Development and validation of a robust integrated thermal power plant model for load loss analysis and identification

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Abstract. The development of deep learning methodologies for the analysis of thermal power plant load losses requires a combination of real plant data and data derived from fundamental physics-based process models. For this purpose, a robust integrated power plant thermofluid process model of a complete +600MW coal-fired power plant was developed within the Flownex Simulation Environment. It consists of standard and compound components, combined with specially developed scripts to ensure complete energy balance, specifically on the two-phase tank components. This enables simulation of the complete plant operation to determine power output as a function of any given set of internal and external operational variables, boundary conditions and component states. The model was validated against real plant design and acceptance test data. In order to demonstrate the ability of the model it was used to evaluate the plant performance related to three specific load loss inducing scenarios. The results show that a combination of mechanical faults, process anomalies and operational phenomena can be analysed. This provides the basis for generating model-based performance data that can be combined with real plant data to facilitate the development of deep learning analytics tools for load loss fault diagnosis and root cause analysis, as well as fault propagation and load loss forecasting.

1 Introduction

With the current shift towards renewable energy, conventional thermal power plants are forced to respond with agility to the fluctuation in demand. This requires operational flexibility while maintaining optimal plant performance. However, conventional designs focussed on efficiency at a fixed operating point, and therefore flexible operation often results in an increase in load loss events.

A load loss is defined by VGB [1] as the incapacity of a power plant to produce electricity at its Maximum Continuous Rating (MCR). A load loss may be caused by any number and combination of internal or external factors, but is commonly categorised as either planned or unplanned, and full or partial. Faults within the mechanical, chemical and electrical equipment are the primary causes of unplanned load losses in the power generation industry,

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followed by human error and external factors. Identifying what portion of load loss is associated with which plant area, system, or equipment plays a critical part in the formulation of operation and maintenance strategies.

Existing load loss classification systems are predominantly physics-based, utilising lumped zero-dimensional thermodynamic models. These models are developed to evaluate each power plant system based on its current performance against the original design [2]. A collective of systems or plant areas is typically integrated within a physics-based model grouping, for example thermal performance or critical electrical plant area trending models. These models provide a specific visualisation of plant performance. Power plant physics-based models are rarely integrated into one model capable of the evaluation of the load losses in relation to specific system faults. Moreover, many power plants still manually identify the causes of load losses.

Various integrated power plant process models have been developed in the past for different purposes. Alobaid et al.[3] provide a comprehensive review of recent dynamic thermal power plant modelling methodologies as well as their development and application. The most notable of these are:

- A 550MW anthracite coal-fired power plant model developed using the ThermoPower library [4] presented by Meinke et al.[5]. It consists of a predefined water/steam cycle, boiler combustion chamber and air passage power plant components that work in conjunction with control schemes. The study focussed on the dynamic behaviour at start-up and different operating modes.
- A 500MW bituminous coal-fired power plant model developed using the gPROMS [6] simulation software presented by Oko et al.[7]. The model consists of a complete power plant, including the flue gas cycle. The accuracy of the model was improved by incorporating first principles modelling equations into the predefined components. The study focussed on identifying optimal load change implementation methods.
- A 750MW anthracite coal-fired power plant developed using the APROS [8] process simulation software presented by Starkloff et al.[9]. The model consists of a complete power plant that includes different furnace firing levels. APROS includes all power plant components and their associated control schemas. The study focussed on power plant operational flexibility.

The dynamic coal-fired power plant models described above were validated against either steady-state or dynamic real plant data and good results were obtained. The models could be used to simulate different operating conditions and evaluate the performance of each plant component under dynamic simulation scenarios. However, the focus was not on load loss analysis or classification.

Deep learning has the potential to provide a reliable approach to the analysis of thermal power plant load losses. However, it requires large training datasets. In the case of load loss analysis, a combination of real plant data and load loss classification data is required. Due to the sparseness of load loss classification data, this study proposes the development of an Integrated Power Plant Process Model (I3PM) for the controlled generation of load loss classification datasets. The objective is therefore the development of a model that enables simulation of the complete power plant operation to determine power output as a function of any given set of internal and external operational variables, boundary conditions and component states. This will enable the generation of model-based load loss classification data that can be combined with real plant data for the training of deep neural networks.

