figure A-1: Basic cycle components and T-S diagram

Several other components form part of the station. However, the focus of the study is on the fundamental thermodynamic process. These other components do not have a significant effect on the efficiency and generation of the station.

Boiler

At the core of every power station, there is a boiler. The primary function of the boiler is to convert solid potential energy, obtained from numerous sources, in this case, coal, and convert it to heat energy which is transferred to water to generate superheated steam. Several different coal-fired boiler designs exist; however, to simplify the background, only the applicable boiler design will be discussed, which in this case, a drum boiler design. This design is illustrated in *Figure A-2*.

The boiler has two basic states of operation, either start-up or steady operating conditions at a target outlet temperature [41].

The boiler receives pulverised coal from the mills through coal pick up from primary air (PA) fans which capture the pulverised coal and transports it to the boiler.

The boiler, at steady-state, has an internal fire temperature in the region of 2000 ℃ and ignites the incoming coal [42]. Diesel fuel burners are sometimes used to regulate the temperature inside the boiler and assist with boiler control.

Several heat transfer mechanisms facilitate the transfer of heat from the combustion of coal to the water/steam. The heat transfer mechanisms include; radiance (largest effect), convection and conduction. The heat concentration and temperatures from the combustion of coal can be seen in *Figure A-3*. Thousands of km’s of piping contains the water/steam, which increases the surface area for heat transfer [43].

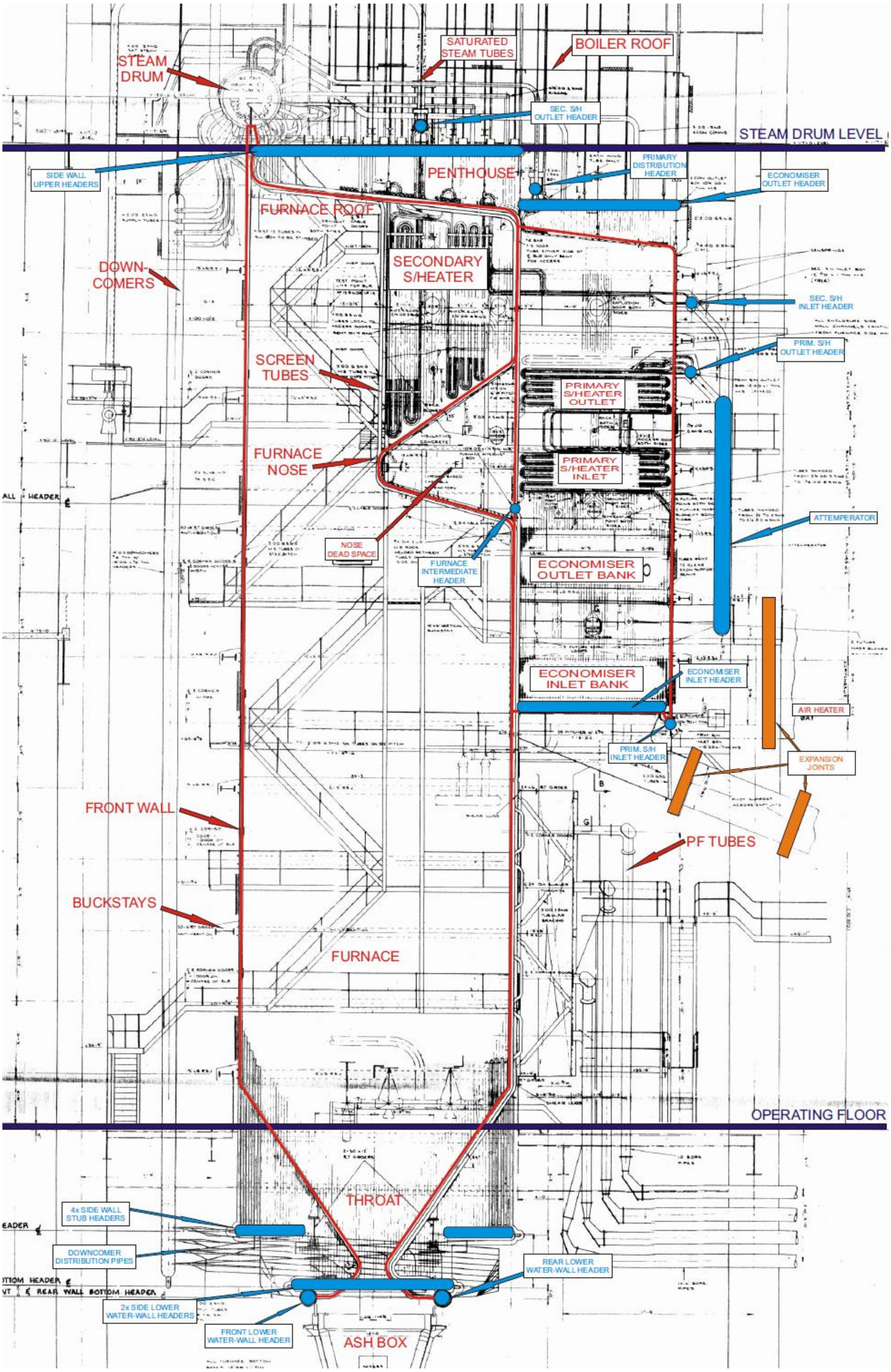


Figure A-2: Drum type boiler side view schematic[41]

[41] Obtained from case study CFPS A

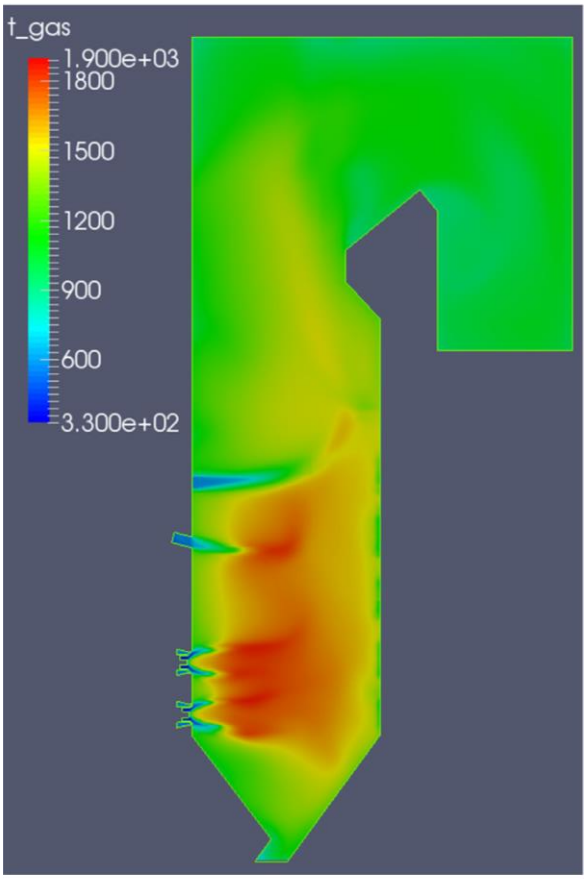


Figure A-3: Internal temperatures of a drum-type boiler [42]

The boiler typically contains several sections to capture all the energy from the combustion of coal, namely:

- Economiser
- Drum
- Wall
- Superheater (several)
- Reheater
- Air heater

Each section is highlighted in *Figure A-2* except for a reheat system. However, it is typically situated after the superheater and before the economiser in the boiler gas flow. Boilers can operate with efficiencies in the upper 90 %[42] [17].

[42] Internal boiler acceptance test document.

Turbine

The function of the turbine is to turn potential heat energy into rotational kinetic energy. This occurs when high pressure, high-temperature steam is allowed to expand through the turbine and as a result, applies a force on the turbine blades which are free to rotate.

