Fully automated coal quality control using digital twin material tracking and statistical model predictive control for yield optimization during production of semi soft coking- and power station coal

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Synopsis

The quality control of a two-stage coal washing process involves several complex components that need to be modelled accurately, to enable autonomous control of the process. The first objective is to develop a method to track the material through the washing process, while ensuring accurate washing prediction models are used. This was achieved through a digital twin model of the Grootegeluk 1 coal processing plant. The model is the amalgamation of manipulating and combining of data-sets from the plant historian, geological wash tables, and mining dispatch servers. This information is then used to control and set the processing medium densities of all 15 modules on the plant, 10 modules in the primary wash and 5 modules in the secondary wash. This controller has been successfully implemented and controlled the plant for 10 days.

Keywords

coal quality, quality control, digital twin.

Introduction

The controller developed in this paper was implemented on the Grootegeluk 1 (GG1) coal processing plant. GG1 forms part of the Exxaro Grootegeluk Coal Complex, which is one of the largest opencast coal mines in the southern hemisphere. Given the vast size of the operation, GG1 is not fed from a single source in the pit, but from several coal blocks. The mixing of the run-of-mine (ROM) material introduces additional complexity since coal from each block reacts different to the washing conditions encountered during processing.

Two coal products are produced at GG1, coal used for electricity generation or power station coal (PSC) with an ash content of 35% and semi-soft coking coal (SSCC) used in the production of steel. SSCC is a higher value product when compared to PSC and has an ash content of 10.3%. The sequence in which these two products are produced depends on the mass fraction of each stream. In a conventional circuit, the higher value product is removed first, followed by the second and finally discarding the waste (Wills, and Finch, 2015).

Due to the high waste fraction of the ROM processed at GG1, the first washing cuts the waste and the second wash cuts the remaining product stream between PSC and SSCC. The exact fraction of each stream is controlled by manipulating the relative density (RD) which directly affects the ash content of the coal (Osborne, 2013).

Problem statement

A time delay of 3–4 hours is observed between the time that the secondary wash products are sampled, and the coal quality results are reported. This implies that by the time the results are reported to the process controllers, the material that has similar properties has long since been through the washing process and thus renders the information outdated to a large extent. Results and discussion

A similar effect is seen when evaluating the time delay between the tipping point to the first wash and from the first wash to the second wash. When combining all the time delays in Table I, a total time delay of approximately 12 hours 50 minutes can be determined. This implies that the material tipped during the current shift will likely be washed only during the next shift, voiding any attempt by the process controllers to wash according to the tipped material's geological properties.

This delay challenge, along with the varying material origins, lead to the fact that the only reasonable way to circumvent these issues is to implement a solution that will have a sufficient granularity along with the ability to track the material through the entire process (Solution objective Table below).

The controller must react on the combined input data-set containing the material properties and location. This will then be used to calculate and set the optimal plant conditions for each of the 15 modules. The controller output will provide the medium density set-point for each module. These outputs will update the current PID controller set-point to that of each module, which is typically adjusted by the plant operator.

Figure 1a is an aerial view indicating the layout of the various areas within GG1. Figure 1b is a schematic diagram of the coal material flow. Area 02 contains 5 dense medium cyclones; Area 03 contains 5 dense medium drums; Area 04 contains 5 dense medium cyclones. The additional fine material of the spirals in Area 05 should also be considered and modelled.

Method

The controller was developed and programmed in the Python version 3.7.6 programming language. The program was sectioned into several main functions with defined inputs and outputs. This will facilitate the updating of an improved algorithm for future revisions of the controller. The main functions of interest are discussed in the following sections. A detailed report containing the explanation of each component is available upon request.

Table I

Time delay between various points in the washing process

Step	Origin	Destination	Time (hh:mm)	Cumulative Time (hh:mm)
1	Truck loading	Tipping bin	0:25	0:25
2	Tipping bin	Primary silos	0:30	0:55
3	Primary silos	Primary wash	5:00	5:55
4	Primary wash	Secondary silos	0:15	6:10
5	Secondary silos	Secondary wash	2:10	8:20
6	Secondary wash	Laboratory	2:00	10:20
7	Laboratory	Preparation	1:00	11:20
8	Preparation	Analysis	1:00	12:20
9	Analysis	Results	0:30	12:50

