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Time-in-State Metric as operational risk management tool for a mining operation: A case study

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Abstract

Globalization and the advent of major industrial disasters have highlighted the need for capital intensive industries to remain competitive and profitable. In order to achieve this, companies have had to focus on mitigating operational risk. Two aspects of operational risk management involve assets and process. Both of these have particular importance to capital intensive industries.

The mining industry still plays an important role in the global and national economy. It is considered a capital intensive industry and is faced with a number of challenges. It is of particular importance to this industry that operational risk be mitigated.

The Time-in-State Metric (TISM) has been designed as a tool to mitigate operational risk, by means of improving process and asset performance.

The TISM presents an overarching metric that delivers a method to manage the process and equipment pro-actively at systems level because the metric is generated in real time, is focused in key operating and equipment parameters, and generates a consistent response recommendation that aligns the operating philosophy of the operational personnel.

The TISM has been successfully developed and implemented at Nkomati Mine, a nickel producing operation in the Mpumalanga Province of South Africa. This will be utilised as a case study to understand the development and implementation process and to evaluate the impact the TISM has had on the process and asset performance of the operation.

Nkomati Mine has seen a significant improvement in its asset performance, with improvements in availability, utilization, reliability, Overall Equipment Effectiveness (OEE) Mean-Time-Between-Failure (MTBF), Mean-Time-to-Restore (MTTR) and the number of failure incidents.

Nkomati Mine has also seen a significant improvement in the process performance. Directly after implementation of the TISM there has been an improvement in feedrate and recovery of nickel. Over the long term, Nkomati Mine has seen improvement in all major performance parameters, including throughput, feedrate, recovery and final concentrate grade.

The TISM has been proven to have a positive impact on the bottom-line of the organization (reduced maintenance cost, improved production, reduced off-mine cost, etc.) and to mitigate Operational Risk.

Keywords

Time-in-State Metric, Overall Equipment Effectiveness, Operational Risk Management

I declare that this research project is my own work. It is submitted in partial fulfilment of the requirements for the degree of Master of Business Administration at the Gordon Institute of Business Science, University of Pretoria. It has not been submitted before for any degree or examination in any other University. I further declare that I have obtained the necessary authorisation and consent to carry out this research.

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1. Definition of Problem and Purpose of Research

1.1 Background

Operational risk management has become increasingly important as a means to ensure profitability and sustainability in a dynamic global economic environment. The need for an effective risk management strategy is particularly important for asset intensive industries, such as mining operations, which are characterised by substantial upfront investment in equipment and infrastructure, volatility in demand based on fluctuating commodity prices and the complex nature of its operations. Operational risks can broadly be classified as people, process and asset risks.

Two of these risks, i.e. process and asset risks, can be mitigated by means of equipment performance monitoring and process efficiency monitoring, respectively.

1.2 Problem Statement

Currently, the methods predominantly utilised in processing industries to address these two risks are inadequate, for the following reasons:

1.) Asset performance is generally measured by means of the Overall Equipment Effectiveness (OEE) metric, which considers availability, quality and performance (Nakajima, 1988). OEE is more applicable to discreet manufacturing operations and has limited application in continuous processes. In addition, OEE is reported as an “after-the-fact” and has little effect on the daily operation of the plant and is also rarely linked to the performance appraisal and reward system of the organization; and

2.) Process efficiency in complex operating environments is heavily dependent on human interpretation. This dependence on human interpretation results in process instability and unpredictability, seeing that a uniform and consistent response cannot be achieved when there is reliance on unique human experience. Hence, there is a need for a set of rules or guidelines that would assist operating and maintenance personnel to make consistent, uniform and predictable decisions to ensure optimal equipment and process performance. In order to unify and align cognitive maps of operating and maintenance personnel, in order to ensure a consistent, uniform and predictable response.

The key to effective risk mitigation lies in the ability of an organization to supply responsible personnel with timely and relevant information to make predictive decisions. Predictive decision making considers historic and current information with the aim of mitigating future risks. In the context of asset performance, predictive decisions would utilise mechanical performance data to predict or prevent future equipment failure. Similarly, predictive decision making in the context of process efficiency would involve interpreting critical process information, comparing these to ideal state conditions, and initiating a consistent response to ensure process parameters are brought closer to the ideal state, where efficiency is highest.

1.3 The Time-in-State Metric

The Time-in-State Metric (TISM) has been developed as a novel way to address the shortcomings encountered both from measuring equipment performance by means of OEE and relying on human interpretation to improve process efficiency. It evaluates the performance of unit operations in a complex, continuous process and defines an operating range, based on key measurements, for each unit operation that will ensure optimal equipment and process efficiency without compromising asset integrity.

The data is supplied in real time and will assist:

1.) Operating personnel to make informed and consistent decisions to ensure optimal process efficiency; and
2.) Maintenance personnel to understand the mechanical status of critical assets and improve OEE.

1.4 Development of the TISM

The following method is employed to develop the TISM:

1. Define what equipment and process efficiency means for the organization. For example, equipment efficiency can be measured as the lifespan of a critical motor or pump utilised in the process; process efficiency can be measured as throughput (e.g. tons per hour), metal recovery, final product specifications (metal concentration in final product), etc.;
2. Evaluate historic data and identify key parameters (KPIs) that directly impact equipment and process efficiency. For example, vibration analysis on a pump or motor, where high vibration points to imminent failure, or the size distribution of the ore fed into the milling process and the effect it has on throughput;

3. Identify the ideal operating range for each of the KPIs that would ensure optimal equipment and process efficiency;
4. Develop a decision tree that would empower maintenance and process personnel to make consistent decisions to ensure KPIs are kept within optimal range. For example, high vibration on a pump would require greasing of bearings or alignment of pump and motor. Should this not successfully bring the KPI within optimal range, alternative recommendations should be made, such as putting the unit on the opportunity maintenance or planned maintenance task list for future change-out; and
5. Measure the amount of time a unit operation or process area spends in the ideal state. Quantify the effect this has had on process and equipment efficiency.

1.5 Implementation of the TISM

Implementation of the metric is usually met with resistance from plant floor personnel. This resistance frequently relates to the impression that the TISM takes away their decision-making capacity. In order to obtain buy-in from relevant personnel, it is essential that:

1. The correlation between equipment and process efficiency and the TISM to be established conclusively. This will require that a sufficiently large data pool be used to establish a statistically significant link between the KPIs and performance with a high degree of statistical significance;
2. This correlation has to be conveyed simply and concisely to relevant personnel in order to establish trust in the new metric;
3. The metric has to be sold as a decision making tool, not a replacement for personnel;
4. A link has to be established between improved performance, enabled through the implementation of the TISM, and the financial performance of the company; and
5. Finally, the improved financial performance of the company needs to be linked to the performance management and reward system of the company.

Seeing that the lack of uptake of the TISM would prevent any of the benefits from being attained, this study will allow for some discussion on the human behavioural aspects, such as the five disciplines of a learning organization proposed by Senge (1997), that would allow for acceptance of the metric by relevant personnel.

1.6 The Case Study

The TISM has been successfully implemented at Nkomati Mine, which is primarily a nickel mining operation in the Mpumalanga Province of South Africa. An account of the methodology followed to implement the TISM and the impact it has had on performance will be discussed in this study. A case study research methodology will be followed to determine what impact the implementation of the TISM has had on the performance of the operation. It was expected that the TISM will improve equipment efficiency through increased plant availability, fewer plant stoppages, increased running time, increased hourly throughput and reduction in maintenance cost. Process efficiency should be improved through increased metal recovery, improved final product specification and improved process stability. The effect of the progressive implementation of the TISM on the performance parameters mentioned above will be evaluated and an attempt will be made to conclusively determine whether the implementation had a positive impact on these stated parameters.

1.7 Aim of the Study

The aim of this study is to:

1.) Discuss the need for improved equipment and process efficiency as a means of mitigating the risk exposure of mining operations;
2.) Evaluate the TISM as a means to improve equipment and process efficiency;
3.) Discuss the development and implementation of the TISM at Nkomati Mine and the effect it has had on the overall performance of the operation;
4.) Track what impact the phased implementation of the TISM has had on the performance of the operation, by means of the case study research methodology;
5.) Evaluate the human behavioural aspects behind the successful implementation of the TISM; and
6.) Establish whether the lessons learned from implementing the TISM at a mining operation can be generalised to other environments.

2. INTRODUCTION

2.1 Justification for Research

Since the advent of globalization, more companies are being put under increased pressure to remain profitable in a dynamic global environment. The ability of an organization to remain profitable has become increasingly difficult in the last decade, with events such as the economic and housing meltdown, as well as the credit crunch and the global increase in unemployment emerging as global economic stressors. In addition, high-impact industrial disasters, such as the BP oil spill in the Gulf of Mexico, the Virginia coal mine explosion, or the copper mining accident in Chile, to name a few, have shown the impact the lack of an effective risk management strategy can have on businesses, stakeholders, customers, regulators, shareholders and individuals (Shah & Littlefield, 2011). The need has arisen for companies to establish an effective risk management strategy in order to improve profitability and ensure sustainability.

For the purpose of this study, the need for an effective risk management strategy will be evaluated in the context of a mining organization. The mining and quarrying industry is still a significant contributor to South Africa's GDP, with the sector directly contributing approximately 8.3% in 2014 to the South African GDP (Trading Economics, 2015), and a further 10% indirectly (International Mineralogical Association, 2014). It would therefore be of significant economic benefit if an effective risk management tool can be developed for the industry, assuming that risk mitigation would positively affect profitability. Furthermore, the ability to generalise the methodology to other asset-intensive industries will be evaluated.

2.2 Research Problem

Operational risk can be broadly classified as people, process and assets (Shah & Littlefield, 2011). This study will evaluate the efficiency of the TISM to address two of these risks, i.e. process and asset risks. As stated previously, mitigating asset risks will ensure improved asset performance, whilst addressing process risks will ensure improved process efficiency.

Failure of critical assets has been determined to be the risk that has the biggest impact on an organization (Ismail, 2012). Failure to address the risks associated with critical assets will lead to deteriorating equipment condition and unscheduled downtime of critical equipment, which will lead to production losses. Improved process efficiency will have a direct positive impact on the bottom line of the company as it will lead to improved production and efficiency.

By implication, risk would be eliminated if we had the ability to predict the future, as no event would be unforeseen or unplanned. Hence, the foundation of any risk management strategy involves the supply the critical information needed for predictive decision making. That is, based on historic information, the following outcome can be predicted with a degree of certainty, and hence a certain course of action is recommended.

2.3 Focus of Research

The TISM has been developed to exploit this relationship between information flow and risk mitigation. The metric looks at historic and real-time asset and process performance data, and suggests a course of action that would mitigate a possible risk that the data reveal (van der Merwe & Greeff, 2014a). As a simple example, the measured vibration on a particular piece of equipment has increased over time and has reached a critical limit. From the historic data it is evident that the asset is not being operated efficiently and that this condition is worsening – failure could even be imminent. A number of practical suggestions could be made: is the alignment of a rotating component off? Are all the fastening bolts in place? Does the unit require lubrication? Is the unit being operated outside of the operating range stipulated by the manufacturer? Does the unit have to be replaced? The objective is to prevent and/or manage future failures of critical equipment.

The same principle can be applied in the context of process performance. For example, a process unit can be used to reduce the size of the material in a processing stream. The size distribution of the feed and the product can be measured and compared. Should the size distribution of the process stream not reduce sufficiently after processing through the unit, this could adversely affect downstream processes. Yet again, a number of practical recommendations can be made once this non-conformity has been identified: Is the size of the gap between the two grinding surfaces too big? Have parts of the equipment been worn and needs to be replaced? Is the size distribution of the feed into the unit optimal? The objective is to ensure that each unit operation in the process runs optimally, which will result in improved overall performance.

Instead of focusing on only the average or overall performance of the operation, this metric is implemented on a production unit level. The behaviour of each production unit is characterised by performance measurements (KPIs). When the production unit is performing optimally, the perfect (or ideal) condition is described by the operating ranges on each measurement and the inter-relationship between the mentioned variables. Future performance is subsequently evaluated against the ideal state. When all production units in the plant meet the ideal state, it counts toward the TISM.

Once all of the critical equipment in the process has been identified and the optimal range of operation of each of the variables associated with the equipment is defined, the data can be compiled into a metric. This metric serves as a recipe for plant and operational personnel to identify unit operations that are not performing optimally and gives guidance as to what to do to get the sub-optimal units back into ideal state.

3. THEORY AND LITERATURE REVIEW

A theory and literature review was conducted on some of the over-arching themes that will be covered in this study:

1. Current situation in the mining industry – locally and globally;
2. Asset and process performance measurement;
3. How the subject matter relates to risk management;
4. How the time-in-state metric is developed and implemented to address these risks;
5. Background on the case study; and
6. How human behavioural aspects can be exploited to effectively implement the time-in-state metric.

3.1 Developments in the Mining Industry

The mining and minerals industry is faced with the most difficult sustainability challenges of any industrial sector (Azapagic, 2004). In an attempt to ensure sustainability, many organizations in the mining sector have moved from labour-intensive to capital-intensive processes as a means of improving productivity, mainly through the process of mechanization and automation (Rajaram, Dutta, & Parameswaran, 2005).

In addition to the significant upfront investment required before a mineral deposit can be exploited (Campbell H. F., 1980), there has also been a significant increase in investment in equipment and instrumentation during the operating phase. As part of the trend towards increasing levels of mechanization and automation, in an attempt to achieve economies of scale, mines are turning to the use of larger equipment (Roman & Daneshmend, 2000). This has resulted in mining operations being recognized as capital intensive, and as such requires the optimum usage of equipment in a manner that minimises operating costs and maximizes the utilization of the equipment (Topal & Ramazan, 2010).

Optimization of the asset life-cycle and operation of expensive assets in an efficient and responsible manner has gained more and more emphasis. For this reason asset management has grown in importance as a means of balancing performance, risk and cost to achieve an optimal solution (Campbell, Jardine, & McGlynn, 2011).

Peterson (2001) proposes that several industry objectives will drive future technology change in the mining industry:

1. Lowering production cost;
2. Enhancing the productivity of workers and equipment;
3. Opening up new reserves and extending the life of existing ore bodies; and
4. Meeting regulatory and stakeholder requirements is areas such as health and safety, environmental and aesthetic impacts, and land use.

In addition to addressing the risks associated with asset performance as a means of mitigating operational risk and ensuring sustainability, mining operations are also focused on improving process performance. Efficient, effective and continuously improved manufacturing processes have been identified as a critical success factor (Gröger, Niedermann, & Mitschang, 2012).

Improved process performance will directly impact the bottom-line in that operating cost is reduced and revenue is increased(Ismail, 2012). In the context of a mining operation, improved process performance would result in increased metal production (through increased throughput, higher metal recovery, reduced losses, etc.), reduced off-mine costs (through improved product quality), reduced operating costs (through improved energy efficiency, lower reagent consumption, etc.) and reduce the impact of the operation on the environment (through the reduction of the size and concentration of the waste stream) (Hilson & Murck, 2000). Therefore, process performance optimization has become a critical means of mitigating operational risk associated with the process.

3.2 Role of Mining in the National and Global Economy

The long and fascinating history of the mining industry – stretching back thousands of years to the Bronze Age, possibly even the Stone Age – so closely tied to the economic development of the human race, gives it some sentimental charm. Unfortunately, this historic value also gives rise to widespread misconceptions about mining – as is the case with other similarly archaic industries, it is considered stodgy with mature and stagnant technologies (Tilton & Landsberg, 1999). One of these misconceptions is that, unlike newer, high-technology industries that usually experience a decrease in cost over time, the costs associated with mining are expected to increase with real wages and as the depletion of the best mineral deposits cause labour productivity to fall (Young, 1991).

In truth however, mining has become a "highly competitive global industry, where the successful firms aggressively pursue new technologies and other cost-reducing innovations" (Tilton &

Landsberg, 1999). Despite the need to exploit more remote and lower grade deposits, which are much more difficult to process, mining costs over the long term have fallen substantially (Barnett & Morse, 1963). The current competitive nature of the mining industry and the fundamental role it plays in the global economy justifies research into improvements in its operating efficiency.

3.2.1 Mining in South Africa

The Gross Domestic Product (GDP) in South Africa expanded by 2.1% in the first quarter of 2015, compared to the same quarter of the previous year (Trading Economics, 2015). South Africa has consistently seen growth below 2% since the first quarter of 2014. The slow economic growth seen in Sub-Saharan Africa can mainly be attributed to poor economic policies and weak institutions (Sachs & Warner, 1997). In addition, in 2014 the nation's economy was affected by significantly weak demand from trading partners and the most protracted industrial action since the fall of apartheid (Kumo, Omilola, & Minsat, 2015). The mining sector was particularly hard-hit by the industrial action. This, in addition to various infrastructure gaps, notably lack of adequate energy supply, poor domestic demand and low investment rates, put downward pressure on GDP growth (Kumo, Omilola, & Minsat, 2015).

Mining and quarrying contributed approximately 8.8% directly, and an additional 10% indirectly, to the national GDP (International Mineralogical Association, 2014). The mining sector and supporting industries employ more than 1 million people; each employee is estimated so support between 7 and 10 dependents, which means the industry supports between 7 and 10 million people (South African Minetrals to Metals Research Institute, 2011). Hence, the mining sector plays a prominent role in the transformation and socio-economic upliftment of the country.

Smit (2013) proposes in a KPMG-sponsored report the following contributions the mining industry has made to the South African economy:

1. The total estimated mineral reserves in South Africa are valued at USD 2.5 trillion, which is a testament to future earning potential;
2. Contributes 18% of GDP and over 50% in foreign exchange earnings;
3. Generates annual earnings in excess of R 330 billion and accounts for 20% of all investment in the country;
4. Approximately R 407 billion of the R 441 billion in expenditure that the mining sector generate is spent locally;
5. Contributed R 18 billion in corporate tax and R 6 billion in royalties;

6. Involved with the establishment of the JSE and still contributes 30% to its market capitalization;
7. Employs over one million people, equating to wages and salaries of R 78 billion, is the largest contributor by value to Black Economic Empowerment (BEE) and provides job mining opportunities to an unskilled and semi-skilled workforce; and
8. The foreign exchange value of the Rand is highly sensitive to commodity prices since minerals and metals significantly contribute to our export revenue.

With the discovery of gold and diamonds, South African moved from a primary to a secondary economy. The country is in the process of transitioning to a tertiary economy, with up to 60% of GDP originating from the services sector. Nonetheless, mining will continue to play an important role in the South African economy, both as a foreign exchange earner and an employer of the people.

3.2.2 Mining around the World

Primary commodities are also of importance in the global economy (Radetzki, 2008). From a recent assessment of global trade, it was found that in 2010 there were approximately 40 countries globally that relied on non-fuel minerals for over 25% of their merchandise exports (OPM, 2011). This number has increased significantly over time: in 1996 there were only 29 mineral reliant economies and in 2005 this number increased to 33. Currently, of the 40 mineral reliant countries, 75% are low and middle income countries. Furthermore, many of these countries have a low Human Development Index (HDI), which highlights the potential of productive sectors, such as mining, to contribute to the upliftment of the populous (ICMM, 2012). Half of these mineral reliant countries are on the African continent.

The ICMM report also highlights the following benefits attributable to the presence of a mining industry that has prominence in a country's economy:

1. Typically contributes more than half of Foreign Direct Investment (FDI), which indicates an ability to attract mining investment even when FDI into other sectors are waning;
2. Contributes significantly to national investment totals, especially when mining activity builds off a low base;
3. Contributes significantly to exports in mineral dependant countries;
4. Generates significant foreign exchange earnings;
5. Contributes significantly to the tax revenues of the country;

6. In mature industrial economies, mining contributes significantly towards GDP, both directly and indirectly; and
7. Contributes significantly to direct and indirect employment creation.

The economic and social importance of the mining sector justifies research into possible methodologies that would mitigate operational risk.

3.3 Performance Measurement

Performance measurement is a fundamental instrument of management. Measuring the performance of a process provides information regarding the status of the process and allows for decisions to be made in terms of required actions or adjustment of parameters and settings to improve the performance of the process (De Ron & Rooda, 2006).

Measurement of performance will be based on two criteria:

1. Asset performance; and
2. Process performance.

A discussion on both these performance measurements is to follow.

3.3.1 Measuring of Asset Performance

Organizations with heavy investments in plant, machinery and equipment spend a significant part of their operating budget on maintenance (Jardine & Kolodny, 1999). As a result, much effort has been made to improve the organization of maintenance and to reduce maintenance costs. More recently, and in the future, greater attention and resources will be paid to avoid and reduce maintenance per se, which will mean increased focus on preventative maintenance work (Cross, 1988). This requires a shift in the maintenance philosophy from one of repair to one of avoidance and reduction/removal, through the gathering and analysis of critical information. Effective preventative maintenance will result in improved plant availability and asset performance (Cross, 1988).

The following measures are widely used to quantify asset performance:

1. Asset availability;
2. Asset utilization;
3. Asset Reliability;
4. Overall equipment effectiveness (OEE);

5. Mean-Time-Between-Failures (MTBF);
6. Mean-Time-To-Restore (MTTR); and
7. Number of Failure Events

3.1.1.1 Asset Availability

Asset availability is defined as the proportion of total time that a piece of equipment or asset is capable of performing its required or specified function (Dunn, 2001). Asset availability is normally expressed as a percentage, which is calculated by dividing the asset available hours by the total number of hours in any given period. A prominent source of disagreement regarding the calculation of asset availability is whether available time should be divided by total time or scheduled operating time.

3.1.1.2 Asset Utilization

Asset utilization is defined as the proportion of available time that a piece of equipment or asset is operating. Asset utilization is normally expressed as a percentage, which is calculated by dividing equipment operating hours by equipment available hours (Dunn, 2001).

3.1.1.3 Asset Reliability

This metric can be considered to be a more accurate reflection of how reliable an asset is based on past performance (Latino, Latino, & Latino, 2011). An asset might have a good availability but not be very reliable. Reliability is calculated as:

$$Reliability = e^{-\theta t}$$

where

$$e = Natural\ logarithmic\ base = 2.718$$

$$\theta = Failure\ rate = \ 1/MTBFR$$

$$t = Mission\ time$$

As will be discussed further, Mean-Time-Before Failure (MTBF) is calculated as:

$$MTBF = Total\ Runtime/Number\ of\ events$$

The mission time is usually a year, which is 365 days.

3.1.1.4 Overall Equipment Effectiveness (OEE)

OEE is a key performance measure in mass-production environments. OEE is directed towards equipment/assets/machines and was introduced by Nakajima (1988) in the context of Total Productivity Maintenance (TPM). It is seen as an effective management tool due to it being a simple and clear overall metric, which aggregates a number of metrics. OEE is deemed a superior metric of measuring productivity as traditional metrics, throughout and utilization, are inadequate for identifying the "problems and underlying improvements needed to improve productivity" (Huang, et al., 2003).

In discussing OEE, Nakajima (1988) defines six major equipment losses:

1. Equipment failure or breakdown losses: time lost under conditions or reduced productivity and quality losses caused by defective products;
2. Setup/adjustment losses: equipment downtime and defective products created in switching from one production item to another;
3. Idling and minor stop losses: loss in production when machines are idling or when a temporary malfunction causes an interruption in production;
4. Reduced speed losses: incurred when there is a difference in the design speed of the equipment and the actual operating speed of the equipment;
5. Reduced yield losses: occurs during the early stage of production from machine startup stabilization; and
6. Quality defects and rework losses: caused by malfunctioning or poorly operated production equipment and machinery.

The availability, V, of the equipment is calculated using the first two losses, which are known as downtime losses. The performance efficiency, P, of the equipment is calculated using the third and fourth losses, which are known as speed losses. , i.e. losses that occur as a result of operating at sub-optimal conditions. The final two losses occur as a result of defects – the higher the number of defects, the lower the quality rate, Q, of the equipment. Finally, OEE is measured as follows:

$$OEE = V \cdot P \cdot Q$$

with

$$V = \frac{loading\ time - downtime}{loading\ time}$$

$$P = \frac{theoretical\ cycle\ time \times processed\ amount}{operating\ time}$$

$$Q = \frac{processed\ amount - defect\ amount}{processed\ amount}$$

The loading time is defined as the working time minus planned downtime, where downtime is the cumulative loss of production time as a result of breakdowns, setup and adjustments.

An alternative definition of OEE involves expressing it entirely in terms of time (SEMI, 2000). According to this definition, SEMI (2001) defines six major states of manufacturing equipment, illustrated in Figure 1. Utilising these major states, the following definition of OEE was derived:

$$OEE = \frac{theoretical\ production\ time\ for\ effective\ units}{total\ time}$$

From this definition, OEE consists of four efficiency parameters – availability efficiency AE, operational efficiency OE, rate efficiency RE, and quality efficiency QE:

$$OEE = AE \cdot (OE \cdot RE) \cdot QE$$

with

$$AE = \frac{equipment\ uptime}{total\ time}$$

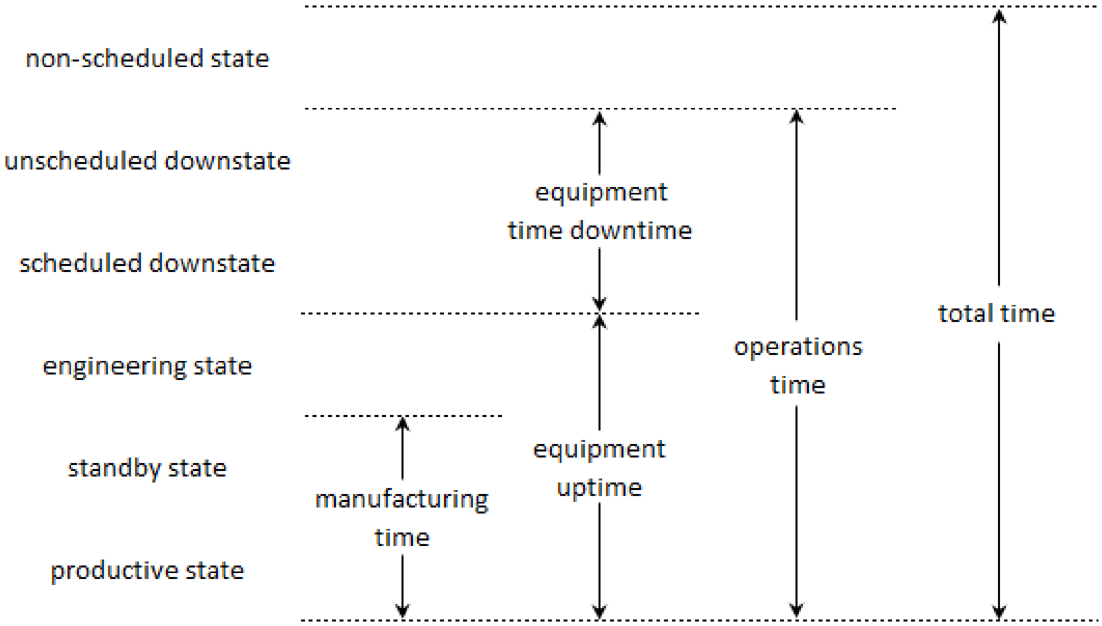
$$OE = \frac{production\ time}{equipment\ uptime}$$

$$RE = \frac{theoretical\ production\ time\ for\ actual\ units}{production\ time}$$

$$A = \frac{theoretical\ production\ time\ for\ effective\ units}{theoretical\ production\ time\ for\ actual\ units}$$

In the above definitions, the concept of theoretical production time is meant as the production time at strictly theoretical rates –no efficiency losses are considered.

Figure 1: Six major OEE states for manufacturing equipment (SEMI, 2001)



It is the latter definition of OEE that will be utilised for evaluation of the effect of the implementation of the Time-in-State metric on asset performance for the purpose of the case study.

3.1.1.5 Mean-Time-Between-Failures (MTBF)

MTBF is a common metric used to calculate the average time between failures (Latino, Latino, & Latino, 2011). Although there exists a number of ways to calculate MTBF, but the most widely used method looks at the total runtime of an asset divided by the total number of failure for that asset, as illustrated in section 3.1.1.3.

3.1.1.6 Mean-Time-To-Restore (MTTR)

As the name suggests, the MTTR calculates the average time it takes to restore the process back to a state of productivity. In the context of a mining operation, it would be described as the average breakdown time, calculated by the total breakdown time over a period divided by the number of failures (Latino, Latino, & Latino, 2011).

$$MTTR = Total\ Downtime/Number\ of\ events$$

3.1.1.7 Number of Failure Events

This concept is self explanatory – the number of critical failures experienced over a specific period, usually a month or a year. Also used in the calculation of MTBF and MTTR.

3.1.1.8 Root Cause Analysis

Effective root cause analysis (RCA) can be considered to be one of the most valuable tools to any organization (Latino, Latino, & Latino, 2011). This is especially true for asset-intensive organizations such as mining operations. The aim of the RCA process in an industrial application is to prevent the organization from becoming reactive in its reliability improvement process. If the root cause of a problem is not addressed, the problem will recur which will have a significant impact on the reliability of the operation.

It is important for an organization to firmly establish the type of failures that will be analysed by means of RCA. Often, the focus of analysis is limited to regulatory issues such as safety and environmental issues. In contrast, equipment or process-related failures are simply corrected and the process restarted without determining the cause of the failure, which induces the risk of the problem recurring. Some external pressure is required to direct personnel toward performing RCA on process-related failures.

In determining which failures to analyse by means of RCA, an organization must clearly determine the metrics to be tracked as it moves into a maintenance and reliability initiative (Latino, Latino, & Latino, 2011). These measurements must be directly related to the performance of the organization and corrective actions have to be taken should the measurements move in the negative direction. It is therefore essential that the goals and objectives of the organization be communicated before a decision is made as to which measures to monitor. For this purpose, strategy maps are often employed, which summarised the objectives into four main categories (Latino, Latino, & Latino, 2011):

1. Corporate;
2. Assets;
3. Work practices; and
4. Knowledge and experience.

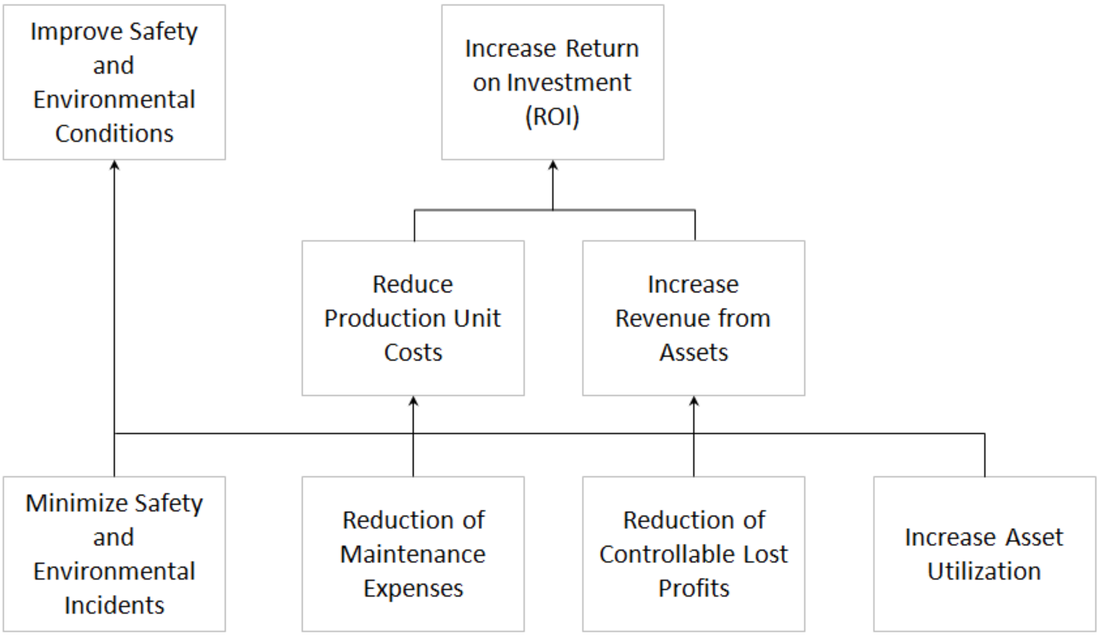
Within each of these perspectives there exist a number of individual objectives. Following is a list of typical perspectives and objectives related to the management of assets:

1. Corporate Perspective
    a. Increase Return on Investment (ROI);
    b. Improve Safety and Environmental Conditions;

    c. Reduction of Controllable Lost Profit;
    d. Reduction of Maintenance Expenses;
    e. Increase Revenue from Assets;
    f. Reduce Production Unit Costs;
    g. Increase Asset Utilization; and
    h. Minimise Safety and Environmental Incidents.
2. Asset Perspective
    a. Minimize Unscheduled Equipment Downtime;
    b. Improve System Availability;
    c. Reduce Scheduled Maintenance Downtime;
    d. Reduce Unscheduled Repairs;
    e. Reduce Non-Equipment Related Downtime; and
    f. Reduce Equipment Failure Time.
3. Work Practices Perspective
    a. Reduce Repair Time;
    b. Reduce Maintenance Material Inefficiencies;
    c. Improve Labour Efficiency;
    d. Improve Material Purchasing;
    e. Perform Predictive Maintenance;
    f. Optimize Time-Based Maintenance;
    g. Optimize Work Processes;
    h. Perform Reliability Studies;
    i. Perform Criticality and Risk Assessments; and
    j. Improve Maintenance Planning and Scheduling.
4. Knowledge and Experience Perspective
    a. Improve Historical Equipment Data Collection;
    b. Improve Operations Communications; and
    c. Train Maintenance and Operational Personnel.

