# Advanced Process Control for Coal Flotation: A Case Study of the Approach and Benefits of a Structured Digitalisation Program

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As part of a broader digital technology-enabled transformation programme, a major mining company is systematically implementing Advanced Process Control (APC) solutions and associated instrumentation throughout their operations. This paper highlights the approach and benefits of this holistic approach for a specific instrumentation installation, and APC installation at a South African coal processing plant. For the coal processing plant under consideration, a systematic approach was followed. Process sections/units are considered from upstream to downstream processing. APC solutions are designed for each process section and each process section is interrogated in terms of availability of sufficient process measurements to ensure stable, capable, and ultimately, optimised performance. Where insufficient process measurements are available, instrumentation upgrades are implemented. Finally, APC solutions are implemented, and evaluated in terms of productivity, safety, health, and environmental benefits. For the flotation section, an opportunity was identified to install froth sensors. The installed froth sensors provide measurements on froth velocity, bubble size, height, colour, and stability. The improved visibility that the froth sensors provided on the flotation process resulted in quick gains in terms of productivity: for example, instability in the feed to the flotation section could be quantified. This resulted in targeted process troubleshooting in an upstream thickener, and subsequent improvement of process stability, and reduced feed variance. The measurements from the froth sensors were further integrated in an APC solution. Proportional mass pull contributions per cell and per line can be inferred from the froth sensors, serving as controlled variables, while pulp level set points serve as the manipulated variables. On-off tests indicated that the advanced process control solution provided increases in yield and product quality.

## 1. INTRODUCTION

### Background: Digitalisation in Mining

Digitilisation and the drive for mining operations to move towards Industry 4.0 to become more efficient, and adaptable has become increasingly prevalent in recent years. According to Young & Rogers (2019) mining is behind many other industries in relative digitalisation. A White Paper by the World Economic Forum (2017) on the digital transformation initiative in the mining and metals industry highlights the challenging outlook for this industry, driven by contributors such as weak global demand, persistent excess capacity, increasing customer requirements, widening workforce skill gaps, and declining resource access and quality. An indicator of these challenging times is mining productivity, as expressed through the MineLens Productivity Index, (MPI), (McKinsey, 2015). The MPI showed a dramatic decrease in the period 2004 to 2013 (an average 3.5% decrease per annum. However, an upswing in the MPI is evident from 2014 to 2016 (2.8% increase per annum) (McKinsey, 2018). McKinsey (2018) postulates that the increase in mining productivity can be attributed in part to technology-enabled transformation, specifically grouped as: 1. Data, computational power and connectivity; 2. Analytics and intelligence; 3. Human-machine interaction; and 4. Digital-to-physical conversion. In turn, the World Economic Forum (2017) provides the following themes that will play a crucial role in the digital transformation of mining and metals: 1. Automation, robotics and operational hardware; 2. Digitally enabled workforce; 3. Integrated enterprise, platforms and ecosystem; and 4. Next-generation analytics and decision support (see Figure 1).

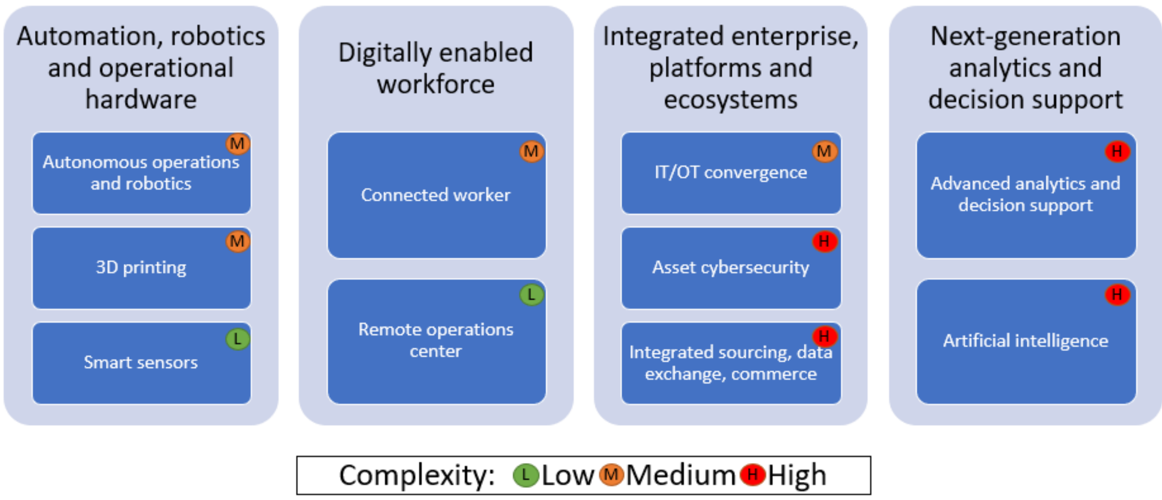


*Figure 1. Digital themes and initiatives in mining and metals, with technology complexity rankings indicated (adapted from World Economic Forum, 2017).*

The realisation of technology-enabled transformation requires concerted digital adoption efforts. Two important factors that affect digital adoption are: 1. The inherent complexity and scalability of the technologies under consideration; and 2. The transformation ambitions of company executives, especially within the constraints enforced by location, access to capital, and legacy issues (World Economic Forum, 2017). In terms of transformation ambitions (World Economic Forum, 2017), enterprises can be classified as resistant to systematic and pro-active digitalisation ("business as usual"); fast followers (willing to roll out tested technologies while slower to experiment untested technologies; or digital first movers (actively investing in trial-and-error approaches and encouraging employees to collaborate on and test digital technologies).