Solution objectives

	Objective	Method of validation
1	Real-time and accurate material tracking through all the different areas within the plant (Figure 1): • From pit to primary silos (ROM to A02/A03) • From primary silos to secondary silos (A02/A03 to A04) • From secondary silos to stock yard (A04 to stockpiles)	To test the entire mass tracking of the model, the predicted values will be compared to the product conveyor belt scales. This will be done for both product streams, PSC and SSCC. It should be noted that each section, for example ROM to A02/A03, will not be validated individually but as a combined total mass balance for PSC and SSCC
2	Combining wash tables (geological coal characteristics) to ensure that mixing and movement of the material within the silo is modelled and accounted for. Eeach module's silo will contain material with different characteristics, depending on the selected silo at the time of material tipping. This will also have the following sub-objectives: • Yield resulting from the selected cut point based on the geological information • Coal product qualities resulting from the selected cut-point	To test the wash table combination of the model, the predicted values will be validated by using both of the following methods: • Compare the calculated output to the output from the current geological models for the material in all 15 silos. • Compare the predicted qualities when using the current plant cut-points and with the quality results reported by the laboratory
3	Performance tracking to evaluate the performance of the controller. This will also assist with the identification of potential future improvements	The following procedures will be employed to validate the efficiency and effective functioning of the controller: • Pre- and post-implementation analysis of the product streams' qualities • Percentage utilization. Operators and management's acceptance of the controller and the resulting qualities