The integrated model development employs an operational plant mirroring framework based on the original plant design, combined with component level fundamental thermofluid physics models in the Flownex Simulation Environment [10].

2 Model development

A South African +600MW lignite coal-fired power plant was used as the design base and for validation of the I3PM. The real power plant design specifications, construction drawings, acceptance tests, c-schedules, control schemes and condition monitoring data were used in the development of each plant component. Flownex was selected for the development of the model based on its collective features and fundamental component-level analysis capabilities that are ideally suited for the development of power plant thermofluid components, as illustrated via studies performed by the Applied Thermofluid Process Modelling Research Unit [11].

Flownex is a simulation software package based on a one-dimensional thermofluid network solver that can simulate various steady-state and dynamic thermofluid process scenarios. Flownex solves the fundamental governing equations using an Implicit Pressure Correction Method set inside a segregated solution algorithm. It consecutively solves the governing equations along with additional component specific equations, enabling the user to manipulate various component and solver parameters and/or criteria. Numerous additional physical domain (mechanical, electrical, C&I, chemical, nuclear, etc.) solvers have been stacked on top of the thermofluid network solver, expanding Flownex's capabilities and general application. Additionally, Flownex enables the creation of custom compound components, has an internal C# script component and a Python API enabling the execution of any additional calculations, algorithms and/or logic that may be required. The C# and Python code executions occur at different computation stages [10].

Each Flownex power plant component was first independently developed and calibrated to its unique operational parameters and design specification before systematically being connected to its respective neighbouring component. The complete Flownex I3PM is presented in Figure 1, where power plant areas are grouped by coloured sections. The modelling methodology of each component will be discussed under its specific plant area.

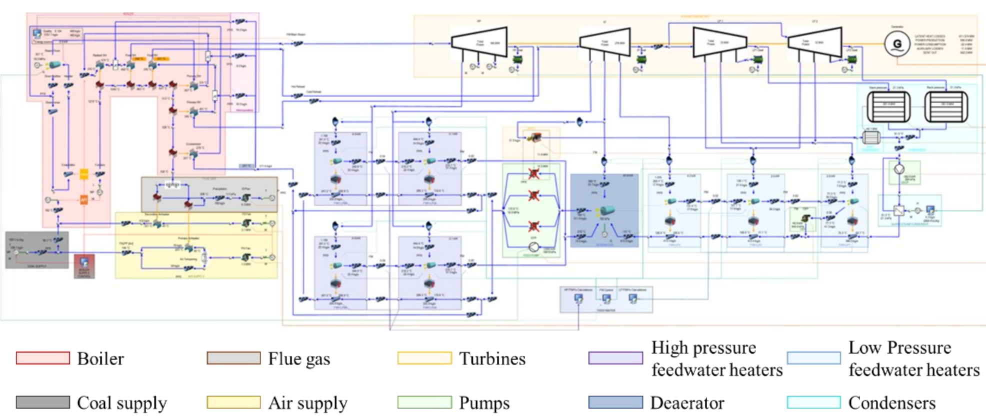

Figure 1: Flownex integrated power plant thermofluid process model.

Since the primary focus of this study is the generation of a load loss classification dataset, the focus was not on the simulation of power plant controls and response to disturbances, as required for dynamic modelling. On the contrary, the I3PM was designed to evaluate the impact of any given set of internal and external operational variables, boundary conditions and component states in steady-state operation before any corrective response could be initialised. This allows for the identification and allocation of load loss to plant areas, systems, or equipment.

2.1 Coal and air supply

The *Coal supply* plant area is comprised of a coal composition and a coal quantity section. The coal composition uses a fluid data reference and boundary condition component that enables the user to define the fuel constituents (coal: carbon, oxygen, ash, water, etc.) and state (temperature, pressure, etc.). In this case, lignite coal is used with a high ash content. The coal quantity is comprised of a coded algorithmic section within a C# script component, the Boiler Supply Control (BSC), which calculates the final coal quantity as a function of the number of active mills, the mass flow rate output of each mill and the performance of each mill. Additionally, the mill power consumption is calculated based on the real power plant mills design. The result of the coal supply plant area is the Pulverized Fuel (PF) condition.