Modern power stations typically utilise three turbines with different designs to operate most efficiently at their respective pressures. There typically exists three pressure ratings for the turbines, namely the:

- High pressure (HP) turbine (*Figure A-4*)
- Intermediate pressure (IP) turbine (*Figure A-4*)
- Low pressure (LP) turbine (*Figure A-5*)

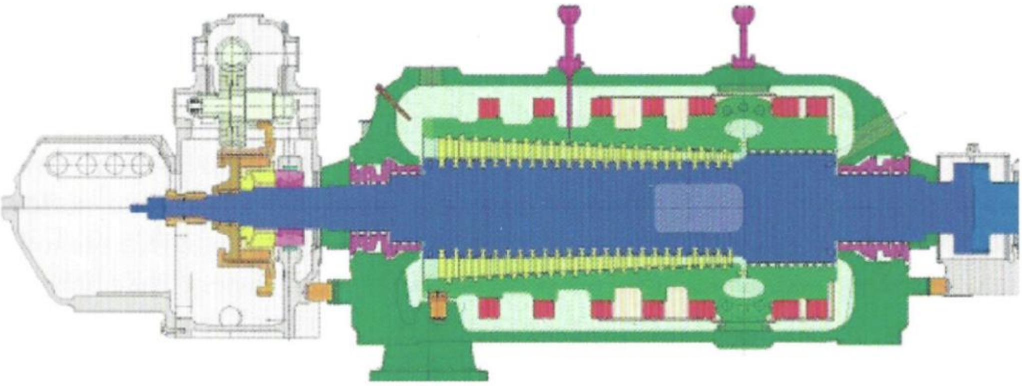


Figure A-4: Typical turbine schematic [44]

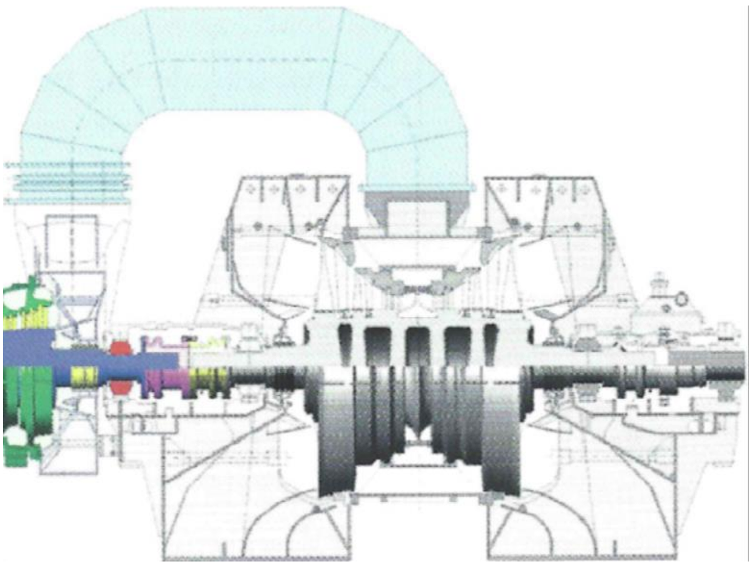


Figure A-5: Low-pressure turbine schematic [44]

Turbines trains found in a typical power station have conditions and performances as shown in *Table A-1* [20], [44], [45], [46], [47].

Table A-1: Typical turbine design conditions and performance

Type	**Upper**	**Lower**
Temperatures	500 – 900 ℃	25 – 35 ℃
Pressure	6 – 35 MPa	4 - 10 kPa
Efficiency	90 %	80 %

Feedwater heaters

The purpose of the feedwater heaters (FWH) is to preheat the feedwater from the condensers before the boiler. The use of FWHs reduces the load on the boiler and increases station efficiency. As a result, the size of the boiler can decrease. The heaters achieve this through a staged arrangement at different pressures and temperatures of steam. The turbine train feeds bled steam into shell and tube heat exchangers at different temperatures and pressures. A steam feedwater heater is shown in *Figure A-6*.

A typical arrangement of FWHs consists of 2-4 HP heaters found after the deaerator (450 kPa to 4 MPa up to 8 MPa) and 2 – 3 LP heaters found before the deaerator (80 kPa to 450 kPa) [20]. Feedwater temperature rise over a single FWH can reach up to a delta T of 50 ℃ and a total temperature rise from FWH train inlet to boiler inlet of 220 ℃.

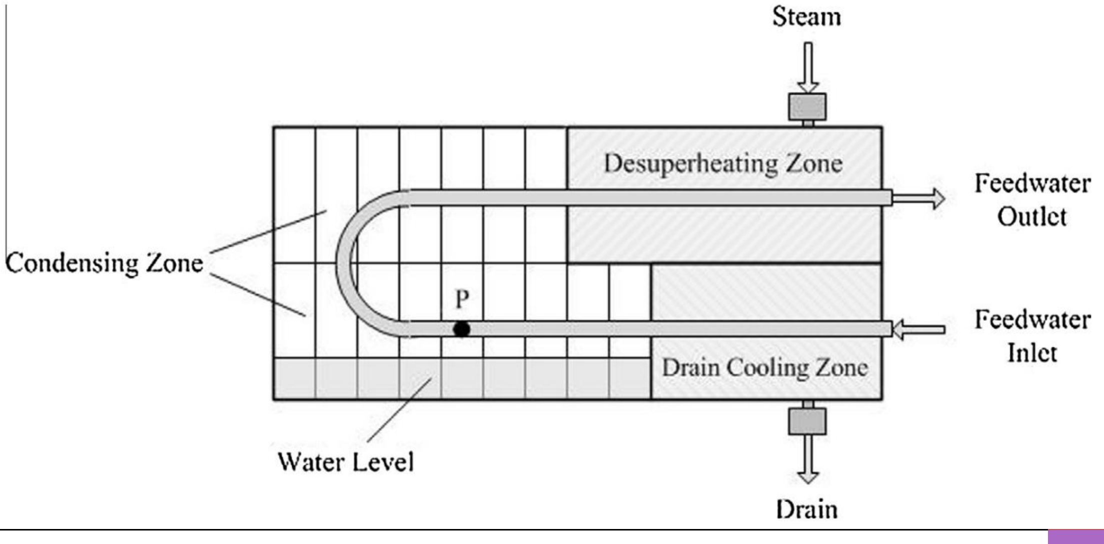


Figure A-6: Feedwater heater schematic [48]

Pumps

There are several stages of pumping in the cycle; most importantly, these serve to return the low-pressure condensate from the condenser to the required high-pressure feedwater. The feedwater returns to the boiler. There are two types of main boiler feed pumps, namely the electric feed pump (*Figure A-7*) and steam feed pump or steam-driven pump (*Figure A-8*).

Figure A-7: Multi-stage electric feed pump

The EFP operation is the same as a standard pump taking condensate from pressures of 200 kPa to 18 MPa. Flow rates can reach 1000 kg/s at 10 MW [49][43].

[43] KSB Boiler feed pump "https://www.ksb.com/centrifugal-pump-lexicon/boiler-feed-pump/191374/"

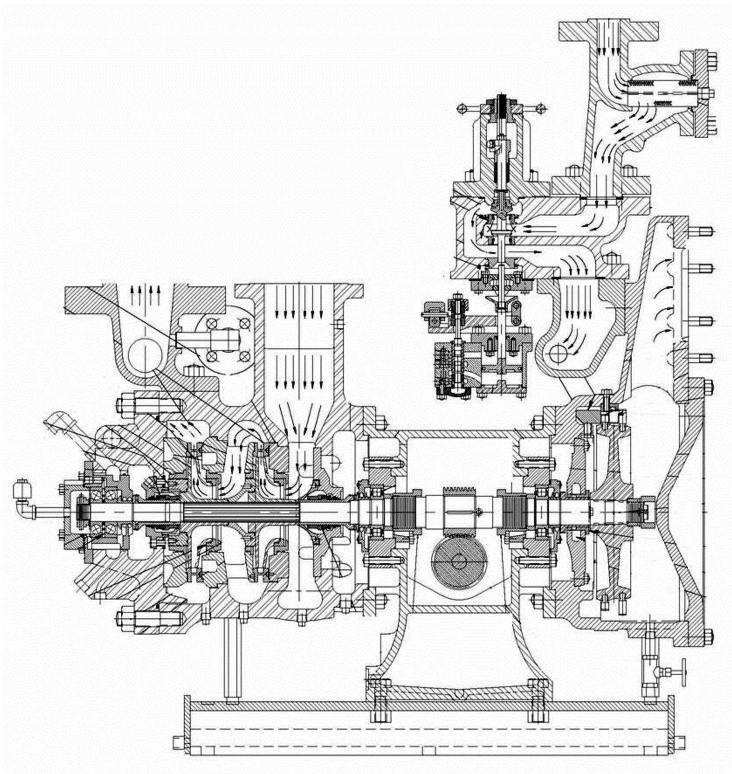


Figure A-8: Multi-stage steam-driven pump schematic[44]

The SFP operation is different from that of an electric pump in the sense that it uses steam from the main cycle to drive the pump. The addition of a steam-driven pump can increase the efficiency of a cycle by up to 1 % [45].