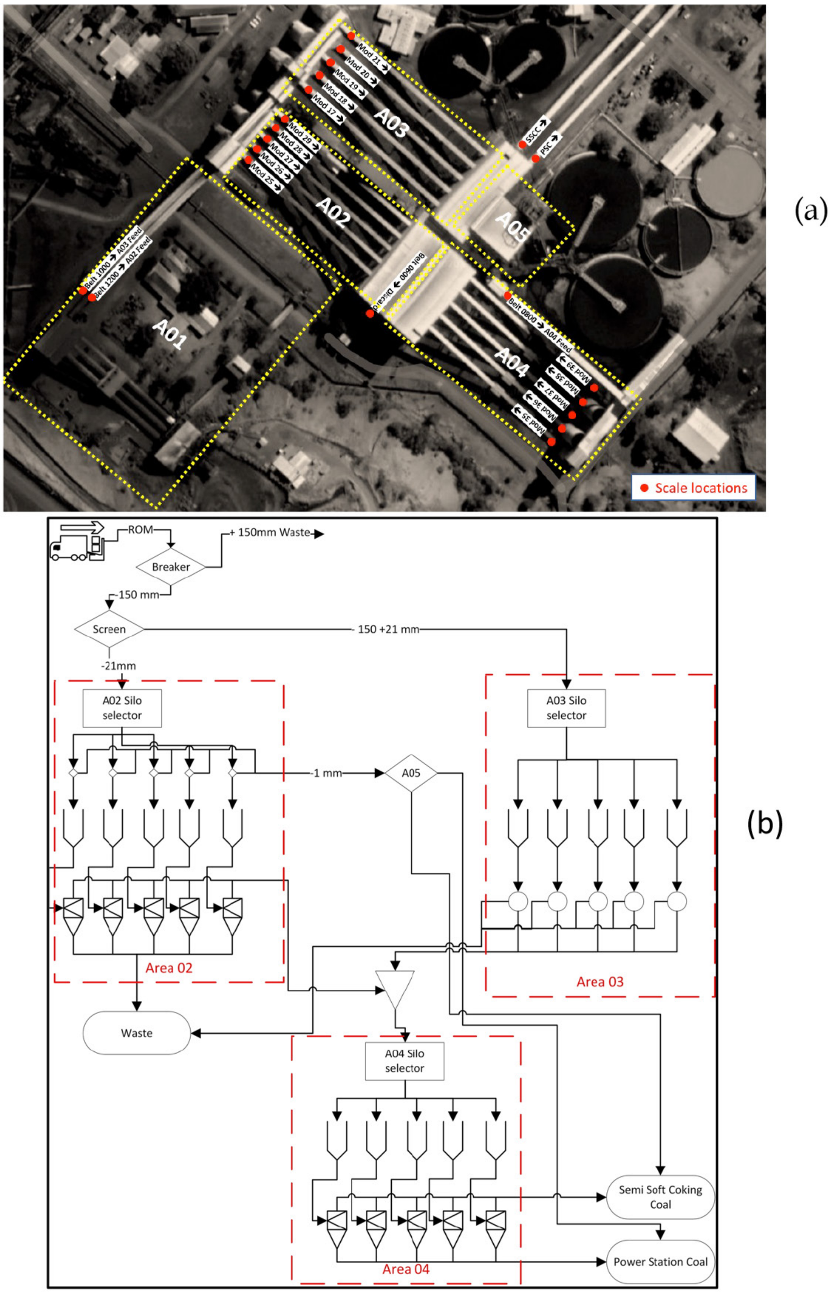

Figure 1—GG1 (a) Aerial view and (b) schematic diagram of coal material flow

Controller execution logic

Upon start up the controller runs through an initialization algorithm to bring the plant digital twin model (PDTM) in line with the current material quality and quantity within the plant. It was seen that it could take several hours for the material to exit as product once it was tipped at the plant's bin. It was decided that the PDTM would have to access data from a week prior to initialization. The extended timeframe was selected to accommodate events where a module was taken out of production for several days with no material movement.

The programming logic of the main execution loop is seen in Figure 2. The main execution loop is executed on an hourly basis due to the analysis results being released on an hourly basis. An increased execution rate will therefore not introduce any benefit to the controller accuracy. The longer duration is also required for the plant to respond to the adjustments in RD set-points.

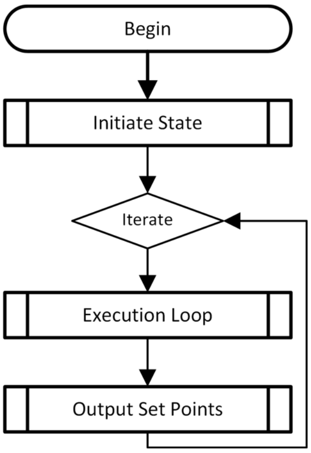

Figure 2—Main controller programming logic flow

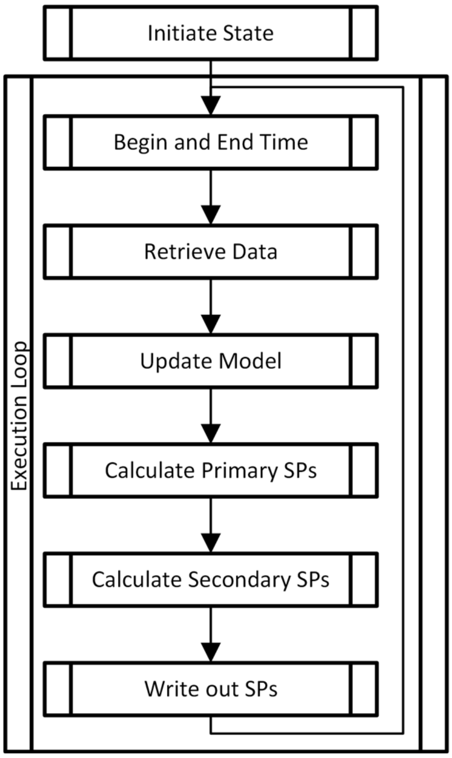

Figure 3—Loop execution containing the sub programming logic flow

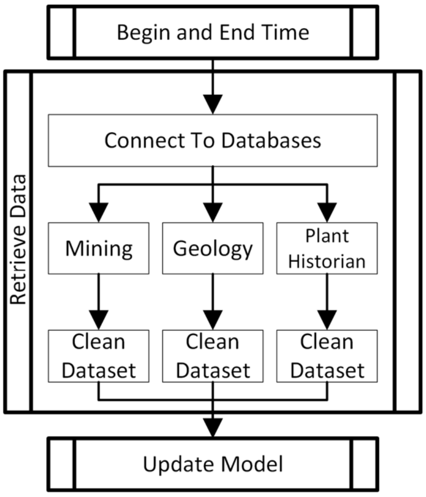

Figure 4—Data retrieval logic flow

Once an hour has lapsed and this logic has been started, the first step is to determine the beginning and end times of the interval to be used. The end time will be the current time; whereas the beginning will be the hour prior. One exception is with the beginning time, when an iteration does not see any new information the beginning time is not updated. In these exceptions the beginning time will therefore be the end time of the last successful iteration.