The *Air supply* plant area is comprised of a Primary Air (PA) and a Secondary Air (SA) section. The PA section is comprised of two PA fan components, calibrated to the real PA fan performance curves. Air is fanned through the air side heat exchanger component of the Primary Airheater (PAH) and then through an Air Tempering (AT) path. The AT ensures that the final PA/PF mixture has a temperature below 100°C, which in practice reduces the probability of spontaneous combustion occurring. The ratio of AT to PA air is controlled by the BSC and a compound splitter valve component developed by Fuls [12]. Similarly, the SA section is comprised of two Forced Draught (FD) fans, calibrated to the real FD fan performance curves. Air is fanned through the Secondary Airheater's (SAH) air side heat exchanger component. Both the PAH and SAH air side heat exchanger components are induced with heat, transferred from their respective flue gas side heat exchanger components. The PA and FD fans draw air from a common ambient boundary condition. The fan power consumptions are calculated by their respective fan components.

The integration of the *Coal* and *Air supply* plant areas occur at two network nodes, the first mixes the PA and PF, the second mixes the SA with the PA/PF mixture. The final air/fuel ratio is either calculated by the BSC, based on the real power plant's combustion design, or can be set manually by the user.

2.2 Boiler and flue gas

The modelled power plant uses a natural circulated steam drum boiler design. The *Boiler* plant area is comprised of a combustion section, an evaporator loop section, and a boiler heat exchangers section. The combustion section is comprised of two custom C# script components, developed by the ATProM research unit [11], namely an Adiabatic Flame Temperature (AFT) component and a Furnace component. The AFT takes in the final air/fuel mixture and calculates the energy released and combustion products produced during the combustion process. The furnace component is based on the widely-used Gurvich method [13]. It takes the AFT results and distributes the energy released based on user defined input parameters. These include burner elevation and fuel flow, furnace geometry and characteristics, and the combustion side water wall elevations. Additionally, it assigns the combustion products and remaining energy to the furnace outlet gas. The combustion section allows the user to induce various known boiler furnace faults.

The evaporative loop section includes a downcomer, an evaporator, a header, and a steam drum. The downcomer is comprised of simple pipe components and the number and geometry of downcomer tubes, including their elevations, are user defined input parameters. The inlet to the downcomer receives a combination of saturated liquid from the bottom of the steam drum component and subcooled liquid from the economiser heat exchanger component. This approach ensures a physically realistic analysis where the feed water from the economiser is fed into the steam drum via a manifold situated below the baffle plate.

Similarly, the evaporator uses a pipe component with the number and geometry of furnace wall tubes, including their elevations, as input parameters. The evaporator is fed water from the downcomer component whilst heat is transferred from the Furnace component onto a set of pipes that are discretised along their length, producing a two-phase water/steam mixture at the outlet. This results in the density of the water within the evaporator being lower than that of the downcomer, which induces the natural circulation effect. The header uses a pipe component to merge the evaporator pipes before feeding the two-phase fluid into the steam drum. For the two-phase boiling heat transfer Flownex uses a combination of heat transfer correlations and lookup tables depending on the boiling regime [14].

The steam drum consists of a two-phase tank component that performs the phase separation of the water/steam mixture, based on the real steam drum geometry and elevation. The drum pressure and water level are specified as boundary values since in reality these are actively controlled via inter alia the feedwater flow rate. The drum water level may be specified either as a volume fraction or as a vapour mass fraction (quality). Since the drum pressure is specified the enthalpies of the saturated vapour main steam flow and saturated liquid leaving towards the downcomer are effectively fixed. The recirculation mass flow rate and enthalpy that enters the drum are determined by the performance of the evaporator heat exchanger. This means that if the drum is assumed to be perfectly insulated from the environment, there will be only one possible main steam mass flow rate that will ensure an energy balance over the drum. It is therefore necessary to determine the resultant main steam mass flow rate for each simulation case. This can be achieved with the aid of a built-in iterative "designer" feature that is available for steady-state simulation [15]. The iterative "designer" feature executes multiple steady state simulations while adjusting user defined parameters (control valve position, quality, pressure, etc.) until the desired outcome is achieved. Unfortunately, using this built-in feature was found to be computationally slow. An alternative approach was therefore developed which is discussed in section 2.8.