**Background: Digitalisation in Anglo Integrated Control Systems**

The context for this paper is the specific holistic approach of Anglo American and the Anglo Integrated Control Systems unit. Their approach to roll out advanced process control (APC) solutions across all Anglo American processing facilities allows technology-enabled transformation to improve mining and mineral processing productivity. A case study at its Greenside Thermal Coal Washing Flotation Plant is used as an illustration of this systematic approach in this paper. Figure 2 shows the relevant digital themes and initiatives for this case study, as well as the required people, workflows, and technology support.

| | Automation, robotics and operational hardware | Digitally enabled workforce | Integrated enterprise, platforms and ecosystems | Next-generation analytics and decision support |
|---|---|---|---|---|
| **People** | Control design and implementation team<br>Process site champion<br>Smart sensor provider | Control support team (remote monitoring center)<br>Sensor support team (remote monitoring center)<br>Process engineers and operators | IT/OT convergence team | Process/control monitoring and analytics teams (in-house and service providers) |
| **Workflows** | Systematic approach (upstream to downstream assessment of required instrumentation and potential for control) | Training, engagement and continuous change management for process engineers and operators<br>Sustainable value through continuous monitoring of implemented solutions | Automation system designed to connect with applications. Data is passed seamlessly between systems and routed as needed with the necessary security measures in place. | Monitoring-as-a-service<br>Structured data analytics studies (e.g., cross-industry standard protocol for data mining) |
| **Technology** | Control infrastructure<br>IIoT smart sensors | Digital data infrastructure (networks and cloud) | Enterprise, operational, SCADA and sensor data management and integration systems | Advanced analytics platforms and packaged solutions |

*Figure 2. Targeted and related digital themes and initiatives, with associated people, workflows, and technology support relevant to the Greenside Thermal Coal Washing Plant structured digitalisation program.*

APC solutions, part of advanced analytics and decision support, can make use of smart sensors and ensure that more parts of the operation can be automated. To support APC solutions, the workforce is digitally enabled (providing workers with up-to-date and relevant information, as well as supporting operations from remote monitoring centres). Integrated enterprises, platforms and ecosystems are required to ensure effective and sustainable APC solutions across sites. The effectiveness of technologies such as APC require increased levels of automation, and where required, smart sensors.

For the coal processing plant under consideration, a systematic approach was followed to implement and support APC solutions. Process sections/units are considered from upstream to downstream processing. APC solutions are designed for each process section and each process section is interrogated in terms of availability of sufficient process measurements to ensure stable, capable, and ultimately, optimised performance. Where insufficient process measurements are available, instrumentation upgrades are implemented. Finally, APC solutions are implemented, and evaluated in terms of productivity, safety, health, and environmental benefits.

**Background: Requirement for advanced process control solutions and context within digitalisation**

Traditionally, operators in control rooms are constantly monitoring processes and adjust process variables to ensure that the process is operating at the required efficiency, and qualities. Due to the complexity of operating large plants, the control room operators do not have the time and ability to operate the process at the required efficiency. Anglo American recognised the need for digital tools and began implementing technologies in process plants to aid operators to more optimally operate plants. The technologies that were implemented at the Greenside plant were APC as well as froth flotation smart sensors which fall in the category of automation and the Internet of Things (IoT).

Implementing digital technologies on mining operations is challenging as studies done by Barnewold and Lottermoser (2020) stated that >37% of leading executives have insufficient knowledge and understanding of digitalisation trends and available options. Masiri and van Dyk (2019) further showed that there is very narrow understanding of digitalisation. A further study by Sganzerla *et al.* (2016) showed that only 10% of mining companies that implemented digital technologies reported quantitative benefits. The lack of understanding and successfully proven results draw sceptics on the implementation of digital technologies. These trends were no different at Greenside. The APC technology was introduced to the Greenside operation in 2018. Management, technical staff, and operational staff bought into the concept of digital initiatives but were apprehensive of the implementation in real time production. The APC was first implemented on the coal feed bins, and the implementation delivered immediate benefits. Over the last three years, over 20 APC controllers, plant wide optimisers, and additional traditional instrumentation and equipment were installed to improve the overall automation of the process. Each implementation and related benefits improved the acceptance of this digital system.

Masiri and Van Dyk (2019) indicated that several organisations experience significant challenges in areas of equipment infrastructure that support Industry 4.0 requirements. Aziz *et al*. (2020) has outlined that mining companies traditionally have the Information Technology (IT) and Operational Technology (OT). They argue that an interconnecting network is required for digital transformation and is known as the Industrial Internet of Things (IIoT) – a network of physical objects, or things, embedded with electronics, sensors, and connectivity to enable that network to achieve greater value and service by exchanging data with the manufacturer, operator, and/or other connected devices. Throughout the APC journey at the Greenside operation, the level of plant automation was increased, and this included automating chutes and installation instrumentation such as level transmitters, weight scale and density meters. The Greenside operation is over 40 years old, and technology has been gradually introduced to the plant. However, the instrument network was the typical 4-20mA and the introduction of the Stone Three froth sensors required the addition of a smart instrumentation network.

**Article structure**

This paper focuses on the flotation optimisation APC solution at Greenside Thermal Coal Washing Flotation Plant. Background on flotation control and optimisation (specifically focusing on mass pull) is given in Section. 2. Section 3 provides an overview of the smart sensor instrumentation that was required for the flotation control system, while section 4 describes the process context. The control description and benefit estimation of the solution are provided in sections 5 and 6, with final conclusions and recommendations in section 7.