The two time intervals are then used to retrieve the data from the three databases, seen in Figures 3 and 4. These databases are the: mining database containing the information of the truck tips, which in turn contains the tipped mass and material origins within the pit; the geological database, which contains the complete proximate analysis of each block in the reserve; and lastly the plant historian, which contains the historical values of the plant sensors. These three data-sets are then cleaned and transformed such that the datasets can be combined.

This information is then prepared and used to update the PDTM material locations within the various sections. The additional material that has been tipped to the plant is moved to the primary silos and the material that was in the primary silos is washed and moved to the secondary silos. Lastly, the material in the secondary silos is allocated to the stockpiles by the PDTM.

The next step Figures 5 and 6, is to calculate the primary RD set-points of the modules in Area 02 and Area 03. Each module is evaluated individually and the combined material properties within each module is considered to determine the optimum RD. These RDs are then used to determine the fraction of waste removed and the remaining material is moved to the secondary silos.

Similarly, each module in Area 04 is then considered individually and the combined material properties are considered. This is then used in combination with the RDs used in the primary area to determine the optimum RD for the secondary wash.

These 15 RD values are then used and written out to the plant's PLC system. The optimized RD values thus become the set-point values for the PID control loops in each individual module. A final communications check is also performed right before the values are written out.

The next step is the interaction with the process operators (Figure 7). It is verified that the controller is switched ON and is operated on SCADA. If the process is not controlled in automatic mode, the controller is not allowed to interact with the plant. This is to ensure that the operator is still able to provide oversight and retain control over the plant. If the controller is switched OFF, the set-points are not written to the PID controllers and the program halts until the next iteration.