The boiler heat exchanger section includes a platen superheater, final and primary superheaters, final and primary reheaters, attemperators and an economiser, all consisting of a gas side heat exchanger component and a steam side heat exchanger component. The radiant superheaters absorb the direct radiation from the furnace or the preceding heat exchanger as well as the radiative and convective heat transfer from the flue gas directly surrounding the heat exchanger tubes. The gas side heat exchanger component transfers the heat absorbed from the gas path into the steam path through a connected steam side heat exchanger component. Each heat exchanger was calibrated to it respective design operating conditions.

In line with the real boiler design, attemperators are used to ensure that the calculated tube metal temperatures do not exceed the real plant boiler metal temperatures. The custom attemperator component [12] mixes the required spray water mass flow into the steam flow to achieve the specified steam outlet temperature. The spray water is extracted from the feedwater flow before it enters the economiser.

The economiser is supplied with feedwater from the final high-pressure Feedwater Heaters (FWH). Similar to the superheaters and reheaters the economiser uses a gas side heat exchanger component that transfers heat to the water side heat exchanger component, thereby heating the water to a temperature just below boiling point. The economiser outlet gas connects to the airheaters whilst the outlet water connects to the manifold at the base of the steam drum below the baffle plate.

The complete *Boiler* plant area was developed by first merging the evaporator and combustion sections while ensuring accurate natural circulation simulation under varying furnace operating conditions. This was followed by connecting the boiler heat exchanger section. Various evaporator loop and furnace operating conditions were tested ensuring accurate gas and steam path simulation. Finally, the attemperators were integrated into the model.

The *Flue gas* plant area consists of a gas side airheater section, Electrostatic Precipitator (ESP) component and an Induction (ID) fan component. As the gas is drawn out of the economiser it is split into PAH and SAH paths. The compound splitter valve component is used in combination with the BSC to assign the PAH to SAH gas ratio. The gas side PAH and SAH consists of heat exchanger components and transfer heat as previously described. The PAH and SAH outlet gas paths merge prior to the air being drawn into the ESP by the ID fans.

The ESP consists of a flow restriction component that enables the user to adjust the design calibration parameters allowing the introduction of component faults. The ID fans follow the same methodology as the PA and FD fans. Two ID fans are calibrated based on the actual fan performance curves. The boiler stack consists of a boundary condition component, set at the real boiler stack outlet elevation and ambient conditions.

The complete boiler model was created by first merging the *Flue gas* plant area with the integrated *Coal* and *Air supply* plant areas, before merging it with the *Boiler* plant area.

2.3 Turbines

The modelled power plant has a High-pressure (HP), Intermediate-pressure (IP) and two Low-pressure (LP) turbines that drive the Generator as well as a low-pressure Boiler Feed Pump Turbine (BFPT) that drives the boiler feedwater pump. The HP, IP and LP's were modelled using a compound steam turbine component [12]. The compound turbine component consists of four default simple turbine components that are optimised with a flow correction and an Ellipse-law loss C# script. The rotational speed and process design parameters of the real steam turbines, including the steam extraction designs, are used to develop the turbine train model. Additionally, a default labyrinth seal component is used to model the turbine gland seals. A default LP turbine component was used to model the BFPT. The complete turbine train model was obtained by integrating the various turbine and gland seal components.

The generator was modelled using a C# script component that determines the gross and net power production. The generator component collects the power production and consumption from each component, via data transfer links, thus capturing the holistic power distribution critical to the accuracy of the generator component calculations.

2.4 Pumps

Numerous pumps and booster pumps exist on a real power plant and for simplification only four pump components are included in the I3PM. These are the Condensate Extraction Pump (CEP), the low-pressure FWH Distillate Pump (FWHDP), the Boiler Feed Pump (BFP) that is driven by the BFPT and the two 50% Electrical Feed Pumps (EFP). The CEP consists of a compound pump component [12] that ensures accurate pressure balance through all the low-pressure FWH's and that the required pressure is obtained in the deaerator.

The FWHDP ensures that the distillate, which cascades down through all the low-pressure FWHs, is pumped into the main feedwater path. A simple pump component was used for the development of the FWHDP. A default variable speed pump component was used to develop the BFP and EFPs. The power consumption of the BFP is matched with the power output of the BFPT, including mechanical losses, while the power consumption of the EFPs is determined by its performance at the specified set point. All pumps were calibrated against their real power plant process design parameters and pump curves.