## 2. LITERATURE: FLOTATION CONTROL AND OPTIMISATION

The aim of coal flotation control is to operate continuously at the optimal point on the grade recovery curve. This is conducted by optimising the flotation cells operating parameters as well as stabilisation control of the feed which has a large effect on grade and recovery (Seitz and Kawatra, 1985).

In order to control flotation processes, appropriate instrumentation is required. Bergh and Yianatos (2011) describe the typical instrumentation requirements for regulatory and supervisory/optimisation control layers: pulp level, chemical reagent addition rate, air addition rate, pulp flow rate and water flow rate measurements typically at a regulatory level; and concentrate/tailings grade measurements typically at a supervisory/optimisation level. Some case studies in hierarchical flotation control (Muller *et al*., 2010; Brooks and Munalula, 2017) utilise pulp level and air addition (regulatory level), pulp flow /mass pull estimate/froth velocity (supervisory level) and grade (optimisation level) measurements for flotation control.

Seitz and Kawatra (1985) suggested that it is difficult to develop a common control strategy across all coal sites. This is due to the varying types of coals which bring about varying responses on the flotation cell. Furthermore, they suggested that the operating philosophy at each site as well as circuit design must be taken into account once developing the control strategy. Proportional Integral Derivative (PID) controllers are commonly used control strategies due to their simplicity to build and execute. However, such applications have a shortcoming in that they are single input single output systems, which therefore does not cater for control interaction. Such feedback controllers can also not fully attenuate the effect of disturbances, since control action intensity is dependent on control error size, cumulative control error and rate of change of control error.

The use of a Model Predictive Controller (MPC) can address these shortcomings through finite model development. The models can handle time lags, and interaction effect between control variables when manipulated variables are moved. These are also known as Multiple Input Multiple Output systems. Initial studies of MPC controllers in flotation cells were conducted for the purpose of maintaining stable level control (Kämpjärvi and Jämsä-Jounela, 2003). The MPCs were able to cater for the interaction amongst different cells which led to more stable control than PID algorithms. Later studies were conducted to optimise flotation cells using MPC control. Van Schalkwyk (2002) found that derived plant models were generally linear across the control region. However, Marais and Aldrich (2011) found that there were non-linear relationships, especially in using imaging sensors in flotation control, and developed an artificial neural network control strategy to cater for these relationships.

Flotation bank optimisation strategies typically fall in one of three categories: air rate profiling, peak air recovery profiling, or mass pull profiling (Maldonado *et al*., 2012). Profiling refers to the fact that different targets are provided for each cell in a flotation bank. For example, studies conducted by Rojas and Cipriano (2010) found that with regards to recovery, MPC control of the individual flotation cells during transient phases showed better performance than just controlling on the final overall product streams. This was due to having sensors on the individual cells upon which their performance could be measured and adjusted. In air rate profiling approaches, the goal is to reduce air rate addition in the first cells in a bank in order to improve selectivity against entrainment. In peak air recovery profiling, the optimal superficial gas velocity (to maximise air recovery in the froth flow over the lip) per cell is targeted, with the assumption that air recovery is directly correlated with valuable material recovery. Finally, mass pull profiling aims to exploit the exponential characteristic of the flotation kinetics curve. With mass pull profiling, the relative mass pull contributions per cell along a bank are designed to decrease from the first to the last cell. Since absolute mass pull per cell is difficult to measure directly, proxies such as froth velocity are often used to infer relative contribution of mass pull per cell to overall bank mass pull. For these different types of flotation optimisation strategies, different measurement sets are required. The first strategy (air rate profiling), requires the fewest online measurements (essentially, only air rate). Peak air recover profiling, and mass pull profiling require more online measurement, especially regarding the froth phase, such as froth velocity and froth height above the lip.

In order to control a flotation bank to deliver a specific mass pull profile, real-time mass pull measurements are required. One approach to estimating mass pull is through computer vision systems (Sweet, 2000; Hatfield and Bradshaw, 2003) – froth velocity is estimated based on the movement of froth bubbles in consecutive frames of froth images and can serve as a proxy for mass pull (even if just relative mass pull per cell contributing to overall bank mass pull).

Examples of advanced process control strategies incorporating mass pull profiling include an industrial copper flotation APC system at First Quantum Minerals Kansanshi (Brooks and Munalula, 2017) and an industrial platinum group metals flotation APC system at Anglo American Platinum (Muller *et al*., 2010) – see Figure 3 for details on the different control layers (regulatory, supervisory and optimisation) for a system that makes use of froth velocity measurements for mass pull profiling.