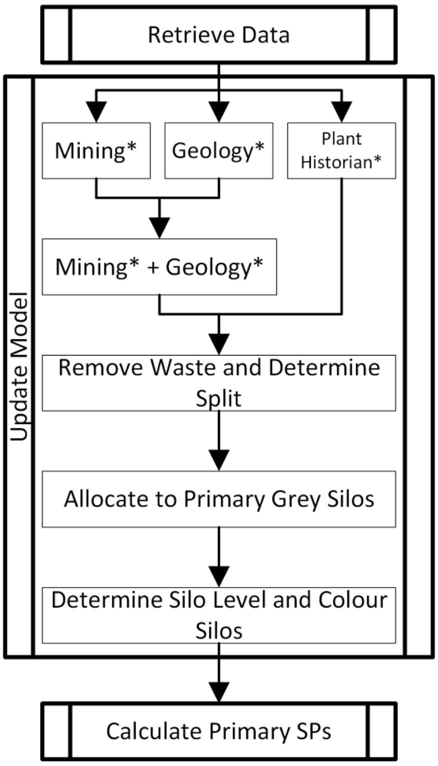

Figure 5—PDTM Update logic flow

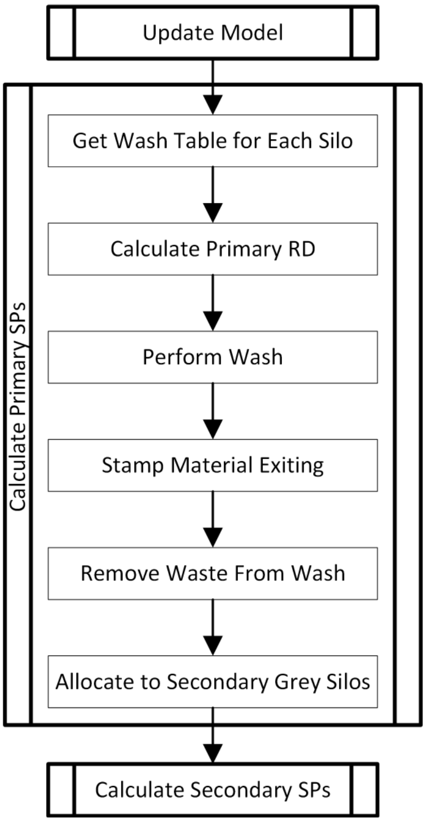

Figure 6—Primary set-points calculation logic flow

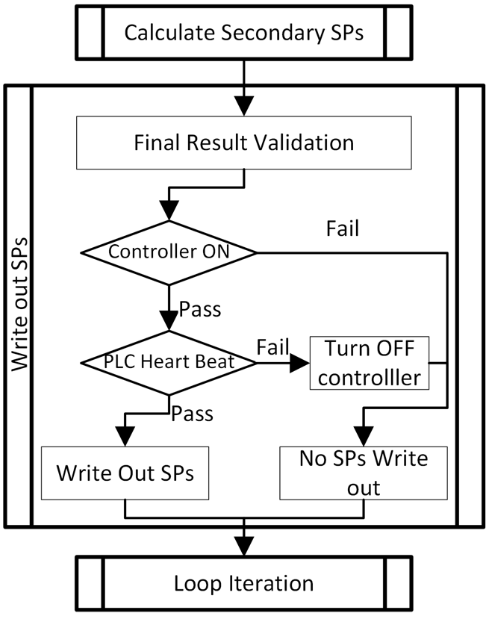

Figure 7—Procedure for writting new SPs to actual plant logic flow

If the plant is operated in automatic mode, the controller checks communication with the three PLCs, one for each respective area in the plant. This is done by using a PLC heartbeat, which is implemented by the controller writing out a value of *e.g.* 58 and the PLC subtracting one each second. This means that if the controller loses connection for a minute, the controller will switch off automatically. If the PLC communication check is successful, the next step takes place and the set-points are written to the PID controllers.

Yield calculation methods

The method used to calculate the yields, the split between the product and waste fractions after each washing stage, evolved through the duration of the project, in an attempt to improve the accuracy of the calculations. The addition and inclusion of several factors greatly increased the complexity of the algorithms used. The algorithms used were applied to the geological wash tables of each block in the pit. An example of this can be seen in Table II.

Each method was given the target to reach a final product ash content of 35% and 10.3% for PSC and SSCC respectively. These RDs were then used in a Whitten model with an Ecart probable (Ep) of 0.025 to evaluate the performance (De Korte, 2008; Wills, and Finch, 2015).

Method A: Interpolation for primary and secondary wash

Method A was the first attempt at reaching a solution. This method interpolates between the data-poins to find the predicted RD based on the cumulative ash column. Both primary and secondary RDs are calculated in the same way, where a perfect separation is assumed with no effect on the near dense material (NDM) incorporated. This method does not consider the interplay effect between the washes. As seen in Table III, this method makes a reasonable attempt at finding the correct solution, but still leaves a lot of room for improvement.

Method B: Single iteration of whitten model for primary and interpolation for secondary wash

Method B is the accepted method to calculate the mine's monthly reconciliation and performance reports. It works on a combination of the interpolation method, used for the secondary wash, and the Whitten model, used for the secondary wash. This

Table II

Example of a combined wash table within a silo

RD	**Yield** (%)	**Ash** (%)	**Calorific value (MJ/kg)**
1.35	7.595	5.998	30.994
1.4	12.426	9.163	30.005
1.45	16.645	11.244	29.288
1.5	20.716	13.260	28.595
1.55	25.379	15.656	27.762
1.6	28.213	17.164	27.233
1.7	33.292	20.131	26.198
1.8	37.086	22.615	25.312
1.9	40.797	25.233	24.383
2.0	45.1039	28.335	23.270
2.1	50.1559	31.826	22.022
2.2	60.1692	38.123	19.768
2.5	100	54.918	14.119

Table III

Comparison of yield calculation methods

Method	**Cut-point**		**Resulting quality (ash content)**	
	Primary	**Secondary**	**PSC**	**SSCC**
Method A	2.104	1.421	37.6%	10.35%
Method B	2.123	1.425	36.6%	10.35%
Method C	2.106	1.427	36.7%	10.44%
Method D	2.056	1.417	35.00%	10.300%

method only performs a single iteration of the calculation. Since this method incorporates the NDM in the primary wash it is already an improvement on Method A.

Method C: Single iteration of whitten model for primary and secondary wash

This was the natural progression Method B, where the adapted Whitten model is used for both washes. It is still, however, only a single iteration and therefore does not fully incorporate the interplay effect between the two washes. Since an Ep is used in both stages, it also allows the difference in separation performance of the different areas to be incorporated.

Method C is the most metallurgicaly sound, since it considers the fractional yield at each RD fraction. This results in accounting for the NDM present close to the cut RD. It can be seen that this method produces a final result that is much closer to the desired value, although it is not yet the optimized value.

Method D: Optimized whitten model for primary and secondary wash

This method makes use of the sample calculation used in Method B, however the functions were developed to iterate until both products are at the desired specification. This iterative approach is used to calculate both washes simultaneously, accounting for the interplay between the two washes.