Once the perspectives and objectives have been defined, the relationship between upper- and lower-level objectives has to be determined. The objectives are then visually represented in a strategy map (see Figure 2). The strategy map is a visual aid that allows employees at all levels to understand the impact they can have on the high-level objectives of the company by performing their day-to-day tasks.

Figure 2: Example of a Strategy Map developed with a Corporate Perspective



In order for the RCA procedure to be executed effectively, a method has to exist that collects data related to the events that affect the performance of our stated objectives. This can take the form of maintenance data, process data, or any other data related to the performance of the process. This data can then be used in determining the root cause of the failure and systems put in place to ensure that the incident does not occur again.

It is essential that the system implemented to prevent recurrence do just that – eliminate the root cause of the problem.

3.1.2 Measuring Process Performance

Process performance will be evaluated in the context of a concentrator plant of a mining operation, which will mainly focus on the following performance indicators, and how they have changed over time:

1. Monthly throughput in tons;
2. Average throughput rate in tons per hour (tph);
3. Metal recovery as a percentage of the metal fed into the process; and

4. Concentrate grade, measured as both metal grade in final concentrate, moisture content in final concentrate and contaminant concentration in final concentrate.

The two most widely accepted measures of assessing metallurgical performance are concentrate grade and recovery (Wills, 2011). The improvements measured in these metrics will be compared with the progressive implementation of the time-in-state metric to quantify the effect that it has had on the performance of critical assets utilised in the process.

3.4 Key Minerals Processing Definitions

The following key definitions were retrieved from Wills' Mineral Processing Technology and are pertinent to the case study (Wills, 2011):

Recovery in the context of minerals processing of a metallic ore is the percentage of the total metal contained in the ore fed to the processing plant that is recovered into the final product or concentrate produced. A recovery of 90% means that 90% of the metal fed to the processing plant in the feed ore has been recovered to the final concentrate or product and 10% has been lost as tailings or waste.

Concentrate grade is the amount of valuable metal contained in the product or final concentrate, expressed as a percentage of the total mass. In other words, if 100 kg of final concentrate contains 10 kg of valuable metal, the concentrate grade is 10%.

Comminution is the process by which the particle size of the ore is progressively reduced until the clean particles of mineral can be separated by such methods as are available. Most valuable minerals contained in ore occur as finely disseminated and intimately associated with the gangue (or waste) material. It is therefore required for the valuable mineral to first be "unlocked" or "liberated" from the gangue minerals before separation can occur. Comminution is a process that is applied for this purpose and is performed by various methods, including blasting, crushing and grinding.

Blasting is considered to be the first stage of comminution and is the method by which explosives are used in mining to remove ores from their natural beds.

Following blasting, ***crushing*** is usually the second phase of comminution that reduces the size of Run-of-Mine (ROM) material in preparation for grinding to be performed. Crushing is accomplished by "compression of the ore against rigid surfaces or by impact against surfaces in a rigidly constrained motion path" (Wills, 2011). Crushing is usually a dry process.

Grinding is usually the third comminution stage, and is accomplished by “abrasion and impact of the ore by the free motion of unconnected media such as rods, balls, or pebbles” (Wills, 2011). It is usually performed as a “wet” process and provides a slurry feed to the concentration process.

A grinding mill is of a cylindrical or cylindro-conical shape that rotates around a horizontal access. The grinding mill is filled with a load of crushing bodies called the grinding media that bear upon the ore particles in the slurry mixture inside the mill with an abrasion and/or impact force sufficient to reduce the size of the particle in order to allow for further downstream processing. Depending on the requirements of the downstream process, grinding may be divided into two stages – primary and secondary. Various parameters can be specified in order to customise the grinding function to a particular application. This may include the rotational speed of the mill, the types of liners utilised on the shell of the mill, the size and shape of the grinding media, etc. The aim is to develop vigorous impact milling in the primary mill (which is performed on a quickly passing stream of ore), followed by gentler abrasive milling in the secondary milling unit (which is conducted on a stream with a higher retention time in the mill) (Pryor, 1985).

Froth flotation is an important and versatile mineral processing technique. It is a selective process that can be used to achieve specific separations from complex ores such as lead-zinc, copper-zinc, etc. It is a “physico-chemical separation process that utilises the difference in surface properties of the valuable minerals and the unwanted gangue minerals” (Wills, 2011). A number of comprehensive studies have been conducted on the concept of froth flotation (Glembotskii, Klassen & Plaksin, 1972; Leja, 1982; Ives, 1984; Jones & Woodcock, 1984; Fuerstenau, 1985; Crozier, 1992; Laskowski & Poling, 1995; Johnson & Munro, 2002; Rao, 2004). Froth flotation is a complex process that involves three phases (solid, water, and froth) with many sub-processes and interactions, which mainly comprises three mechanisms (see Figure 3):

1.) *True flotation*: selective attachment of mineral particles to air bubbles;
2.) *Entrainment*: transportation of mineral particles in the water that passes through the froth; and
3.) *Entrapment or aggregation*: physical transportation of mineral particles between particles in the froth attached to air bubbles.

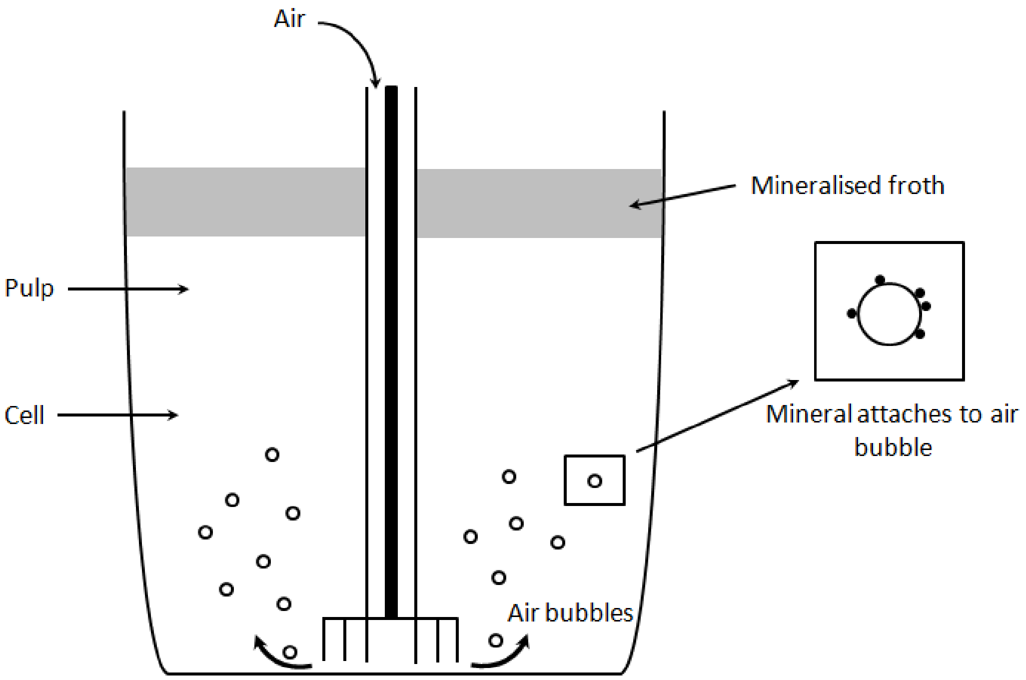
True flotation is the dominant mechanism by which valuable minerals are separated from gangue or waste material; however the separation efficiency is dependant of the degree of entrainment and entrapment that occurs during the flotation process. True flotation is chemically selective to the mineral surface properties, whilst entrainment and entrapment are not considered selective processes – both gangue and valuable minerals are recovered. Draining of unwanted gangue or waste particles occurs in the froth phase, which prevents these unwanted minerals from reporting to the final product. It is essential to control the stability of this phase in order to ensure efficient separation of valuable minerals from gangue or waste minerals.

Because entrainment of unwanted minerals in an industrial flotation plant application is common, several stages of flotation (also referred to as “circuits”) are often utilised to achieve an economically acceptable quality of valuable mineral in the final product (Wills, 2011).

True flotation exploits the differences in the physico-chemical surface properties of the various mineral particles in the pulp or slurry that is treated in the flotation plant. In order to exacerbate these differences in surface properties, reagents are added to the slurry, and with the addition of air bubbles, true flotation can occur in that the mineral particles attach to the bubble and accumulate in the mineralised froth on the surface of the slurry.

The principles of mechanical flotation are illustrated in Figure 3.

Figure 3: Principle of froth flotation (Wills, 2011)



Collision of particles and bubbles which results in attachment between the bubbles and the valuable mineral particles are enabled through the turbulence created in the pulp phase by the agitator and infusion of the air through the agitator shaft (Wills, 2011). The bubbles then rise to the surface through their natural buoyancy, and accumulate in the mineralised froth on the surface of the pulp.

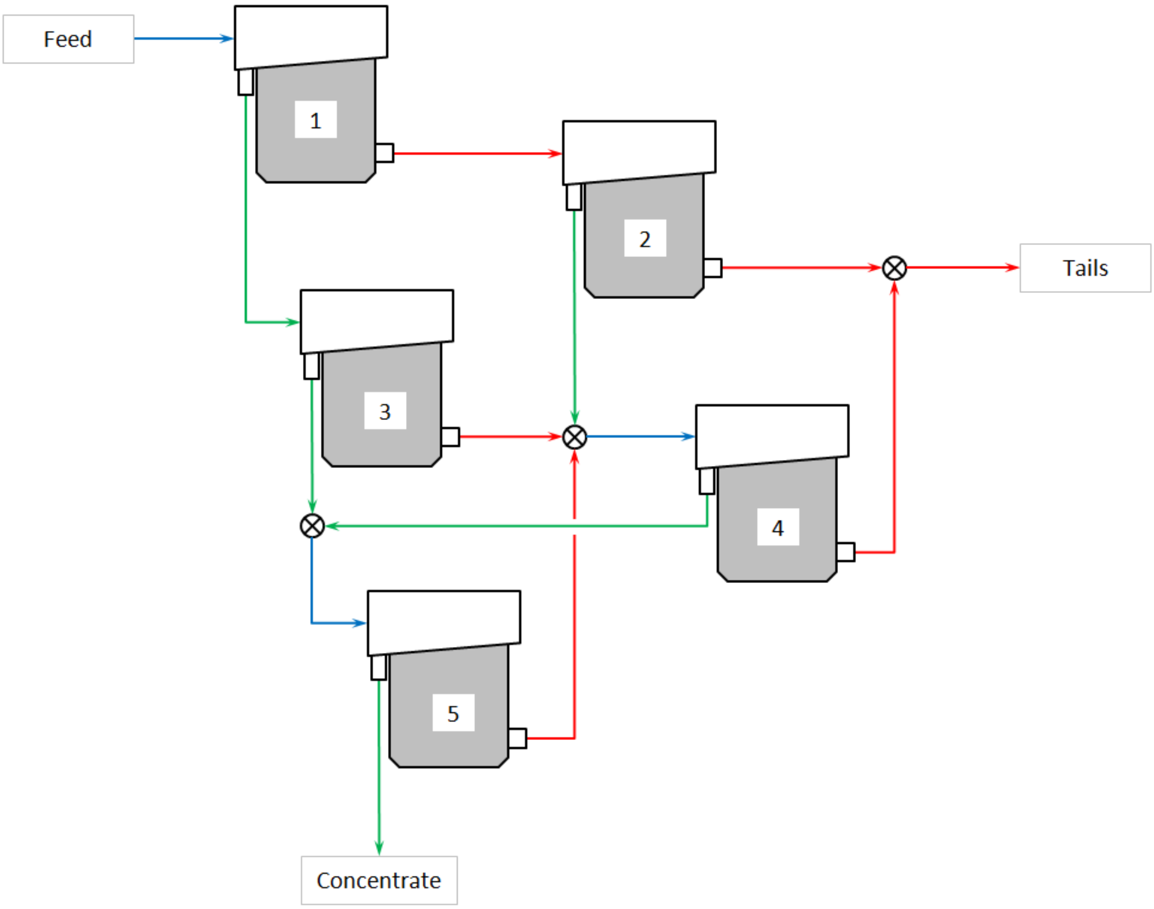
In order to ensure adequate drainage of the entrained and entrapped gangue minerals, it is essential that a stable froth be maintained at an appropriate depth. If effectively controlled, the mineralised froth should be at a significantly higher concentration than the pulp phase – hence, upgrading of the slurry has occurred in the froth phase. The mineralised froth is collected and processed through additional flotation stages, which results in progressively improved froth quality.

Following application of the final flotation stage, a saleable concentrate should be produced, in additional to a barren waste stream (Figure 4). The waste stream must contain as little valuable mineral particles as possible. As stated previously, the amount of valuable minerals collected in the final concentrate, relative the amount of valuable minerals fed to the process, is defined as the process recovery. The concentrate can undergo multiple stages of cleaning, and the tailings or waste stream generated from each stage can either be recycled to previous stages or discarded as waste (Figure 4).

Most often, a grinding process precedes a froth flotation stage in a concentrator plant (Gonçalves, Andrade, & Peres, 2003). A detailed understanding of the fundamental aspects that affect the two operations is crucial for improving the concentrator performance.

As stated previously, the floatability of ores and the selectivity of the separation process they are subjected to are determined by the surface properties of the mineral particles contained in it. These surface properties are mostly determined by the grinding processes and conditions (Xiang & Yen, 1998). It is therefore essential that the optimal conditions established for both the grinding and froth flotation stages be maintained as consistently as possible to ensure process performance is maximised.

Figure 4: An example of the various stages of froth flotation employed in an industrial circuit



The first stage of flotation (unit number 1 in Figure 4) is generally referred to as the rougher stage. The stages that is utilised to clean the concentrate produced from the rougher stage is referred to as the cleaner stage (unit number 3 in Figure 4), and the subsequent stage used to further clean the concentrate generated from the cleaner stage is referred to as the re-cleaner stage (unit number 5 in Figure 4). The stages that are utilised to further process the tailings generated from flotation stages are referred to as scavengers, and can be applied anywhere in the circuit. For example, unit number 2 in Figure 4 is utilised to further process the tailings from the rougher stage, and is thus referred to as the rougher-scavenger stage. Similarly, unit number 4 in Figure 4 is applied to further process the tailings from the cleaner stage and is thus referred to as the cleaner-scavenger stage.

In Figure 4 the re-cleaner tailings is recycled back to the cleaner scavenger-stage and the cleaner-scavenger tailings is rejected as waste along with the rougher tailings.

Flotation is mainly used to treat very fine particles, because if the particle is too large, the weight of the particle will be greater than the force of adhesion between the particle and the bubble, and it will therefore drop the particle. An optimal size range has been determined for the flotation process (Trahar & Warren, 1976; Crawford & Ralston, 1988; Finch & Dobby, 1990). This optimal size distribution has to be achieved through the comminution stages mentioned before.

The froth phase aims to enhance the overall selectivity of the flotation process. This is achieved by preferentially retaining the attached material and reducing the recovery of entrained material to the concentrate stream. This increases the concentration of the metals in the concentrate (also referred to as the grade) whilst limiting as far as possible the reduction of recovery of valuable (Wills, 2011).

There exists a trade-off between grade and recovery to the final concentrate that needs to be managed according to operational constraints and is incorporated in the management of an optimum froth flotation. The froth phase is a critical determinant of the grade and recovery to be achieved from the flotation process, as it is the final separation stage in a flotation cell.

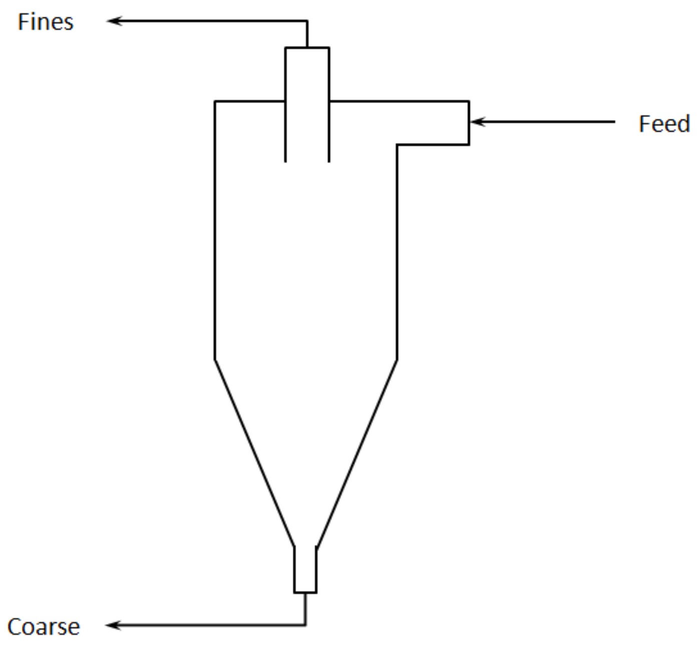
In order to allow for the mineral particles to attach to the bubbles, the surfaces of the particles need to be water-repellent of ***hydrophobic***. Once attached to the surface, the air bubbles need to form a stable froth; otherwise the bubbles will burst and drop the particles that were attached. Various chemical compounds, referred to as flotation reagents, are used to achieve and maintain these favourable conditions (Ranney, 1980; Crozier, 1984; Nagaraj & Avotins, 1988; Suttill, 1991; Fuerstenau & Somasundaran, 2003). The term hydrophobicity and floatability are often used interchangeably.

Minerals in their natural state are mostly not water-repellent and reagents need to be added to the pulp to induce this characteristic on the mineral surface. Some of the most important flotation reagents are the following (Wills, 2011):

1. ***Collectors*** which will attach to the surface of the mineral particle, rendering it hydrophobic and facilitating bubble attachment;
2. ***Frothers*** aid in maintaining froth stability; and
3. ***Regulators*** are applied to control the flotation process. These reagents are used to manipulate the pH of the pulp, thereby either activating or depressing the attachment of certain minerals to the air bubbles.

Generally, the grinding stage is considered to be key cost factor of the process and flotation is considered to be the key efficiency factor (Coleman, 1980). ***Classification*** is considered to be the link between the two, and is therefore considered to be a critical step in determining the overall concentrator performance. If the classification stage is not efficient, both the grinding and flotation processes cannot be optimized or operated efficiently (Mainza, Powell, & Knopjes, 2004). The basic function of the classification stage in grinding operations is to remove fine material from the grinding circuit and feed it to the flotation circuit, and to re-circulate the coarse material to the grinding mill for further grinding (size reduction). IF the classification circuit operates efficiently, only material that meets the size requirement for the flotation circuit will escape the grinding stream – the coarse material is retained in the stream and re-circulated to the grinding mill for further size reduction (Mainza, Powell, & Knopjes, 2004). The most widely used commercial classifiers are hydrocyclones, or **cyclones** for short. Operating of the classification stage at optimal efficiency means that only particles in the size range that maximises recovery report to the froth flotation stage. Cyclones classify the feed material into two products – the fine overflow (for further processing) and the coarse underflow (re-circulated to the grinding mill) (see Figure 5).

Figure 5: The process streams in a cycloning application



The following parameters are to be carefully controlled in the operation of the cyclone:

1. The density of the material feeding the cyclone;
2. The flowrate of the material entering the cyclone; and

3. The pressure at which the cyclone is operated.

Once optimal operating conditions have been established it is essential that these conditions be maintained in order to ensure that efficient classification is obtained in the cyclone. A number of authors have discussed the main features and operations of conventional hydrocyclones (Kelsall, 1953; Bradley, 1965; Svarovsky, 1984).

The size of the particles in a process stream is referred to as the **grind** of the stream. It is usually expressed as a percentage passing a certain size – i.e. 80% passing 250 mm of 50% passing 75 µm. A grind of 80% passing 75 µm mans that 80% of the particles in the stream will be smaller than 75 µm. When the grind of the feed stream is described, it is usually indicated as F_{80} in short. If it is applied to a product stream, it is referred to as P_{80} in short.

3.5 Risk and Risk Management

There exist a number of definitions for risk and risk management. According to the ISO Guide 73, risk is the “effect of uncertainty on objectives” (Leitch, 2010). Further to this definition, Guide 73 also states that an “effect may be positive, negative or a deviation from the expected, and that risk can often be described by an event, a change in circumstances or a consequence”. This definition links the risk faced in an organization with its objectives. Therefore, risk management would involve identification of potential event that would jeopardise the ability of the organization to achieve its objectives. These events are analysed based on probability and severity. The combination of severity and severity yields the criticality of the risk and hence implores the risk manager to either prevent the event from occurring or allowing the event to play out and minimize the resulting fallout from it.

By definition, the objectives of the organization have to be clearly understood in order to make effective risk management possible (Brodeur & Pritsch, 2008). The response informed by a strategic risk management strategy should be proportional to the level of risk faced by the organization (dependent of the capital intensity, nature and complexity of the company).

Risk management has become a growing concern for stakeholders and is an increasingly important business driver. The need for a comprehensive risk management strategy is highlighted by the publication of the international standard, ISO 31000 ‘Risk management – Code of practice’.

The risk management strategy can be classified into two categories, based on the focus area of the strategic response: Enterprise Risk Management (ERM) addresses financial risks related to credit, markets, liquidity, etc. and Operational Risk Management (ORM) addresses operational risks related to people, processes, assets and the environment (SAP Solution Brief, 2011). As stated previously, ORM will be the focus of this study and it will be addressed by means of improvements in asset and process performance.

In many instances, mining operations are characterised by significant upfront investment in equipment and infrastructure. In addition, these mining processes are often very complex and are exposed to unpredictability in demand due to fluctuations in commodity prices (despite having the benefit of being a continuous operation offering low variety at high volume). Hence, mining operations are under pressure to protect critical assets by prolonging lifecycle and lowering CAPEX and OPEX, along with maximising Return on Assets (ROA).

The concept of ORM involves creating a strategy that will assist directors and executives, as well as maintenance and operational personnel comprehend and manage the risks impacting the organization, generate processes to effectively mitigate these risks, and implement the procedures for both preventative and corrective actions.

The art of reducing risk lies in the “ability of an organization to provide employees with timely and precise operational information and establish predictive models in order to make intelligent decisions” (Shah & Littlefield, 2011). The information has to be relevant in order to address the operational risks associated with people, process and assets.

In the South African context, as an emerging market, “South Africa poses a challenging array of long-term political, economic, financial and operational risks to investors” (van Wyk, Dahmer, & Custy, 2004). Therefore, the introduction of a tool that can effectively be used in the strategic risk management arsenal would be of significant benefit.

An integrated operational risk management strategy that can be implemented by an asset intensive operation involves two strategic focus points:

1.) Protecting physical assets: monitoring the performance of critical assets to assist in the predictive nature of effective preventative maintenance. This will enable organizations to empower their workforce with information to make predictive decisions while reducing the overall risk profile of the organization (Shah & Littlefield, 2011). This will prevent financial damages related to production losses and premature, unplanned failure of critical assets; and

2.) Process optimization: Complex processing plants observe significant variance in performance irrespective of sophisticated process control systems. Since process performance variance impacts profitability, it is of great significance to understand the circumstances that realize exceptional as well as poor performance. This revolves around interpretation and decision making within the production environment.

3.6 Time-in-State Metric

3.6.1 Introduction to the Time-in-State Metric (van der Merwe & Greeff, 2014a)

The TISM has been designed to supply relevant timely information to decision makers in order to enable a predictive environment that will assist in ensuring critical assets perform optimally and to enable personnel on the plant floor to run the process optimally and consistently. This enables the organization to address two major operational risks: 1.) protecting critical assets through performance monitoring and predictive maintenance; and 2.) ensuring that the process is consistently operated optimally and to prompt and assist plant operators to make appropriate decisions when the process deviates from the optimal norm.

In a mining environment, decision-making by plant and maintenance personnel, even though assisted by sophisticated control systems, significantly affects the performance of the process. Many of these decisions are made based on personal experience and intuition, which means that there is rarely a consistent response from different plant operators when sub-optimal performance has to be addressed. Operational personnel typically need to make decisions related to reagent dosing rate, feed rates, level, temperature, flow, pH setpoints, etc. These decisions are applied at a functional unit level. Multiple functional units are combined or configured to complete the value-add or conversion process. Typical processing industry functional units include pumping systems, milling or grinding processes, evaporators, flotation circuits, thickeners, reactors, autoclaves, etc.

The performance of the production process is measured in terms of the financial performance across the total process. Due to the nature of continuous processes, performance measurements are based on aggregated production numbers. Typical management performance measurements include production cost per weight or volume, OEE, contribution margin per weight or volume, and so on.

A disconnect is thus deemed to exist between the production team and management. Management measures performance in monetary terms whereas the operation team deals with setpoints to manage process stability, availability, process balances or energy usage at the functional unit level.

By the time the production team receives feedback on their performance (using measurements such as OEE and production cost), it merely serves as a recording of past performance.

The TISM was developed with the objective of empowering operational personnel to pro-actively affect performance. The TISM is also designed to provide a single performance measurement useful for management and operational personnel. In other words, the TISM used by operational personnel is rolled up to present an overall TIS value for the total production process. TIS defines the percentage time that a functional unit demonstrates a specific behaviour or state. Behaviour or state is described by the inter-relationship between process measurements associated with the selected functional unit.

Once the baseline state has been defined it is possible to track when and how close the functional unit is operating to baseline. It also describes which Key Influencing Factors (KIFs) are causing to deviate from the ideal state. This monitoring and feedback takes place in real-time to facilitate pro-active management of the production process.

The OEE metric has been applied in many industries over the past few years as a means to measure asset performance (Godfrey, 2002). It is a useful metric and has contributed significantly to the improvement of the operations of some companies (Muchiri & Pintelon, 2006). OEE can be expressed as the ratio of the actual output of the equipment divided by the maximum output of the equipment under the best performance condition (Almeanazel, 2010). OEE is equal to the multiplication of the three major contributors to production losses:

1.) Availability refers to downtime losses, which is classified as equipment breakdowns, and setup and adjustment slowdowns;
2.) Performance refers to speed losses, which can be attributed to idling and short-term stoppages and start-up/restart losses; and
3.) Quality refers to defects or quality losses, which can be attributed to scrap and rework losses.

$$OEE = Availability \times Performance\ Rate \times Quality\ Rate$$

However, OEE is more relevant to discrete manufacturing operations, where throughput, quality and machine availability has a direct and measurable impact on the profitability of the organization, which can be measured in real time.

A performance metric for continuous processes will require a metric that takes into account the issues related to the process and not necessary related to availability, throughput or quality. The metric should be aimed at improving the quality of control related to factors influencing yield and recovery, such as feed quality, process parameters, reaction times and reaction ratios.

The TISM is a tool that incorporates the issues associated with continuous processes. It does not only take into account throughput, but also incorporates factors in the process that influence yield, quality and equipment availability, and applies this metric to the unit level, which ensures that the unit is operated at its optimal level of efficiency.

The dynamism which the TISM enables is another aspect that is particularly useful for continuous processes. The ideal state can change frequently and without much warning. For this reason, the TISM is designed to take into account the changing nature of the process and its objectives. In addition, the TISM can also be expanded to evaluate the performance of a number of unit operations, depending on the inter-connectivity and relationships between units in an area.

The TISM continuously measures the total amount of time a unit operation spends in the ideal state. The ideal state has been determined, through the evaluation of historic data, to correspond to a condition where the plant operates at the maximum level of efficiency, reliability, stability, predictability, yield, etc.

The rationale behind enabling the expansion of the TISM model to evaluate performance at the area level, in addition to the unit level, is because frequently the output of a unit in an continuous process in the input to a subsequent unit. In addition, operating personnel makes changes to affect the state of a specific unit operation, since they have control over individual units. The aim is to enable decision makers to operate each process unit in its ideal state, which will mean the process as a whole will realize overall performance.

The TISM addresses operational risks associated with Equipment Performance and the Production Process. Both metrics are reported in real time to ensure that the unit operations contained in the process are operated in such a way to ensure optimal process efficiency without compromising the integrity of the equipment. Each of the two metrics has unique inputs.

3.6.2 Time-in-State Metric Implementation Methodology (van der Merwe & Greeff, 2014b)

Adoption of the TIMS is strongly dependent on the human element. Plant operators develop mental models over time, and decision making is executed with the backdrop of unique experience. This creates a problem, whereby the processing plants are operated in different ways, based on the experience of the operating personnel on the floor. This induces unpredictability and instability, which is detrimental to the continuous operation of the plant. Successful implementation of the TISM requires that these metal models be unlearnt and that trust be instilled in the value of the TISM. Senge (1997) was the first to acknowledge that the "basic obstacle to the success of a business in an era of constant change and intensifying competition is its reluctance or inability to learn". By utilising Senge's five disciplines of a learning organization (Senge, 1997), the TISM can be successfully implemented and institutionalised in the operation. The Five Disciplines are (Yeo, 2005):

1.) Team learning – group dynamics;
2.) Personal mastery – willingness to learn new skills;
3.) Systems thinking – big picture of the business operations;
4.) Mental models – Influencing others with independent thinking; and
5.) Shared vision – shared energy.

The implementation of the TISM invokes "psychological aspects, systems thinking, root cause analysis, change management and innovation to deliver deeper understanding of the industrial process" (van der Merwe & Greef, 2014b).

4. Research Propositions

The research question that has to be answered is: can the TISM be used to mitigate the operational risk of a mining operation, through optimization of asset and process performance.

The operational risks that will be the focus of this study are the risks related to process and assets.

The aim of the research is to explore the following propositions:

> ***Proposition 1***: The TISM can be effectively employed to address operational risks associated with the *process* of a mining operation; and
>
> ***Proposition 2***: The TISM can be effectively employed to address the operational risks associated with the *assets* of a mining operation.

Once it has been confirmed that the TISM can be effectively employed to address operational risks, the following proposition will be explored:

> ***Proposition 3***: Following the implementation of the TISM, the progressive improvement and refinement of the TIMS leads to the progressive improvement in asset and process performance, until a plateau is reached.

Finally, the following propositions will be explored:

> ***Proposition 4***: The TISM can be employed in other capital intensive industries with similar benefits.

Furthermore, a brief investigation will be conducted to determine what human behavioural aspects can be employed to ensure the effective implementation of the TISM by ensuring buy-in from all required parties:

> **Proposition 5**: Human behavioural aspects can be utilised to successfully implement the TISM in an organization.