Full cycle

The combination of the critical components results in a closed steam cycle that generates electricity from the combustion of bituminous coal [17]. There are more efficient cycles that use combined cycles, low-pressure systems and heat recovery systems. However, for this study, only the conventional configuration will be considered as all of Eskom's power stations follow a standard Rankine cycle[46]. *Figure A-9* shows a functioning power station with all the key components and placement.

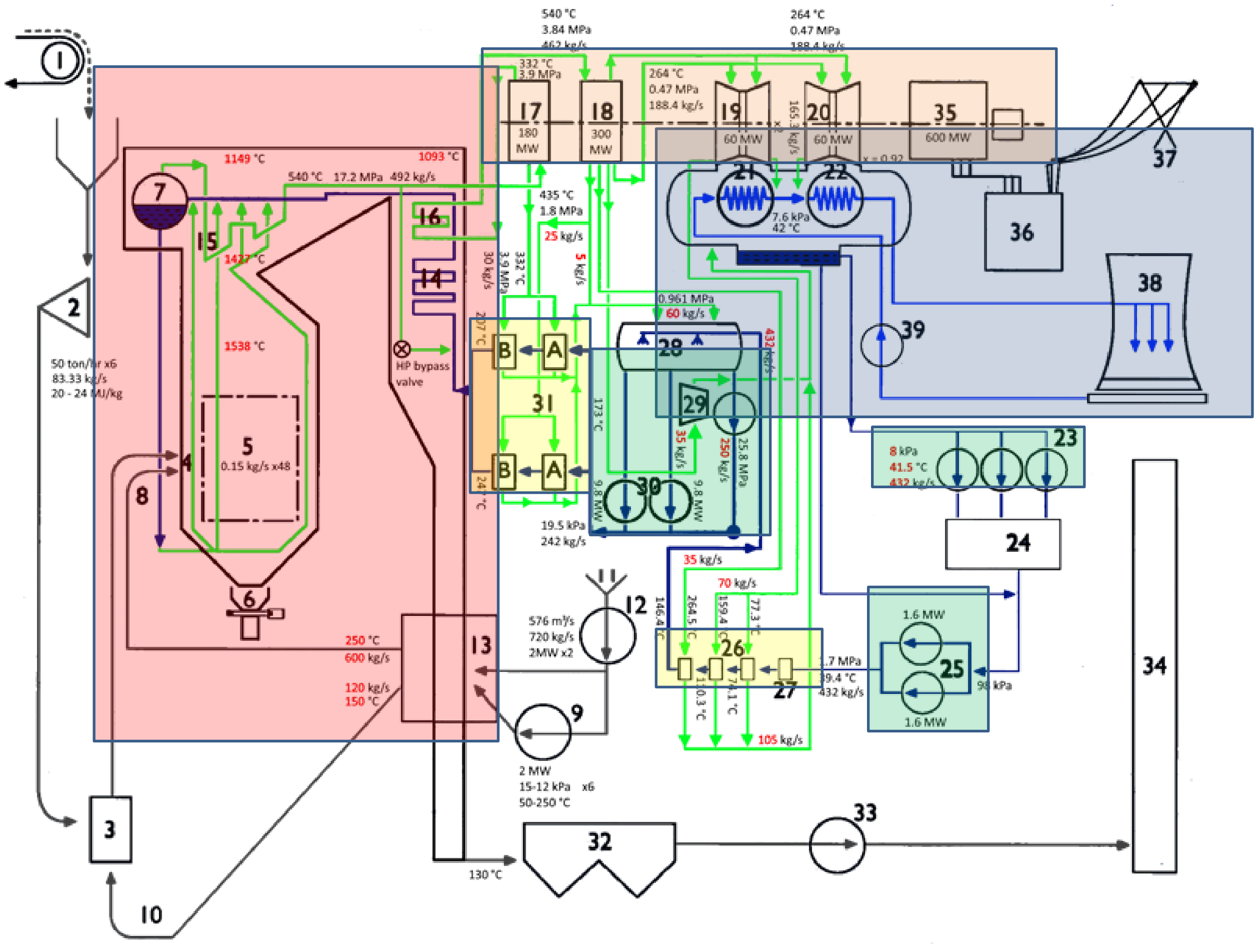
[44] Turbine Driven Boiler Feed Pumps "http://coffinpump.com/products/pumps/turbine-driven-boiler-feed-pumps"

[45] Turbine Driven Boiler Feed Pumps "http://coffinpump.com/products/pumps/turbine-driven-boiler-feed-pumps"

[46] Eskom heritage website "*www.eskom.co.za/sites/heritage*"

The five fundamental thermodynamic components are and highlighted as:

- Boiler: RED
- Turbines: ORANGE
- Cooling circuit BLUE
- Feedwater heaters: YELLOW
- Pumps: GREEN



MATLA CIRCUIT DIAGRAM

Figure A-9: Typical coal fired power station layout and cycle

Plotting the typical CFPS process on a T-S diagram (Figure1-5), we obtain *Figure A-10*. This includes additional heat recovery systems and staged turbines not shown in Figure 1-5). The T-S diagram only provides a broad overview of the process flows found in the power generation process. However, we can see the added complexity and flow paths as compared to the simple cycle with additional turbine stages and pressure stages on the FWH (write out fully) side.

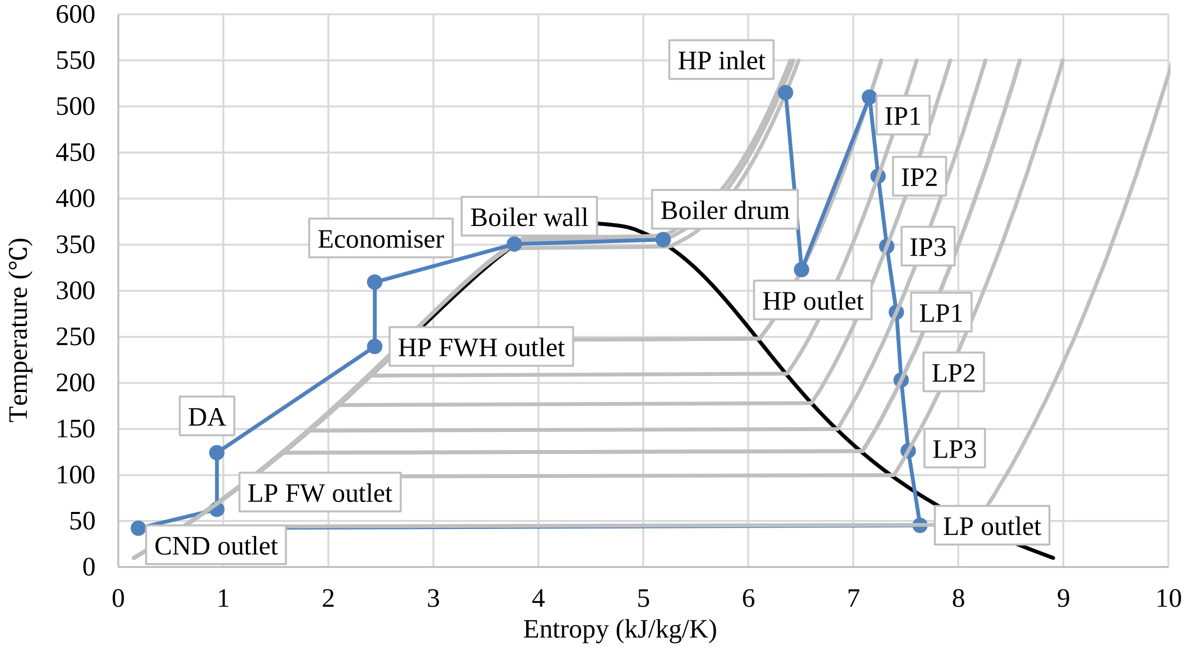


Figure A-10: Temperature vs entropy for typical coal fired power stations[47]

To better explain the process and indicate each component's influence the energy and entropy of the system, *Table A-2* summarises these aspects.