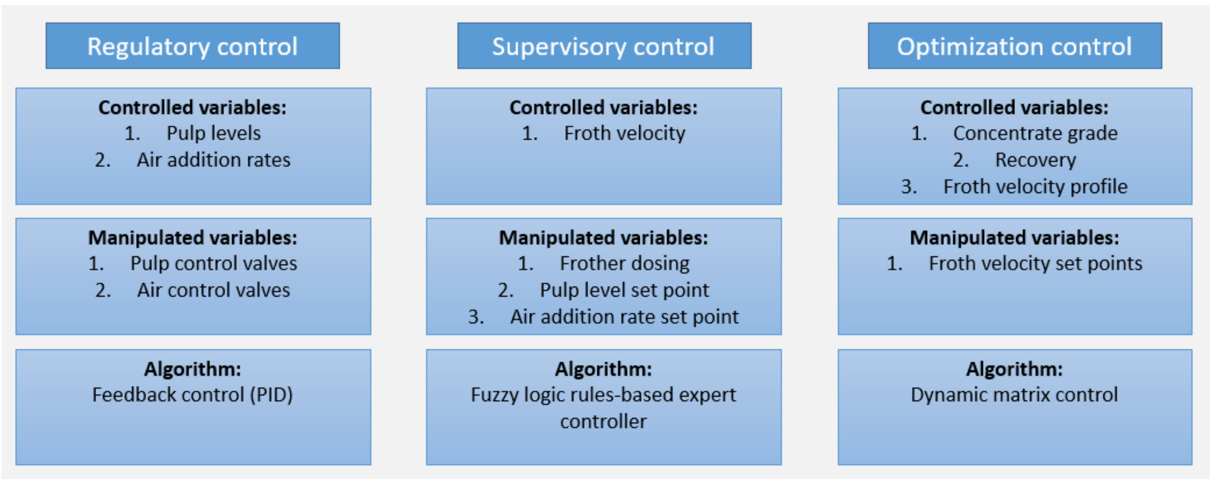


*Figure 3. Flotation APC structure at a copper concentrator (Brooks and Munalula, 2017).*

MPC applications for flotation optimisation are most often found for high-value commodities (e.g., platinum group metals, copper, zinc, and lead), and these applications have been well-researched. However, the industrial application of MPC specifically for coal is hampered by a lack of references to such control systems applied in industry as well as the challenging operational environment on coal plants (specifically, the presence of dust and grime which can interfere with computer vision systems). This work reports the first industrial MPC application in coal flotation (to the best of the authors' knowledge), enabled by a robust smart sensor for froth measurement and an enabling environment for digitisation (refer to Figure 2).

## 3. INSTRUMENTATION FOR MASS PULL PROFILING

Froth imaging sensors vary in physical implementation, inferential sensing models, and outputs. Typically, a camera system is mounted above key flotation cells to capture live images of top of flotation froth, and provide information derived from the froth images.

The Stone Three froth sensors deployed at Greenside provide froth velocity, froth height above the lip, bubble size, and other froth metrics (useful for regular monitoring and troubleshooting) and the froth velocity measurements are directly used in the APC solution to infer per cell contribution to overall mass pull (see equations 1 and 2 in section 5).

Stone Three has developed a rugged froth imaging sensor solution to survive continuous deployment under field conditions, and integrate with industry standard distributed control systems. Specifically, the Stone Three froth sensors are robust in the challenging coal process environment, due to a specially designed housing that extends to near the surface of the froth, minimising the effect of dust and grime on the image capture. The Greenside deployment consists of 16 froth sensors across eight flotation cells, split into two cells per module as shown below (Figure 4).

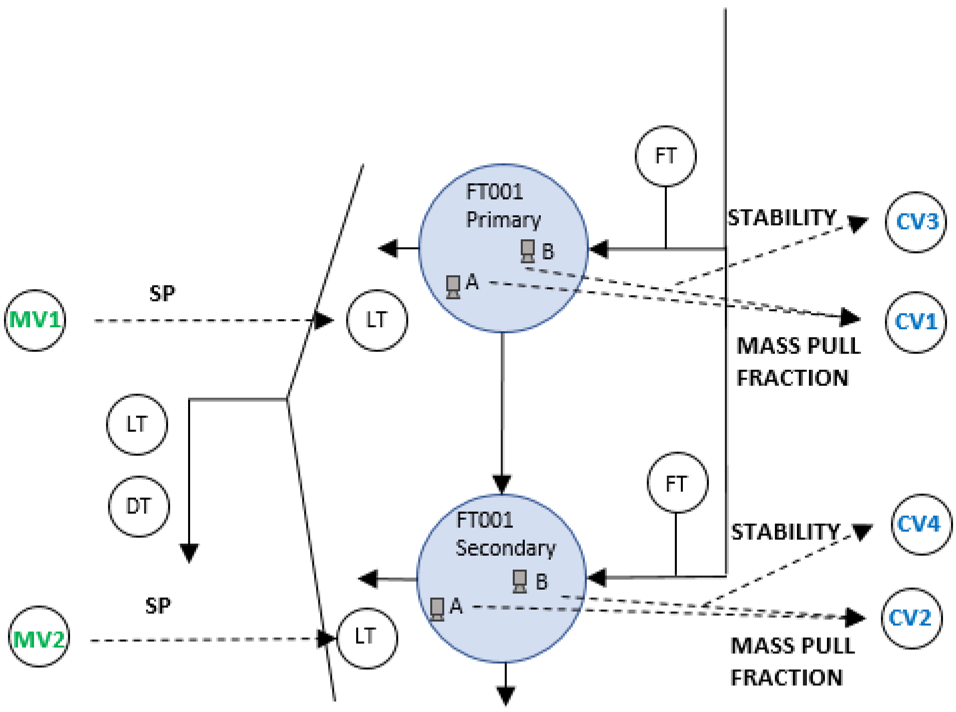


*Figure 4. Flotation measurement and control setup per plant module.*

Each flotation cell has two froth sensors due to the fact that conditions vary across the top of froth as driven by changing hydrodynamics across the cell volume and over time. One sensor (A) focuses on conditions near the edge of the flotation froth while the other observes inner conditions (B) near froth launders. The flow vectors of froth across the cell surface are influenced by the layout of the radial and circumferential launders – by providing froth sensors at different locations, a more representative total measurement of the froth flow can be achieved. The inferred outputs from both sensors for each cell are reconciled within the APC model (see equations 1 and 2 in section 5).