5. Research Methodology

A case study methodology will be utilised to explore the abovementioned propositions. A case study represents a research approach designed to understand a relevant topic in its context through obtaining evidence from multiple sources (Saunders & Lewis, 2012).

The TISM has been successfully implemented at a mining operation in South Africa: Nkomati Mine is primarily a nickel producing mining operation located in the Mpumalanga Province in South Africa (African Rainbow Minerals, 2014). As a mining operation, which was established by significant capital investment from two equal partners in a joint venture, namely African Rainbow Minerals and Norilsk Nickel Africa, Nkomati Mine can be classified as an asset intensive industry. Profitability is dependent on volatile demand in nickel as a commodity; the process contains expensive equipment and is complex in nature.

Over the past two years, Nkomati Mine has implemented the TISM on its concentrator plant. Nkomati Mine has seen significant improvements in equipment performance and process efficiency. The aim is to determine whether the improvements are attributable to the implementation of the TISM.

Full access to all performance data was obtained. For the purpose of determining the effect of TISM on asset performance, availability and utilisation data was utilised. Improvements in process performance was investigated by analysing production data generated from the operation. Progressive changes in both performance criteria will be analysed to explore proposition 3.

Next, relevant academic sources were sought to determine if similarities between capital intensive industries can be exploited to successfully implement the TISM in related capital intensive-industries. Finally, academic sources were sought to determine the human behavioural aspects that have to be considered to ensure the effective roll-out of the TIMS in an organization.

5.1 Research Design

Quantitative research and analysis involves the collection of numerical data in a standardised way, while qualitative research and analysis involves data collected in a non-standardised way and is analysed through means of developing and testing propositions (Saunders & Lewis, 2012). Both a quantitative and qualitative research approach will be followed to explore each of the propositions. Propositions 1 to 3 will employ a quantitative research approach, as numerical data will be used to substantiate or disprove the propositions. Proposition 4 will utilise a qualitative research approach as academic sources will be sought to explore the proposition. Similarly, a qualitative research approach will be utilised to understand the human behavioural aspects involved in implementing the TIMS in an organization successfully.

A longitudinal study implies the study conducted over an extended period of time, while a cross-sectional study implies a study conducted at a point in time, a “snap-shot” (Saunders & Lewis, 2012). Data collected over three years will be used to investigate propositions 1 to 3, which implies that a longitudinal study will be performed. Information collected to explore proposition 4 will be summarised from existing academic sources.

5.2 Universe and Sampling

The universe under investigation will be the case study, i.e. Nkomati Mine. The universe will be expanded to include all capital intensive industries for the purpose of proposition 4.

Sampling will not be utilised for the purpose of this investigation. Data collection will focus on existing availability, utilisation and production data for the purpose of propositions 1 to 3. Existing research will be compiled for the purpose of exploring propositions 4 and 5.

5.3 Potential Research Limitations

The following were identified as potential limitations to the study:

1. The closeness of researcher to the study may be a source of bias;
2. The case study is of a South African mining firm, and its applicability to firms based in other countries is debatable due to the uniqueness of the South African context; and
3. As this is a single case study, the findings may not be applicable to other industries or firms.

6. The Case Study

6.1 Background

Nkomati Nickel Mine is a joint venture between African Rainbow Minerals (ARM, 50%) and Norilsk Nickel Africa (50%), who jointly manages the mine and project (Wolmarans & Morgan, 2009). The nickel, copper, cobalt and Platinum Group Metals (PGM) mineralisation is contained within the Uitkomst Complex, which is situated between Badplaas, Machadodorp, Baberton and Waterval-Boven in the Mpumalanga Province of South Africa (Bradford, et al., 1998).

A feasibility and design study was completed in 1998. The aim of the study was to determine the feasibility of exploitation of the Main Mineralised Zone (MMZ) ore body, from Run-of-Mine (ROM) to final concentrate production, with the following objectives(Bradford, et al., 1998):

1. Maximum utilisation of the existing infrastructure that was erected to mine and treat the small tonnage of high-grade Massive Sulphide Body (MSB) a few years earlier;
2. Development of a “first world”, high productivity mining operation, which will be staffed by a small, highly educated and trained workforce, with reliance on a high level of process automation; and
3. Concentrating on the core business and outsourcing of non-core activities, as part of local business development initiative and to minimise fixed costs.

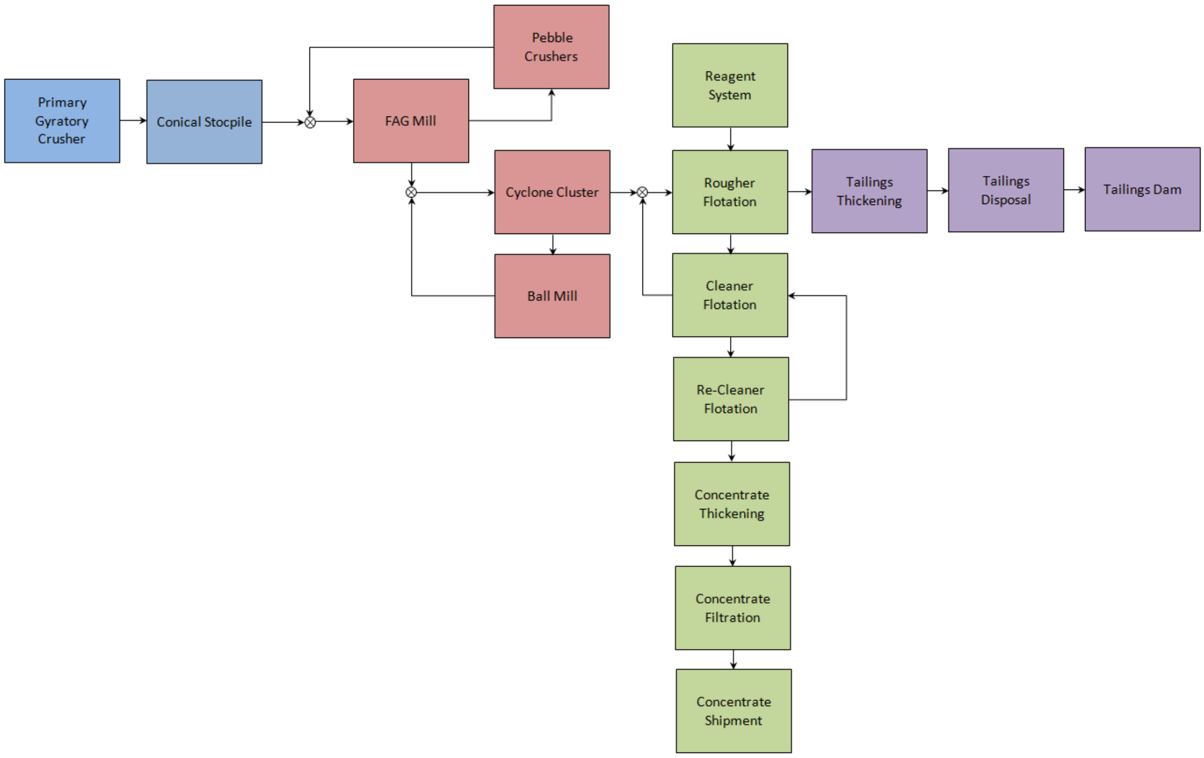
The MMZ plant was designed to treat approximately 375 ktpm of ore from two sources – 90% of the feed from an open pit mining operation and 10% of the feed from an underground shaft mining operation. The ore was deemed to be readily treated through froth flotation (Lyalinov, Lebedeva, & Vakhrusheva, 2011).

The process flow contains the following unit operations (see Figure 6):

1. *Gyratory crusher*: which accepts ROM ore from the open pit operation and pre-treats the ore for subsequent grinding;
2. *Grinding circuit*: which consists of a fully autogenous (FAG) mill, a ball mill, pebble crushing circuit and cyclone cluster which pre-treats the plant feed for subsequent froth flotation;
3. *Flotation circuit*: which generates a final product and discardable waste or tailings stream;
4. *Tailings disposal*: consists of a tailings thickener and pumping circuit to dispose the waste stream on the tailings facility; and

5. *Concentrate handling*: consists of two thickening and one filtration stage to remove water from the concentrate stream. Also includes logistics for transportation of filtered concentrate to a number of smelters.

Figure 6: Schematic flow diagram of the MMZ operation of the Nkomati Nickel Mine



A brief discussion on each of the processes mentioned above is to follow.

6.2 Process Description

A brief description of each of the units utilised in the MMZ process is to follow.

6.2.1 Primary Gyratory Crusher

Nkomati Mine utilises a Metso 54” × 75” gyratory crusher to crush the ROM material extracted from the open pit mining operation. The gyratory crusher is fed at an average feedrate of 1800 tph and to top-size of the material fed to the crusher is 1 000 mm, i.e. F_{100} = 1 000 mm. A picture of the gyratory crusher is given in Figure 7.

Crushing is performed by a 450 kW motor and crushed mater is discharged into a 130 m^3 rockbox from which crushed ore is extracted by an apron feeder. The apron feeder discharges onto a conveyor belt. The crushed material is transferred to a stockpile, approximately 6 km away, by means of a series of five overland conveyors.

Figure 7: Metso 54" × 75" gyratory crusher used to treat ROM material at Nkomati Mine

With an open-side setting (OSS) of 175 mm, the crusher reduces the top-size of the fed material from a maximum of 1 000 mm to 270 mm, i.e. P_{100} = 270 mm. It is critical that the crusher not be fed with material greater than 1 000 mm, and for this purpose a Split System is utilised, which is a camera system which optically analyses the size the rocks in the bucket of the tipper truck, and rejects a truck in the event of over-size material being present.

Maintenance is conducted on a weekly basis by the original equipment manufacturer (OEM), which is Metso.

6.2.2 Stockpile

The crushed material is fed onto a stockpile prior to being fed to the concentrator plant. A picture of the stockpile is given in Figure 8. The stockpile has a live capacity of approximately 16 hours.

The concentrator plant is fed by means of four apron feeders situated below the stockpile. It is essential that an adequate ratio of inner and outer feeders be maintained to ensure that the stockpile gets drawn down evenly, which will maximise the live capacity of the stockpile. A strong correlation has been found between the stockpile level and the feedrate into the plant – should the stockpile level become low, a bulldozer has to be used to reclaim the material and feed the apron feeders, which means that a highly variable and non-homogeneous ore blend is fed to the primary FAG mill, which has a severe impact on the efficiency of this grinding stage. The FAG mil is well known to be sensitive to the characteristics of the material being fed to it(Bradford, et al., 1998) and hence variability in the feed characteristics will affect grinding efficiency.

In addition, the outer feeders are used to reclaim the coarser rocks that rolled to the outside of the stockpile and the inner feeders are used to reclaim the finer material situated at the centre of the stockpile. An optimum size distribution is required to ensure grinding efficiency in the FAG mill – i.e. optimum selection of the coarse-to-fine ratio by selection of the speed of the inner and outer apron feeders below the stockpile.

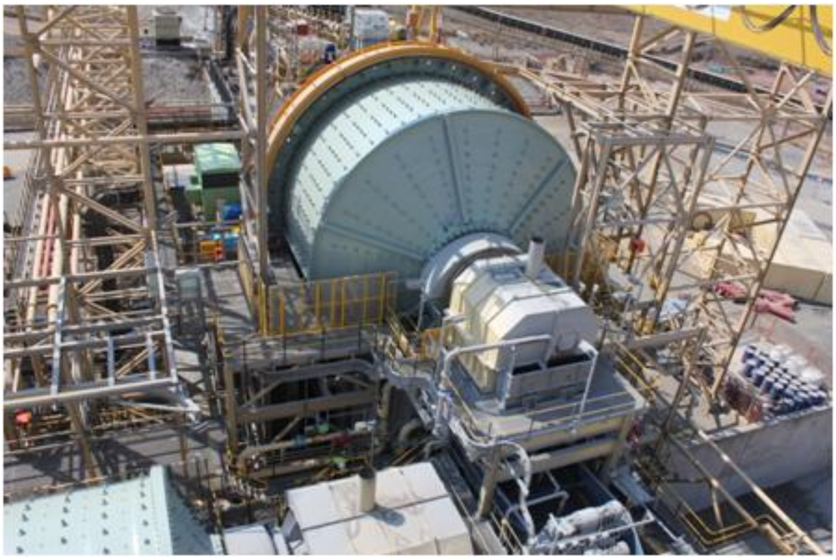
Figure 8: Stockpile of material prior to feeding concentrator plant

6.2.3 Primary FAG Mill

The material extracted from the stockpile is fed into a FAG mill by means of a conveyor belt. The FAG mill is a rotating drum which has a length of 5.34 m and a diameter of 10.516 m. As the name suggests, the mill is fully autogenous, which means that it does not utilise a grinding medium but relies on the material itself to supply the impact inside the mill cavity which is required to grind the material into a finer product stream.

The FAG mill utilises two motors to induce the tumbling action required for grinding, with each mill motor being 5.2 MW in size. A picture of the FAG mill is given in Figure 9.

Figure 9: FAG mill utilised as the primary grinding stage of the Nkomati concentrator plant



The mill is fed at a rate of between 580 tph and 680 tph – depending on the characteristics of the material being fed into the mill and the grinding efficiency achieved. After discharging the FAG mill, the product stream is classified by means of a series of screens into a coarse stream and a fines stream. The coarse stream is sent to the pebble crushers for further size reduction, and the fines stream is fed to a cyclone cluster for further classification.

6.2.4 Pebble Crushers

The pebble crushers used to further grind the coarse stream generated from the FAG mill are a set of two Raptor XL 600 pebble crushers manufactured by FLSmidth (see Figure 10). Only one pebble crusher is operated at a time, which means that there is 100% redundancy on the unit. The reason for this is to allow for maintenance on the units without affecting production and to alleviate the risk associated with a breakdown of a pebble crusher unit.

A pebble crusher operates at a current of approximately 380 to 550 Amps. The unit is fed at a rate of approximately 450 tph and reduces the size of the particles from an F_{80} of 65 mm to a P_{80} of 18 mm by means of a minimum closed-side setting (CSS) of 12 mm. Following crushing of the material, the product is fed back into the FAG mill and discharged onto the same screening section as another attempt is made to ensure the material report to the fines stream.

The pebble crushers undergo weekly maintenance by the OEM, which is FLSmidth.

Figure 10: FAG mill utilised as the primary grinding stage of the Nkomati concentrator plant

6.2.5 Cyclone Cluster

The fines stream is pumped to a cyclone cluster which is the classification stage utilised on the fines stream generated from the FAG mill. As stated in section 3.4, the cyclone is a classification unit that generates two streams, i.e. a coarse stream and a fines stream. The coarse stream is sent to the secondary ball mill for further grinding. The fines stream is deemed to be the final product from the milling and classification circuit and is sent to the froth flotation stage for concentration.

A picture of the cyclone used at Nkomati Mine is given in Figure 11. The unit is a 16 unit cyclone cluster, i.e. it contains 16 individual cyclone units, and generally between 8 and 10 cyclones are in operation. Again, the redundancy allows for maintenance to be performed on the units without production being affected.

The cyclones were supplied by Multotec, which are the OEM of the units. Planned maintenance on the units is conducted on a monthly basis by the OEM. Each cyclone has an internal diameter of 420 mm and a cone angle of 20 degrees. Each unit utilises a vortex finder of 164 mm and a spigot which is 100 mm in size and constructed of ceramic material to ensure longevity.

It is essential that the density of the feed stream, as well as the feedrate and the operating pressure of the cyclones be maintained within an optimal range. The following parameters have been established for the operating of the cyclone cluster at Nkomati Mine:

1. Feed density (SG) between 1.55 and 1.65;

2. Feedrate between 1800 m^3/h and 2400 m^3/h (corresponding to a plant feedrate of between 580 tph and 680 tph, and the addition of water to the dry solids to achieve the abovementioned optimal feed density); and
3. Cyclone pressure of between 65 kPa and 75 kPa.

The aim is to generate a fines stream exhibiting a grind of 70% passing 75 µm for the froth flotation stage. Not achieving the required grind will mean that the valuable minerals are not adequately liberated, which will result in a loss of recovery in the flotation stage. On the other hand, generating excessive fines will also negatively impact flotation as the froth flotation mechanism is not effective at recovering ultra-fine particles. Hence it is essential that the grind of the product stream from the classification circuit be closely monitored and controlled.

Figure 11: Cyclone cluster utilised as classification stage at Nkomati concentrator plant

6.2.6 Secondary Ball Mill

The coarse stream generated from the cyclone cluster is sent to the ball mill for further grinding. As the name suggests, the ball mill contains grinding media to assist with the grinding process. In the case of Nkomati, the grinding medium is 50 mm high-chrome steel balls. The reason for the addition of the grinding media is because the fineness of the ore does not allow for autogenous milling as was the case for the FAG mill.

A picture of the ball mill is given in Figure 12. The ball mill has a length of 9.45 m and a diameter of 7.01 m. Similar to the FAG mill, it has two mill motors, each with an installed power of 5.2 MW. The reason for this is to have commonality of spares, which will reduce the stock holding of spare units and thus reduce the capital cost of the operation.

Figure 12: Ball mill utilised for the secondary grinding stage of the Nkomati concentrator plant

As stated previously, the ball mill utilises 50 mm high-chrome steel balls as grinding medium and the cavity of the mill is charged to between 23% and 26% of the volume with media. During operation the ball mill consumes approximately 350 g of steel balls per ton of material fed to it. The density of the material fed to the ball mill is 2.1.

The product from the ball mill is sent, along with the fines stream from the FAG mill, to the cyclone cluster in a second attempt to allow the material to be classified as fines and sent to the flotation stage.

6.2.7 Froth Flotation Circuit

The fines product from the cyclone cluster (at a grind of 70% passing 75 µm) is fed to the froth flotation circuit for concentration. As stated previously, the flotation circuit consists of roughers, cleaners and re-cleaners.

The target density of the material fed to the flotation circuit is approximately 1.32. Firstly it is fed to a conditioning tank, where the required flotation reagents is added to the material and allowed sufficient residence time to allow for sufficient adsorption of the chemical to the surface of the mineral particles.

Subsequently, the first stage of the flotation process is conducted by the roughers which consist of two banks of flotation cells, each containing five cells with a capacity of 130 m^3. The tailings from each of the rougher banks are fed to the scavengers, which contains three cells with a capacity of 100 m^3 in each bank. The tailings from the two scavenger banks are combined into a single stream and sent to the tails thickener prior to being discarded.

The concentrate from the roughers and scavengers are combined into a single stream and sent to the cleaner stage for further concentration. The cleaner stage consists of five flotation cells, each with a capacity of 50 m^3. The tailings stream from the cleaner sage is returned to the roughers for re-processing. The concentrate from the cleaner stage is sent to the re-cleaners for further concentration.

The re-cleaner stage consists of three flotation cells, each with a capacity of 30 m^3. The tailings from the re-cleaner stage is returned to the cleaner stage for processing whilst the concentrate is sent for further processing as the final product. This involves removal of moisture through thickening and filtration.

A picture of the flotation circuit is given in Figure 13.

Figure 13: Overview of the flotation circuit utilised in the concentrator plant

6.2.8 Concentrate Thickening

As stated previously, the concentrate from the re-cleaner stage of the flotation circuit is sent to the thickener for water removal. The aim is to remove as much water as possible and t send a thickened stream to the subsequent filtration stage. Concentrate thickening is conducted in a Delkor thickener with a diameter of 20 m. It produces a thickened concentrate as an under-flow product with a density of between 1.6 and 2.1.

The over-flow from the thickener may still contain some solids, so it is sent to a clarifier. This is essentially another thickener, which is smaller in size, that produces a clear over-flow and a thickened under-flow that is sent back to the initial concentrate thickener. A picture of the concentrate thickener is given in Figure 14.

Figure 14: Picture of the concentrate thickener (background) and clarifier (foreground) used to thicken the concentrate produced from the flotation circuit

6.2.9 Concentrate Filtration

The thickened concentrate under-flow from the thickener is sent to a filtration stage for final dewatering. This is done by means of a filter press. The concentrate is pumped into multiple chambers and pressed between a filter cloth to remove the moisture. The unit used at Nkomati mine is manufactured by Larox and has a surface area of 132 m^2. A picture of the unit is given in Figure 15.

Various cloth types can be utilised, depending on the type of material being filtered. The most important characteristic of a cloth is its permeability, which can range from 1 to 28 $m^3/m^2 \bullet min$.

Filtration aids can be utilised to speed up the filtration process and reduce the amount of moisture in the filtered product. The Larox filter press at Nkomati Mine performs filtration in cycles, where one cycle takes approximately 11 minutes and yields a dried concentrate of 11 tons and a moisture content of approximately 11% water.

The unit is both operated and maintained by the OEM, as it is a critical piece of equipment with no redundancy – that is, should the unit not be available, production will be affected. It is therefore essential that the unit have a maximum availability.

Figure 15: The Larox filter press utilised during the filtration process at Nkomati Mine

6.2.10 Tails Thickening

Finally, the final tailings or waste produced from the filtration process is thickened prior to being discarded on the tailings storage facility. For this purpose, a Delkor tailings thickener is used for this purpose, which has a diameter of 40 meters (see Figure 16).

The thickened product from the tailings thickener exists as the under-flow from the unit at a density of between 1.55 and 1.65. From there, it is pumped to the Onverwacht tailings storage facility (TSF) approximately 14 km from the site.

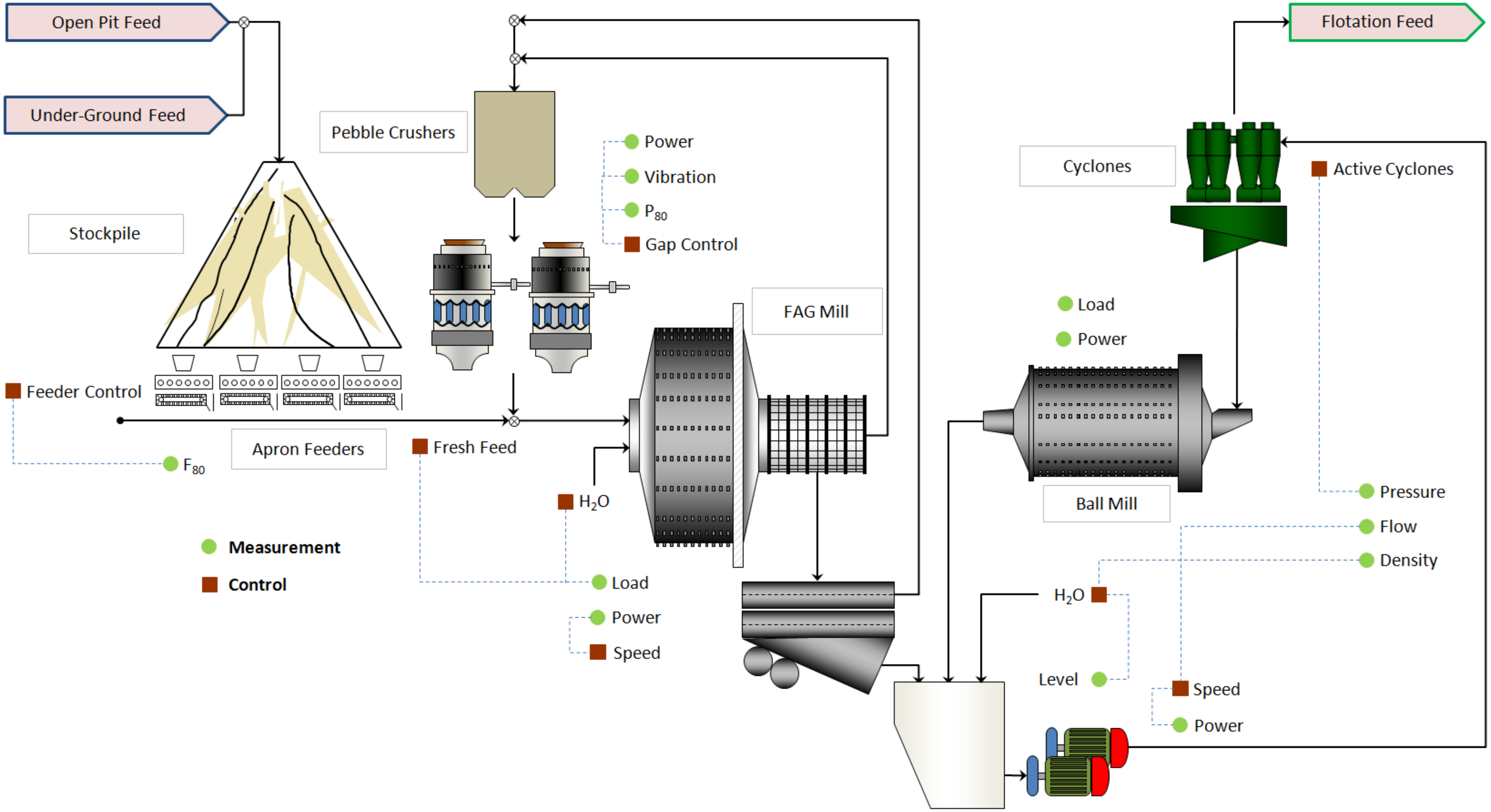
It is essential that the clarified overflow from the tailings thickener be as clear as possible, as it will be returned to the process as process water and any solids in the stream may affect downstream equipment.

Figure 16: Tailings thickener utilised for dewatering of the final tailings or waste stream from the concentrator process

An overview of the grinding circuit is given in Figure 17. It clearly shows how the coarse fraction from the FAG mill is fed to the pebble crushers and returned to the feed of the mill and the how the cyclone under-flow is fed to the ball mill and returned to the cyclone feed stream for classification. Figure 17 also indicates the measured and controlled variables for each of the major pieces of equipment. Some of these controlled variables will be included in the TISM to ensure each of the critical pieces of equipment is operated at optimal conditions to ensure the overall performance of the plant is optimised.

The TISM also included the generation of engineering reports specifically containing critical engineering information regarding each of the critical pieces of equipment that will aid in the execution of planned maintenance and to improve the asset performance of each of these units.

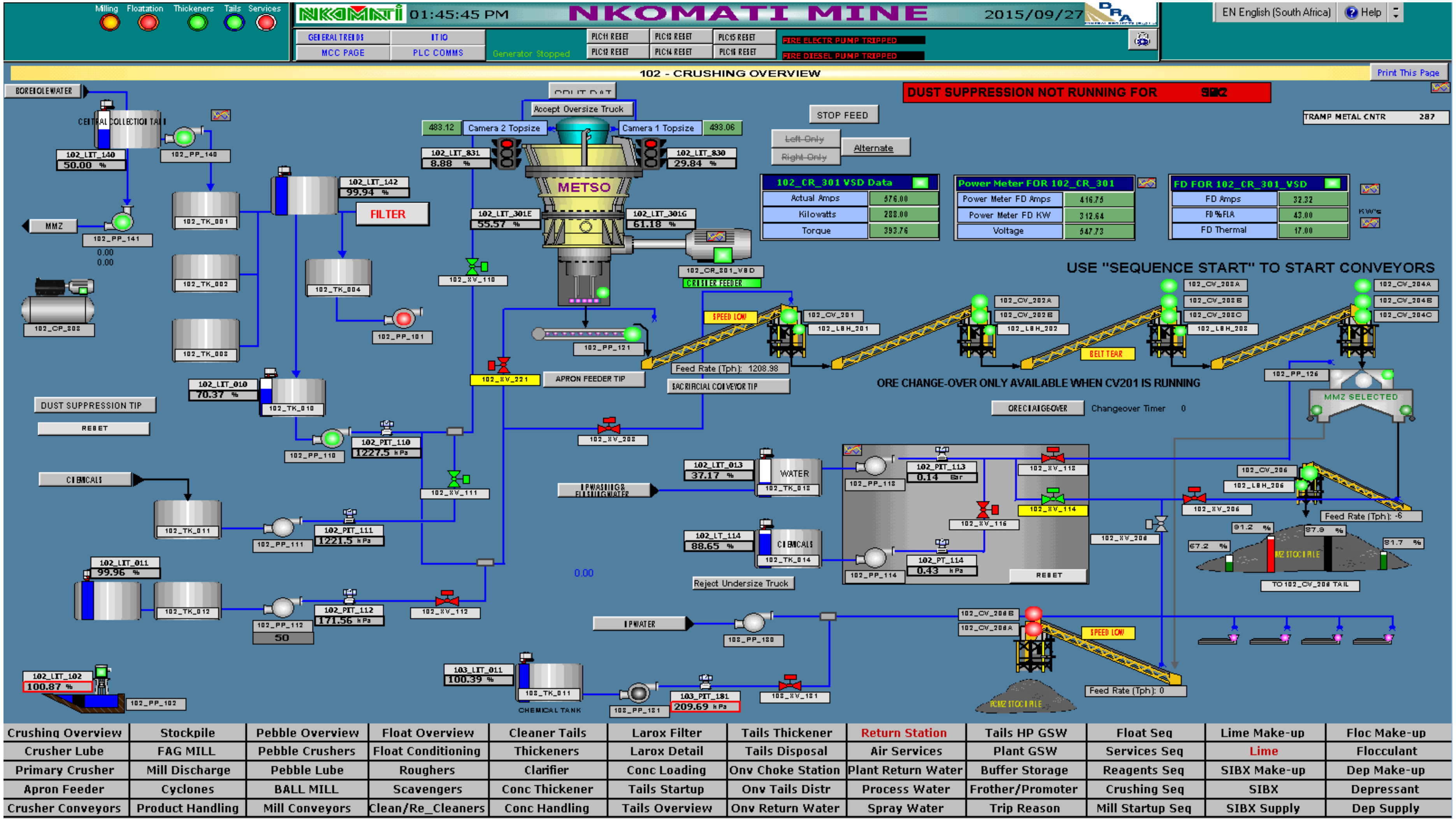
Figure 17: Schematic of the grinding circuit employed at Nkomati concentrator plant



As stated is section 6.1, the concentrator plant was designed with a high level of automation (Bradford, et al., 1998). This meant that a vast network of measurement and control instruments were employed in the design and construction of the process. Constant real-time feedback is obtained from these instruments and complex control decisions made by the Programmable Logic Controller (PLC), which is a digital computer used for automation of typically industrial electromechanical processes. This vast array of information is displayed on multiple screens in the plant control room and is permanently monitored by control room operators, under the guidance of the plant foreman. Should human intervention be required, the foreman dispatches one of the many field operators to a particular location in the plant to address an issue that may have arisen from a specific piece of equipment of process.