Table A-2: Explanation of the T-S diagram

Item	**Acronym**	**Description**	**Operation**
1	CND outlet	Condenser outlet	Reduces entropy and temperature of steam flow (cools/condenses).
2	LP FW outlet	Low-pressure feedwater heater outlet	Increases entropy and temperature of steam flow through bled steam from the LP turbine stages.
3	DA	Deaerator	Mixes feedwater with steam increasing entropy and temperature.
4	HP FWH outlet	High-pressure feedwater heater outlet	Increases entropy and temperature of steam flow through bled steam from the HP and IP turbine stages.
	Economiser		Pre heats feedwater, increasing temperature and entropy, from boiler flue gas before entering the boiler.
	Boiler wall		Increases temperature and entropy inside the boiler using radiation and convection heat transfer.
	Boiler drum		Increases temperature and entropy inside the boiler using radiation and convection heat transfer.
8	HP inlet	High-pressure turbine inlet	Entropy increase due to inefficiencies and reduction in

[47] Vertical lines indicate pressure changes occurring from pumping (increase) and generation or expansion (decrease).

			pressure and temperature from generation.
9	HP outlet	High-pressure turbine outlet	Entropy increase due to inefficiencies and reduction in pressure and temperature from generation.
10	IP1-3	Intermediate pressure turbine stage 1 to 3	Entropy increase due to inefficiencies and reduction in pressure and temperature from generation.
11	LP1-3	Low-pressure turbine stage 1 to 3	Entropy increase due to inefficiencies and reduction in pressure and temperature from generation.
12	LP Outlet	Low-pressure turbine outlet or condenser inlet	Final stage outlet of the LP turbine, quality in the region of 0.9.

B. APPENDIX B: Condenser fouling

Fouling dramatically reduces heat transfer contact area and the heat transfer coefficient as a result of reduced thermal conductivity. Scaling has lower thermal conductivity than that of the tube material (scaling 0.35 $W/m.K$) and (tubing 35 $W/m.K$ [50]). Unfavourable flow dynamics i.e. change in Reynolds number different from design specifications also influence performance.

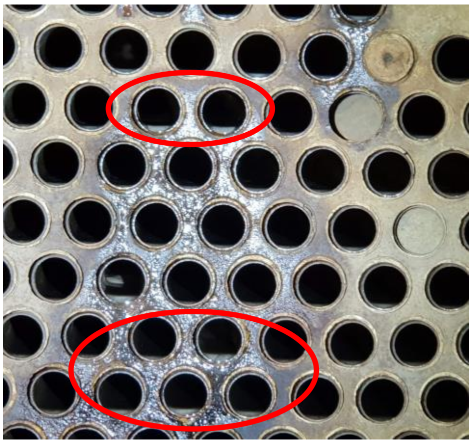


Figure B-1: Fouling in tubes

The reduction in contact surface area and heat transfer coefficient reduces the quantity of heat transferred from the low-pressure steam to the cooling water [16]. A larger delta T is then required to remove enough heat from the steam for it to form a condensate. The effect is evident from *Equation B-1*.

Equation B-1: Convective heat transfer equation

$$Q = hA_s\Delta T$$

where Q is the heat transfer rate in W, h is the heat transfer coefficient in W/m^2K, A_s the contact surface area in m^2 and ΔT is the difference in temperature (^{0}C) between the fluids/surfaces.

The condenser naturally increases its vacuum temperature and back pressure to ensure condensation occurs in the condenser. The effect is due to the delta T (ΔT) being the driving force behind *Equation B-1*. The increased back pressure reduces the amount of power available for extraction from the cycle. The reduced power is due to pressure and temperature being a driving force behind the amount of power available for extraction. *Figure B-2* shows the entire effect on a T-S diagram [51].

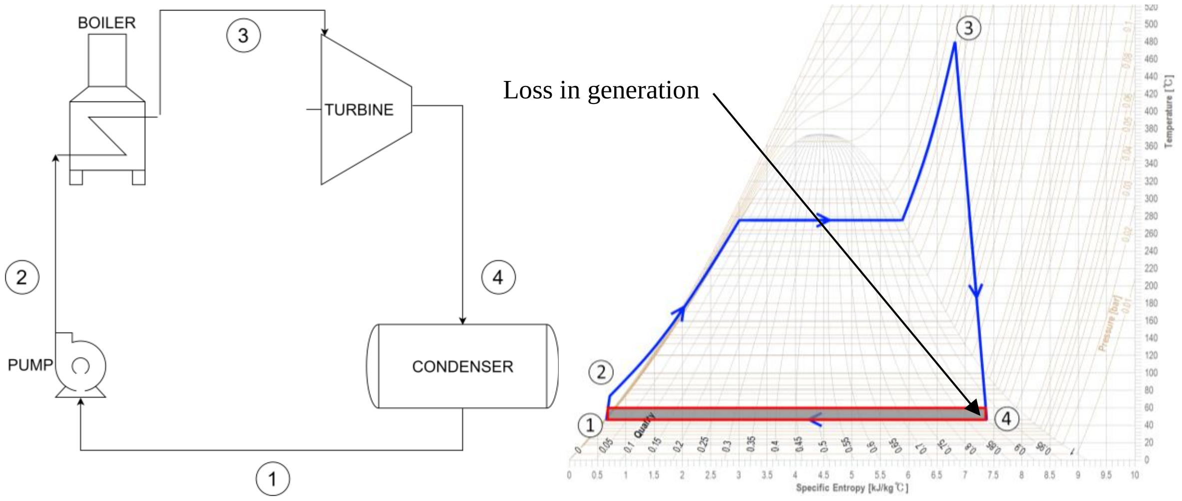


Figure B-2: Effect of poor condenser performance

C. APPENDIX C: Maintenance study summaries

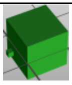
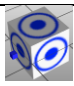
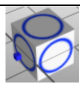
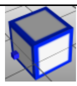
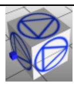
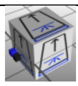
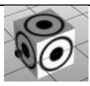
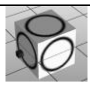
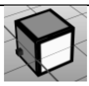
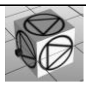
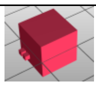
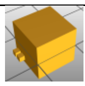
Table C-1: Summary of maintenance studies

Study	Title	Findings
[13]	Power Stations Maintenance Optimization Based on CBM Techniques	Power station orientated Discusses condition-based maintenance Used the Markov Chain method Applied to slag and ash pumping system System probability of success 0.975
[23]	Condenser maintenance cost optimisation using genetic algorithms	960 MW gas fired power station Focused on condenser maintenance Six dual pass, single pressure, under slung condensers Developed an integrated cost model regarding degradation Used cost model and found optimised maintenance schedule Found that a bi-annual maintenance schedule is best (four months separation)
[24]	Criticality-based maintenance of a coal-fired power station	Focussed around Reliability Cantered Maintenance (RCM) Developed a method for critical station equipment determination Applied to a flue gas desulfurization system Generic and can be applied to any coal-powered electricity generation station
[28]	Weighted fouling model for power station condenser monitoring	Developed weighted fouling method Determined the effect of fouling as a result of different number of condenser cleans per year Determined the operating cost according to increased fouling and number of condenser cleans per year Detailed discussion of fouling found in study [23]
[29]	Maintenance planning of power station elements based on avoided risk value	Component specific analysis Focused specifically on steam piping Detailed stress analysis on piping during operation A rounded steam pipe was used Found probability of failure in a 50-year service life The best net profit value (NPV) for replacement was found to be approximately 40-years
[30]	Failure and maintenance data extraction from power station maintenance management databases	Focussed on coal mills Contributes to 10 – 20 % of total production losses Service intervals of 3 to 4.5 months Outages are as a result of production decisions, internal faults (failures), incipient internal faults (degraded states) and process failures