The functional components within each sensor are a hybrid of commercial off the shelf technology, and Stone Three custom hardware. This allows rapid and economical repair of equipment in the field while sensor inference is flexibly performed at a central compute resource (physical or virtualised) within the site datacentre. Froth sensors connect to a local industrial ethernet switch at the flotation bank before being connected to the plant data network for access from the central computation server as also shown in Figure 5 via dedicated hardware links. This is required due to the significant data flow from image-based sensors when compared to typical process sensors or those that perform inference within the sensor units themselves.

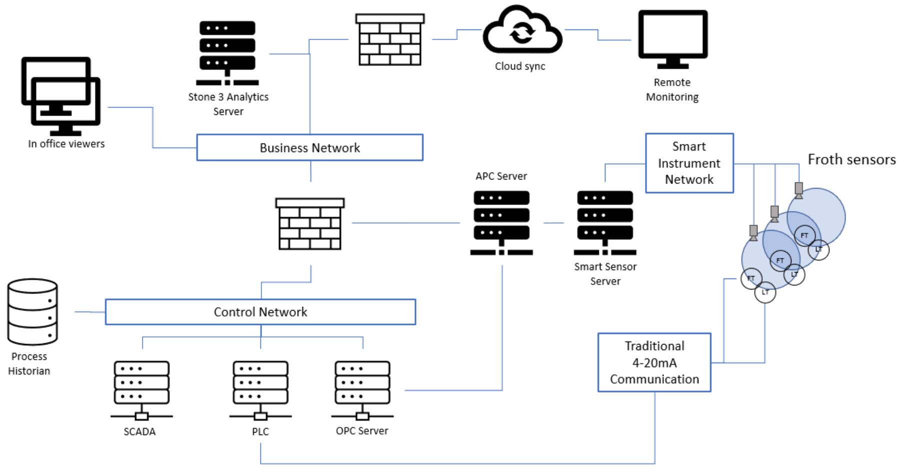


*Figure 5: Data flow from sensor IoT devices to computation and display servers.*

Froth images from the sensor units are processed at the central compute server through a combination of fundamental image processing algorithms and deep neural network architecture. Deep neural networks for froth image monitoring have been discussed in academic research (see for example Horn *et al.*, 2017 as well as Fu and Aldrich, 2019) – the Stone Three froth sensor applies related principles in an industrial setting. GPU accelerated segmentation and pattern matching is utilised to support many in-field sensors per server.

Once image processing is completed, the inferred sensor values are made available for historisation and control systems via standard OPC interfaces. Additionally, all inferred sensor values are made available for remote monitoring and diagnostics by Stone Three and key stakeholders at Greenside via the Stone Three Analytics platform as shown in Figure 6. Such a platform, coupled with remote sensor support, ensures the sustainability of the APC solution, which relies on uptime and sufficient data quality from these froth sensors.

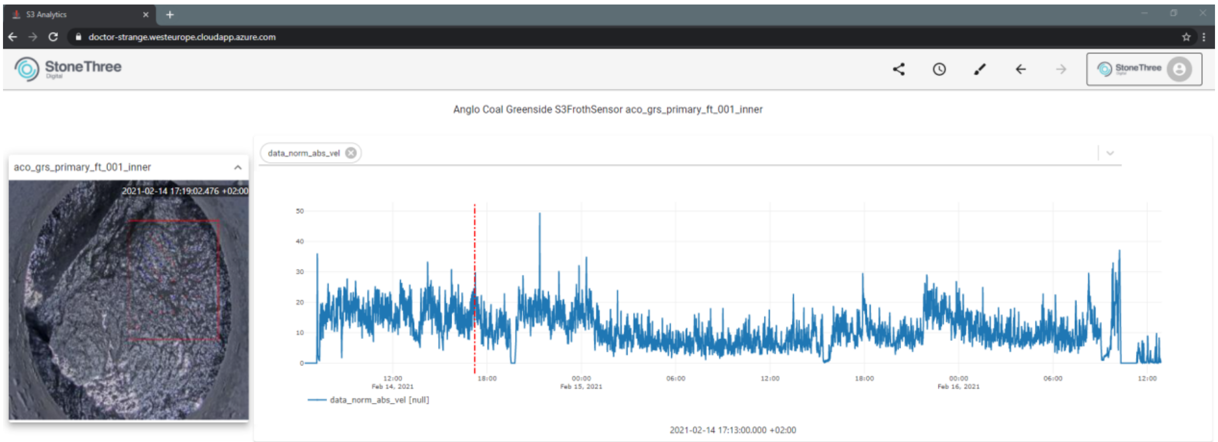


*Figure 6, Remote (cloud) froth sensor monitoring platform with an example of froth sensor measurements. All froth sensors on site can be accessed from the cloud with real-time as well as historical data available for monitoring.*

## 4. PROCESS DESCRIPTION

The Greenside 4 Seam washing plant consists of three, near identical modules, processing virgin 4 Seam coal from an underground board and pillar mine, at a nominal throughput of 750 $t \cdot h^{-1}$. The slimes fraction, which amounts to approximately 6% of the head-feed, is removed from the main circuit via a screening stage, followed by two stages of hydrocyclones. The pulp is subsequently thickened and pumped to a distribution box, where it is gravity fed to Enprotec's Dual Cell Flotation System. This cell arrangement utilises a secondary cell to refine the tailings of the primary cell in one pass. Four lines of dual cells are available, amounting to a total processing capacity of 60 $t \cdot h^{-1}$. To aid the flotation process, a mixture of frother, and collector is dosed in proportion to the solids content of the feed. Air addition is possible through manual control and can be considered a constant.