2.5 Low- and high-pressure feedwater heaters

The modelled power plant has six FWH stages. There are three low-pressure FWHs and four high-pressure FWHs with the high-pressure FWH split into two banks, namely paths A and B. The development of the FWH components expands on the Flownex feedwater heater modelling methodology presented by le Grange [16]. Each FWH consists of a two-phase tank component that represents the shell side, a pipe component that represents the tube bundle, and a heat transfer component that represents the convection-conduction-convection heat transfer path between the turbine bled-steam mixed with cascaded distillate, and the feedwater.

The tube bundle is modelled in a similar manner as the evaporator component, whilst the FWH shell follows the two-phase tank methodology described for the boiler steam drum. An added capability that the heat transfer component brings is the ability to model the level of fouling inside the FWH. Additionally, a low- and high -pressure FWH performance C# script component is used to determine the FWH's terminal temperature difference (TTD) and drain cooler approach (DCA).

2.6 Deaerator

The modelled power plant deaerator has a stork spray feedwater tank configuration that uses the mixing process of turbine bled-steam, high-pressure cascaded distillate, and feedwater to remove the non-condensable gasses from the water/steam cycle. The deaerator tank was modelled by using the two-phase tank methodology described for the boiler steam drum. The ventilation of the non-condensable gases is not included.

The *Low-pressure feedwater heaters* and *Deaerator* plant areas, along with the FWH distillate pump, were merged into a low-pressure feedwater train. The *High-pressure feedwater heaters* and the Boiler/Electrical Feed Pumps were merged into a high-pressure feedwater train. Both low- and high-pressure feedwater trains were tested under various operating conditions before being integrated into a complete feedwater train model.

2.7 Condensers

The *Condenser* plant area consists of two main condensers that extract steam from the LP turbine, an auxiliary condenser that extracts steam from the BFPT, and a gland steam condenser (GSC) that extracts the steam from all the turbine gland seals. A compound condenser component [12] was used to model the main and auxiliary condensers. The condensers are calibrated against the real condenser process design and enables the user to manipulate the back pressure with ease. The compound condenser component enforces a saturated liquid outlet flow, ensuring a complete phase change of the extracted turbine steam. As C# script component is used to ensure the mass and energy balance of the component.

A GSC is more accurately described as a low-pressure noncontact feedwater heater that discharges distillate to the condenser via a flash box. Therefore, the GSC model consists of a compound gland steam condenser component [12] that discharges distillate from the steam side into the condensate path through a common condenser flash box modelled with a flow restriction component.

The main condensers merge into a single condensate path before being connected to the condenser flash box. The flash box connects the outlet at the top of the auxiliary condensers to the discharge at the base of the GSC. The condensate is then pumped from the condenser flash box into the GSC condensate side by the CEP, which completes the condensate train model.

2.8 Operational plant mirroring framework

An operational plant mirroring framework was used in the development of the I3PM which consists of a systematic model development methodology that approximates the construction and commissioning of a power plant. The various component models are developed (manufactured) before being merged (assembled) into plant area sections. Plant area sections are tested (inspected) before being integrated into a complete plant area model. What remains is the integration of all plant area models. The complete boiler model is merged with the feedwater train model simulating the feedwater supply to the boiler, whilst the turbine train model is merged with the condensate train model enabling the simulation of the power production. This is followed by connecting the boiler to the turbines, the turbines' bled-steam extractions to their respective FWH's and connecting the condensate to the feedwater. The final model development step involves connecting the generator to all the relevant power producing and consuming components.

The mirroring framework next imposes a systematic control methodology that approximates the control of a real power plant. An I3PM control methodology is required to ensures complete mass, energy, and momentum balance throughout the cycle for any given set of steady-state input parameters, specifically on the two-phase tank components. The control methodology development was informed by the hierarchical power plant control approaches described by Busa et al. [17]. A custom-built iterative C# – Python control method was developed.

Two C# script components (drum control and feedwater control) were developed to balance the mass, energy, and momentum of the two-phase tank components used for the modelling of the steam drum, deaerator and FWH's. The C# scripts evaluate any imbalance that may occur within a two-phase tank and corrects by adjusting a corresponding control valve. The size of the correction is based on a scaled thermofluid process balancing calculation. Like the default "designer" feature described earlier, multiple iterations are required to reach each balance point with a sufficiently small residual value.