[31]	Reliability modelling and availability analysis of combined cycle power stations	Critically assessed each component on the station for importance Focused on combined cycle power station (CCPP) Investigated the gas turbine power station (GTPP) and steam turbine power station (STPP) separately Generic approach Determined mean time to failure of each station Water balance, turbines and feedwater heaters was deemed the most critical components of the STPP. No boiler in a combined cycle.
[52]	Online Intelligent Condition Monitoring Maintenance Management for Thermal Power Station	920 MW CFPS, only generating 400 MW due to poor maintenance Focused on condition-based maintenance (CBM) Low vacuum pressure of the condenser was a contributing factor Due to dirty/plugged tubes, air ingress and tube leaks. Condition monitoring improved generation losses by 84 %

D. APPENDIX D: PTB components breakdown

Table D-1: PTB components

Category	Description	Image	Detail
Steam	Steam pressure boundary		Control volume boundary $(T, P, x, -, -)$
	Steam node		Point of calculation and measurement for the steam network. $(T, P, h, x, -, -)$
	Steam pipe		Facilitates the flow of steam and condensate between nodes. $(\dot{m})$
	Steam turbine		Converts potential and thermal energy to electric energy. $(\dot{m}, power, P, -, -)$
	Steam pump		Adds potential energy to condensate, increases pressure. $(\dot{m}, power, P, -, -)$
Water	Water pressure boundary		Control volume boundary $(T, P, -, -)$
	Water node		Point of calculation and measurement for the water network. $(T, P, h, -, -)$
	Water pipe		Facilitates the flow of water between nodes. $(\dot{m})$
	Water pump		Adds potential energy to condensate, increases pressure. $(\dot{m}, power, P, -, -)$
	Water dam		Water storage. $(m^3, -, -)$
	Cooling tower		Water to air heat exchanger. $(UA, Duty, -, -)$
Air	Air pressure boundary		Control volume boundary $(T, P, rh, -, -)$
	Air node		Point of calculation and measurement for the air network. $(T, P, h, x, -, -)$
	Air pipe		Facilitates the flow of air between nodes. $(\dot{m})$
	Air fan		Adds potential energy to condensate, increases pressure. $(\dot{m}, power, P, -, -)$
General	PI controller		Takes an input and outputs a control variable to reach a user-specified setpoint according to the input.
	Air coal burner		Adds energy to airflow in the form of heat input. $(CV, coal\ usage, pwer, -, -)$
	Heat transfer		Provides heat transfer between two nodes. $(A_s, h, -, -)$