A flow diagram of a module of the plant can be seen in Figure 7.

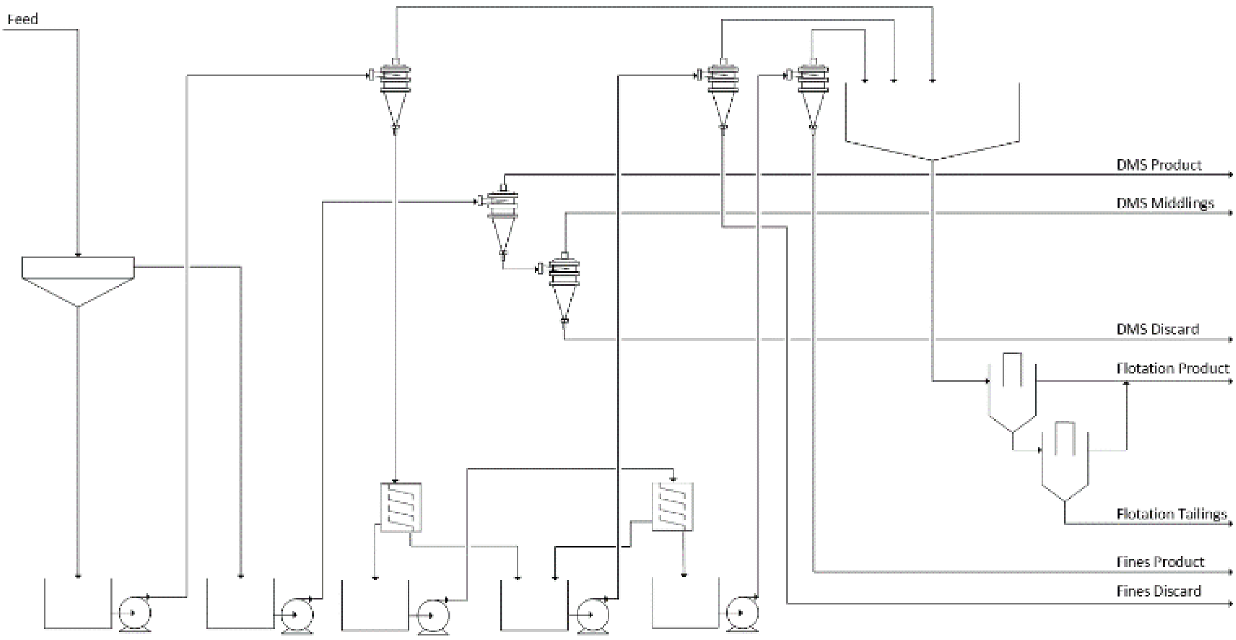


*Figure 7. Process flow diagram for one module of the Greenside washing plant.*

Electromagnetic flowmeters and nuclear densitometers are available on all thickener underflow lines allowing for precise monitoring of the dry ton addition to the flotation process. Additionally, flowmeters are available on the lines exiting the distribution box to equalise the material reporting to each flotation bank.

An important consideration in the optimisation of the flotation cells was the stability of the downstream process feeding the flotation cells.  Literature is contradictory on the effect that feed pulp density has on flotation performance, with some arguing that it has little effect on rate, and therefore only affects total recovery through the residence time (Mehrotra & Kapur, 1974; Runge *et al.*, 2012) . Others have found a positive correlation between the reduction of the pulp density, and the flotation rate (Frew, 1982). This is obviously the case at high concentrations, although this is more likely to be due to the large displaced volume than the mineral mass. Finally, others still report an increase in rate with an increase in pulp concentration, as is the case of the study performed on lignite by Vamvuka & Agridiotis (2001). In either case, in as far as it affects the reagent dosage, the stability of the feed density is important. Overdosing either frother or collector may lead to selectivity issues (Vamvuka & Agridiotis, 2001) as well as process issues such as overflowing launders. To stabilise the feed to the flotation cells, MPC was implemented on the thickener underflows. A comparison between the previous, total mass flow orientated control, and the current, density orientated control is given in Figure 8.

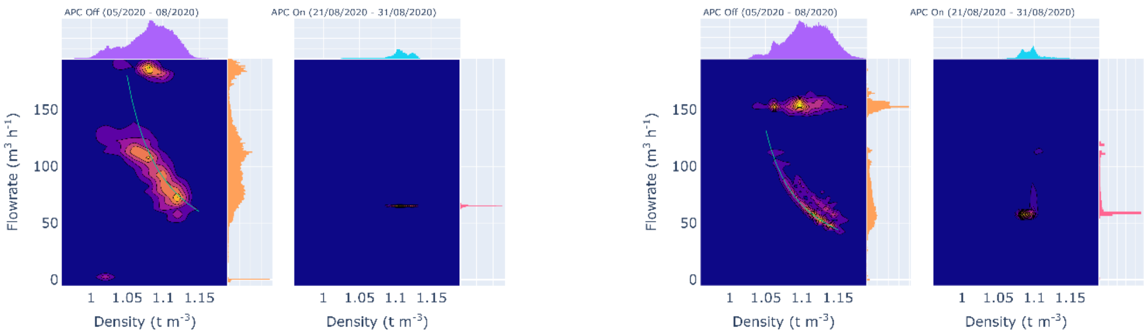


*Figure 8. Thickener underflow density and flowrate comparisons for APC off and on cases (left: Module 1 and 2; right: module 3).*

The introduction of MPC on the thickener underflow lines resulted in a 56% reduction in standard deviation of the underflow density on one circuit and a 78% reduction on the other, significantly improving feed stability and allowing for manual optimisation of reagent addition.