The Python API runs multiple steady-state simulations while allowing the C# script components to balance the model using a linear programming optimization algorithm. The computational time that already outperformed the "designer" feature was further improved by implementing a hierarchical power plant control approach, using a multilevel optimization algorithm that first balances the steam drum, then the deaerator, followed by the FWH's.

2.9 Data generation

The Python API is used for the controlled generation of load loss classification datasets. The API enables the altering of any I3PM parameter, which allows for the simulation of a wide range of operational anomalies and different states of component degradation. A list of load loss inducing I3PM parameters was derived from mechanical and process anomalies identified in historic load loss event manual root cause analysis data.

A Monte-Carlo (MC) algorithm was developed for the induction of I3PM component level faults that will result in a load loss. The MC algorithm assigns new randomly generated values, that lie within the operational and component design limits, to selected component parameters. This means that the values will not force a scenario onto the I3PM that would cause the real plant to trip or result in a severe component failure.

After the MC algorithm induces faults, and a simulation has converged, the results are stored and the I3PM is reset to a default state. The stored results are comprised of I3PM parameters that correspond to existing plant condition monitoring measurements as well as the specific MC algorithm configuration, enabling the classification of the generated data.

3 Model validation

To evaluate the accuracy and appropriateness of the results produced by the I3PM different steady state validation simulations were conducted. The boundary conditions were configured to simulate 60%, 80% and 100% MCR in accordance with the real power plant acceptance test data. Additionally, 69% and 97% MCR were simulated to specifically evaluate the boiler gas path against the manufacturers' design data. The validation temperature results are summarised in Figure 2.