E. APPENDIX E: Detailed PTB inputs and outputs

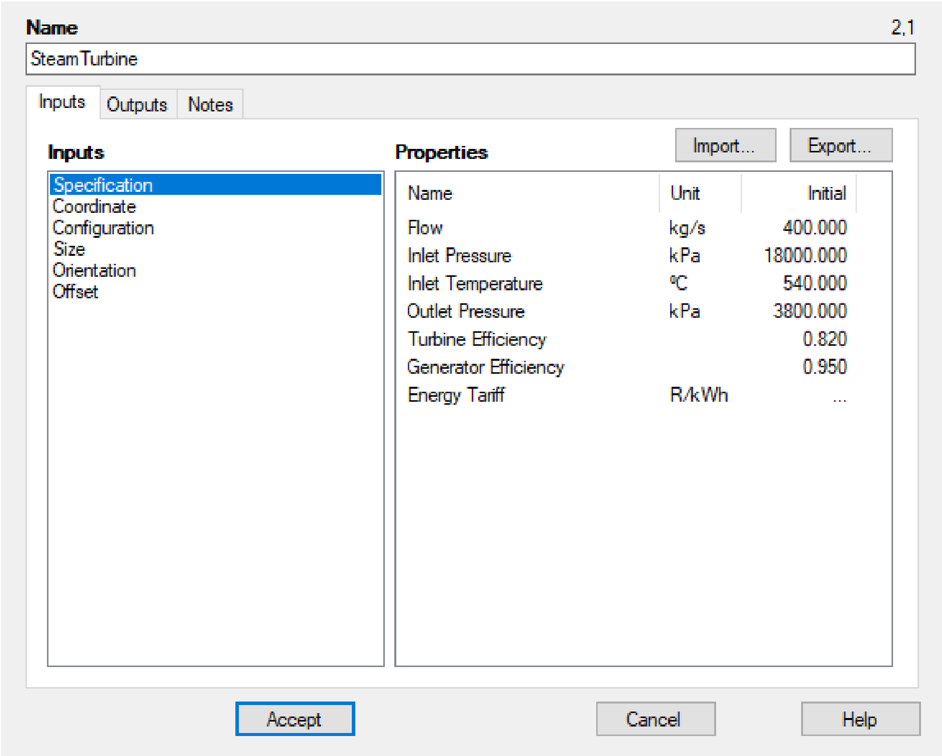


Figure E-1: Turbine component inputs

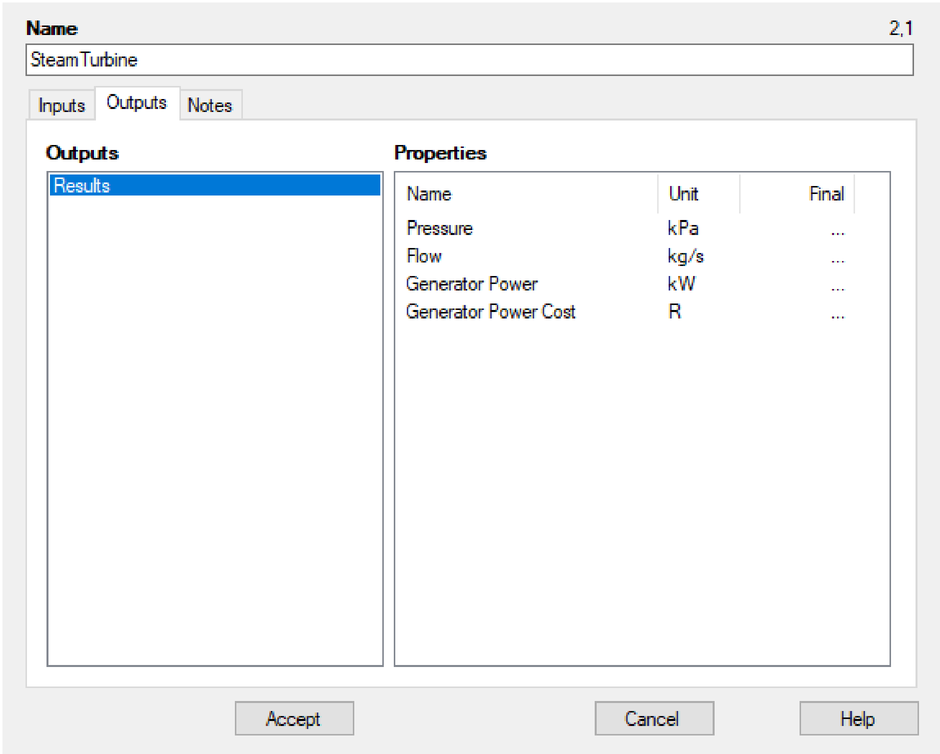


Figure E-2: Turbine component outputs

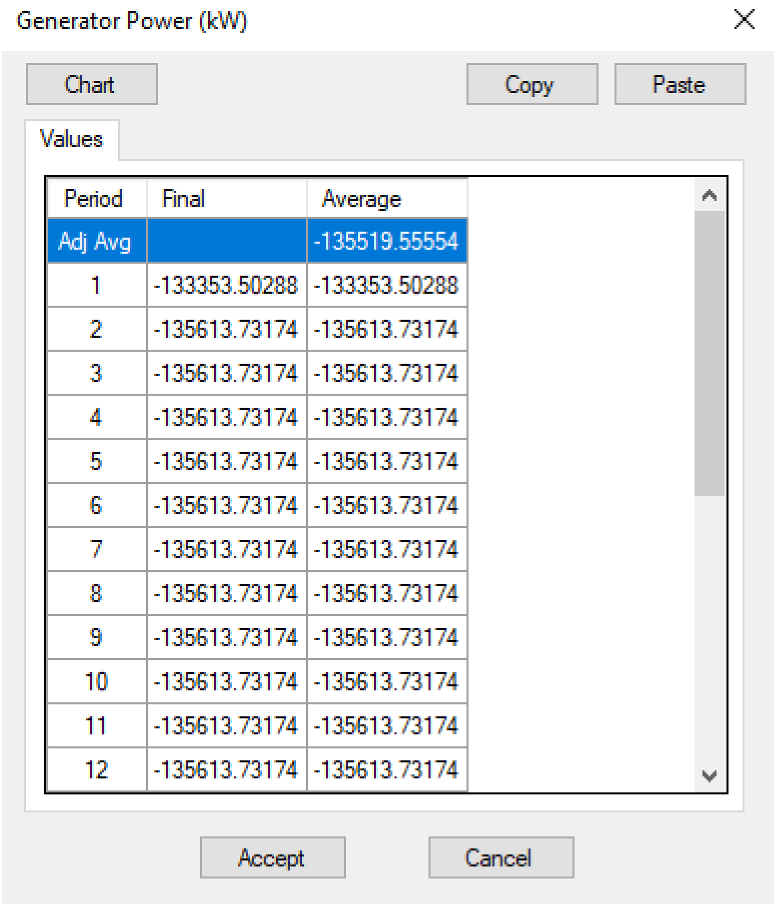


Figure E-3: Generator output list

F. APPENDIX F: Baseline calibration results

Table F-1: Baseline results

OVERALL				
	Unit	**Simulation**	**Actual**	**Error**
Gross power	(MW)	60.11	60.20	0.15 %
HP	(MW)	47.05	not available	NA
LP	(MW)	13.05	not available	NA
Net power	(MW)	57.90	58.00	0.16 %
Auxiliary power	(MW)	2.20	2.20	0.00 %
Coal usage	(ton/hr)	36.37	36.00	1.02 %
Heat input	(MW)	247.50	247.50	0.00 %
Thermal efficiency	(%)	23.39%	23.43%	0.16 %
Power produced per day	(MWh)	1389.65	1391.88	0.16 %

BOILER				
	Unit	**Simulation**	**Actual**	**Error**
Flow	(kg/s)	71.00	not available	NA
Inlet	(˚C)	171.34	176.00	2.68 %
	(MPa)	6.83	not available	NA
Economiser outlet	(˚C)	281.78	not available	NA
Boiler drum	(˚C)	279.30	not available	NA
	(MPa)	6.64	6.59	0.73 %
SH outlet	(˚C)	479.96	480.00	0.01 %
	(MPa)	6.26	6.20	0.98 %

TURBINES				
	Unit	**Simulation**	**Actual**	**Error**
HP 1				
Power	(MW)	19.73	not available	NA
Flow	(kg/s)	71.00	not available	NA
Inlet	(˚C)	479.99	480.00	0.00 %
	(kPa)	6268.12	6268.12	0.00 %
Outlet	(˚C)	313.14	305.00	2.63 %
	(kPa)	1663.95	1600.00	3.92 %
HP 2				
Power	(MW)	9.64	not available	NA

Flow	(kg/s)	67.85	not available	NA
Inlet	(˚C)	313.14	305.00	2.63 %
	(kPa)	1663.95	1600.00	3.92 %
Outlet	(˚C)	228.14	220.00	3.57 %
	(kPa)	736.23	725.00	1.54 %
HP 3				
Power	(MW)	7.63	not available	NA
Flow	(kg/s)	63.50	not available	NA
Inlet	(˚C)	228.14	220.00	3.57 %
	(kPa)	736.23	725.00	1.54 %
Outlet	(˚C)	156.96	150.00	4.53 %
	(kPa)	355.32	345.00	2.95 %
HP 4				
Power	(MW)	10.06	not available	NA
Flow	(kg/s)	59.86	not available	NA
Inlet	(˚C)	156.96	150.00	4.53 %
	(kPa)	355.32	345.00	2.95 %
Outlet	(˚C)	99.19	100.00	0.81 %
	(kPa)	98.66	103.00	4.30 %
LP 1				
Power	(MW)	5.51	not available	NA
Flow	(kg/s)	57.31	not available	NA
Inlet	(˚C)	99.19	100.00	0.81 %
	(kPa)	98.66	103.00	4.30 %
Outlet	(˚C)	78.19	80.00	2.29 %
	(kPa)	44.57	46.00	3.16 %
LP 2				
Power	(MW)	7.54	not available	NA
Flow	(kg/s)	54.79	not available	NA
Inlet	(˚C)	78.19	80.00	2.29 %
	(kPa)	44.57	46.00	3.16 %
Outlet	(˚C)	49.46	51.00	3.06 %
	(kPa)	12.04	12.20	1.32 %

CONDENSER				
	Unit	**Simulation**	**Actual**	**Error**
Steam inlet	(˚C)	49.46	51.00	3.06 %
Quality at inlet	(x)	0.89	not available	NA
Condensate outlet	(˚C)	47.17	48.00	1.75%
CW inlet	(˚C)	23.50	23.00	2.16 %

CW outlet	(˚C)	35.47	34.00	4.23 %
Pressure	(kPa abs)	12.04	12.20	1.32 %

FEEDWATER HEATERS				
	Unit	**Simulation**	**Actual**	**Error**
LP 1				
Steam flow	(kg/s)	2.52	not available	NA
Inlet	(˚C)	51.90	52.00	0.20 %
Outlet	(˚C)	69.76	72.30	3.58 %
HP 2				
Steam flow	(kg/s)	2.55	not available	NA
Inlet	(˚C)	70.34	72.30	2.75 %
Outlet	(˚C)	87.33	86.00	1.54 %
HP 3				
Steam flow	(kg/s)	3.64	not available	NA
Inlet	(˚C)	87.33	86.00	1.54 %
Outlet	(˚C)	114.26	119.00	4.06 %
HP 4				
Steam flow	(kg/s)	4.35	not available	NA
Inlet	(˚C)	114.26	119.00	4.06 %
Outlet	(˚C)	146.33	152.00	3.80 %
HP 5				
Steam flow	(kg/s)	3.15	not available	NA
Inlet	(˚C)	146.33	152.00	3.80 %
Outlet	(˚C)	171.34	176.00	2.68 %