The system used to display the plant information is called the SCADA system. Examples of the display screens for a number of plant sections are given in Figure 18 to Figure 26

Figure 18: SCADA display of gyratory crusher and overland conveyors at Nkomati Mine concentrator plant



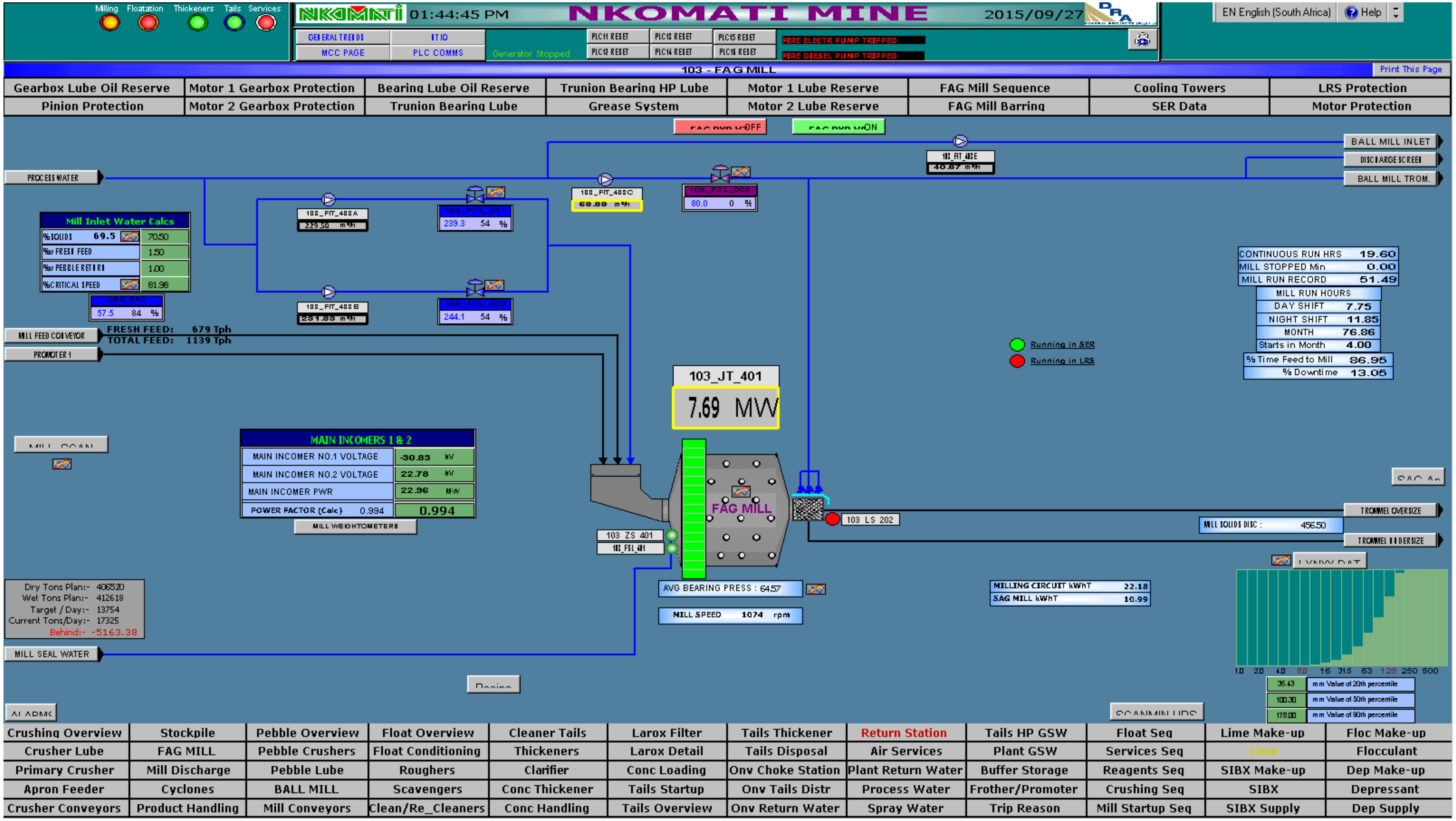
102_CR_301 VSD Data	
Actual Amps	576.00
Kilowatts	288.00
Torque	393.76

Power Meter FOR 102_CR_301	
Power Meter FD Amps	416.75
Power Meter FD KW	312.64
Voltage	547.73

FD FOR 102_CR_301_VSD	
FD Amps	32.32
FD %FLA	43.00
FD Thermal	17.00

Crushing Overview	Stockpile	Pebble Overview	Float Overview	Cleaner Tails	Larox Filter	Tails Thickener	Return Station	Tails HP GSW	Float Seq	Lime Make-up	Floc Make-up
Crusher Lube	FAG MILL	Pebble Crushers	Float Conditioning	Thickeners	Larox Detail	Tails Disposal	Air Services	Plant GSW	Services Seq	Lime	Flocculant
Primary Crusher	Mill Discharge	Pebble Lube	Roughers	Clarifier	Conc Loading	Onv Choke Station	Plant Return Water	Buffer Storage	Reagents Seq	SIBX Make-up	Dep Make-up
Apron Feeder	Cyclones	BALL MILL	Scavengers	Conc Thickener	Tails Startup	Onv Tails Distr	Process Water	Frother/Promoter	Crushing Seq	SIBX	Depressant
Crusher Conveyors	Product Handling	Mill Conveyors	Clean/Re_Cleaners	Conc Handling	Tails Overview	Onv Return Water	Spray Water	Trip Reason	Mill Startup Seq	SIBX Supply	Dep Supply

Figure 19: SCADA display of FAG mill at Nkomati Mine concentrator plant



01:44:45 PM
2015/09/27
Generator Stopped
FIRE ELECTR PUMP TRIPPED
FIRE DIESEL PUMP TRIPPED

103_FIT_403A 229.50 m³/h
103_FCL_001 239.3 54 %
103_FIT_403B 231.83 m³/h
103_FCL_002 244.1 54 %
103_FIT_403C 68.89 m³/h
103_FCL_003 80.0 0 %
103_FIT_403E 40.87 m³/h

Mill Inlet Water Calcs

%SOLIDS	69.5	70.50
%w FRESH FEED		1.50
%w PEBBLE RETURN		1.00
%CRITICAL SPEED		81.98

CRIT_SPD 57.5 84 %

FRESH FEED: 679 Tph
TOTAL FEED: 1139 Tph

103_JT_401 7.69 MW

CONTINUOUS RUN HRS	19.60
MILL STOPPED Min	0.00
MILL RUN RECORD	51.49
MILL RUN HOURS	
DAY SHIFT	7.75
NIGHT SHIFT	11.85
MONTH	76.86
Starts in Month	4.00
% Time Feed to Mill	86.95
% Downtime	13.05

MAIN INCOMERS 1 & 2

MAIN INCOMER NO.1 VOLTAGE	-30.83 KV
MAIN INCOMER NO.2 VOLTAGE	22.78 KV
MAIN INCOMER PWR	22.96 MW
POWER FACTOR (Calc) 0.994	0.994

Dry Tons Plan:- 406520
Wet Tons Plan:- 412618
Target / Day:- 13754
Current Tons/Day:- 17325
Behind:- -5163.38

AVG BEARING PRESS : 64.57
MILL SPEED 10.74 rpm

MILL SOLIDS DISC : 456.50

MILLING CIRCUIT kWhT	22.18
SAG MILL kWhT	10.99

35.43	mm Value of 20th percentile
100.30	mm Value of 50th percentile
178.00	mm Value of 80th percentile

Figure 20: SCADA display of mill discharge sump and cyclone feed stream at Nkomati Mine concentrator plant

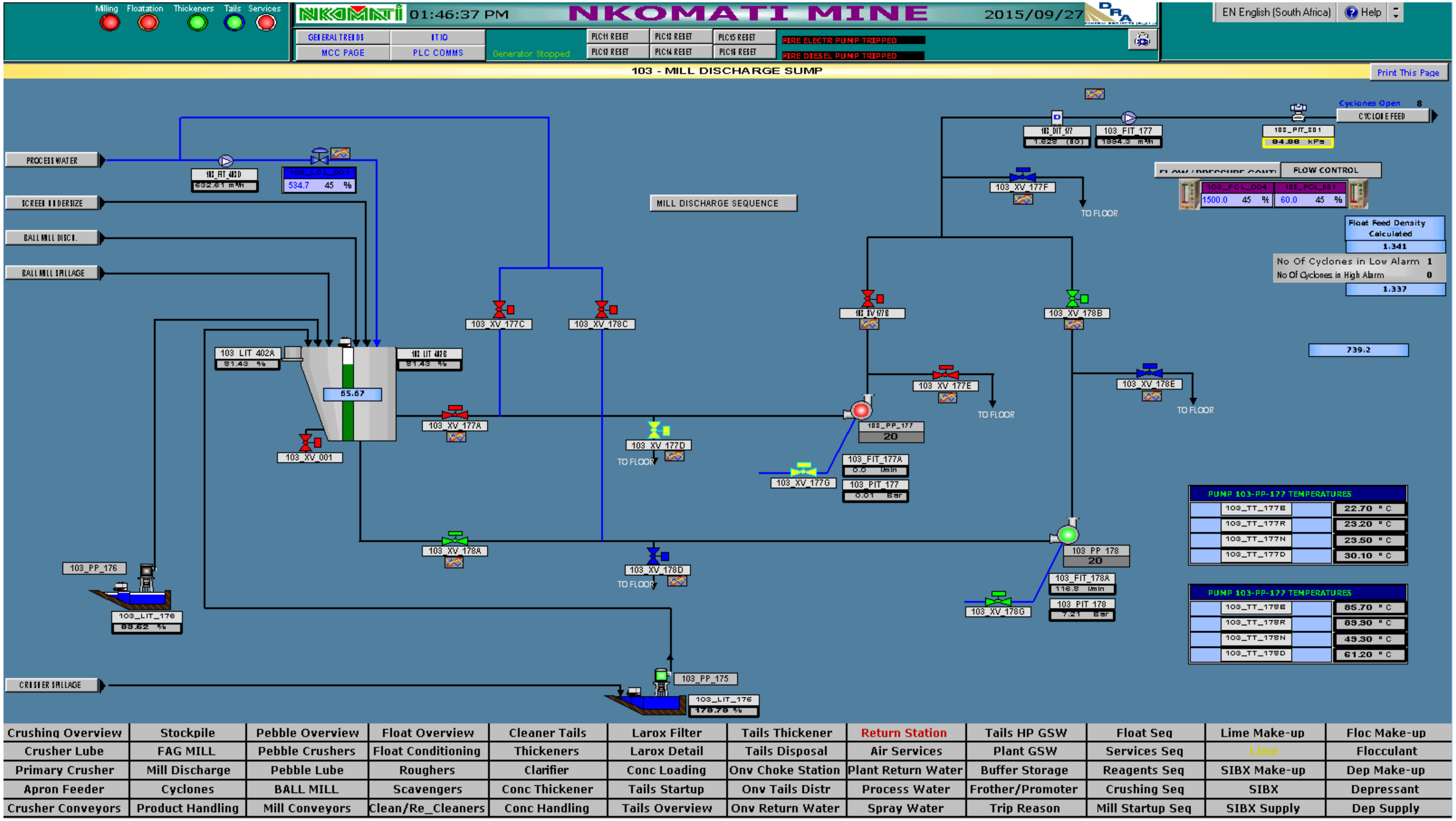
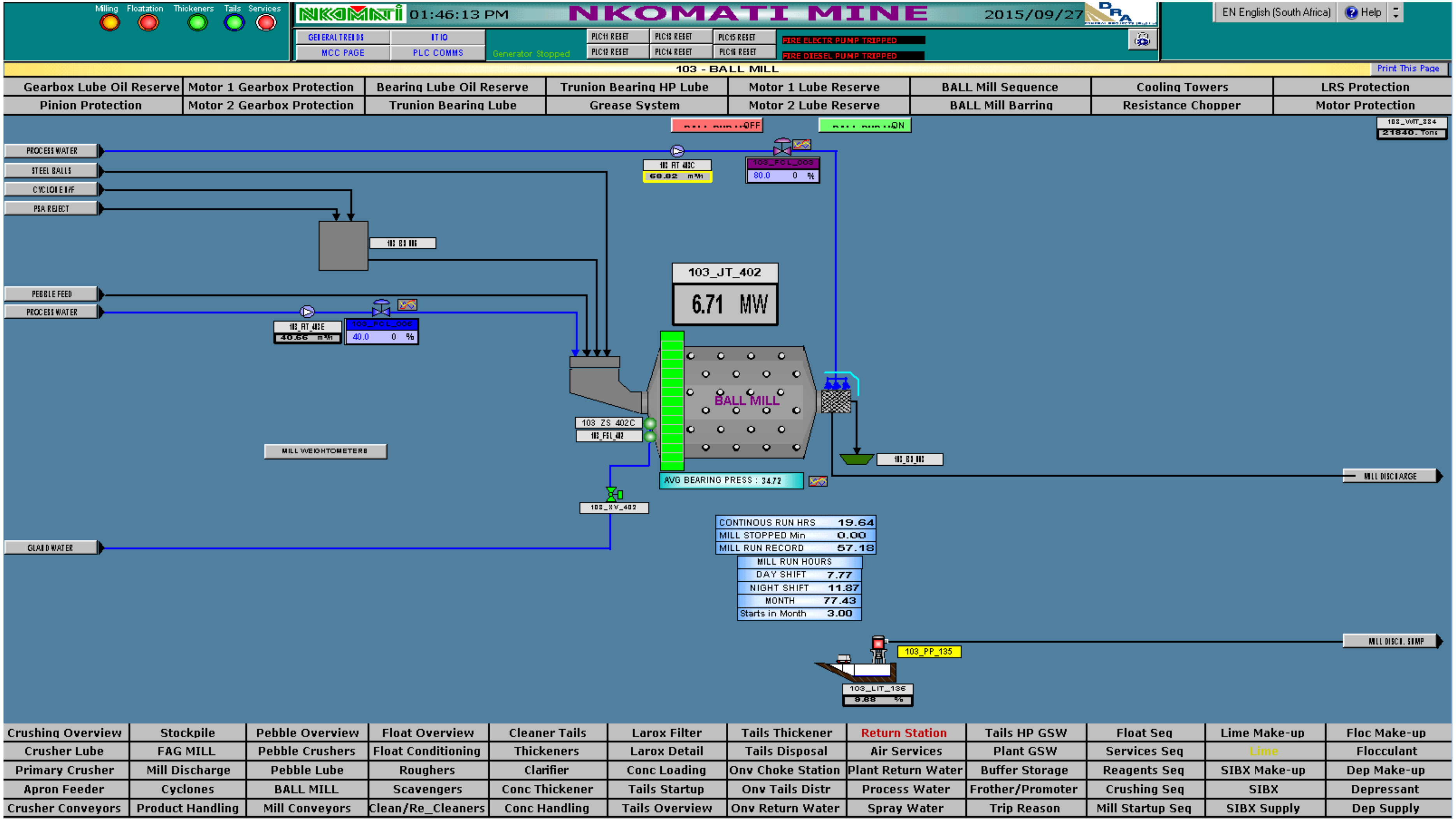


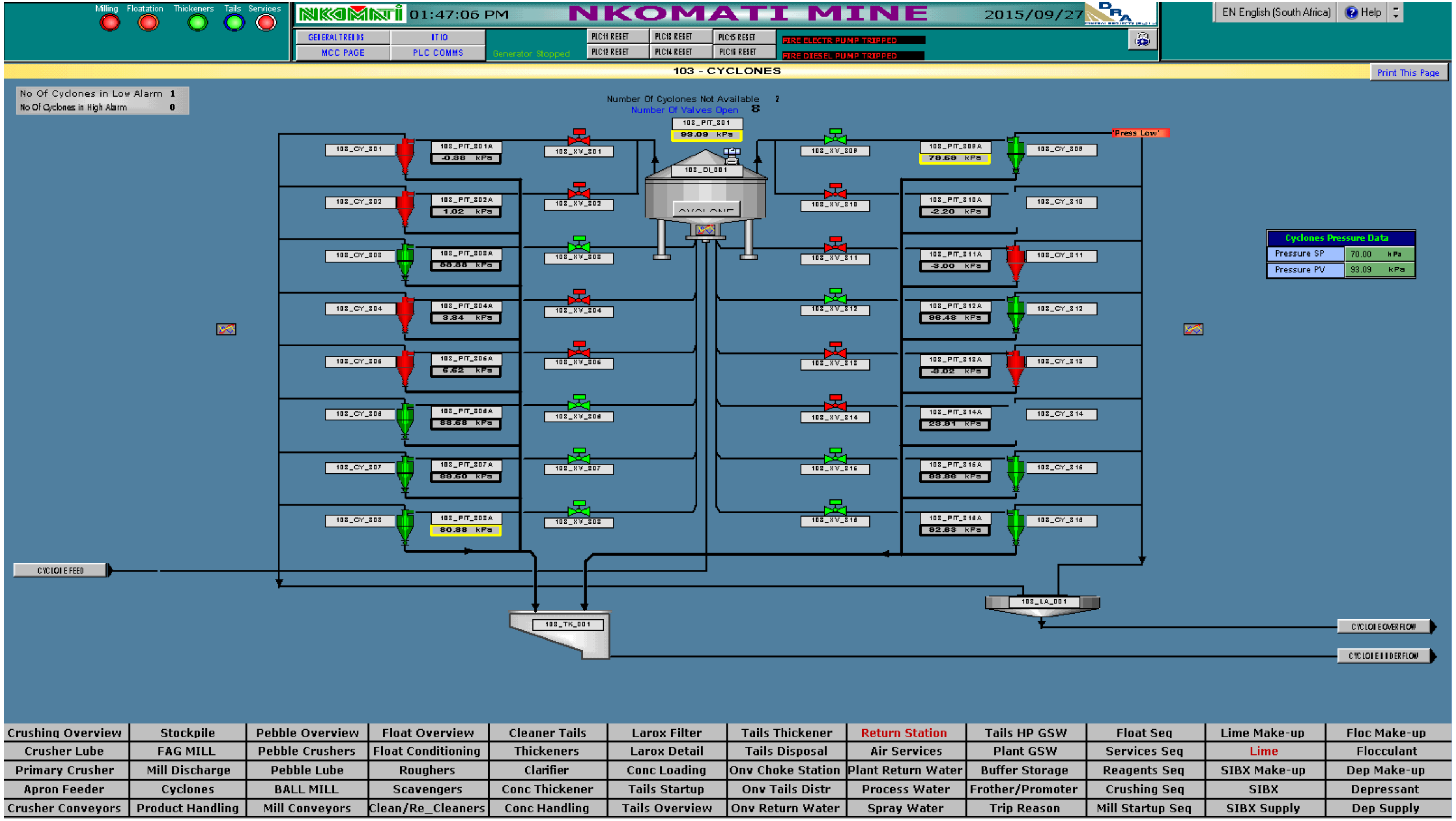
Figure 21: SCADA display of ball mill at Nkomati Mine concentrator plant



CONTINOUS RUN HRS 19.64
MILL STOPPED Min 0.00
MILL RUN RECORD 57.18

MILL RUN HOURS
DAY SHIFT 7.77
NIGHT SHIFT 11.87
MONTH 77.43
Starts in Month 3.00

Figure 22: SCADA display of cyclone custer at Nkomati Mine concentrator plant


NKOMATI MINE 01:47:06 PM 2015/09/27

Generator Stopped

FIRE ELECTR PUMP TRIPPED

FIRE DIESEL PUMP TRIPPED

103 - CYCLONES

No Of Cyclones in Low Alarm 1
No Of Cyclones in High Alarm 0

Number Of Cyclones Not Available 2
Number Of Valves Open 8

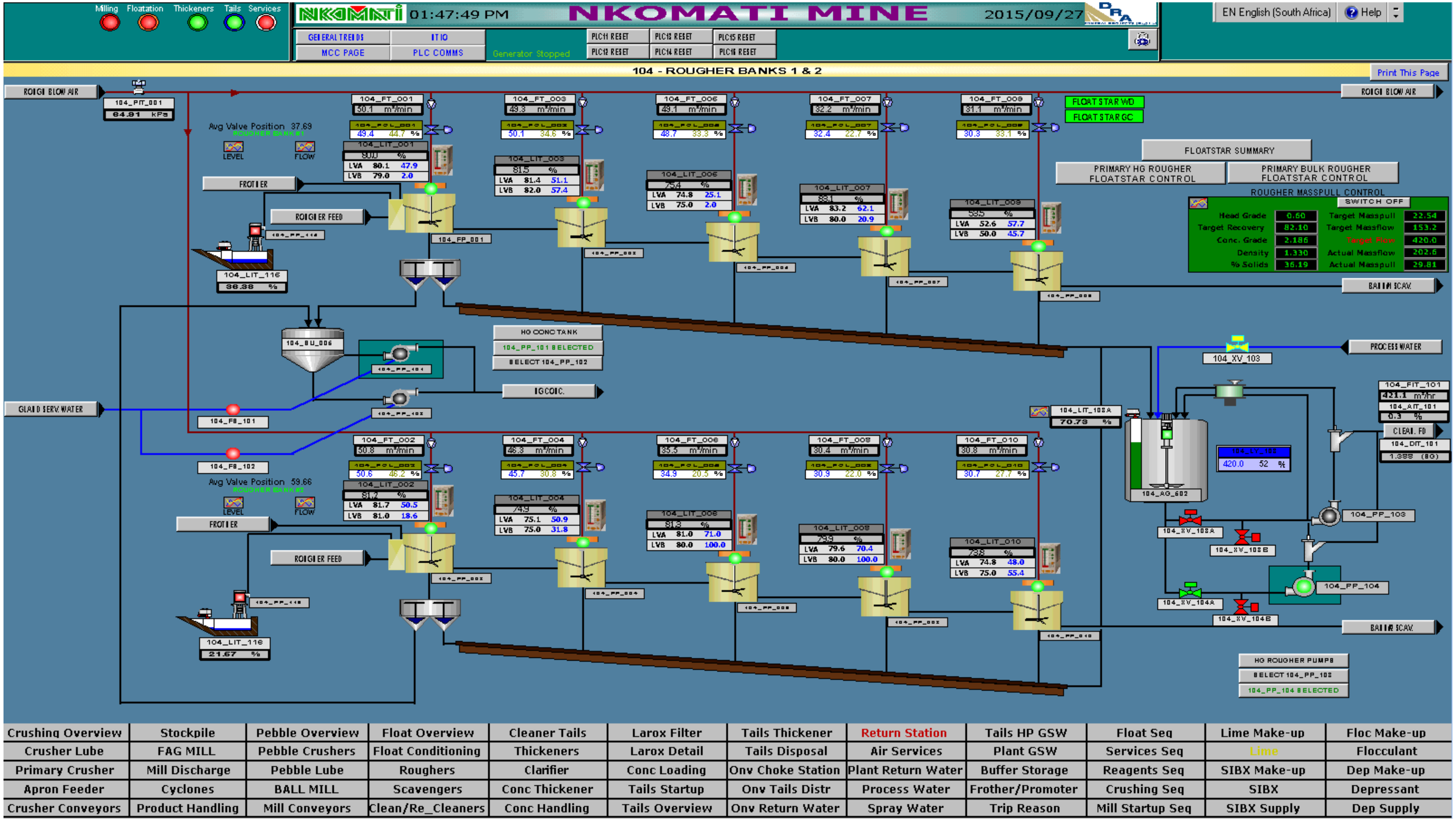
103_PIT_301 93.09 kPa

Cyclones Pressure Data		
Pressure SP	70.00	kPa
Pressure PV	93.09	kPa

Tag	Value
103_PIT_301A	-0.38 kPa
103_PIT_302A	1.02 kPa
103_PIT_303A	99.88 kPa
103_PIT_304A	3.84 kPa
103_PIT_305A	6.62 kPa
103_PIT_306A	88.68 kPa
103_PIT_307A	89.60 kPa
103_PIT_308A	80.88 kPa
103_PIT_309A	79.69 kPa
103_PIT_310A	-2.20 kPa
103_PIT_311A	-3.00 kPa
103_PIT_312A	96.48 kPa
103_PIT_313A	-3.02 kPa
103_PIT_314A	23.81 kPa
103_PIT_315A	93.86 kPa
103_PIT_316A	92.83 kPa

'Press Low'

Figure 23: SCADA display of rougher flotation circuit at Nkomati Mine concentrator plant



NKOMATI MINE 01:47:49 PM 2015/09/27

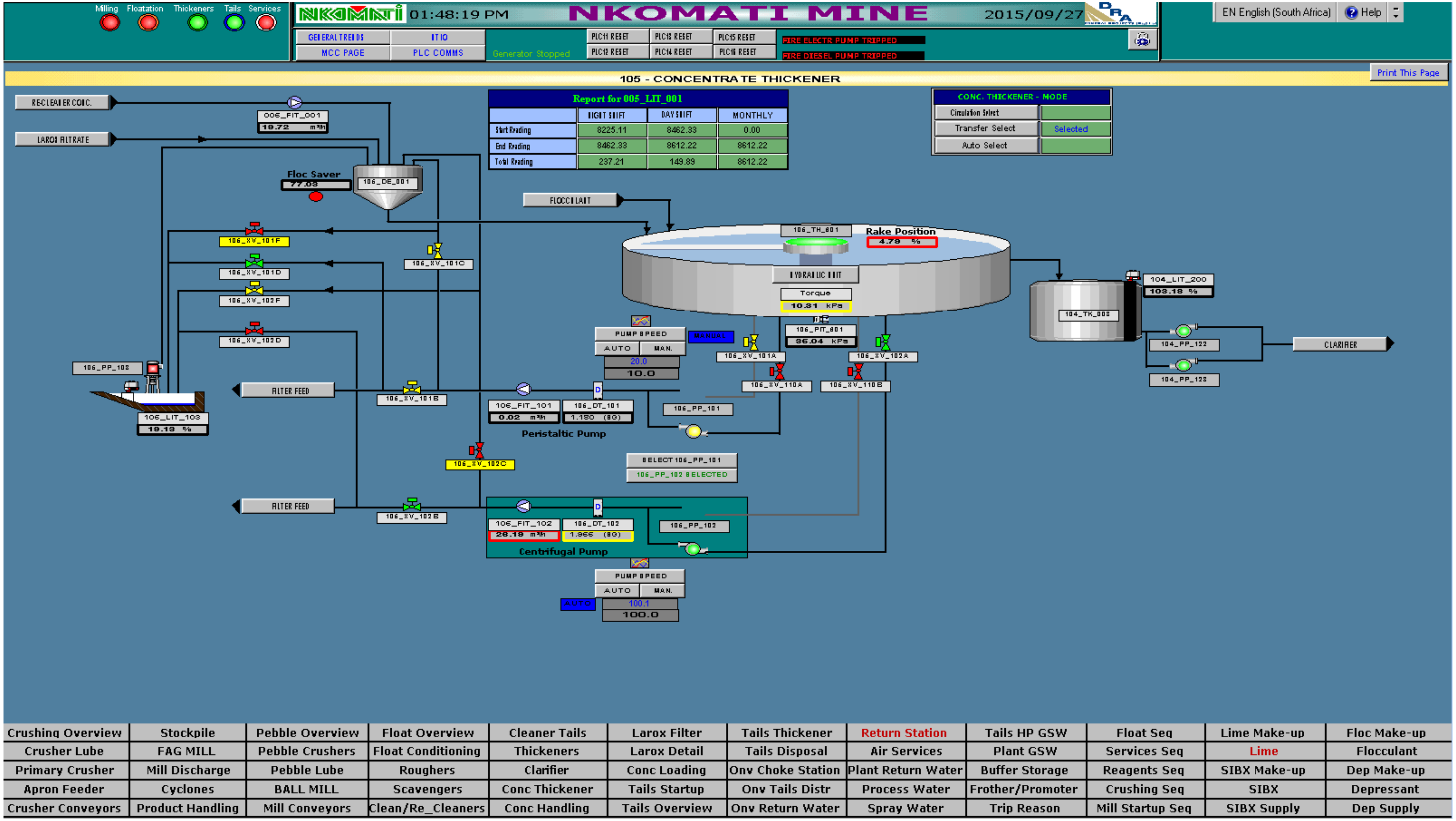
104 - ROUGHER BANKS 1 & 2

ROUGHER MASSPULL CONTROL

Head Grade	0.60	Target Masspull	22.54
Target Recovery	82.10	Target Massflow	153.2
Conc. Grade	2.186	Target Flow	420.0
Density	1.330	Actual Massflow	202.6
% Solids	36.19	Actual Masspull	29.81

Generator Stopped

Figure 24: SCADA display of concentrate thickener at Nkomati Mine concentrator plant



Report for 005_LIT_001

	NIGHT SHIFT	DAY SHIFT	MONTHLY
Start Reading	8225.11	8462.33	0.00
End Reading	8462.33	8612.22	8612.22
Total Reading	237.21	149.89	8612.22

Figure 25: SCADA display of Larox filter press at Nkomati Mine concentrator plant

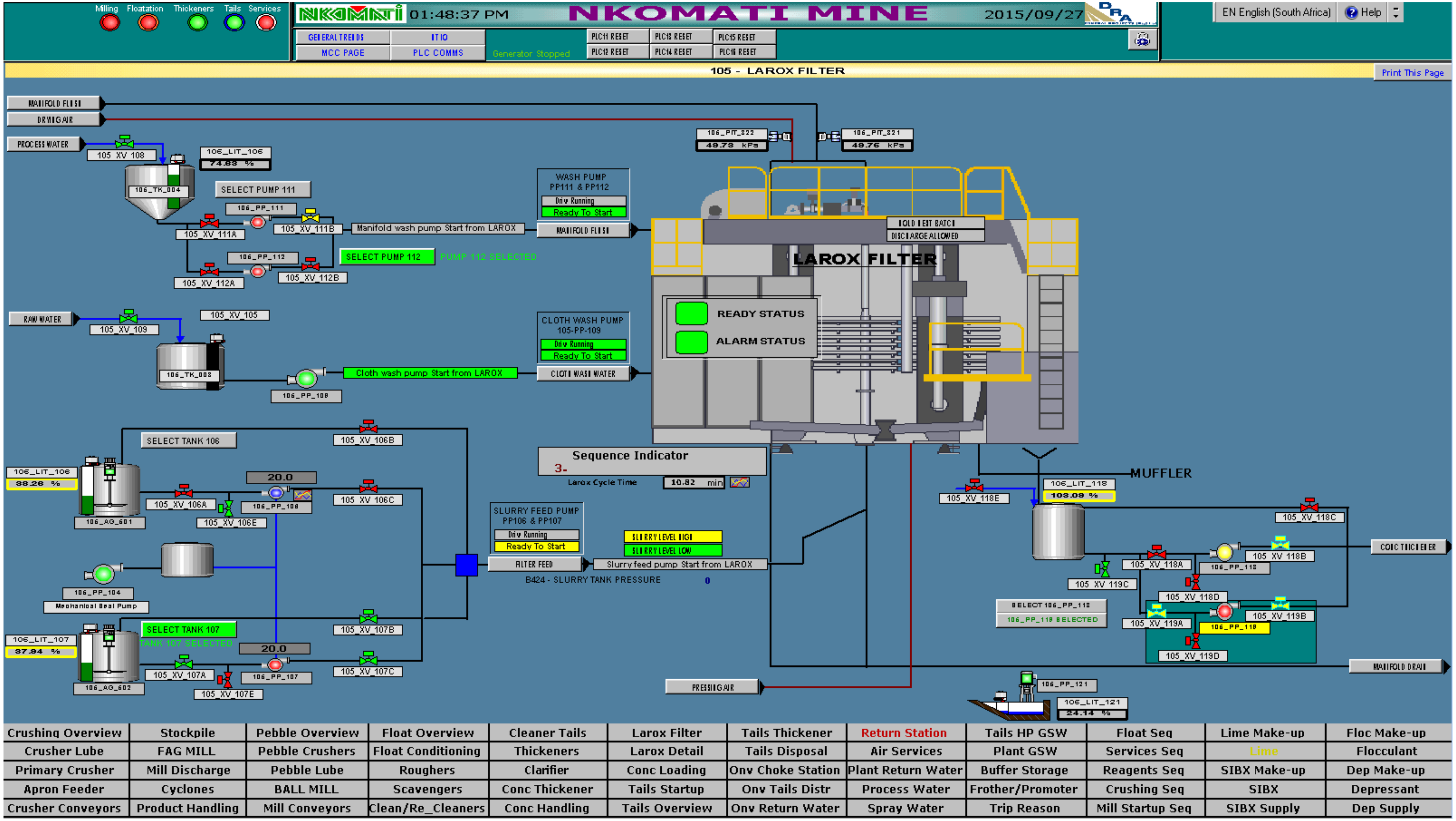
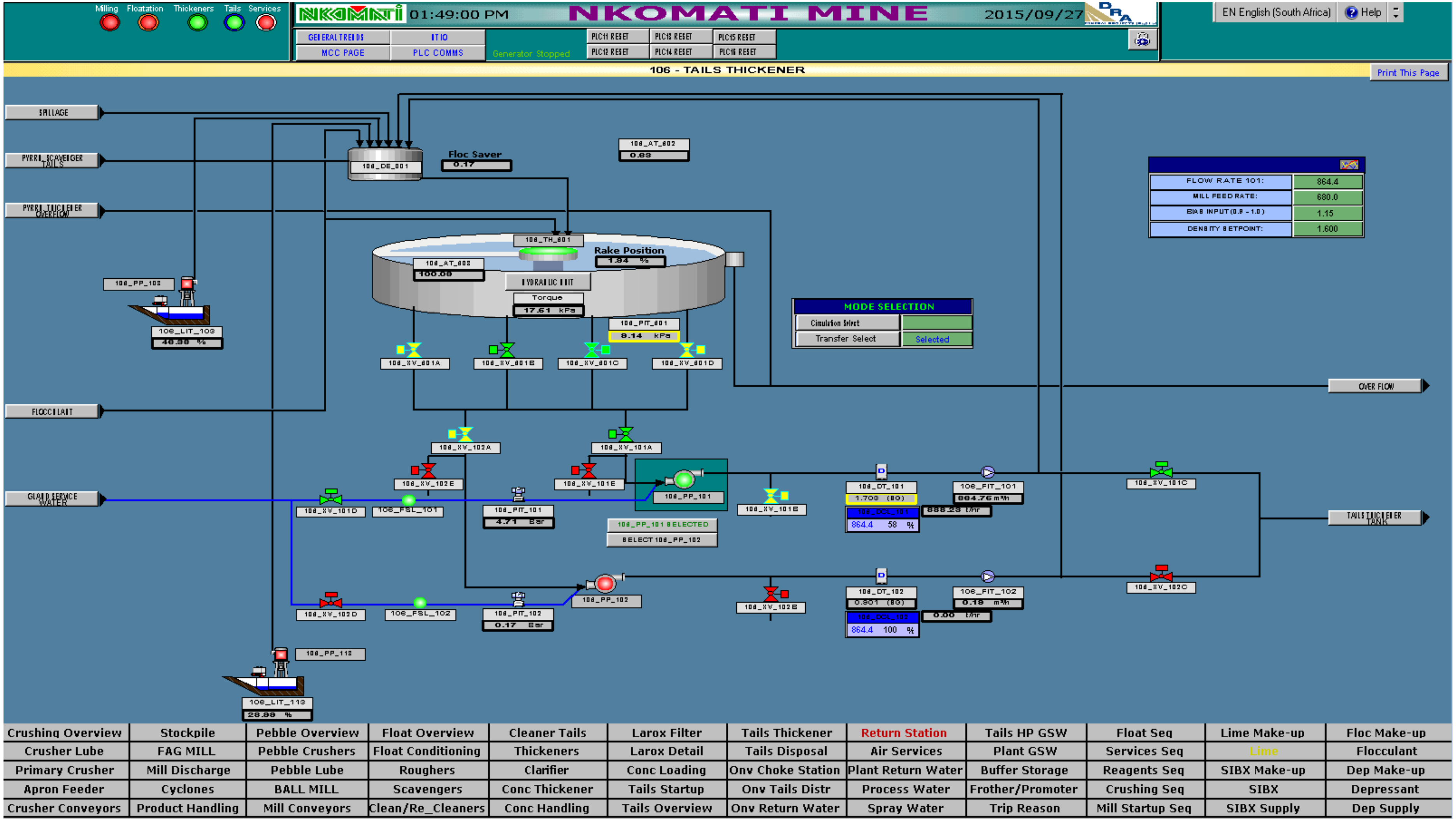


Figure 26: SCADA display of tailings thickener at Nkomati Mine concentrator plant



Floc Saver 0.17
106_AT_002 0.83
Rake Position 1.94 %
106_AT_003 100.09
Torque 17.61 kPa
106_PIT_001 9.14 kPa
106_LIT_103 46.38 %
106_PIT_101 4.71 Bar
106_DT_101 1.703 (SG)
106_FIT_101 864.76 m³/h
888.28 t/hr
106_DCL_101 864.4 58 %
106_PIT_102 0.17 Bar
106_DT_102 0.901 (SG)
106_FIT_102 0.18 m³/h
0.00 t/hr
106_DCL_102 864.4 100 %
106_LIT_113 28.99 %

FLOW RATE 101: 864.4
MILL FEED RATE: 680.0
BIAS INPUT (0.8 - 1.0): 1.15
DENSITY SETPOINT: 1.600

In addition to the data captured and displayed on the SCADA system, a number of slurry streams in the flotation circuit are sampled and analysed in the laboratory to determine its nickel, copper, cobalt, iron and magnesium oxide content, amongst other elements and compounds.