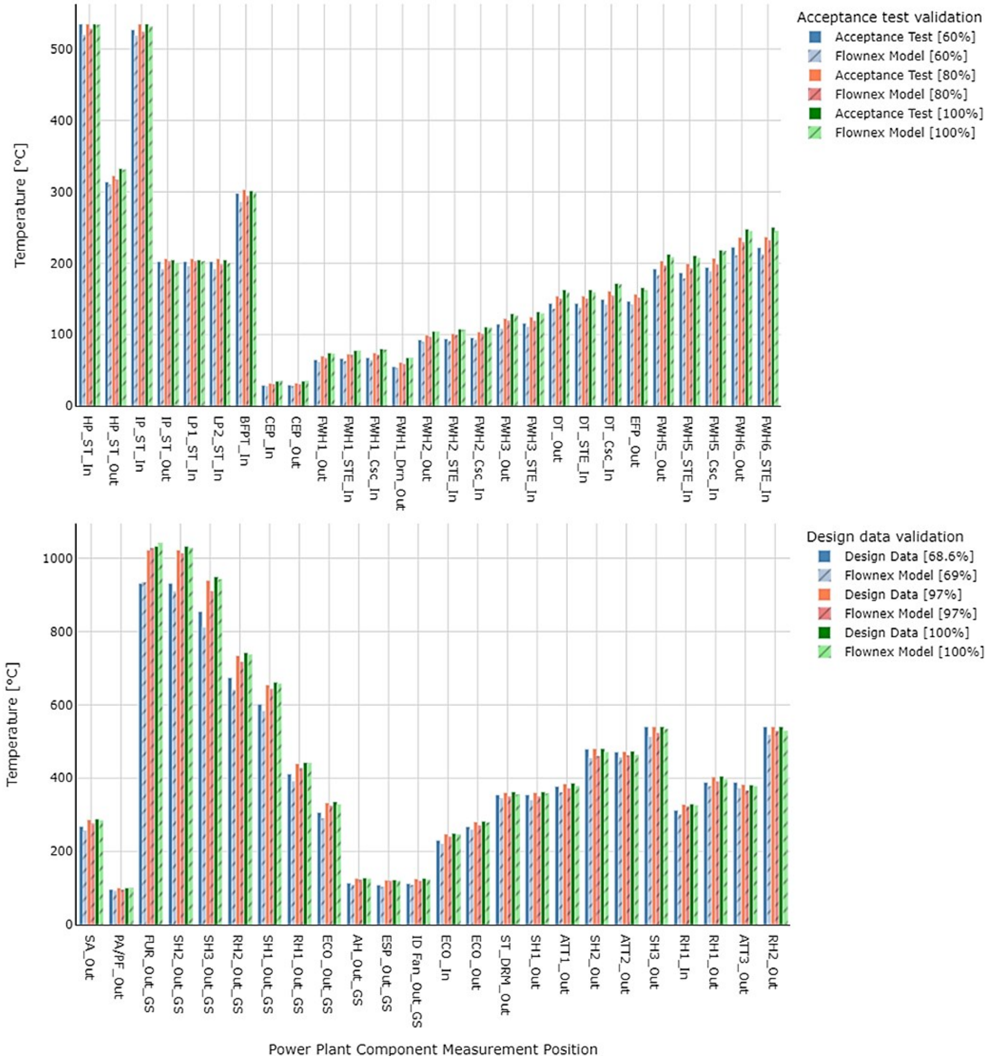

Figure 2: Integrated power plant thermal process model validation results

Only measurable parameters (temperature, pressure, and mass) were used for the validation of the model to align it more closely to the real power plant. As shown in Figure 2 the results from the validation simulations are all within 5% compared to the acceptance test data and a relative error of less than 8% when compared to the boiler manufacturer's design data.

The validation results established confidence in the ability of the I3PM to predict the performance of a real power plant with sufficient accuracy based on a component level configuration.

4 Data generation results

To demonstrate the ability of the I3PM to capture the effect of different combinations of anomalies it was used to evaluate the plant performance related to three specific load loss inducing scenarios. These are the use of low-grade coal, poor condenser performance and the plugging of feedwater tubes. The specific plant parameters used to represent these scenarios are a reduction in the Gross Calorific Value of the coal, an increase in the back pressure in the main condenser and an increase in the number of plugged tubes in the second low-pressure FWH, respectively. First, each of the three parameters were perturbed independently via the MC algorithm and for each case the I3PM simulation was run to determine the impact on the overall power output and cycle thermal efficiency. Following this, random combinations of any two of the three parameters were tested, and finally random combinations of all three of the parameters.

4.1 Single parameter scenarios

The results of the single parameter scenarios are presented in Figure 3. The figure shows each of the three parameter values on the y-axes together with the resultant cycle thermal efficiency on the x-axis, while the colour coding indicates the resultant load loss compared to the original design specification. The results show that the plugging of tubes has the least severe impact on plant performance, whilst poor coal quality has the greatest. Poor condenser performance primarily affects the plant efficiency. The results are aligned with expectations.

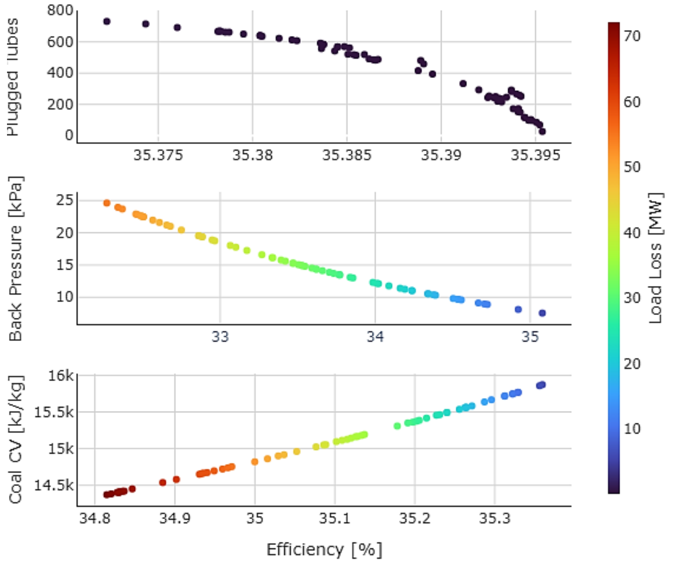

Figure 3: Single parameter scenarios

4.2 Dual parameter scenarios

The results of the dual parameter scenarios are presented in Figure 4 with parameter 1 on the x-axis and parameter 2 on the y-axis, while the colour coding indicates the magnitude of the resultant load loss. The combination of poor coal quality and poor condenser performance has the greatest impact on plant performance. The relative insignificance of the number of plugged tubes is visible on both the top and bottom graphs, since there is very little variation in the load loss in the y-axis direction. All results are again aligned with expectations.