G. APPENDIX G: Predictive maintenance model (Excel sheet and VBA code)

Day	Breakdowns		Days in operation	Days from	Maintenance		Condensate temperature	Efficiency	Generation	Coal CV	Coal ton/hr	Cost to run	Cost to repair	Energy sold	Profit
	Counter	Status			Counter	Status	°C	%	MW	GJ/ton	ton/hr	R/day	R/day	R/day	R/day
1	0	1	1	99	0	1	43.00	23.60	57.95	24.50	36.08	R0.00	R0.00	R1 196 015.76	R1 196 015.76
2	0	0	1	196	0	1	43.00	23.60	57.95	24.50	36.08	R0.00	R0.00	R0.00	R0.00
3	1	1	2	99	0	1	43.00	23.60	57.95	24.50	36.08	R0.00	R0.00	R1 196 015.62	R1 196 015.62
4	1	1	3	99	0	1	43.00	23.60	57.95	24.50	36.08	R0.00	R0.00	R1 196 015.34	R1 196 015.34
5	1	1	4	99	0	1	43.00	23.60	57.95	24.50	36.08	R0.00	R0.00	R1 196 014.82	R1 196 014.82
6	1	1	5	99	0	1	43.00	23.60	57.95	24.50	36.08	R0.00	R0.00	R1 196 014.00	R1 196 014.00
7	1	1	6	99	0	1	43.00	23.60	57.95	24.50	36.08	R0.00	R0.00	R1 196 012.83	R1 196 012.83
8	1	1	7	99	0	1	43.00	23.60	57.95	24.50	36.08	R0.00	R0.00	R1 196 011.25	R1 196 011.25
9	1	1	8	99	0	1	43.00	23.60	57.95	24.50	36.08	R0.00	R0.00	R1 196 009.20	R1 196 009.20
10	1	1	9	99	0	1	43.00	23.60	57.95	24.50	36.08	R0.00	R0.00	R1 196 006.64	R1 196 006.64
11	1	1	10	99	0	1	43.00	23.60	57.95	24.50	36.08	R0.00	R0.00	R1 196 003.51	R1 196 003.51
12	1	1	11	99	0	1	43.00	23.60	57.95	24.50	36.08	R0.00	R0.00	R1 195 999.76	R1 195 999.76
13	1	1	12	99	0	1	43.00	23.60	57.95	24.50	36.08	R0.00	R0.00	R1 195 995.35	R1 195 995.35
14	1	1	13	99	0	1	43.01	23.60	57.95	24.50	36.08	R0.00	R0.00	R1 195 990.22	R1 195 990.22
15	1	1	14	99	0	1	43.01	23.60	57.94	24.50	36.08	R0.00	R0.00	R1 195 984.33	R1 195 984.33
16	1	1	15	99	0	1	43.01	23.60	57.94	24.50	36.08	R0.00	R0.00	R1 195 977.63	R1 195 977.63
17	1	1	16	99	0	1	43.01	23.60	57.94	24.50	36.08	R0.00	R0.00	R1 195 970.08	R1 195 970.08
18	1	1	17	99	0	1	43.01	23.60	57.94	24.50	36.08	R0.00	R0.00	R1 195 961.63	R1 195 961.63
19	1	1	18	99	0	1	43.02	23.60	57.94	24.50	36.08	R0.00	R0.00	R1 195 952.24	R1 195 952.24
20	1	1	19	99	0	1	43.02	23.60	57.94	24.50	36.08	R0.00	R0.00	R1 195 941.85	R1 195 941.85
21	1	1	20	99	0	1	43.02	23.60	57.94	24.50	36.08	R0.00	R0.00	R1 195 930.44	R1 195 930.44
22	1	1	21	99	0	1	43.02	23.60	57.94	24.50	36.08	R0.00	R0.00	R1 195 917.95	R1 195 917.95
23	1	1	22	99	0	1	43.03	23.60	57.94	24.50	36.08	R0.00	R0.00	R1 195 904.34	R1 195 904.34
24	1	1	23	99	0	1	43.03	23.60	57.94	24.50	36.08	R0.00	R0.00	R1 195 889.57	R1 195 889.57
25	1	1	24	99	0	1	43.03	23.60	57.94	24.50	36.08	R0.00	R0.00	R1 195 873.60	R1 195 873.60
26	1	1	25	99	0	1	43.04	23.60	57.94	24.50	36.08	R0.00	R0.00	R1 195 856.39	R1 195 856.39
27	1	1	26	99	0	1	43.04	23.60	57.94	24.50	36.08	R0.00	R0.00	R1 195 837.89	R1 195 837.89
28	1	1	27	99	0	1	43.05	23.60	57.94	24.50	36.08	R0.00	R0.00	R1 195 818.07	R1 195 818.07
29	1	1	28	99	0	1	43.05	23.60	57.94	24.50	36.08	R0.00	R0.00	R1 195 796.88	R1 195 796.88
30	1	1	29	99	0	1	43.06	23.60	57.93	24.50	36.08	R0.00	R0.00	R1 195 774.28	R1 195 774.28
31	1	1	30	99	0	1	43.06	23.60	57.93	24.50	36.08	R0.00	R0.00	R1 195 750.23	R1 195 750.23
32	1	1	31	99	0	1	43.07	23.59	57.93	24.50	36.08	R0.00	R0.00	R1 195 724.70	R1 195 724.70
33	1	1	32	99	0	1	43.08	23.59	57.93	24.50	36.08	R0.00	R0.00	R1 195 697.64	R1 195 697.64
34	1	1	33	99	0	1	43.08	23.59	57.93	24.50	36.08	R0.00	R0.00	R1 195 669.01	R1 195 669.01
35	1	1	34	99	0	1	43.09	23.59	57.93	24.50	36.08	R0.00	R0.00	R1 195 638.78	R1 195 638.78
36	1	1	35	99	0	1	43.10	23.59	57.93	24.50	36.08	R0.00	R0.00	R1 195 606.91	R1 195 606.91
37	1	1	36	99	0	1	43.11	23.59	57.93	24.50	36.08	R0.00	R0.00	R1 195 573.36	R1 195 573.36
38	1	1	37	99	0	1	43.12	23.59	57.92	24.50	36.08	R0.00	R0.00	R1 195 538.08	R1 195 538.08
39	1	1	38	99	0	1	43.12	23.59	57.92	24.50	36.08	R0.00	R0.00	R1 195 501.05	R1 195 501.05

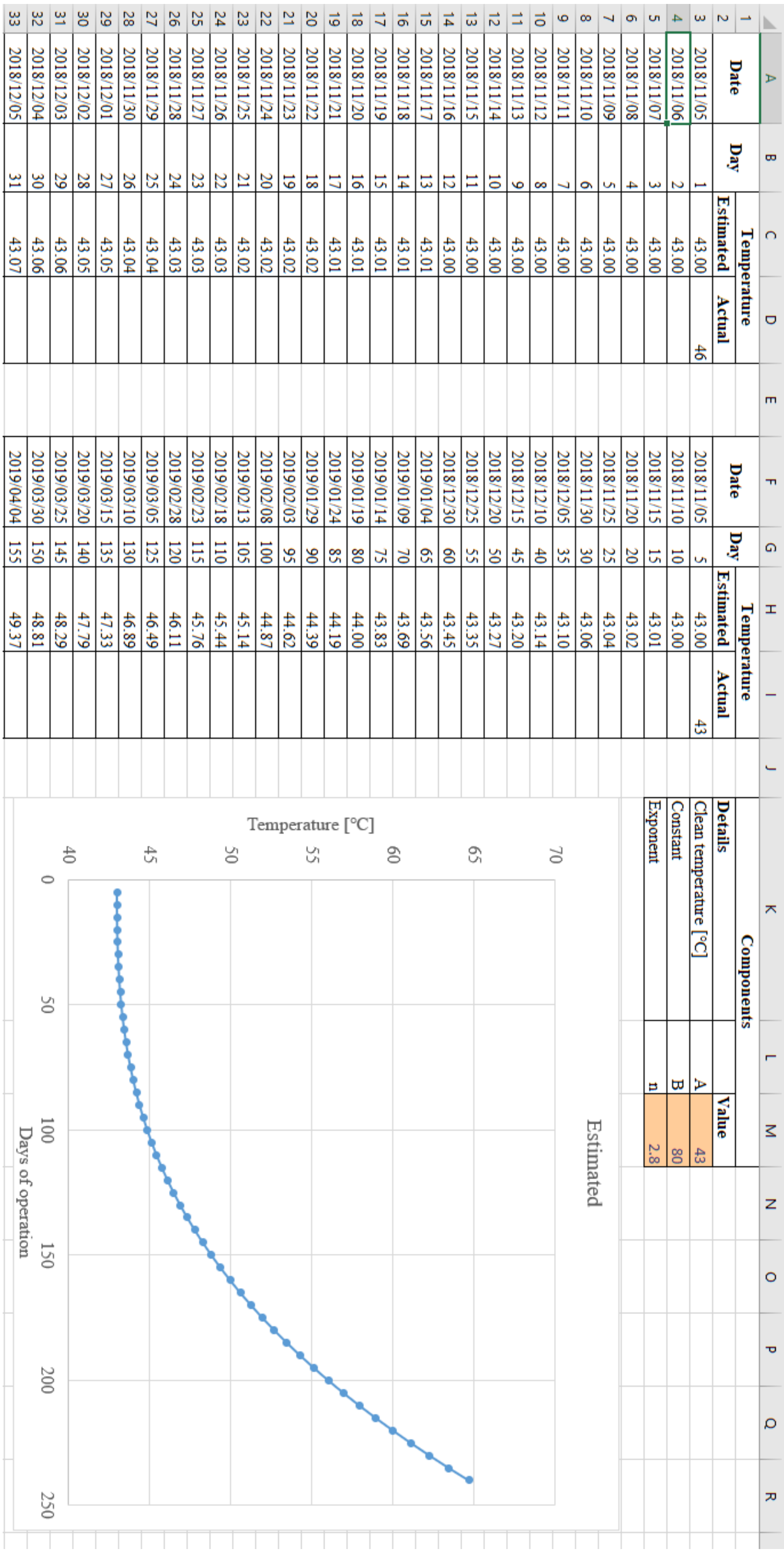
Figure G-1: Daily performance and cost calculations