It is understandable that this vast amount of information can become confusing and overwhelming to even an experienced plant operator. Very often plant operators and foremen are left wondering:

- What information should be prioritised?
- What is the optimum range for a particular parameter to be operated at?
- What should be done if a parameter is not in this optimal range?
- How does each of the various parameters influence each other?
- What is the operating philosophy of the plant?

Very often, this confusion leads to instability, as each operator operates the plant in a unique way based on their own interpretation of the information. There exists a need to align the cognitive maps of the various process operators to ensure a consistent approach to the operation of the plant and to ensure process variables are maintained within a range that will ensure optimal results.

The overall aim in operating the processing plant is to ensure the following:

1. Maximise ***throughout*** into the process by increasing the rate at which the plant is fed in tph;
    - *Optimise*: set up the plant in order to maintain a maximum throughput rate of 680 tph;
2. Maximise the ***recovery*** of the nickel produced from the process, i.e. recovery as much nickel into the concentrate and lose as little as possible nickel into the tailings;
    - *Optimise*: consistently operate the flotation circuit above the head grade-recovery curve;
3. Ensure the required ***specification*** of the final product is met, i.e. an iron-magnesium oxide (Fe:MgO) ratio of at least 5 is maintained and at least 10% nickel in final concentrate; and
    - *Optimise*: consistently maintain on-specification final product without sacrificing recovery.

The aim of the TISM is to:

1. make sense of the data being generated by the process;
2. Identify the major drivers that influence the objectives of the process;

3. Stipulate the optimal range for these major drivers;
4. Dictate what actions should be taken should a major driver not be in range; and
5. Repeat the iteration in order to make sure the stipulated process recipe is always relevant and optimised.

In addition to the real-time reporting of essential process data, the TISM is also enabled to generate daily or weekly reports on critical operating parameters to assist in identifying long term drifts in process and engineering trends.

If the TISM real-time and historic reporting tools are combined with a root cause analysis system, the process can be adequately maintained within optimal operating range and drifts from ideal conditions be progressively minimised.

6.3 Development of the Time-in-State Metric

The actual process and laboratory data from the MMZ plant and Nkomati mine was utilised for the evaluation of the TISM. Approval was obtained to utilise all required information for the purpose of this study (see Appendix A).

The process of the TISM development is conducted in a number of stages:

- *Stage 1*: The first stage involves extensive data analysis to determine the optimal operating state for the equipment or process parameters. To determine the optimal operating state for equipment, the information supplied by the Original Equipment Manufacturer (OEM) or the design company can be utilised. Determination of the optimal operating state for process parameters is a little more laborious. For this, the overall optimal operating state firstly has to be specified, and then the process parameters obtained under these conditions are recorded as the ideal state. This will be elaborated upon later;
- *Stage 2*: Once the optimal equipment and process parameters have been established, the targets have to be communicated in real-time in a user-friendly format. The actual condition has to be reported relative to the ideal state and in the event of there being deviations from the ideal state, recommendations have to be made to eliminate the discrepancy between the two;
- *Stage 3*: Finally, reporting platforms have to be developed to indicate the amount of time the process has spent in the ideal state and, where deviated, what the reason for the

deviation was. This reporting will be done on historic data and will allow for the evaluation of the performance of the process over an extended period.

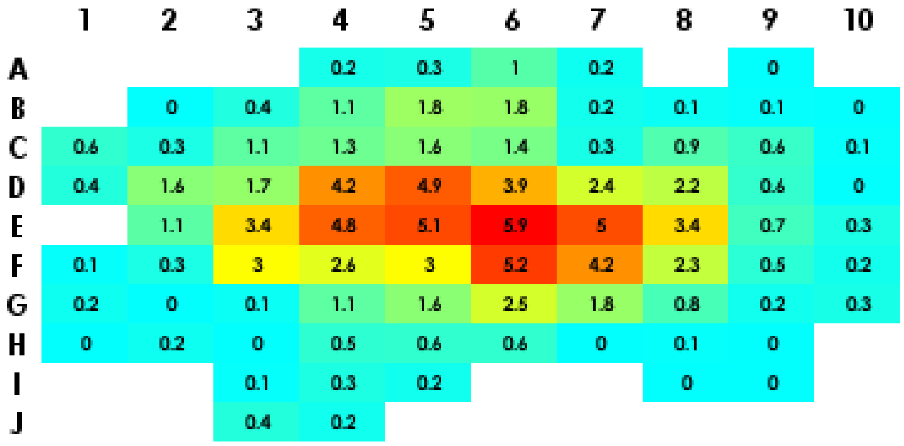
The overall aim of the MMZ plant at Nkomati mine is as follows:

1. Maximisation of the **throughput** into the processing plant. This will involve both optimising the availability and utilisation of the process and the rate at which the process is fed with fresh feed material;
2. Maximisation of the **recovery** of metal to the final concentrate or product of the process; and
3. Ensuring that a saleable product is produced by maintaining an **Fe:MgO** ratio in the final product of at least 5. This is a specification that is stipulated in the off-take agreement that the mine enters into with a smelter which further concentrates the metal contained in the concentrate.

An example of the data analysis phase of the development of the TISM will be discussed in the context of the flotation circuit of the MMZ process. A matrix method is used to group the data into a more manageable and visible format. Firstly, all the relevant data is extracted from the central data base. Then a distribution matrix is compiled which indicates the number of occurrences of a specific set of conditions. For example, a condition whereby the head grade of the material fed to the flotation process is 0.42% nickel, the cyclone feed density (SG) is 1.55, the cyclone feed flowrate is 1800 m^3/h, the flotation feed density (SG) is 1.32, the recovery is 76.5% and the Fe:MgO ratio is 5.5 is one condition. Should this condition be experienced 5% of the time during the period over which the data has been extracted, the distribution matrix will have a 5% distribution allocated in the position of the matrix which represents this condition, for example 5F. Subsequently, all corresponding data matrices will have the values of the parameters that correspond to this condition in the same position, i.e. 5F.

An example of a density distribution matrix is given in Figure 27. A number of corresponding process parameter matrices are given in Figure 28.

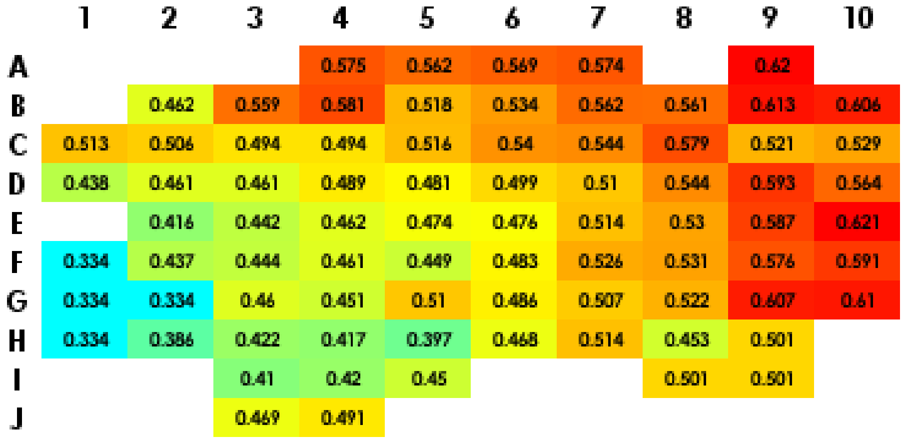
Figure 27: An example of a density distribution matrix compiled for the flotation circuit of the MMZ process at Nkomati mine



	1	2	3	4	5	6	7	8	9	10
A				0.2	0.3	1	0.2		0	
B		0	0.4	1.1	1.8	1.8	0.2	0.1	0.1	0
C	0.6	0.3	1.1	1.3	1.6	1.4	0.3	0.9	0.6	0.1
D	0.4	1.6	1.7	4.2	4.9	3.9	2.4	2.2	0.6	0
E		1.1	3.4	4.8	5.1	5.9	5	3.4	0.7	0.3
F	0.1	0.3	3	2.6	3	5.2	4.2	2.3	0.5	0.2
G	0.2	0	0.1	1.1	1.6	2.5	1.8	0.8	0.2	0.3
H	0	0.2	0	0.5	0.6	0.6	0	0.1	0	
I			0.1	0.3	0.2			0	0	
J			0.4	0.2						

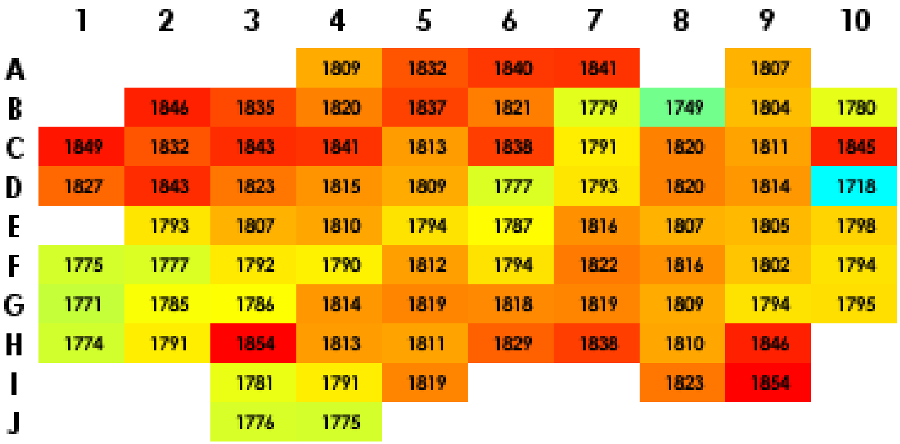
Figure 28: The corresponding process parameter matrices for the flotation circuit of the MMZ process at Nkomati mine

i. Flotation feed grade matrix (% nickel)



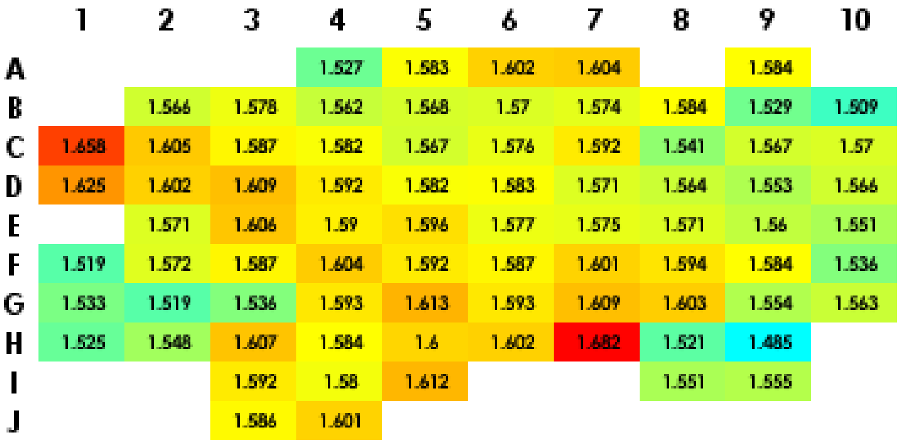
	1	2	3	4	5	6	7	8	9	10
A				0.575	0.562	0.569	0.574		0.62	
B		0.462	0.559	0.581	0.518	0.534	0.562	0.561	0.613	0.606
C	0.513	0.506	0.494	0.494	0.516	0.54	0.544	0.579	0.521	0.529
D	0.438	0.461	0.461	0.489	0.481	0.499	0.51	0.544	0.593	0.564
E		0.416	0.442	0.462	0.474	0.476	0.514	0.53	0.587	0.621
F	0.334	0.437	0.444	0.461	0.449	0.483	0.526	0.531	0.576	0.591
G	0.334	0.334	0.46	0.451	0.51	0.486	0.507	0.522	0.607	0.61
H	0.334	0.386	0.422	0.417	0.397	0.468	0.514	0.453	0.501	
I			0.41	0.42	0.45			0.501	0.501	
J			0.469	0.491						

ii. Cyclone feed flowrate matrix (m^3/h)



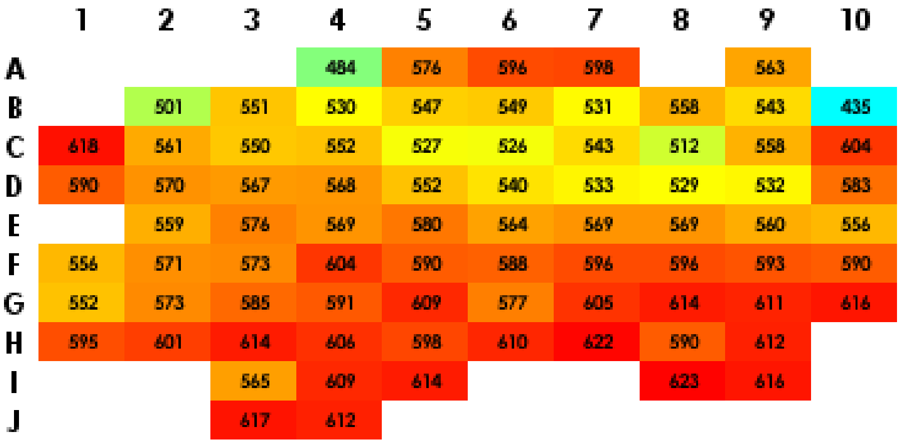
	1	2	3	4	5	6	7	8	9	10
A				1809	1832	1840	1841		1807	
B		1846	1835	1820	1837	1821	1779	1749	1804	1780
C	1849	1832	1843	1841	1813	1838	1791	1820	1811	1845
D	1827	1843	1823	1815	1809	1777	1793	1820	1814	1718
E		1793	1807	1810	1794	1787	1816	1807	1805	1798
F	1775	1777	1792	1790	1812	1794	1822	1816	1802	1794
G	1771	1785	1786	1814	1819	1818	1819	1809	1794	1795
H	1774	1791	1854	1813	1811	1829	1838	1810	1846	
I			1781	1791	1819			1823	1854	
J			1776	1775						

iii. Cyclone feed density matrix (SG)



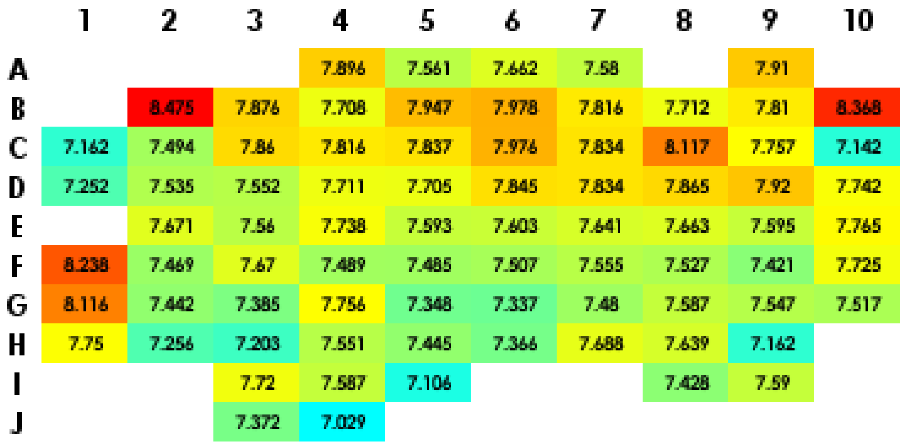
	1	2	3	4	5	6	7	8	9	10
A				1.527	1.583	1.602	1.604		1.584	
B		1.566	1.578	1.562	1.568	1.57	1.574	1.584	1.529	1.509
C	1.658	1.605	1.587	1.582	1.567	1.576	1.592	1.541	1.567	1.57
D	1.625	1.602	1.609	1.592	1.582	1.583	1.571	1.564	1.553	1.566
E		1.571	1.606	1.59	1.596	1.577	1.575	1.571	1.56	1.551
F	1.519	1.572	1.587	1.604	1.592	1.587	1.601	1.594	1.584	1.536
G	1.533	1.519	1.536	1.593	1.613	1.593	1.609	1.603	1.554	1.563
H	1.525	1.548	1.607	1.584	1.6	1.602	1.682	1.521	1.485	
I			1.592	1.58	1.612			1.551	1.555	
J			1.586	1.601						

iv. Plant feedrate matrix (tons / hour)



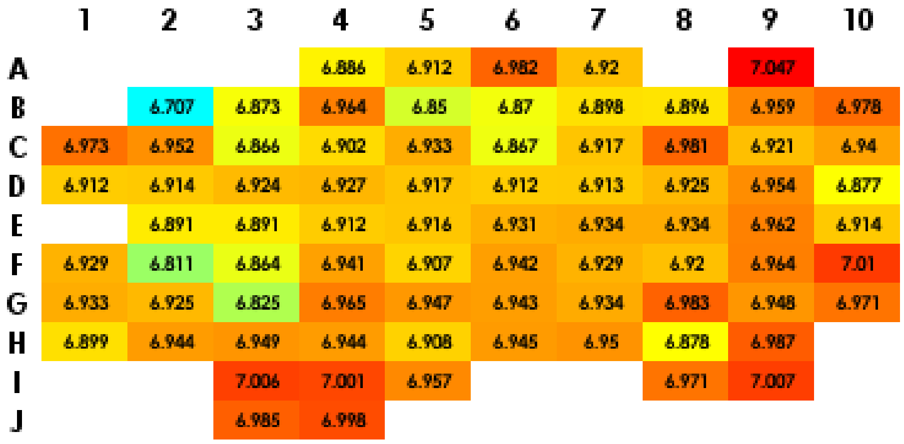
	1	2	3	4	5	6	7	8	9	10
A				484	576	596	598		563	
B		501	551	530	547	549	531	558	543	435
C	618	561	550	552	527	526	543	512	558	604
D	590	570	567	568	552	540	533	529	532	583
E		559	576	569	580	564	569	569	560	556
F	556	571	573	604	590	588	596	596	593	590
G	552	573	585	591	609	577	605	614	611	616
H	595	601	614	606	598	610	622	590	612	
I			565	609	614			623	616	
J			617	612						

v. *FAG mill power matrix (MW)*



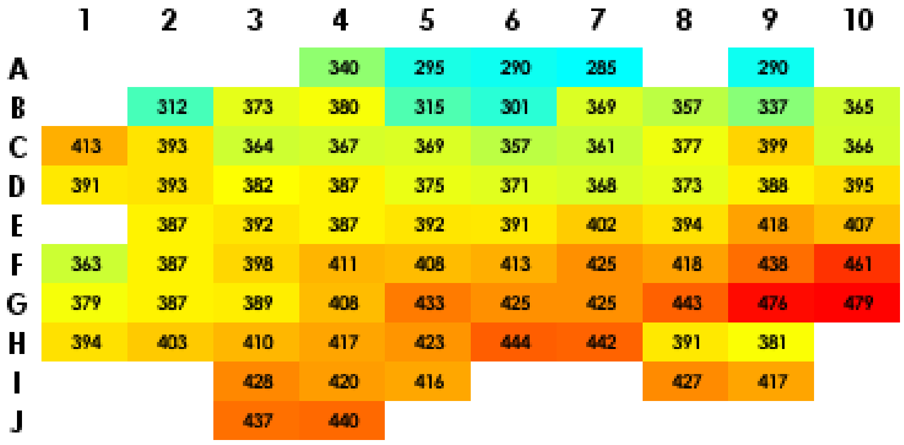
	1	2	3	4	5	6	7	8	9	10
A				7.896	7.561	7.662	7.58		7.91	
B		8.475	7.876	7.708	7.947	7.978	7.816	7.712	7.81	8.368
C	7.162	7.494	7.86	7.816	7.837	7.976	7.834	8.117	7.757	7.142
D	7.252	7.535	7.552	7.711	7.705	7.845	7.834	7.865	7.92	7.742
E		7.671	7.56	7.738	7.593	7.603	7.641	7.663	7.595	7.765
F	8.238	7.469	7.67	7.489	7.485	7.507	7.555	7.527	7.421	7.725
G	8.116	7.442	7.385	7.756	7.348	7.337	7.48	7.587	7.547	7.517
H	7.75	7.256	7.203	7.551	7.445	7.366	7.688	7.639	7.162	
I			7.72	7.587	7.106			7.428	7.59	
J			7.372	7.029						

vi. *Ball mill power matrix (MW)*



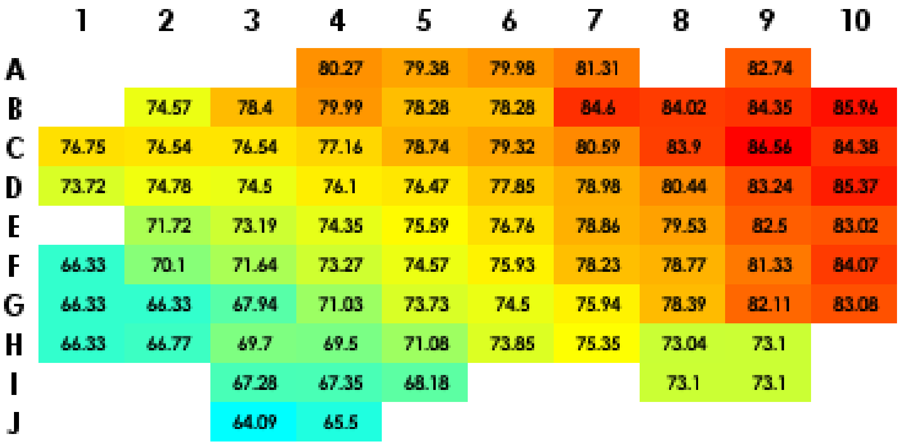
	1	2	3	4	5	6	7	8	9	10
A				6.886	6.912	6.982	6.92		7.047	
B		6.707	6.873	6.964	6.85	6.87	6.898	6.896	6.959	6.978
C	6.973	6.952	6.866	6.902	6.933	6.867	6.917	6.981	6.921	6.94
D	6.912	6.914	6.924	6.927	6.917	6.912	6.913	6.925	6.954	6.877
E		6.891	6.891	6.912	6.916	6.931	6.934	6.934	6.962	6.914
F	6.929	6.811	6.864	6.941	6.907	6.942	6.929	6.92	6.964	7.01
G	6.933	6.925	6.825	6.965	6.947	6.943	6.934	6.983	6.948	6.971
H	6.899	6.944	6.949	6.944	6.908	6.945	6.95	6.878	6.987	
I			7.006	7.001	6.957			6.971	7.007	
J			6.985	6.998						

vii. *Cleaner concentrate flowrate matrix (m^3/h)*



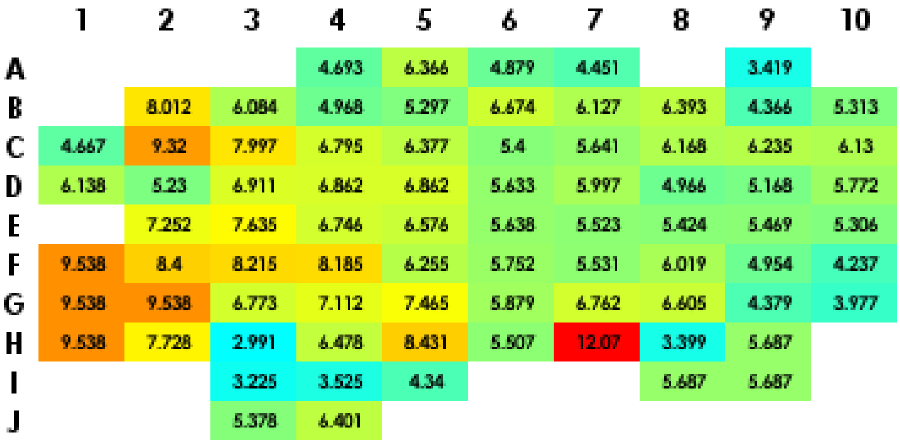
	1	2	3	4	5	6	7	8	9	10
A				340	295	290	285		290	
B		312	373	380	315	301	369	357	337	365
C	413	393	364	367	369	357	361	377	399	366
D	391	393	382	387	375	371	368	373	388	395
E		387	392	387	392	391	402	394	418	407
F	363	387	398	411	408	413	425	418	438	461
G	379	387	389	408	433	425	425	443	476	479
H	394	403	410	417	423	444	442	391	381	
I			428	420	416			427	417	
J			437	440						

viii. Overall recovery matrix (% nickel recovered)



	1	2	3	4	5	6	7	8	9	10
A				80.27	79.38	79.98	81.31		82.74	
B		74.57	78.4	79.99	78.28	78.28	84.6	84.02	84.35	85.96
C	76.75	76.54	76.54	77.16	78.74	79.32	80.59	83.9	86.56	84.38
D	73.72	74.78	74.5	76.1	76.47	77.85	78.98	80.44	83.24	85.37
E		71.72	73.19	74.35	75.59	76.76	78.86	79.53	82.5	83.02
F	66.33	70.1	71.64	73.27	74.57	75.93	78.23	78.77	81.33	84.07
G	66.33	66.33	67.94	71.03	73.73	74.5	75.94	78.39	82.11	83.08
H	66.33	66.77	69.7	69.5	71.08	73.85	75.35	73.04	73.1	
I			67.28	67.35	68.18			73.1	73.1	
J			64.09	65.5						

ix. Final concentrate Fe:MgO ratio matrix



	1	2	3	4	5	6	7	8	9	10
A				4.693	6.366	4.879	4.451		3.419	
B		8.012	6.084	4.968	5.297	6.674	6.127	6.393	4.366	5.313
C	4.667	9.32	7.997	6.795	6.377	5.4	5.641	6.168	6.235	6.13
D	6.138	5.23	6.911	6.862	6.862	5.633	5.997	4.966	5.168	5.772
E		7.252	7.635	6.746	6.576	5.638	5.523	5.424	5.469	5.306
F	9.538	8.4	8.215	8.185	6.255	5.752	5.531	6.019	4.954	4.237
G	9.538	9.538	6.773	7.112	7.465	5.879	6.762	6.605	4.379	3.977
H	9.538	7.728	2.991	6.478	8.431	5.507	12.07	3.399	5.687	
I			3.225	3.525	4.34			5.687	5.687	
J			5.378	6.401						

As stated previously, each block in the matrices represents a specific set of conditions. For example, block E6, the most highly prevalent condition set (at 5.9% density distribution) has the following process parameters associated with it:

- Nickel head grade of 0.476%;
- Cyclone feed flowrate of 1787 m^3/h;
- Cyclone feed density (SG) of 1.577;
- Plant fresh feedrate of 564 tph;
- FAG mill power of 7.603 MW;
- Ball mill power of 6.931 MW;
- Cleaner concentrate flowrate of 391 m^3/h;
- Overall nickel recovery of 76.76; and

- Final concentrate Fe:MgO ratio of 5.638.

From the above matrix analysis, one can establish the overall conditions in the plant where the ideal state, corresponding to optimal process performance, is attained. Once this has been established, a real-time reporting tool can be developed to track each of these parameters to determine whether the conditions required for ideal state is being achieved.

The ideal state conditions can effectively be viewed as a process recipe – the components required to achieve a desired outcome. After the initial process recipe has been established, it can undergo a number of iterations to refine the recipe and to modify the recipe as the conditions of the plant or the characteristics of the feed material change over time. A full re-evaluation report, conducted on the 28th of April 2014, is given in Appendix B.