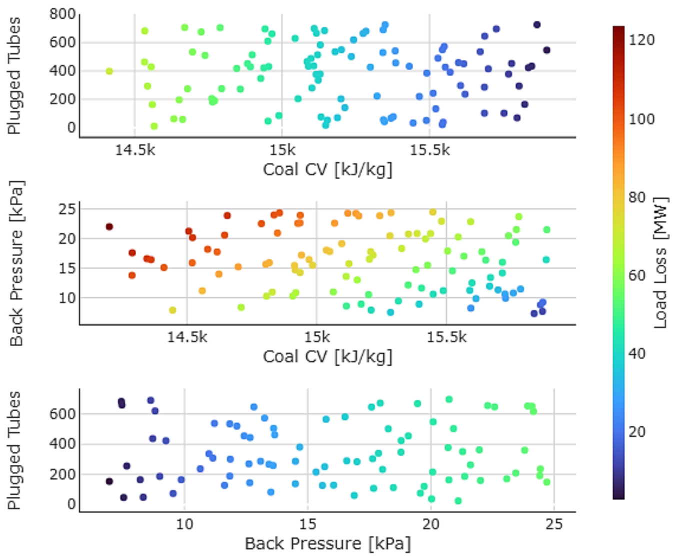

Figure 4: Dual parameter scenarios

4.3 Triple parameter scenarios

The results of the triple parameter scenarios are presented in Figure 5 with the three parameters represented on the x, y and z-axes respectively, while the colour coding indicates the magnitude of the resultant load loss. As expected, the results show that the combination of poor coal quality and poor condenser performance still has the greatest impact on plant performance relative to the number of plugged tubes. However, it also shows that the simultaneous impact of a combination of parameters can be determined, which will be required in order to emulate physically realistic load loss scenarios.

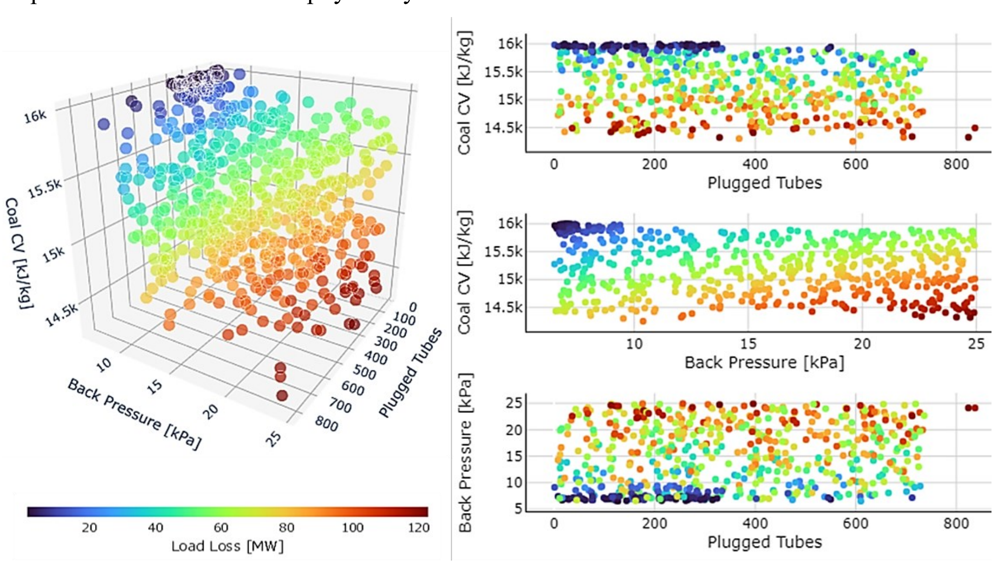

Figure 5: Triple parameter scenarios

5 Conclusion

In this study an Integrated Power Plant Thermofluid Process Model (I3PM) was developed for the controlled generation of load loss classification datasets. The validation showed that the model can successfully emulate real power plant operating conditions. The results from the single and multiple parameter load loss scenarios show that the simultaneous impact of a combination of parameters can be determined, which will be required in order to emulate physically realistic load loss scenarios. The model further establishes its suitability and capability to generate load loss classification data.

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