Since this calculation will be performed for each of the 15 modules in each execution step it was optimized to reach a solution as fast as possible. The function was also developed to incorporate the physical constraints as well as a convergence time limit. The final solution implemented was able to reach an optimized value in roughly 20 milliseconds.

Data structure architecture

Figure 9 depicts a schematic diagram of the controller configuration on the plant. It can be seen how the various sources are connected to the controller, namely the plant historian, geological database, and mining data-sets. These data-sets are combined to update the internal models and the updated models are used to calculate new controller set-points.

This process results in the output SPs for all 15 modules, which in turn are send to the OPC server through the OPC connection component. The process operator remains the gatekeeper of the instructions. This is to ensure the process operator still retains ultimate control of the process.

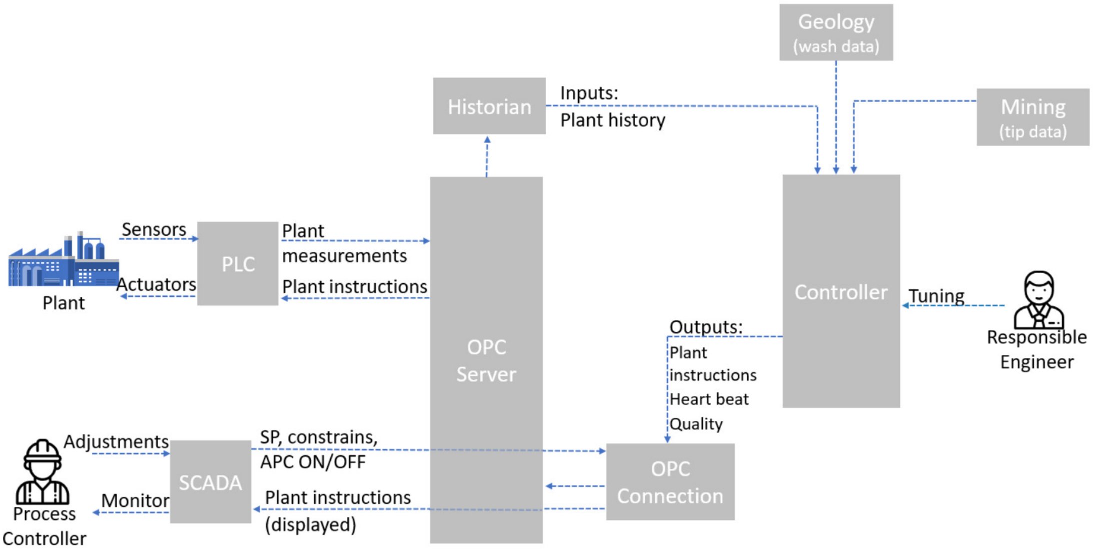

Figure 8—Schematic data architecture

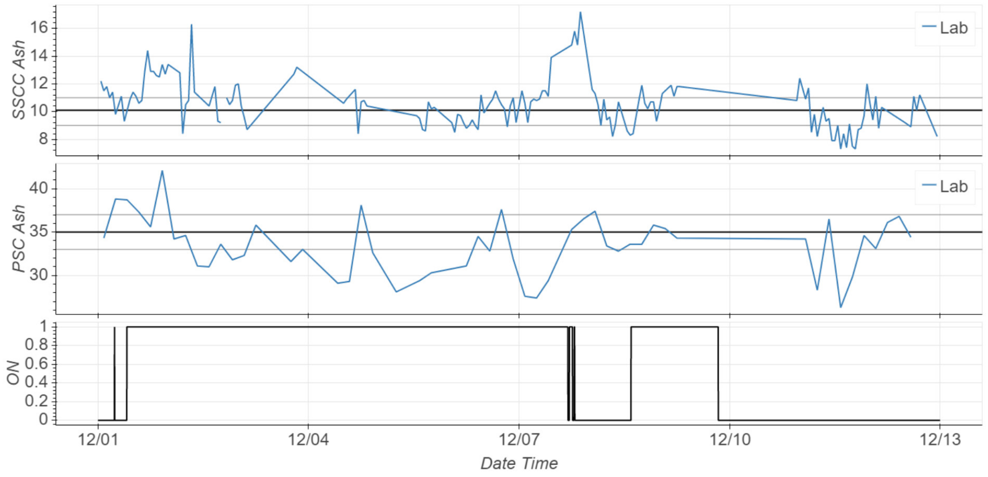

Figure 9—Quality Results

The controller can be switched ON and OFF from the plant SCADA screen. Several other key parameters are also shown on the same screen, for example the heartbeat check.