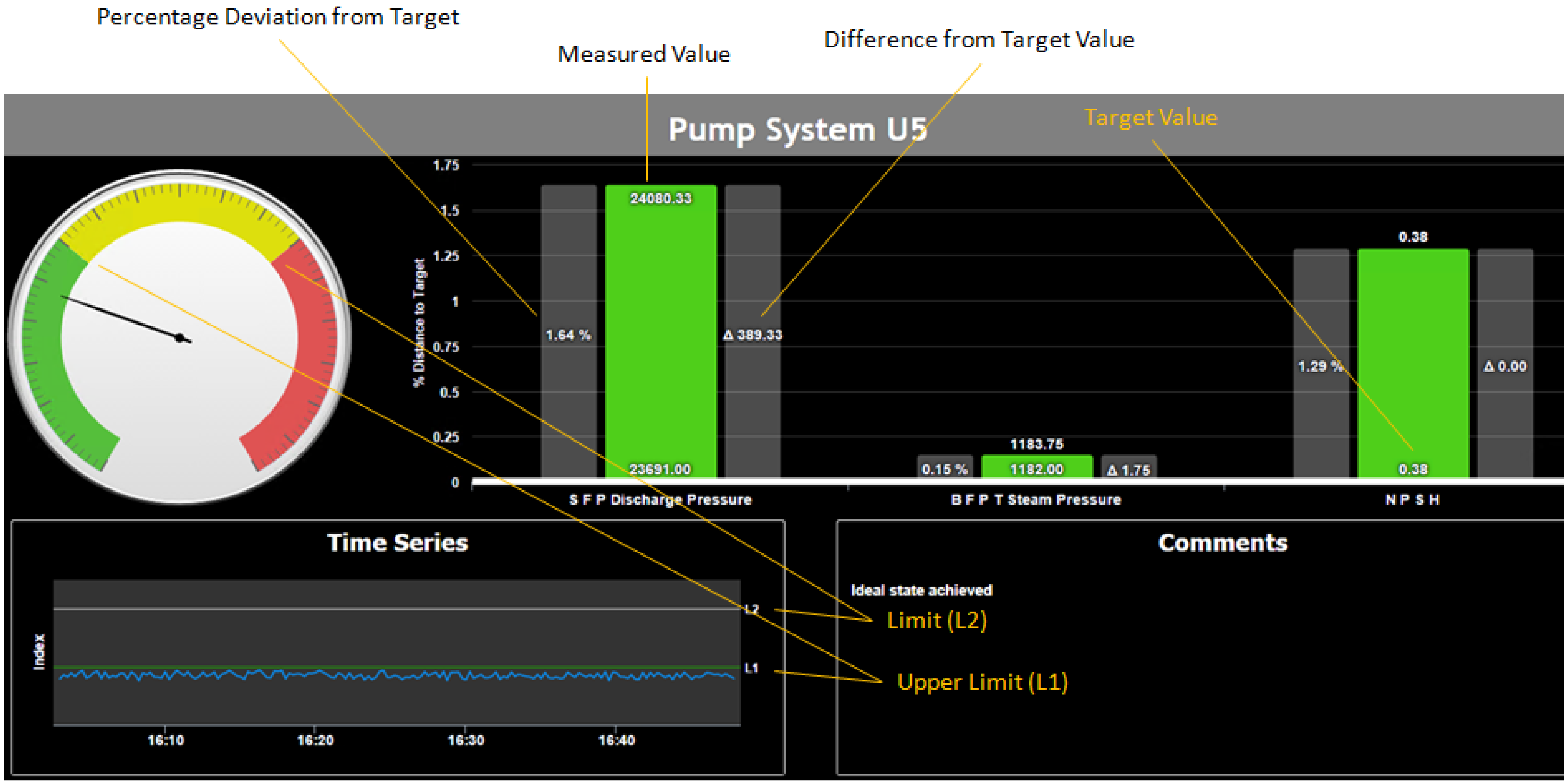
As stated previously, in a highly automated process such as the MMZ concentrator plant at Nkomati Mine, there is a multitude of parameters that can be evaluated by using the matrix method. However, it is the responsibility of the developer of the recipe to identify and isolate those parameters that have the most significant effect on the process performance, and include only these in the process recipe. It is also important to note that only process parameters that can be changed or manipulated by operators be included in the recipe – there would be little use in including parameters which plant personnel have no control over.

In addition, a histogram method can be used to determine an ideal operating *range*, as opposed to a single operating value. In the attached report in Appendix B, for example, after identification of the blocks of the various matrices where it is desired to operate, a histogram distribution of the parameters contained in each of the matrices is compiled, and the values that represent a significant proportion of the histogram distribution can be used to compile an operating range.

Once the ideal state conditions of the various parameters have been established, a reporting platform is developed to notify process personnel in real-time whether the various parameters of interest are within range. The interface of this platform can be modified to suit the needs of the process or the level of expertise of the individuals that will be using it.

An example of a generic real-time Time-in-State interface is given in Figure 29.

Figure 29: An example of a generic real-time Time-in-State interface



Ideal state achieved

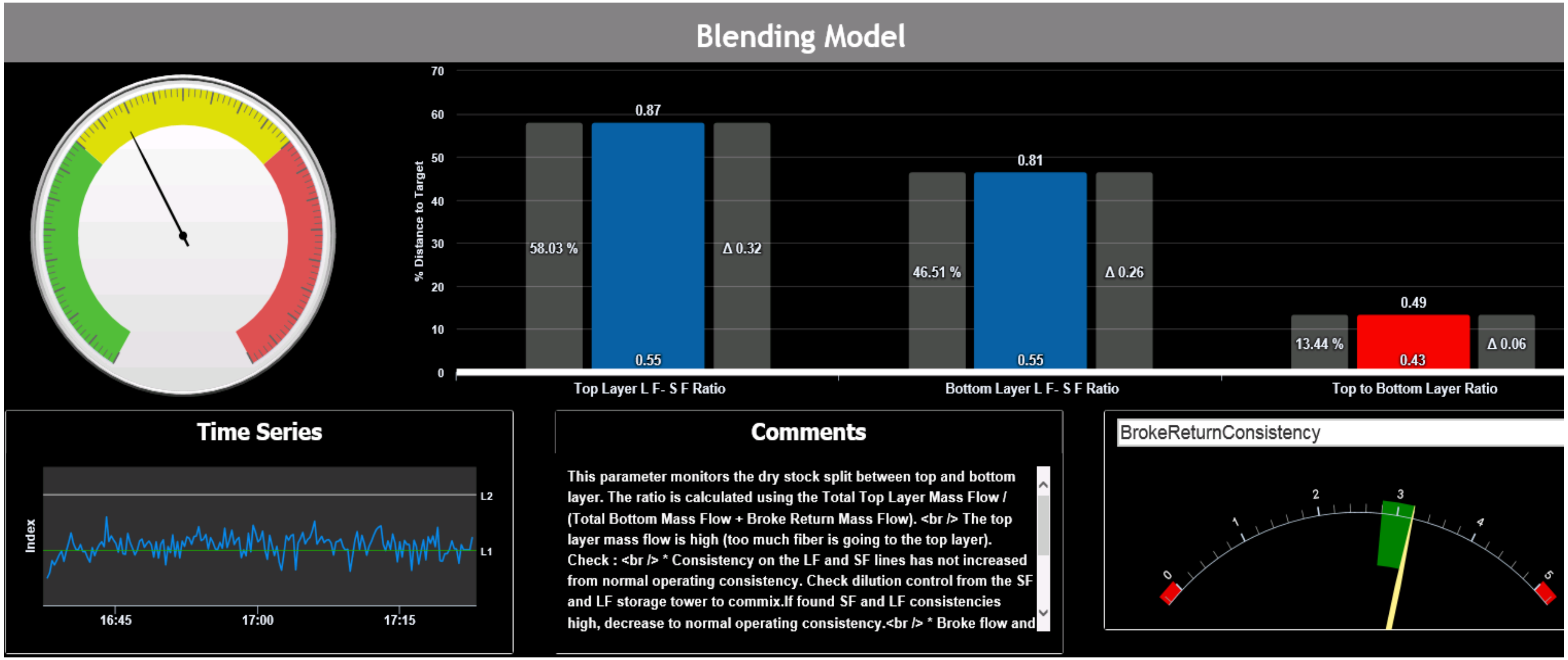
The three bar charts in the centre of the screen show the target value, the actual value and the percentage deviation and difference between these two values. The cumulative Time-in-State performance is illustrated with a dial on the left of the screen – if the system is in ideal state (i.e. all three measured parameters in the system are within optimal range), the dial will be green. If the system is not in ideal state, the needle of the dial will move outside the green portion and, depending on the degree of deviation from ideal state, move either into the yellow or red portions.

An example of a Time-in-State interface where the system is outside ideal operating conditions is given in Figure 30. Note that in this example, one of the bar charts have turned red. This means that that particular variable is outside ideal conditions and that the operator should focus on first on this variable. Each variables contribution is weighted to yield the performance indication on the overall performance dial.

In addition to indicating which variable in the section is not performing optimally, there is also a comments section which gives recommendations as to the suggested course of action to following that will result in the variable being brought back to ideal state conditions. These recommendations are setup prior to launching the TIS interface.

A short history of the TIS performance of the section is also given in the lower left corner of the interface screen. This will enable the operator to determine whether a particular course of action is improving or exacerbating the situation. Should the TIS performance of the system be improving, this will prevent the operator from making any further changes that might negatively affect the improving performance of the system.

Figure 30: An example of a Time-in-State interface when the system is operating outside ideal state



This parameter monitors the dry stock split between top and bottom layer. The ratio is calculated using the Total Top Layer Mass Flow / (Total Bottom Mass Flow + Broke Return Mass Flow).
 The top layer mass flow is high (too much fiber is going to the top layer). Check :
 * Consistency on the LF and SF lines has not increased from normal operating consistency. Check dilution control from the SF and LF storage tower to commix.If found SF and LF consistencies high, decrease to normal operating consistency.
 * Broke flow and

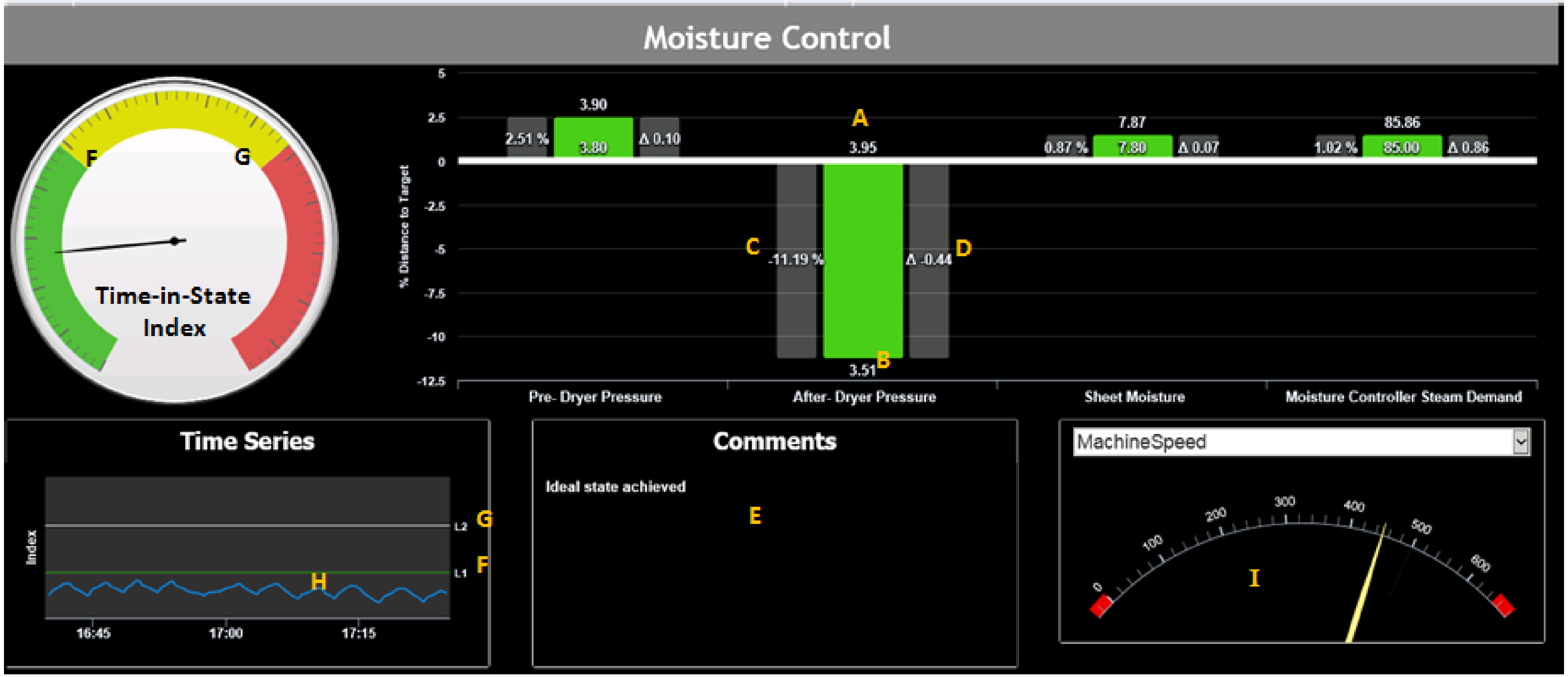
Another example of a TIS interface where the system has achieved ideal state is given in Figure 31. When the dial is operating within the green range the system matches the ideal state determined by the matrix analysis method. This ideal state represents the highest probability of realising highest efficiency and effectiveness.

It is essential that the TIS interface be designed to be user-friendly and simplistic. An overly complicated interface will not capture the attention of the operating staff as well as it should. In addition, it should be stated again that only parameters that operators have control over should be included on the TISM. This will enable the operating staff to materially affect the TIS performance of the operation and to not feel helpless when the system is outside ideal state.

Similarly, a TISM and interface can be developed for the optimal engineering parameters of the equipment in the process. The TIS interface that has been developed for Nkomati mine for some the critical pieces of equipment is given in Appendix D.

Figure 31: Detailed layout of the Time-in-State interface when the system has achieved ideal state

A	Target Value	**F**	Limit 1
B	Measured Value	**G**	Limit 2
C	% Distance from Target	**H**	Time-in-State Index trace
D	Difference from target	**I**	Additional parameter
E	Context sensitive information		



Ideal state achieved

6.4 Reporting on the Time-in-State Metric

There are two components of reporting on the TISM:

1. Reporting on the percentage of Time-in-State; and
2. Condition reporting.

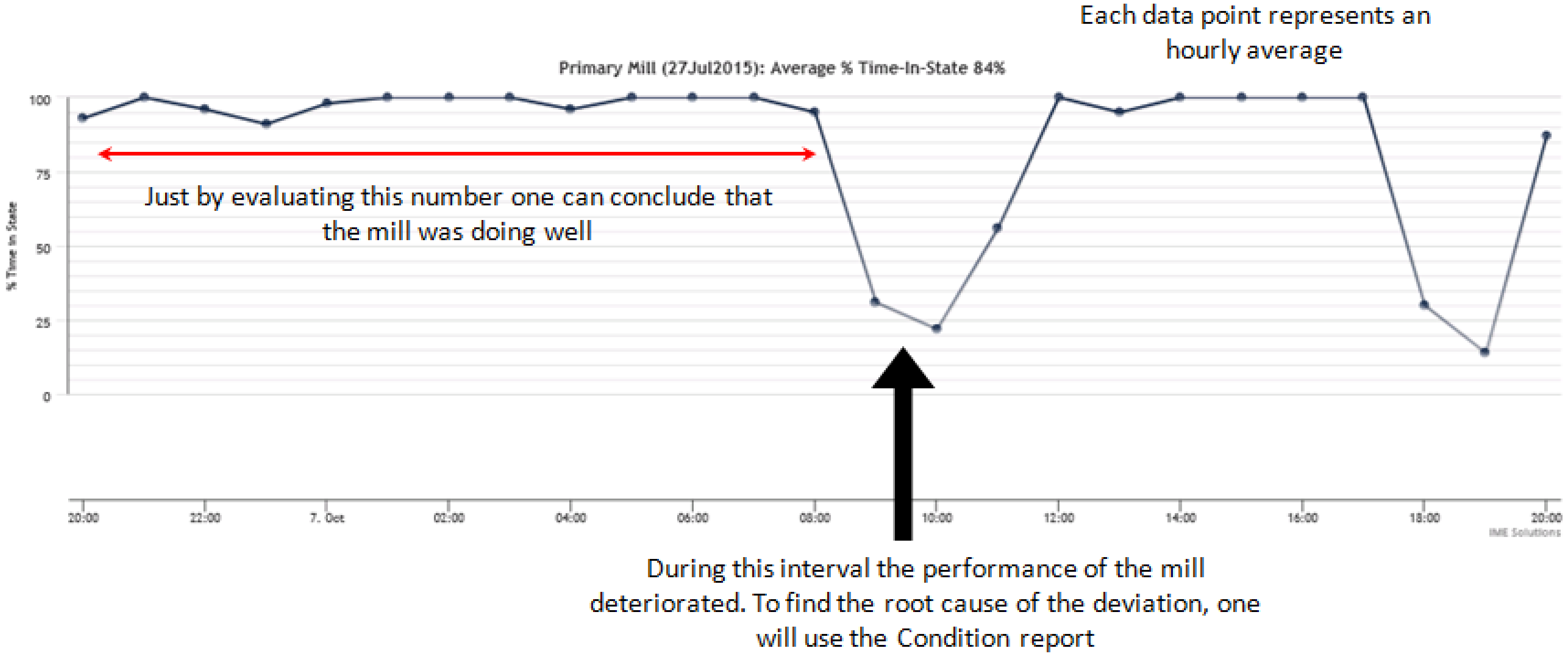
The percentage of TIS indicates the percentage of time that the selected unit operated within ideal state or optimum operating envelope – the higher the percentage of TIS value, the better. This value will be monitored over time to determine if the actions taken by the operating personnel are delivering the required improvement, i.e., and increased in the percentage of TIS. If the percentage TIS decreases, it implies that the performance of the unit is deteriorating.

The percentage of TIS correlates with Key Performance Indicators (KPI's) such as OEE, operating cost, maintenance cost, availability, reliability and stability. However, all of the latter are generated or reported retrospectively over a designated period, such as a month or a week. The TISM presents an overarching metric that delivers a method to manage the process and equipment pro-actively at systems level because the metric is generated in real time, is focused in key operating and equipment parameters, and generates a consistent response recommendation that aligns the operating philosophy of the operational personnel.

An example of a percentage TIS report is given in Figure 32. The graph was compiled for the Primary Mill in the MMZ plant. Each of the data points represents an hourly average of the performance of each of the individual parameters included in the determination of the TIS on the unit. It is clear that from 20:00 to approximately 08:00 the unit was operating in ideal state of within the optimum performance envelope. From 08:00 to 12:00 the unit did not operate within ideal state, but the situation was rectified and the unit was returned to ideal state.

In order to determine the root cause of the deviation from ideal state conditions, the condition report is extracted. The condition report gives a breakdown of all the critical parameters associated with a specific piece of equipment or process. For example the corresponding condition report for the percentage TIS graph given in Figure 32 is given in Figure 33.

Figure 32: Percentage of Time-in-State report generated for the Primary Mill over a 24 hour period

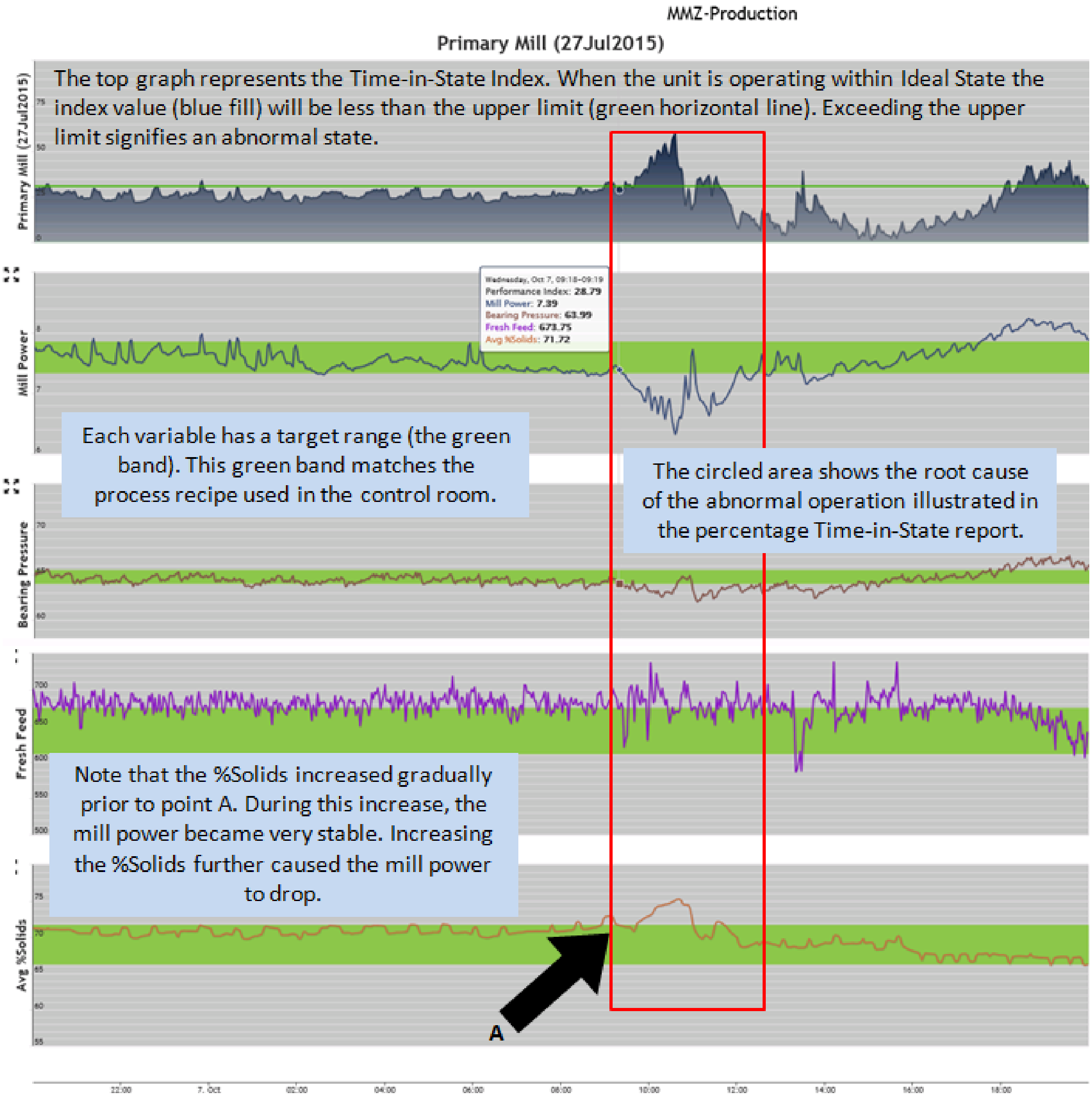


Each data point represents an hourly average

Just by evaluating this number one can conclude that the mill was doing well

During this interval the performance of the mill deteriorated. To find the root cause of the deviation, one will use the Condition report

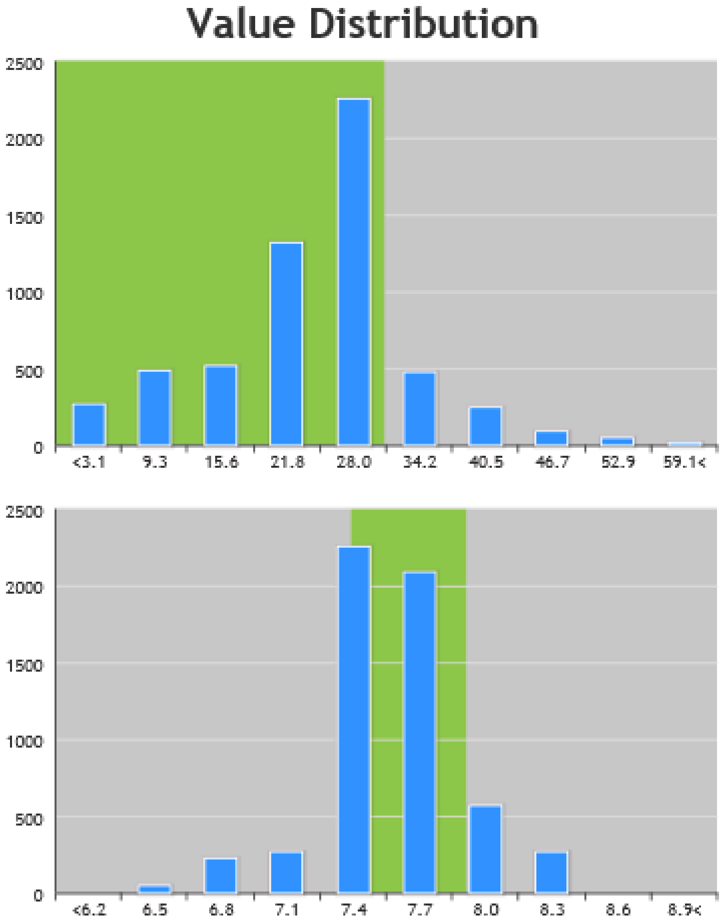
Figure 33: Condition report generated for the Primary Mill over a 24 hour period



The top graph in the condition report indicates the TIS performance of the process over a period of time – if the process unit operates within ideal state, the graph will lie below the green horizontal line. Exceeding the green line means the process has moved outside the optimum performance envelope. The four graphs below the TIS graph represent the performance of the parameters that make up the TIS performance index. For the primary mill, these four indicators are the mill power, the mill bearing pressure, the fresh feed rate and the average percentage solids inside the mill. For each of these variables, the target range is indicated by a green band that runs horizontally across the graph. The circled area shows the root cause of the abnormal operation illustrated in the percentage TIS report. From this it is clear that the percent solids inside the mill gradually increased over a period, until it went outside the optimal performance envelope, causing the mill power to drop significantly. As a result of this, the mill fresh feed became erratic and the bearing pressure also reduced marginally. This enables the operator to understand the reason for the poor performance experienced over the period highlighted in the percentage TIS report.

In addition to the graphs given in Figure 33, there are also histogram graphs supplied to the right of each performance indicator (see Figure 34). The green band again represents the target range for each variable. The blue bars represent the frequency distribution, i.e. the histogram aims to provide a high overview of the variable's value frequency distribution.

Figure 34: Histogram generated for a number of parameters in the condition report



In addition to the reports generated above, a number of reports can be set up according to the needs of the reader or to establish a focus on a particular process area. The period over which the report is generated can also be stipulated and customised. A number of useful reports have been compiled at Nkomati Mine and is incorporated into the daily reporting structure to facilitate discussion on certain performance shortcomings or improvements.

Some of the reports generated for the MMZ plant are:

1. *Engineering Reports*: a series of critical engineering parameters were compiled into a single engineering report. It contains information regarding the four mill motors (two motors on the FAG mill and two motors on the ball mill), such as lubrication temperatures, pressures and flows and well as grease temperatures and compressed air pressure. The period of the report is set on approximately ***7 days***, as mechanical degradation of a piece of equipment can occur over an extended period and a trend is required to visualise the steady drifting of the parameter;
2. *Manager's Summary Report*: contains a summary of the critical engineering and process parameters for the past ***24 hours***. Information such as total runtime and critical control parameters are included in the report. This gives a high-level summary of the operation for the past 24 hours. It also contains a number of pertinent comments on critical parameters;
3. *Foreman Reports*: a series of critical process parameters are included into the Foreman Report. It is generated on a shiftly basis (i.e. ***12 hours***) and includes the data gathered over the period that the production foreman was on shift. This enables a discussion to be had on the performance of the plant over the period and the foreman is expected to give feedback on the actions taken where the process deviated from ideal state;
4. *Recovery Report*: seeing that recovery is a major performance measure for the operation, an entire report is dedicated to tracking the recovery of the process over time. Seeing that recovery can fluctuate over a number of days depending on the nature of the ore being fed to the plant and the setup of the process, it is useful to compile the report over a period of **7 days**. It is a very basic report spread over one page;
5. *Rougher and Scavenger Report*: this report is focused on delivering the information regarding the rougher and scavenger cells in the flotation circuit. It is generated on a shiftly basis and spans a period of ***12 hours***. It contains information such as the flotation cell levels and air flow addition, and the control responses generated for each of these. Also, the critical flowrates of streams in the flotation circuit and the reagent additions; and
6. *Cleaner and Re-Cleaner Report*: similar to the Rougher and Scavenger Report, this report is generated for a ***12 hour*** period and contains critical information regarding the cleaner and re-cleaner flotation cells.

In order to gain the full benefit from the TISM, all of the abovementioned tools must be implemented. Free flow of information is essential to guarantee the success of the TISM. The primary component is the real-time TIS tool that guides the process personnel to make the right decisions and to maintain the process in the optimum operating envelope. The TIS reporting tool will assist in determining whether the process condition is improving or deteriorating. And finally, the detailed reporting tools will give an overall view of the process and prompt corrective steps where required. An efficient root cause analysis (RCA) tool must be combined with this to ensure that issues encountered over a period does not recur but is rather engineered out completely. This will ultimately lead to improvements in both process and asset performance.

6.5 Implementation of the Time-in-State Metric

Adoption of the TIMS is strongly dependent on the human element. Plant operators develop mental models over time, and decision making is executed with the backdrop of unique experience. This creates a problem, whereby the processing plants are operated in different ways, based on the experience of the operating personnel on the floor. This induces unpredictability and instability, which is detrimental to the continuous operation of the plant. Successful implementation of the TISM requires that these metal models be unlearnt and that trust be instilled in the value of the TISM. Senge (1997) was the first to acknowledge that the “basic obstacle to the success of a business in an era of constant change and intensifying competition is its reluctance or inability to learn”. By utilising Senge’s five disciplines of a learning organization (Senge, 1997), the TISM can be successfully implemented and institutionalised in the operation. The Five Disciplines are (Yeo, 2005):

1.) Team learning – group dynamics;
2.) Personal mastery – willingness to learn new skills;
3.) Systems thinking – big picture of the business operations;
4.) Mental models – Influencing others with independent thinking; and
5.) Shared vision – shared energy.

Each of these will be dealt with separately in the context of the case study:

6.5.1 Team Learning

The process of implementation of the TISM was done with the production team as a whole. This eliminated a lot of the resistance one would get from isolating a specific group and testing the viability of the system in a trial basis. The implementation of the TISM was given as a non-negotiable as it was evident that the system would result in a financial return. This team dynamic, with some healthy competition included, resulted in the successful implementation of the TISM.

6.5.2 Personal Mastery

The TIS interface and the various reporting tools associated with it have to be sufficiently simplistic to allow for personal mastery. Once mastered, the system will be embedded in the operating procedure of the process personnel. In addition, an extensive training campaign was required to ensure the TIS interface is sufficiently understood and all the associated tools can be accessed and utilised.

6.5.3 Systems Thinking

It was essential that the overall impact of the successful implementation of the TISM will have on the overall success of the business. The percentage of TIS correlates with KPI's such as OEE, operating cost, maintenance cost, availability, reliability and stability. This will have a direct impact on the bottom-line of the organization. This impact has to be clearly articulated in order for the relevant personnel to understand what impact the implementation of the TISM will have on the overall business picture.

6.5.4 Metal Models

As stated previously, each process operator brings their own level of experience and metal models to the way they operate the plant. Very often these metal models are not aligned amongst different operating personnel. In order to align these metal models, the TISM gives recommendations as to how to correct the performance of the operation if it deviates from ideal state and in the process aligns the different mental models of operating personnel.

6.5.5 Shared Vision

Successful implementation of the TISM requires the clear articulation of the ultimate goal and the active involvement of role players to create a culture of a shared vision. This will result in a shared energy that will positively impact the execution process.

Senge's principles are by no means unique to the mining industry – they are applicable to any learning organization. Hence, it can be deduced that the TISM can be successfully implemented in any capital intensive industry, should the abovementioned principles be incorporated in the execution process.