The implementation of the froth sensors on the flotation cells brought with it the historisation of process data on the APC historian. The benefits of this for site personnel are numerous: quick comparisons between current conditions, and known stable periods allow for troubleshooting of equipment, significantly reducing downtime, and allowing for the planning of work. Additionally, daily reports can be generated, giving site metallurgists a detailed overview, and ensuring the continued proper operation of the flotation bank.

## 5. CONTROL DESCRIPTION

### Control Objectives and Algorithms

The aim of coal flotation control is to operate continuously at the optimal point on the grade recovery curve. This is conducted by optimising the flotation cells' operating parameters as well as stabilisation control of the feed.  An MPC approach was employed at Greenside. The proprietary MPC software used was the Honeywell Profit suite (Honeywell, 2020).  The Profit suite software uses linear process models to maximise production value by predicting future process behaviour. The control system can handle model-plant mismatch due to non-linear effects. The Range Control Algorithm maintains the control variables (CVs) within the desired limits, while only moving the manipulated variables (MVs) within the defined limits set.

**Control Philosophy**

Before the structured digitalisation of the Greenside washing plant, the lack of historical data made it difficult for process engineers to continually monitor performance, and troubleshoot any issues experienced on the flotation cells. The first step of the APC project was to historise all process data on site which allowed the APC as well Process team to conduct a baseline study to understand the issues experienced. It was found that the varying feed qualities as well flow rates affected the flotation cell performance. To stabilise the feed quality to the flotation cells, a MPC controller was built on the thickener (refer to the previous section). This ensured a more stable density to the flotation bank as seen in Figure 8. In terms of flotation control, the previous control strategy on the flotation cells was to maintain a constant froth height setpoint, and adjust the air according to lab samples taken on the concentrate as well as visual inspections conducted by plant operators. This manual process resulted in time lags which resulted in loss of recovery during periods where process conditions changed.

The new flotation control strategy involved individual APCs for each flotation bank. The key controlled variables are the mass pull as well as froth stability on each cell.

Froth stability is defined as the amount of bubble bursts per unit area in the upper layer of the froth. Instability can occur due to a weak bubble structure which consequently causes it to burst (Marais., 2010). It was noted at Greenside that under certain process conditions there was a large amount of bubble breakage which resulted in reduced froth formation at the top of the cell. It was therefore important to maintain bubble stability by operating in a certain region.

For the purpose of mass pull profiling for flotation optimisation, the individual mass pull on the primary and secondary flotation cells is inferred through the average velocity fraction from the inner and outer cell velocity across both cells.

$$Inferred\ Mass\ Pull\ cell\ 1 = \frac{IVC1+OVC1}{IVC1+OVC1+IVC2+OVC2} \quad [1]$$

$$Inferred\ Mass\ Pull\ cell\ 2 = \frac{IVC2+OVC2}{IVC1+OVC1+IVC2+OVC2} \quad [2]$$

Where:

$IVC\ 1 = Cell\ 1\ Inner\ Cell\ Velocity$

$OVC\ 1 = Cell\ 1\ Outer\ Cell\ Velocity$

$IVC\ 2 = Cell\ 2\ Inner\ Cell\ Velocity$

$OVC\ 2 = Cell\ 2\ Outer\ Cell\ Velocity$

The individual MPC controller on a single Flotation Bank consist of a 4x2 matrix, with CVs and MVs as indicated in Table 1 and illustrated in Figure 4. The MV-CV responses are shown in Figure 9.

*Table 1. MPC controlled and manipulated variables*

| Controlled Variables | Manipulated Variables |
|---|---|
| Inferred Mass Pull Cell 1<br>Inferred Mass Pull Cell 2<br>Froth Level Stability Cell 1<br>Froth Level Stability Cell 2 | Float Cell 1 Pulp Height<br>Float Cell 2 Pulp Height |

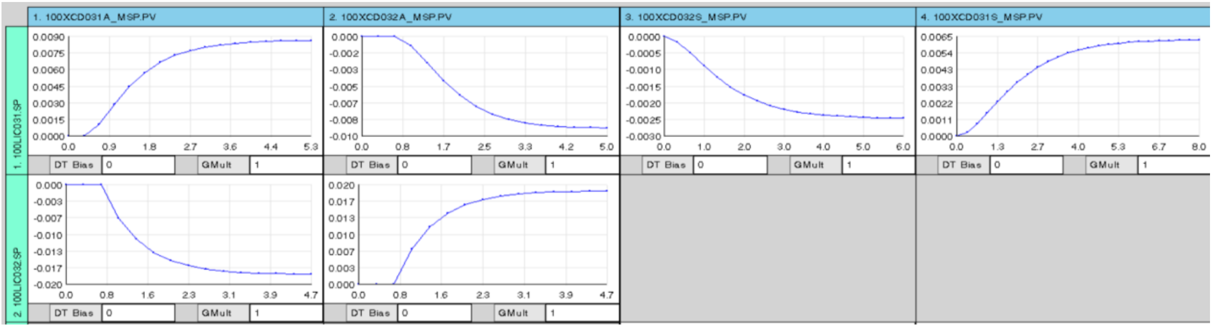


*Figure 9. Example MV-CV responses for the flotation process.*

The air rate additions to the cells are manually manipulated, and therefore form unmeasured disturbances. The controller caters for this through control feedback. The air rate additions to the cells are only required to be changed manually if the APC is constrained, i.e., when the manipulated variables are at their limits and the controller cannot find a feasible solution to keep both mass pulls at their targets. Reagent control is treated in a similar manner.