Results and discussion

The controller was commissioned and implemented on 2 December, 2020. The controller operated for ten days until the author was reassigned to a sister mine. Thereafter, the mine expressed interest in upskilling the onsite personnel to receive a handover of the project. The controller's performance can be seen in Figure 9 and Table IV. The implementation of this controller made GG1 the first fully automated quality control plant within Exxaro.

The light grey lines indicate the acceptable range in which the qualities should be maintained. It should be noted that the SSCC was sampled once an hour whereas the PSC was only sampled once every four hours, leading to the fewer data-points.

During the initial activation there were several lessons learned, one of which was with regard to the RD values observed on SCADA and the actual RDs sampled on the plant. When the plant is controlled manually by the process operator, very little to no attention is paid to the wash tables during operation. The quality control philosophy centres around the operators reacting on the produced qualities; when the ash values are lower than the target value, the operators must increase the RD set point values, and the extent of the adjustment is based on each operator's experience. The same is true for the opposite case when the ash values are higher than expected.

This can lead to a marginal deviation between the observed and actual RD values, since the actual RD is not considered but only the relative difference while still producing coal with qualities that are acceptable. Luckily this was a simple fix where the SCADA RD values were calibrated more frequently. Once this was accomplished the controller was able to successfully control the plant.

When the controller was initialized, there was a spike caused by the RD difference discussed in the paragraph above. There is also a second spike where the controller is switched OFF. This was the result of a communication failure caused by a power failure, which led to the controller handing control back to the operators. Several of the plant's sensors were affected, which led to the large deviation. Once the plant was in stable operation the controller was switched on again.

The process response and controller set-points are indicated in Figure 10. The controller is implemented in a cascaded manner where the SP instruction to the PID loop controlling the water valve is updated.

Table IV

Controller performance results

Period	Average	Max	Min	Std dev
SSCC Pre	10.31	14.7	5.1	1.39
SSCC Post	10.13	13.2	7.3	1.24
PSC Pre	32.25	40.4	28.2	2.41
PSC Post	32.88	38.1	28.1	2.52

The water valve supplies additional water which in turn regulates the RD of the dense medium. The process value did not always follow the RD set-point. This was another lesson learned since failure to do so will result in the inability to effectively judge the performance of the controller, *i.e.*, when the clarified water lines are blocked or the medium tank is at full capacity. This issue was identified on several modules in each area, indicating areas for further improvement.

During this testing phase the SSCC target value was set to 10.1% ash. The reason for this was twofold. Firstly, a conservative value was selected to ensure no product rejections were obtained. Secondly, the production team requested a lower value to be used since the average bed qualities were already above the required 10.3% ash, and thus be brought back down.

With the exclusion of these two cases, a clear improvement is seen in the minimum and maximum values as well as a reduction in standard deviation of 1.39 % to 1.24 % ash for the SSCC.

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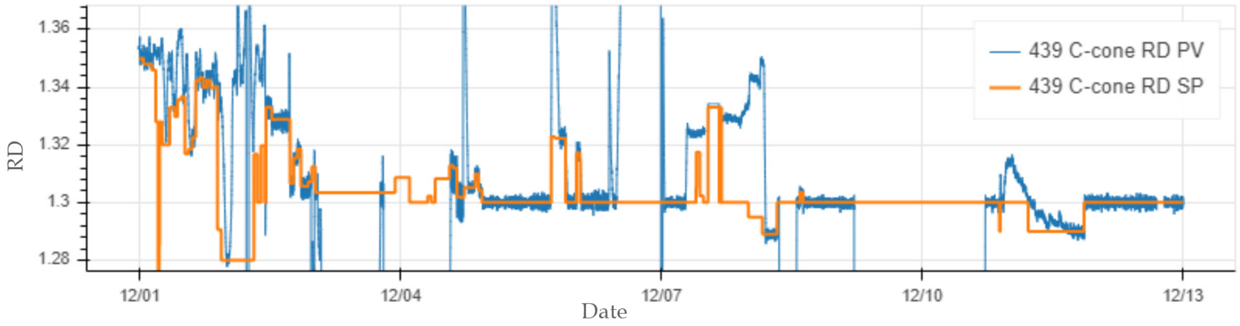

Figure 10—Module 439 SP changes and PV tracking