7. Results

7.1 Asset Performance Results

As stated in Section 3.1.1.8, the major objectives of an organization can be categorized into four main groups (Latino, Latino, & Latino, 2011):

1. Corporate;
2. Assets;
3. Work practices; and
4. Knowledge and experience.

Within the asset perspective, following is a list of typical perspectives and objectives that are related to the management of assets:

- Minimize Unscheduled Equipment Downtime;
- Improve System Availability;
- Reduce Scheduled Maintenance Downtime;
- Reduce Unscheduled Repairs;
- Reduce Non-Equipment Related Downtime; and
- Reduce Equipment Failure Time.

In addition to the abovementioned, an effective asset management strategy will also impact the following asset performance measures:

- Asset availability;
- Asset utilization;
- Asset Reliability;
- Overall equipment effectiveness (OEE);
- Mean-Time-Between-Failures (MTBF);
- Mean-Time-To-Restore (MTTR); and
- Number of Failure Events.

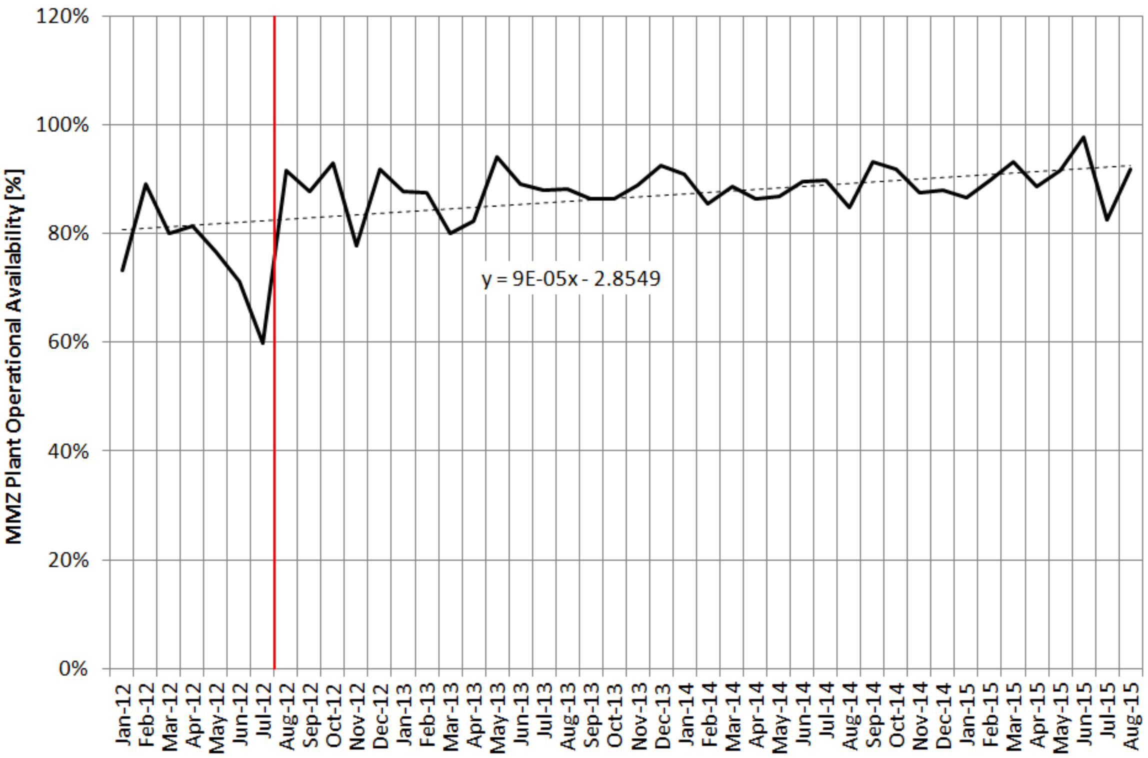
The TISM was first implemented at Nkomati Mine in August 2012. It has undergone a number of iterations (full and partial) since then, but some version of the TISM has been available since August 2012. The change, if any, in asset performance since then will be evaluated.

7.1.1 Asset Availability

The progressive change in asset availability is given in Figure 35. Please note that the reported parameter is the Operational Availability, which includes downtime attributable to:

- Engineering breakdowns (electrical, instrumentation and mechanical);
- Planned maintenance;
- Eskom power failure and shortages;
- Ore shortages;
- Over-size material; and
- Miscellaneous.

Figure 35: Graph of progressive change in Operational Availability



The linear regression performed on the data resulted in a line with a positive slope. This means that there was an increasing and positive impact on Operational Availability over time.

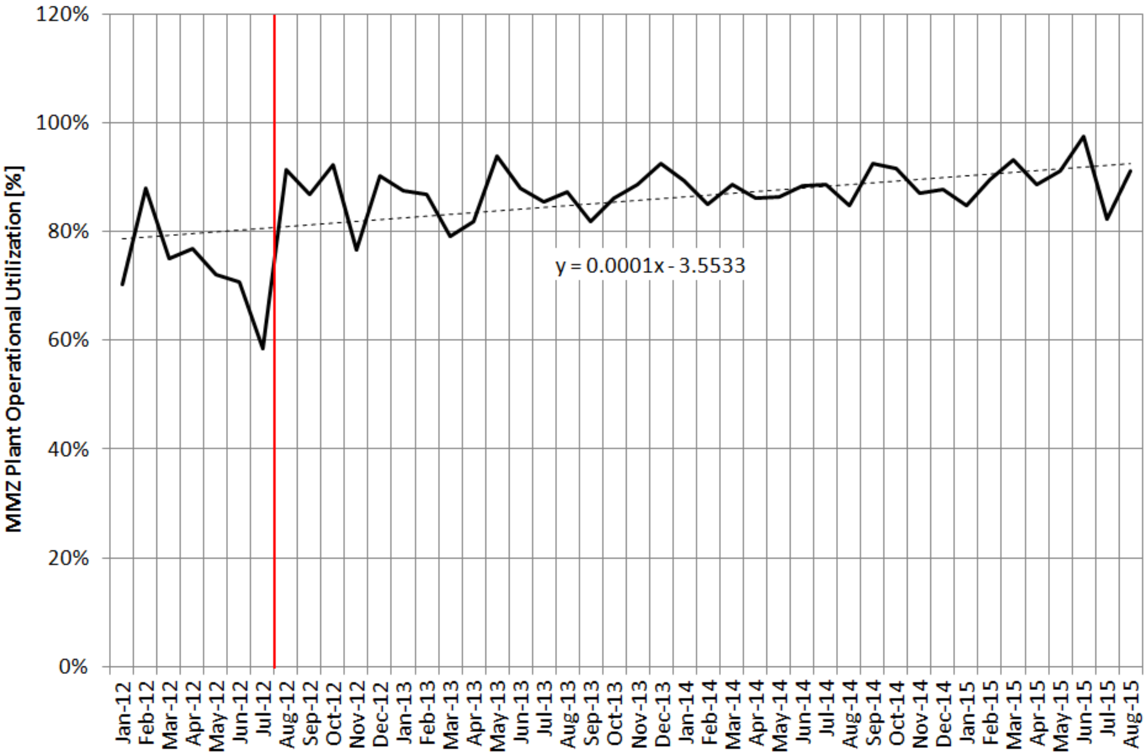
7.1.2 Asset Utilization

Adding the following downtimes to the calculation results in Operational Utilization:

- Operational Downtime;
- Chokes; and
- Full silos.

The progressive change in Operational Utilization is given in Figure 36.

Figure 36: Graph of progressive change in Operational Utilization

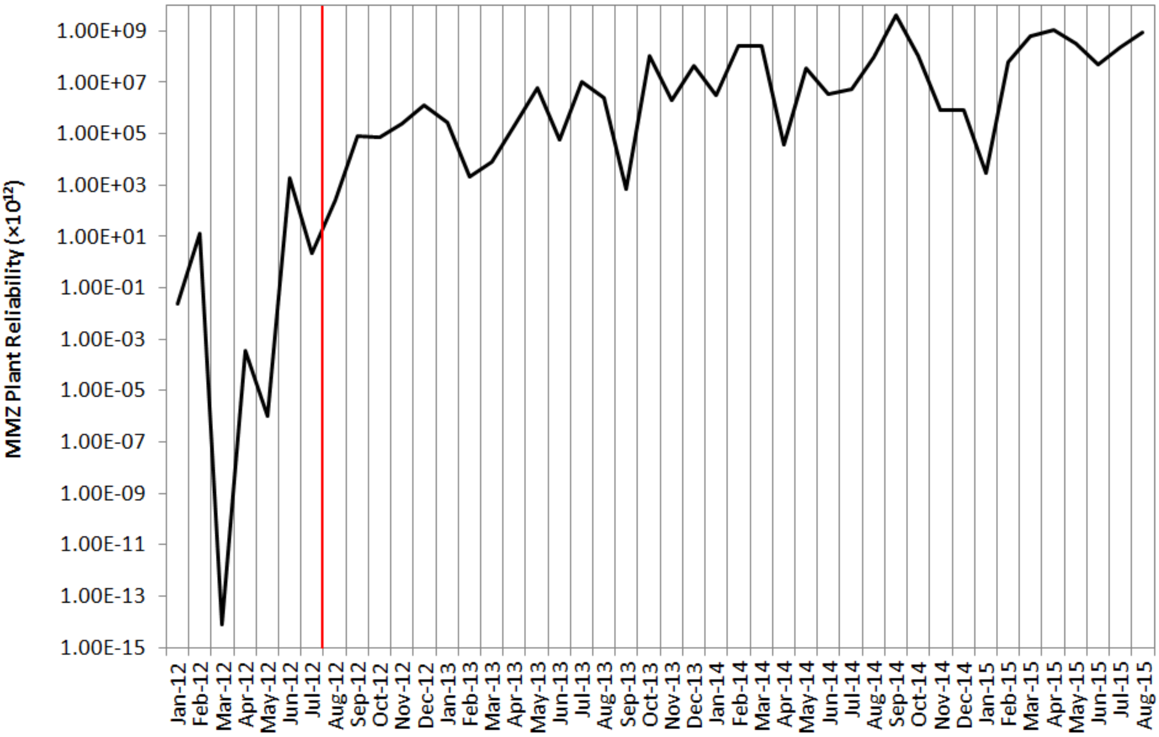


Again, the positive slope of the regression analysis performed on the data shows that there was a progressive improvement in the Operational Utilization over time.

7.1.3 Asset Reliability

The progressive change in asset reliability is given in Figure 37. In order to allow for more manageable numbers and improved visualization the asset reliability was multiplied with 10^{12} and the plot drawn on the logarithmic scale. Again, an increase in asset reliability is observed since implementation.

Figure 37: Graph of progressive change in Asset Reliability

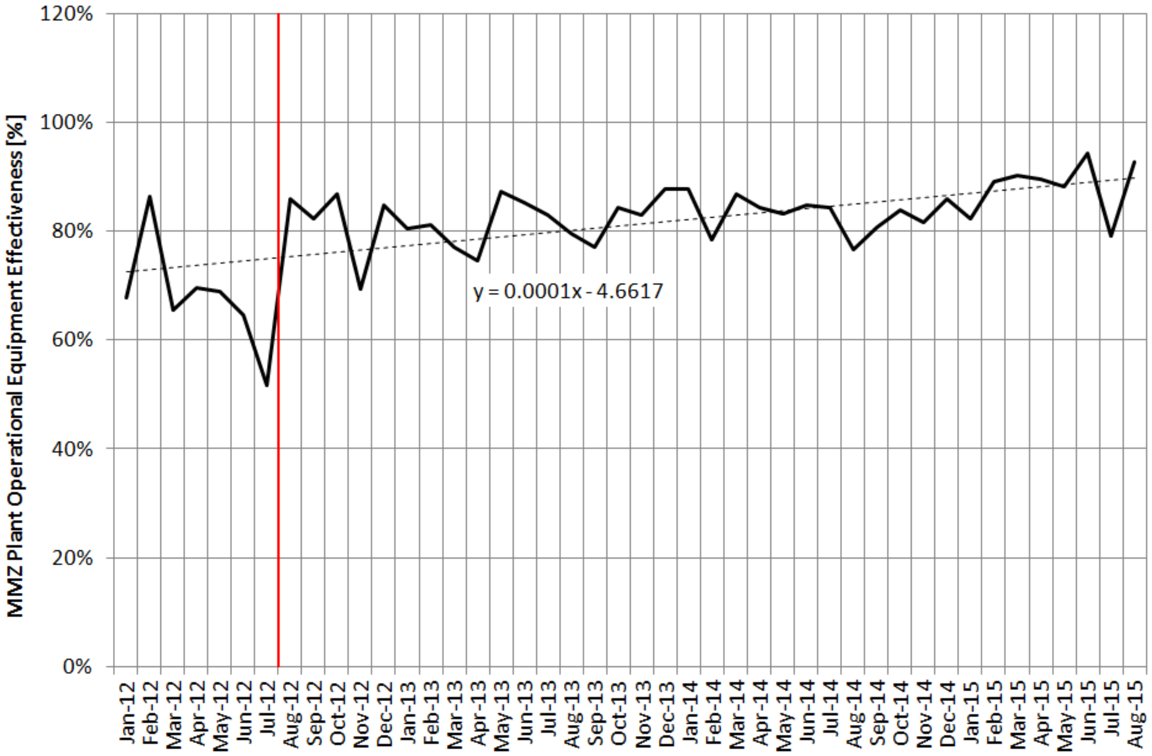


7.1.4 Operational Equipment Effectiveness (OEE)

The progressive change in OEE is given in Figure 38. Again, the linear regression performed on the data yields a line with a positive slope, which indicates that there was a progressive increase in the OEE over time. This positively establishes the correlation between implementation of the TISM and the improvement in the OEE of the operation. This is significant as the TISM is based on real-time reporting whilst the OEE is reported over a fixed period, for example a month.

The implementation of the TISM has been proven to be successful at improving the primary asset performance parameters (availability, utilization, reliability and OEE). The effect on the secondary asset performance parameters (duration of failure, time between failures and number of failures) will now be explored.

Figure 38: Graph of progressive change in Overall Equipment Effectiveness (OEE)



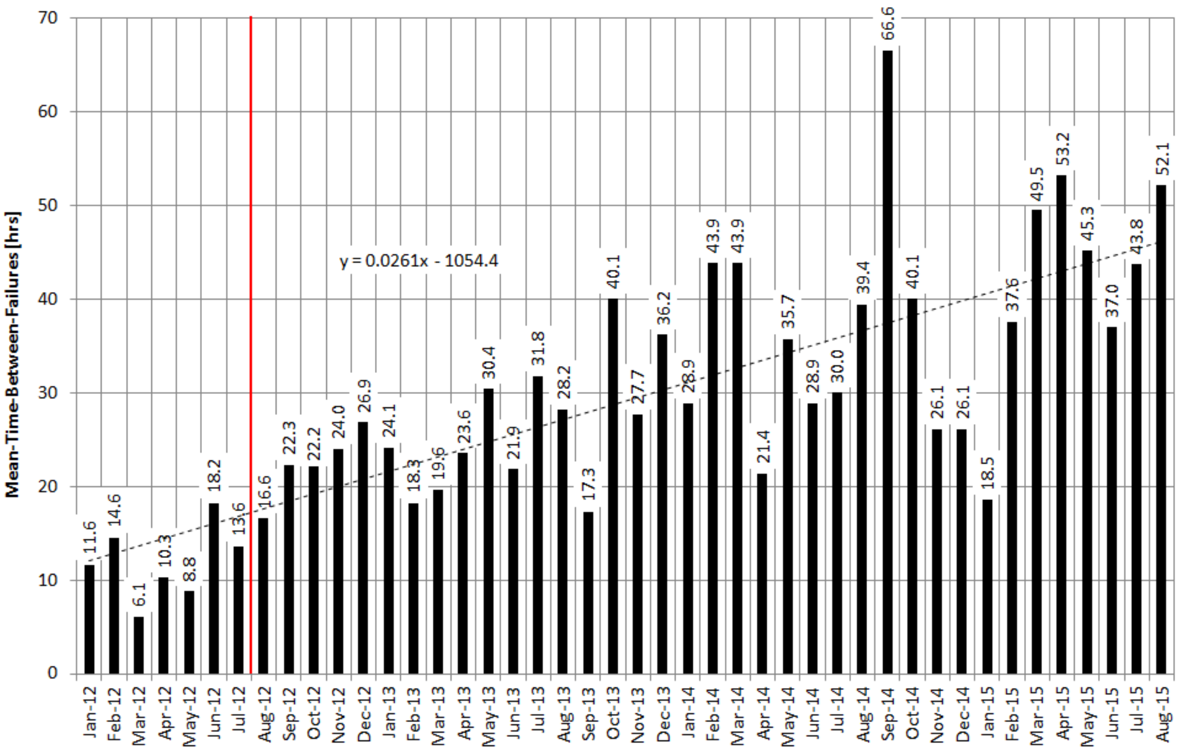
7.1.5 Mean-Time-Between-Failures (MTBF)

The progressive change in MTBF is given in Figure 39. As was the case with the previous asset performance parameters, the MTBF rate showed a significant improvement over the period from August 2012 to August 2015.

There still existed a number of months where the MTBF rate was as low as it was prior to the implementation of the TISM (such as January 2015), but on average the rate improved, as is evident from the positive slope obtained for the linear regression performed on the data.

The highest MTBF rate was achieved in September 2014 where the plant ran for an average of 66.6 hours between stoppages.

Figure 39: Graph of progressive change in Mean-Time-Between Failures (MTBF)

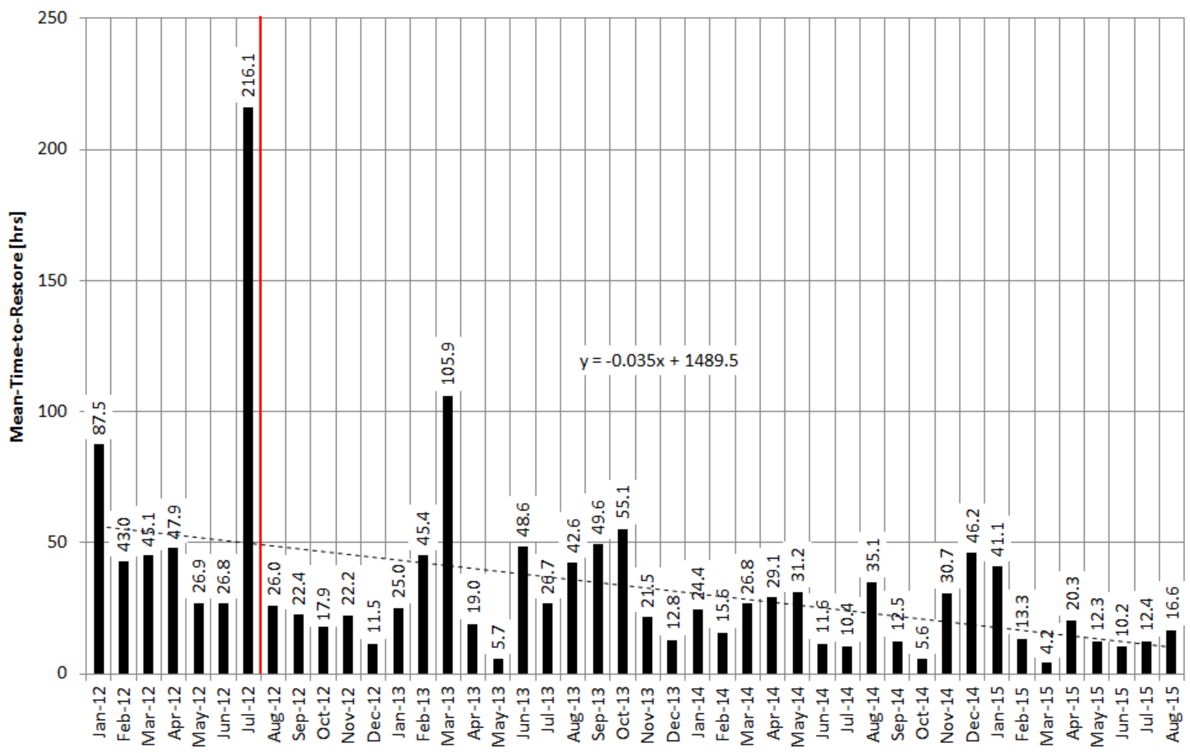


7.1.6 Mean-Time-to-Restore (MTTR)

The progressive change in MTTR is given in Figure 40. The negative slope obtained from the linear regression analysis indicates that there was a reduction in the MTTR rate, which means that the metric was improving.

However, the improvement in the MTTR rate seems to have reached a plateau from December 2013 onwards. The highest MTTR rate was incurred in January 2012, where it took approximately 216.1 hours to restore the process to operation following a stoppage. The lowest MTTR rate was achieved in March 2015 where it took 4.2 hours to restore the plat to an operational state following a production delay.

Figure 40: Graph of progressive change in Mean-Time-to-Restore (MTTR)

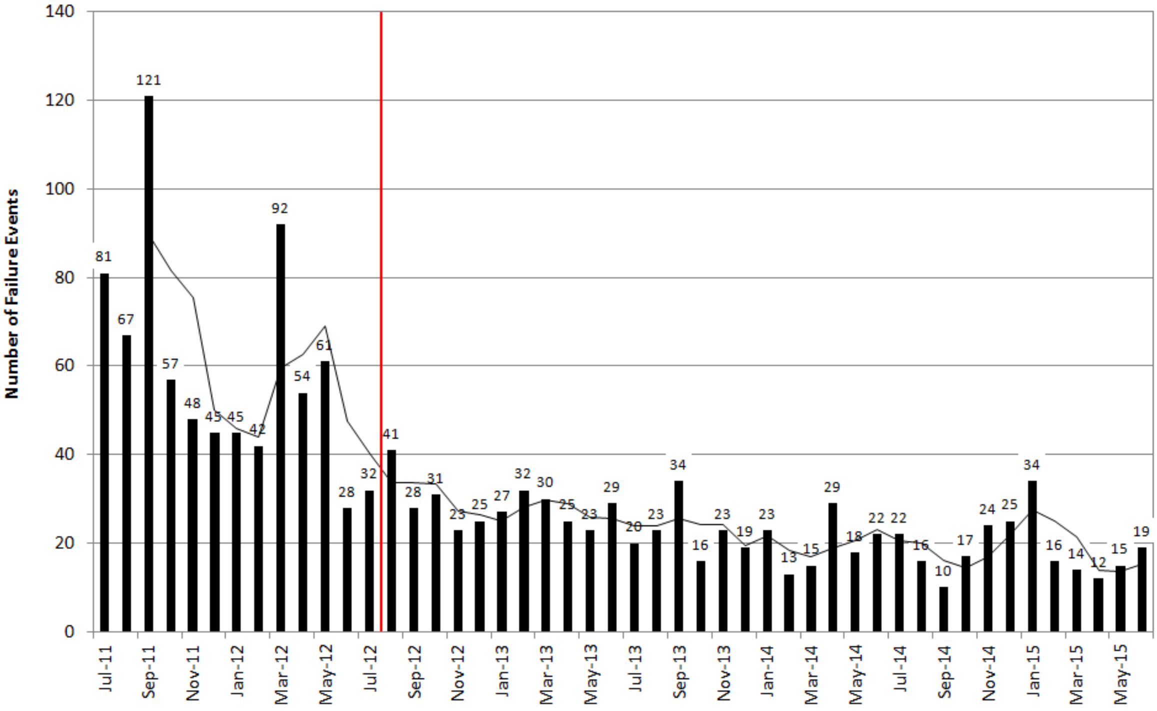


7.1.7 Number of Failure Events

Finally, the change in the number of failure events over time is given in Figure 41. There was a dramatic decrease in the number of failure events experienced over the period under investigation. The highest number of failure events occurred in September 2012, with a total of 121 failure events. The lowest number of failure events occurred in September 2014, with 10 failure events.

Persistent stopping and starting of the process has a detrimental effect on both the equipment in the process and the performance of the process itself. A reduction in the number of failure events will have a significant impact on the maintenance cost associated with the plant and the improved process performance will positively impact the bottom-line of the organization.

Figure 41: Graph of progressive change in Number of Failure Events



7.2 Process Performance Results

7.2.1 Instantaneous Effect of TISM on Process Performance

The instantaneous effect of the TISM implementation was determined by evaluating the performance of the process before and after the implementation. A refinement of the TISM was conducted on the 12th of June 2015. The data before the implementation of the refined recipe was evaluated from the 1st of June 2015. The process performance after the implementation of the refined recipe evaluated data until the 29th of June 2015.

A summary of the change in process performance is as follows:

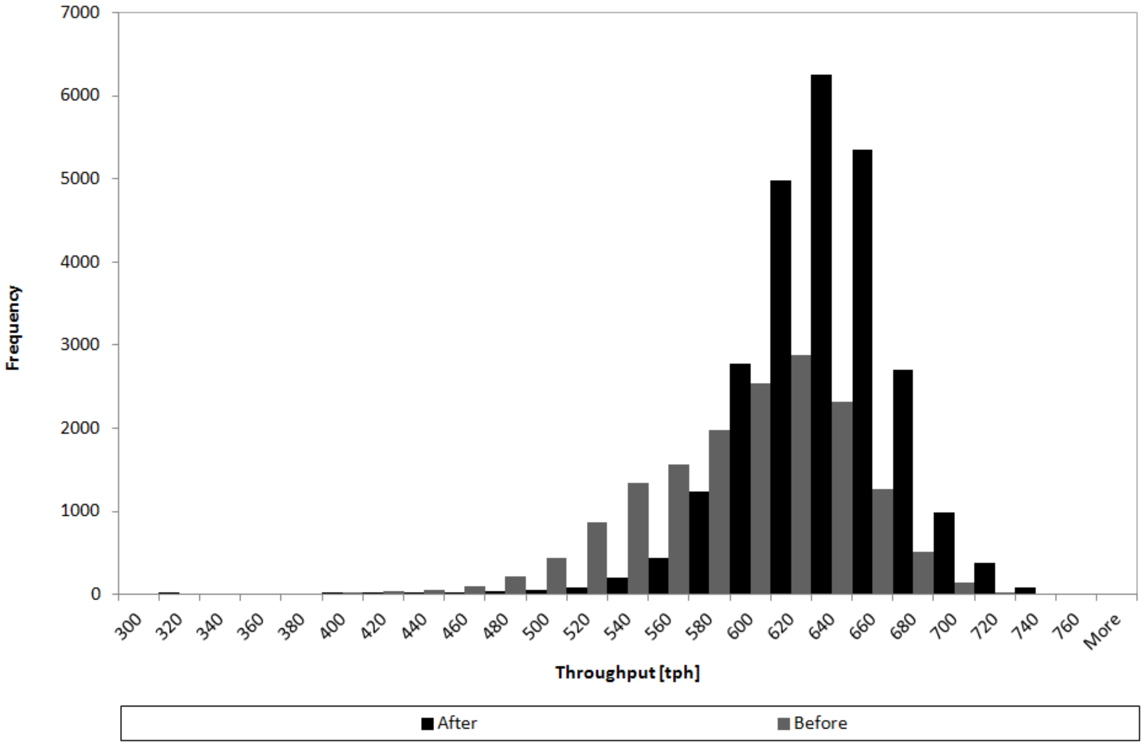
1. Flotation feed grade before the implementation of the revised metric was 0.47% nickel. After the implementation, the head grade reduced to 0.41%;
2. Before the implementation of the revised metric the rougher and overall recoveries were 78.3% and 75.1%, respectively. According to laboratory data, the expected rougher and overall recoveries are 79.3% and 75.7%. Hence, the anticipated recoveries were not met by 1.1% and 0.6% for the rougher and overall recoveries respectively. After the implementation

of the revised metric the rougher and overall recoveries were 77.2% and 73.7%, respectively. The expected rougher and overall recoveries were 76.3% and 72.7%, respectively, which means that expected recovery was exceeded by 0.9% and 1.0%, respectively;

3. The fresh feedrate into the mill before the implementation was 585 tph. After the implementation, the throughput increased to 626 tph;
4. From the above it can be calculated that, relative to the baseline or the norm, the implementation of the revised metric resulted in an increase in annual nickel production of 369 tons. Assuming a nickel price of USD 10 000, this results in an annual increase in revenue of USD 3 688 185.

A histogram of feedrate into the mill before and after the implementation of the revised TISM is given below (see Figure 42). It is clear that the frequency distribution is skewed significantly more towards the positive end following the implementation. As a result of this, the average feedrate into the mill increased from 585 tph to 626 tph, as stated above.

Figure 42: Histogram plot of the feedrate distribution before and after the implementation of the revised TISM



From the above evaluation it is clear that the implementation of the revised metric has a positive impact on the throughput and recovery performance of the plant, which will positively impact the bottom-line of the organization.

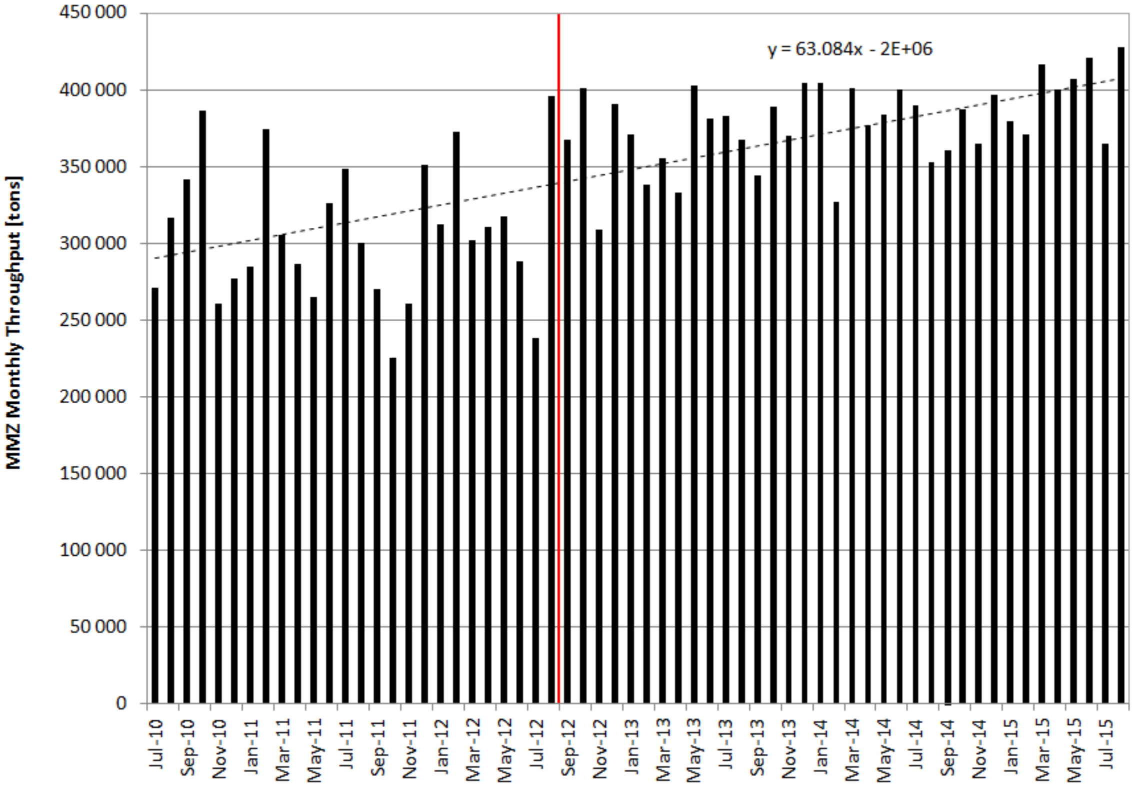
7.2.2 Long-Term Effect of TISM on Process Performance

In addition to seeing an instantaneous improvement in process performance, the implementation of the TISM has also had a significant long-term impact on the process. An evaluation of the major performance criteria over time was done.

7.2.2.1 Throughput

The progressive improvement in the throughput, since the implementation of the TISM in August 2012 and the various iterations since, is evident from Figure 43.