V	W	X	Y	Z	AA	AB	AC
Days between clean	**Calculated**	**Smoothed**	**Profit loss**	**Profit loss**	**Days from ideal**	**Date of maintenance**	**Condensate temp**
Days	**R**	**R**	**R**	**R 100k**	**days**	**dd-mm-yyyy**	**°C**
105	R1 120 719.59	R1 122 357.00	R5 631 423.31	R56.31	-92	2019/02/18	50.35
107	R1 122 321.73	R1 123 025.37	R5 387 470.52	R53.87	-90	2019/02/20	50.49
109	R1 121 962.06	R1 123 678.93	R5 148 919.08	R51.49	-88	2019/02/22	50.63
111	R1 122 971.24	R1 124 317.70	R4 915 769.00	R49.16	-86	2019/02/24	50.77
113	R1 124 372.24	R1 124 941.67	R4 688 020.27	R46.88	-84	2019/02/26	50.91
115	R1 124 332.90	R1 125 550.84	R4 465 672.91	R44.66	-82	2019/02/28	51.05
117	R1 125 074.89	R1 126 145.21	R4 248 726.90	R42.49	-80	2019/03/02	51.19
119	R1 125 739.64	R1 126 724.79	R4 037 182.25	R40.37	-78	2019/03/04	51.33
121	R1 127 225.49	R1 127 289.56	R3 831 038.96	R38.31	-76	2019/03/06	51.47
123	R1 127 944.06	R1 127 839.54	R3 630 297.03	R36.30	-74	2019/03/08	51.61
125	R1 129 103.22	R1 128 374.72	R3 434 956.45	R34.35	-72	2019/03/10	51.75
127	R1 128 773.37	R1 128 895.10	R3 245 017.23	R32.45	-70	2019/03/12	51.89
129	R1 129 921.52	R1 129 400.69	R3 060 479.37	R30.60	-68	2019/03/14	52.03
131	R1 130 662.12	R1 129 891.47	R2 881 342.87	R28.81	-66	2019/03/16	52.17
133	R1 130 770.59	R1 130 367.46	R2 707 607.73	R27.08	-64	2019/03/18	52.31
135	R1 131 761.77	R1 130 828.65	R2 539 273.94	R25.39	-62	2019/03/20	52.45
137	R1 132 804.04	R1 131 275.04	R2 376 341.51	R23.76	-60	2019/03/22	52.59
139	R1 132 463.66	R1 131 706.63	R2 218 810.44	R22.19	-58	2019/03/24	52.73
141	R1 132 889.51	R1 132 123.42	R2 066 680.73	R20.67	-56	2019/03/26	52.87
143	R1 133 123.68	R1 132 525.42	R1 919 952.37	R19.20	-54	2019/03/28	53.01
145	R1 133 271.27	R1 132 912.61	R1 778 625.37	R17.79	-52	2019/03/30	53.15
147	R1 133 904.75	R1 133 285.01	R1 642 699.73	R16.43	-50	2019/04/01	53.29
149	R1 133 934.84	R1 133 642.61	R1 512 175.45	R15.12	-48	2019/04/03	53.43
151	R1 134 428.75	R1 133 985.42	R1 387 052.52	R13.87	-46	2019/04/05	53.57
153	R1 135 663.97	R1 134 313.42	R1 267 330.96	R12.67	-44	2019/04/07	53.71
155	R1 135 927.06	R1 134 626.63	R1 153 010.75	R11.53	-42	2019/04/09	53.85
157	R1 135 546.59	R1 134 925.03	R1 044 091.90	R10.44	-40	2019/04/11	53.99
159	R1 135 880.39	R1 135 208.64	R940 574.40	R9.41	-38	2019/04/13	54.13
161	R1 135 986.09	R1 135 477.46	R842 458.27	R8.42	-36	2019/04/15	54.27
163	R1 136 548.69	R1 135 731.47	R749 743.49	R7.50	-34	2019/04/17	54.41
165	R1 136 504.03	R1 135 970.68	R662 430.07	R6.62	-32	2019/04/19	54.55
167	R1 136 709.98	R1 136 195.10	R580 518.01	R5.81	-30	2019/04/21	54.69
169	R1 136 964.07	R1 136 404.72	R504 007.30	R5.04	-28	2019/04/23	54.83
171	R1 137 290.34	R1 136 599.54	R432 897.95	R4.33	-26	2019/04/25	54.97
173	R1 137 234.21	R1 136 779.56	R367 189.96	R3.67	-24	2019/04/27	55.11
175	R1 136 529.84	R1 136 944.78	R306 883.33	R3.07	-22	2019/04/29	55.25
177	R1 137 604.23	R1 137 095.21	R251 978.06	R2.52	-20	2019/05/01	55.39
179	R1 138 036.78	R1 137 230.84	R202 474.14	R2.02	-18	2019/05/03	55.53
181	R1 137 641.81	R1 137 351.67	R158 371.59	R1.58	-16	2019/05/05	55.67

Figure G-2: Profit and loss calculations

Comparison with ideal		
Chosen days between clean	Days	221
Chosen date of next clean	Date	2019/06/14
Cost per day	R/day	R1 124.95
Cost per month	R/month	R34 220.88
Cost per year	R/year	R410 650.55
Equation components		
C1	Coefficient	726.3352849
C2	Coefficient	-1.84978006
B	Coefficient	1066485.624

Figure G-3: Tool for comparing actual to ideal and fitting curve components



Date	Day	Temperature Estimated	Temperature Actual
2018/11/05	1	43.00	46
2018/11/06	2	43.00	
2018/11/07	3	43.00	
2018/11/08	4	43.00	
2018/11/09	5	43.00	
2018/11/10	6	43.00	
2018/11/11	7	43.00	
2018/11/12	8	43.00	
2018/11/13	9	43.00	
2018/11/14	10	43.00	
2018/11/15	11	43.00	
2018/11/16	12	43.00	
2018/11/17	13	43.01	
2018/11/18	14	43.01	
2018/11/19	15	43.01	
2018/11/20	16	43.01	
2018/11/21	17	43.01	
2018/11/22	18	43.02	
2018/11/23	19	43.02	
2018/11/24	20	43.02	
2018/11/25	21	43.02	
2018/11/26	22	43.03	
2018/11/27	23	43.03	
2018/11/28	24	43.03	
2018/11/29	25	43.04	
2018/11/30	26	43.04	
2018/12/01	27	43.05	
2018/12/02	28	43.05	
2018/12/03	29	43.06	
2018/12/04	30	43.06	
2018/12/05	31	43.07	

Date	Day	Temperature Estimated	Temperature Actual
2018/11/05	5	43.00	43
2018/11/10	10	43.00	
2018/11/15	15	43.01	
2018/11/20	20	43.02	
2018/11/25	25	43.04	
2018/11/30	30	43.06	
2018/12/05	35	43.10	
2018/12/10	40	43.14	
2018/12/15	45	43.20	
2018/12/20	50	43.27	
2018/12/25	55	43.35	
2018/12/30	60	43.45	
2019/01/04	65	43.56	
2019/01/09	70	43.69	
2019/01/14	75	43.83	
2019/01/19	80	44.00	
2019/01/24	85	44.19	
2019/01/29	90	44.39	
2019/02/03	95	44.62	
2019/02/08	100	44.87	
2019/02/13	105	45.14	
2019/02/18	110	45.44	
2019/02/23	115	45.76	
2019/02/28	120	46.11	
2019/03/05	125	46.49	
2019/03/10	130	46.89	
2019/03/15	135	47.33	
2019/03/20	140	47.79	
2019/03/25	145	48.29	
2019/03/30	150	48.81	
2019/04/04	155	49.37	

Components: Details		Value
Clean temperature [°C]	A	43
Constant	B	80
Exponent	n	2.8

Figure G-4: Temperature curve parameterisation

```
Private Sub Update_Click()

For i = 3 To 93

    Cells(4, "T") = Cells(i, "V")
    Worksheets(1).Calculate
    Cells(i, "W") = Cells(18, "T")

Next i

Cells(4, "T") = Cells(22, "T")

End Sub
```

Figure G-5: Predictive maintenance model VBA code