The controller aims to maintain the froth stability above a predefined limit. This low limit is used to infer the minimum bubble formation required for the froth depth to be maintained.

The individual mass pulls targets on each flotation cell were predefined from analysis conducted from Greenside, based on optimal individual cell performance, aimed at equalising the separation factor for both cells on a line. This was achieved, as a function of the desired yield, via a component balance over the cells. Greenside's high efficiency dense medium separation circuit was taken as a baseline for these calculations. These form quadratic optimisation targets in the APC algorithm. The APC algorithm thus uses the level control setpoints on each individual cell as control handles (MVs) to distribute the material across both cells as well as exiting to the tailings section. This is to maintain the stability low limit as well as mass pull targets.

The controller will prioritise maintaining the stability over the mass pull targets. Once the controller can meet the minimum stability limit, the APC will then priorities the mass pull targets. Due to the APC incorporating control interactions, it does not cause the float cell to cycle between stability and mass pull control.

## 6. RESULTS

Through the implementation of the froth sensor control system, as well as the MPC on the thickener underflows, the product quality stabilised significantly. This has, in turn reduced the amount of misplaced material from 13.32% to 3.38% over the trial period, while de-risking the operation from receiving penalties on below-specification product. This result is an overall plant yield increase (normalised to the head feed) by 0.3%. The increase in yield as well as the reduction in quality fluctuations is attributed to a decrease in variance of the cell mass pull. This is shown in Figure 10.

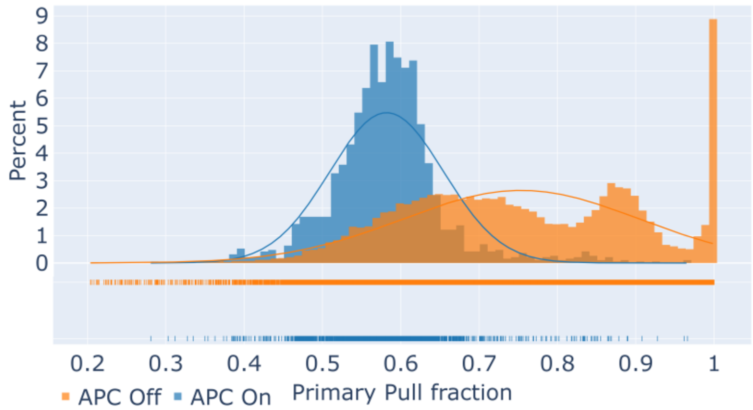


*Figure 10. Primary cell mass pull comparison for APC off and on cases.*

Implementation of the flotation control system drastically increases the utilisation of the secondary cell, allowing for significantly greater separation.

Additional Safety, Health and Environmental benefits incurred through this project include a reduction in water consumption due to a lowered risk of surging tanks as a result of the MPC implemented on the thickener underflows, and a reduction in the potential for high risk work due to improved control on flowrates.

Implementing new technologies such as APC and smart instrumentation require ongoing experienced maintenance and support to maintain optimal operation and value delivery. Failure to provide such support over a period of 6-12 months will result in erosion of benefits. This is mitigated by Anglo American with the implementation of an Integrated Expertise Centre (IEC). The IEC aims to sustain and maximise control system value delivery. Support from the IEC includes expertise such as APC, OT, Training, Systems Support and access to global experts when required. In addition, service level agreements are put in place with Stone Three as froth sensor supplier to ensure the optimal functionality of smart instruments, and that support and maintenance are available.

The lack of understanding and lack of prior successfully proven results drew sceptics at the Greenside operation on the implementation of digital technologies. The implementation of APC and smart froth sensors at the Greenside operation has delivered both real monetary value and safety benefits. These benefits, coupled with a strong support model provided by the IEC, builds confidence amongst plant operators, and the management team, in systems such as APC. Successful implementations of these increase understanding, and acceptance of digital solutions, which in turn increases the usage of current digital technologies, and the appetite for further implementations.

## 7. CONCLUSIONS AND RECOMMENDATIONS

A systematic (upstream to downstream) and holistic (incorporating people, workflows, and technology) digitalisation drive has been implemented at Greenside Coal Washing Plant. This digitalisation drive involved upgrading and integrating enterprise, platforms, and ecosystems (e.g., modern OT versus historical 4-20mA instrumentation networks); implementing appropriate automation and operational hardware (smart sensors and APC); creating and maintaining a digitally enabled workforce (through appropriate digital data infrastructure, as well as remote support from IEC and the smart sensor supplier); as well as leveraging next-generation analytics and decision support.

Specifically, a novel coal flotation APC solution has been implemented, where image-based froth sensors are used in the challenging coal processing environment to enable mass pull profiling control, with benefits realised in terms of increased overall yield and reduction in product variance. Future improvements in the coal flotation APC solution include incorporating an automated optimisation control layer (which would require the installation of an online ash analyser), as well as further characterising and exploiting the relationship between froth stability, froth velocity and mass pull.

To ensure the sustainability of the digitalisation innovations put in place at the Greenside Coal Washing plant, centralised remote support is made available (e.g., the IEC and smart sensor remote monitoring support).

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