Figure 43: Progressive change in the throughput into the process over time

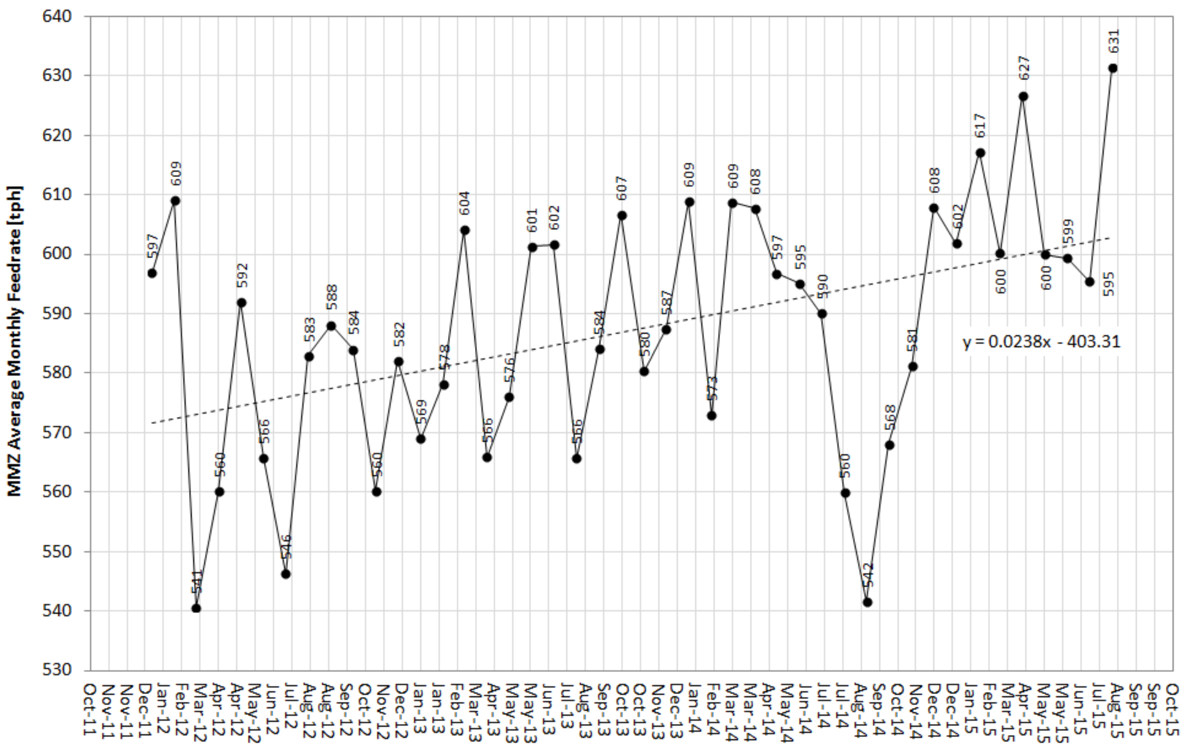


The linear regression analysis performed on the data had a significant positive slope, which means that there was a substantial improvement in the throughput achieved from the process over time. Again, the impact of this improvement will be reflected directly on the bottom-line of the organization.

7.2.2.2 Feedrate

The progressive movement in the monthly average feedrate into the process is given in Figure 44. Again there was a significant improvement in the feedrate into the plant over time. There was a period between June 2014 and December 2014 where there was a noticeable drop in the feedrate, but following further investigation is was determined to be correlated with low stockpile situation that were caused be a lack of ore availability from the open pit. Since then there has been a consistent improvement in the feedrate into the process.

Figure 44: Progressive change in the feedrate into the process over time

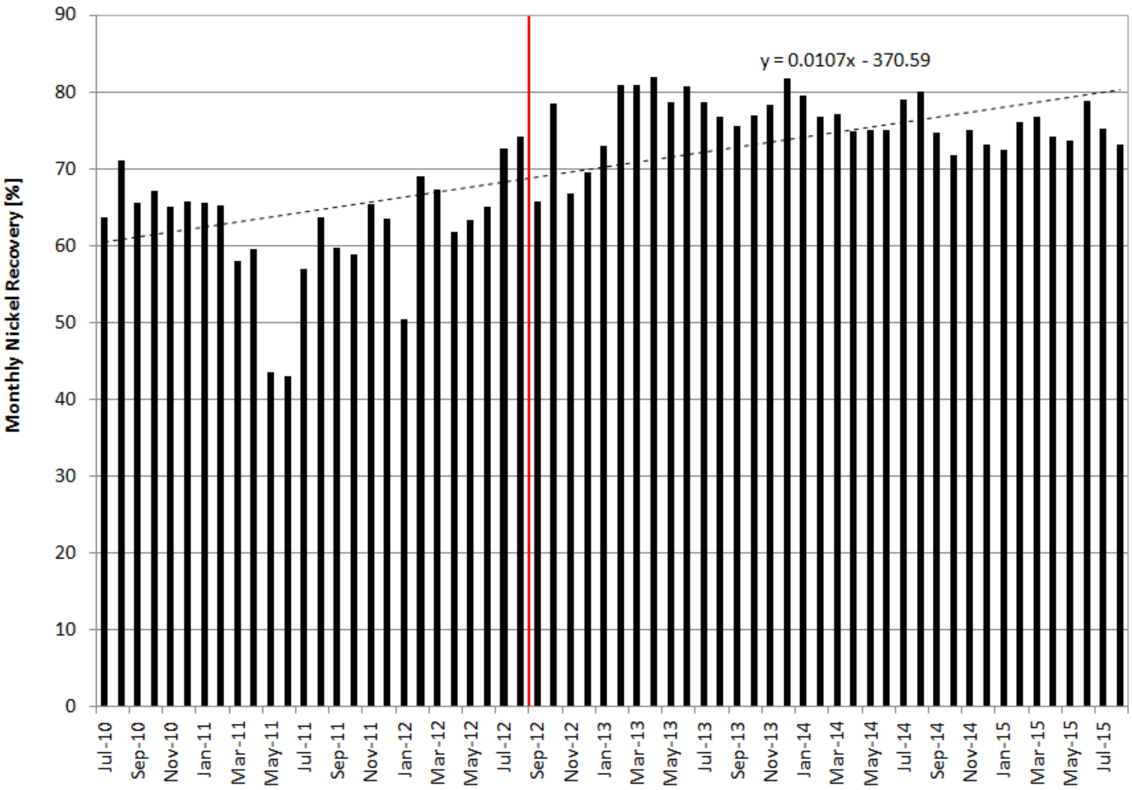


This improved feedrate, coupled with improved availability and utilization has resulted in the improved throughput for the process, which is evident in Figure 43.

7.2.2.3 Recovery

The progressive change in the nickel recovery obtained from the process is given in Figure 45. As previously, there has been a consistent improvement in the nickel recovery over time.

Figure 45: Progressive change in the feedrate into the process over time

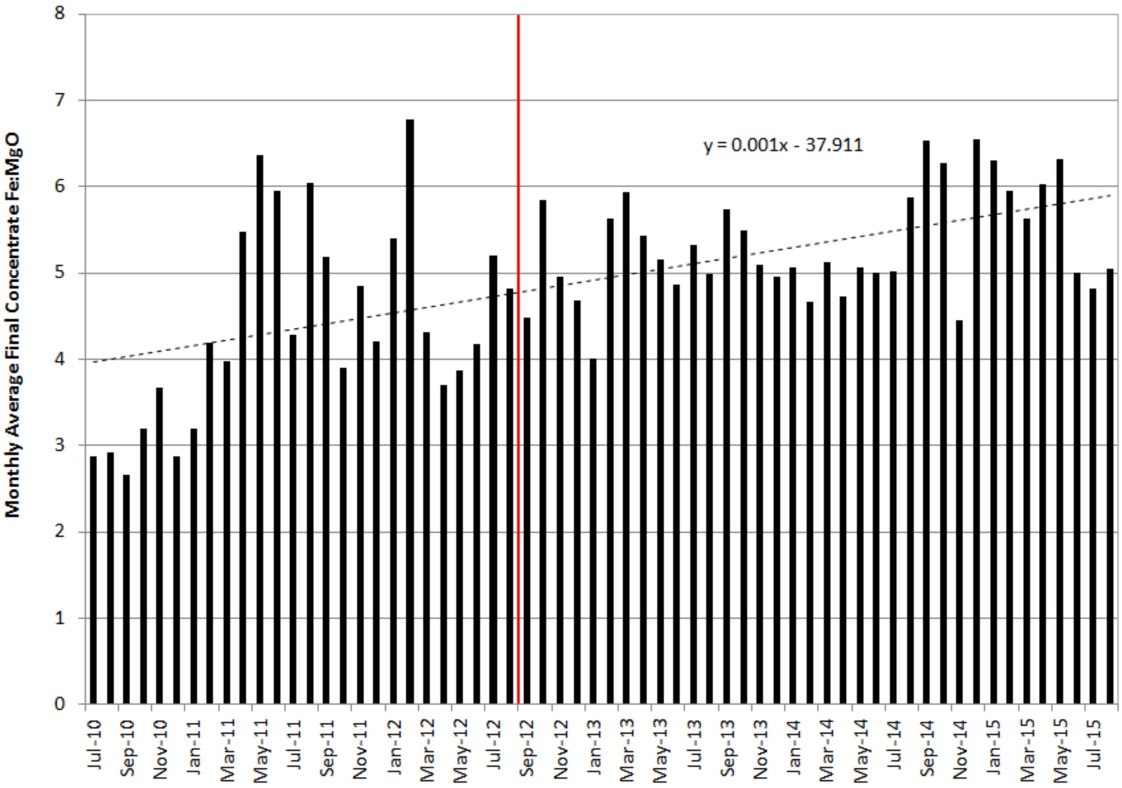


It is also clear that the recovery performance has reached a plateau since January 2013, and that there has not been a significant step-change in recovery performance since then. In this case, the aim is to retain the current performance and not allow to operational personnel to become complacent in monitoring the TISM.

7.2.2.4 Final Concentrate Fe:MgO

The progressive change in the final concentrate Fe:MgO grade is given in Figure 46. Again, the linear regression analysis resulted in a positive slope, which means that there was a progressive improvement in the Fe:MgO over time.

Figure 46: Progressive change in the feedrate into the process over time



8. Discussion of Results

The discussion of the results will be conducted with each of the propositions in mind:

> ***Proposition 1***: The TISM can be effectively employed to address operational risks associated with the *process* of a mining operation.

As was showed in the results section, all of the primary and secondary asset performance indicators improved over time following the implementation of the TISM. Hence, it can be stated that Proposition 1 has been proven to be correct.

> ***Proposition 2***: The TISM can be effectively employed to address the operational risks associated with the *assets* of a mining operation.

As was showed in the results section, all of the process performance indicators improved over time following the implementation of the TISM. Hence, it can be stated that Proposition 2 has been proven to be correct.

> ***Proposition 3***: Following the implementation of the TISM, the progressive improvement and refinement of the TIMS leads to the progressive improvement in asset and process performance, until a plateau is reached.

As was shown in the results section, the performance indicators improved progressively as the TISM was refined over successive iterations. Some of the metrics, most notably the recovery of the process, reached a plateau and did not show any further improvements. Hence, it can be stated that Proposition 3 has been proved to be accurate.

> ***Proposition 4***: The TISM can be employed in other capital intensive industries with similar benefits.

The process of developing and implementation of the TISM utilised equipment and process data. Should this information be available from other capital intensive industries, the TISM can be developed. Since implementation at Nkomati Mine, the TISM has also been rolled out at an Omnia operation, with similar success. Eskom has also indicated interest in the metric. Hence, it can be stated that the TISM can be applied to other capital intensive industries.

> **Proposition 5**: Human behavioural aspects can be utilised to successfully implement the TISM in an organization.

The TISM was implemented at Nkomati Mine, and the Senge's rules of a learning organization were leveraged to ensure successful uptake. As discussed previously, human behavioural aspects had to be considered in the implementation process to ensure previous mental models are eradicated and a new process is accepted. Thus, Proposition 5 has been conclusively proven in the implementation of the TISM at Nkomati Mine.

9. CONCLUSIONS

This study has described a methodology to mitigate operational risks through the evaluation of the effectiveness of the TISM in supplying timely and relevant information to responsible personnel to enable predictive decision making. This has become a pertinent and relevant topic due to the need for organizations to remain profitable, sustainable and competitive in a dynamic global environment. The management system has been successfully implemented at Nkomati Mine and operational risk has been mitigated as a result.

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APPENDICES

Appendix A

Approval obtained from Nkomati Mine to utilise asset and process data

NKOMATI

NKOMATI JOINT VENTURE

A PARTNERSHIP BETWEEN AFRICAN RAINBOW MINERALS LIMITED AND NORILSK NICKEL AFRICA (PTY) LIMITED
PO Box 562, Machadodorp, 1170
Staalhoek Farm 540JT, Waterval Boven District
Phone: +27 13 712 8200, Fax: +27 13 712 8300
VAT Registration number: 4820229436

To whom it may concern,

Approval is hereby given to use the asset and process data from Nkomati MMZ concentrator plant for the purpose of a research study conducted by Stephan van Zyl, MBA student at GIBS.

The data will include, but is not limited to, asset availability and utilization data, overall equipment efficiency, and related asset performance data as well as process data, which includes throughput, recovery, and concentrate grade data.

The data can only be used for the purpose of the study and the name of the organization of origin, Nkomati Mine, can be revealed.

Regards,

Manie Potgieter
HOD: CP

AFRICAN RAINBOW MINERALS LIMITED
Registration No: 1933/004580/06
Directors: PT Motsepe (Executive Chairman), MP Schmidt (Chief Executive Officer), F Abbott**, M Arnold, Dr MMM Bakane-Tuoane**, TA Boardman**, AD Botha**, JA Chissano (Mozambican)**, WM Gule*, AK Maditsi**, HL Mkatshana, Dr RV Simelane**, ZB Swanepoel**, AJ Wilkens

(*Non-executive, **independent non-executive)

Company secretary: AN D'Oyley (Canadian)

NORILSK NICKEL AFRICA (PTY) LIMITED
Registration No: 2004/020841/07
Directors: MP Marriott (Australian), DE Fulling (Irish), OV Lafitsky (Russian), BI Kuzhel (Russian)

Last Revision: 30 April 2015

Appendix B

Process recipe re-evaluation report conducted on 28 April 2014

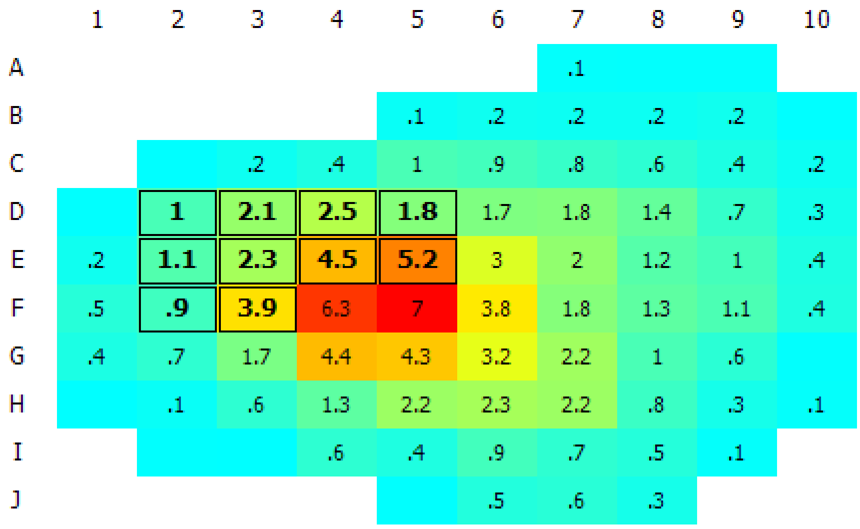
Confirmation of Process Recipe

28 April 2014

Performance Map Comments

- The performance map was constructed from data for the operating interval 20 Feb to 15 Apr 2014. These performance maps exclude all intervals where the primary mill power was less than 6MW and where the feed rate to the mill was interrupted.

The Density Distribution



	1	2	3	4	5	6	7	8	9	10
A							.1			
B					.1	.2	.2	.2	.2	
C			.2	.4	1	.9	.8	.6	.4	.2
D		**1**	**2.1**	**2.5**	**1.8**	1.7	1.8	1.4	.7	.3
E	.2	**1.1**	**2.3**	**4.5**	**5.2**	3	2	1.2	1	.4
F	.5	**.9**	**3.9**	6.3	7	3.8	1.8	1.3	1.1	.4
G	.4	.7	1.7	4.4	4.3	3.2	2.2	1	.6	
H		.1	.6	1.3	2.2	2.3	2.2	.8	.3	.1
I				.6	.4	.9	.7	.5	.1	
J						.5	.6	.3		

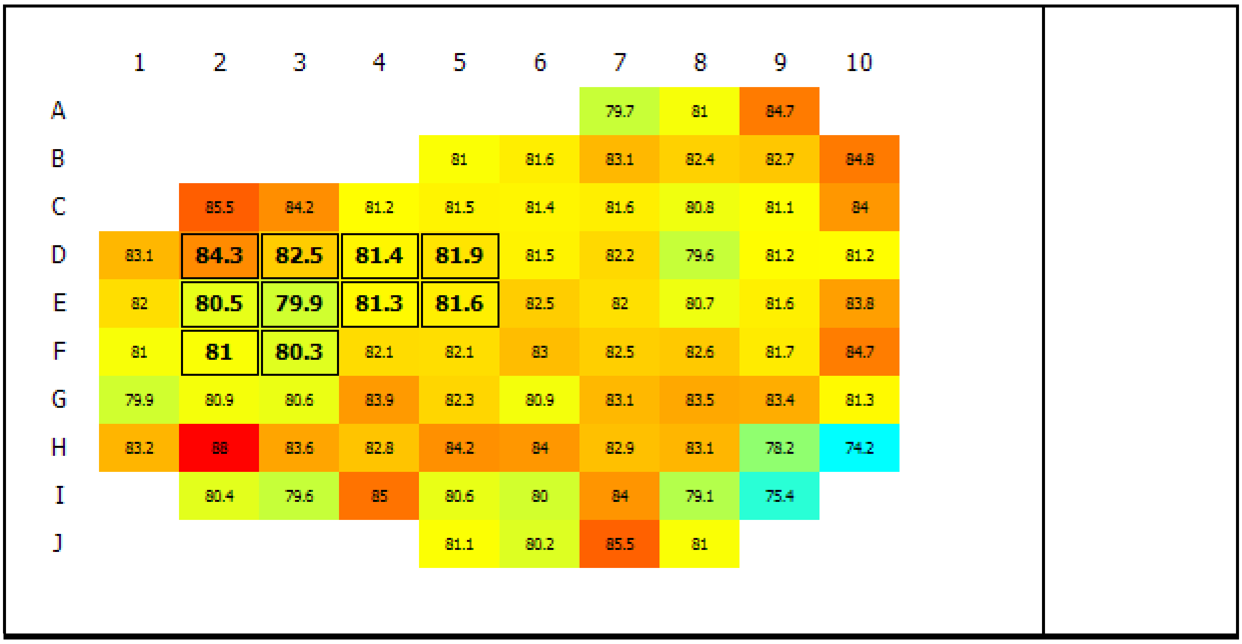
Note regarding the histograms contained in this report:

- Histograms titled "Distribution of <u>all</u> values" shows the distribution of all samples included in the compilation of the performance map
- Histograms titled "Distribution of **<u>selected</u>** values" shows the distribution of values contained within the selected positions of the performance map. In this report, the selected positions in the performance map refer to the operating conditions that realized optimal / ideal performance. This distribution can be used to set the upper and lower limits of for the process recipe.

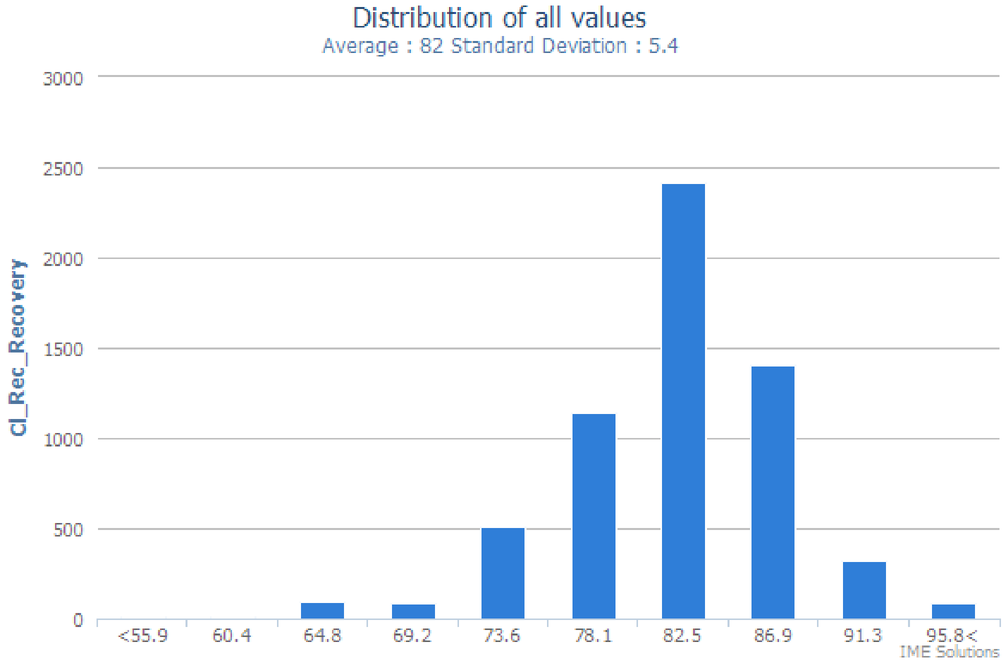
The average and standard deviation is shown in the heading of each histogram.

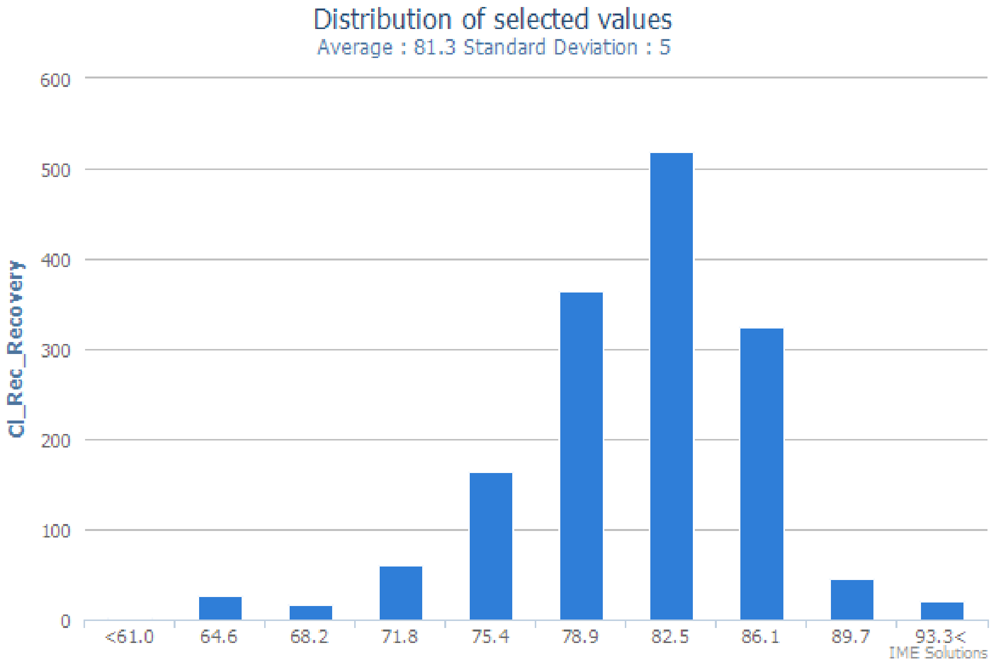
The green range contained on certain histogram illustrates the **current** (prior to this assessment) upper and lower limits set on the process recipe.

Cleaner Recovery

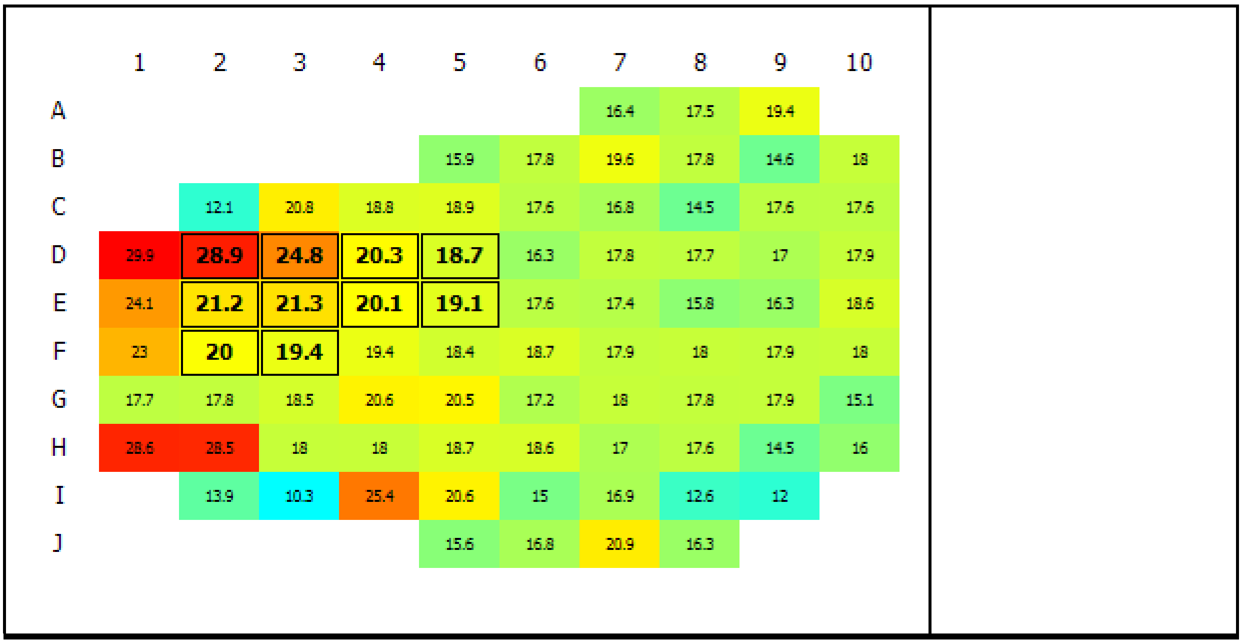


	1	2	3	4	5	6	7	8	9	10
A							79.7	81	84.7	
B					81	81.6	83.1	82.4	82.7	84.8
C		85.5	84.2	81.2	81.5	81.4	81.6	80.8	81.1	84
D	83.1	**84.3**	**82.5**	**81.4**	**81.9**	81.5	82.2	79.6	81.2	81.2
E	82	**80.5**	**79.9**	**81.3**	**81.6**	82.5	82	80.7	81.6	83.8
F	81	**81**	**80.3**	82.1	82.1	83	82.5	82.6	81.7	84.7
G	79.9	80.9	80.6	83.9	82.3	80.9	83.1	83.5	83.4	81.3
H	83.2	88	83.6	82.8	84.2	84	82.9	83.1	78.2	74.2
I		80.4	79.6	85	80.6	80	84	79.1	75.4	
J					81.1	80.2	85.5	81		

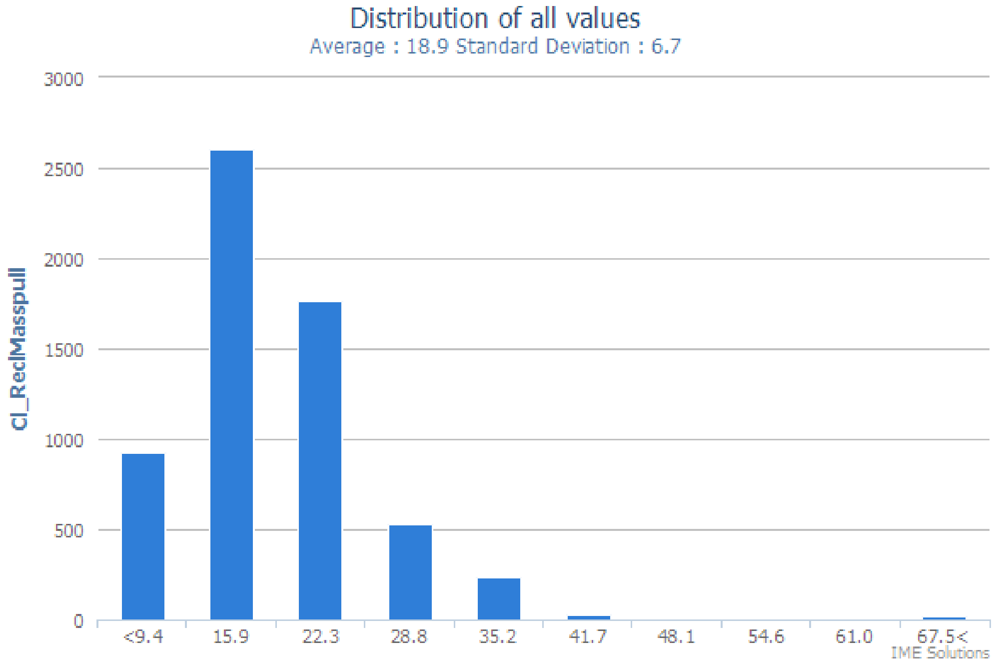


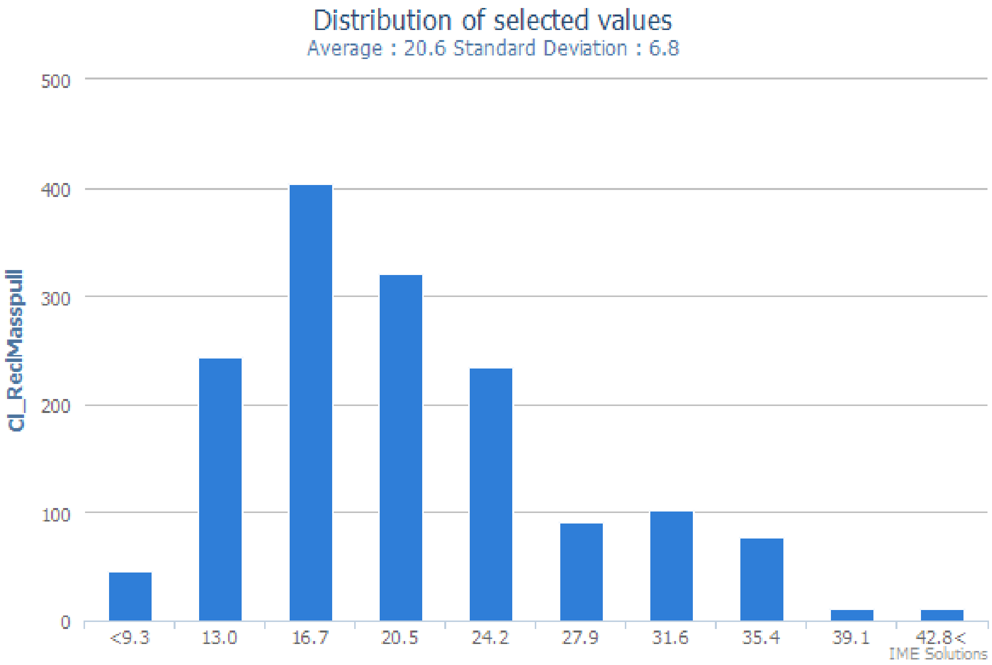

Distribution of selected values
Average : 81.3 Standard Deviation : 5
Cl_Rec_Recovery
600
500
400
300
200
100
0
<61.0
64.6
68.2
71.8
75.4
78.9
82.5
86.1
89.7
93.3<
IME Solutions

Cleaner Mass Pull

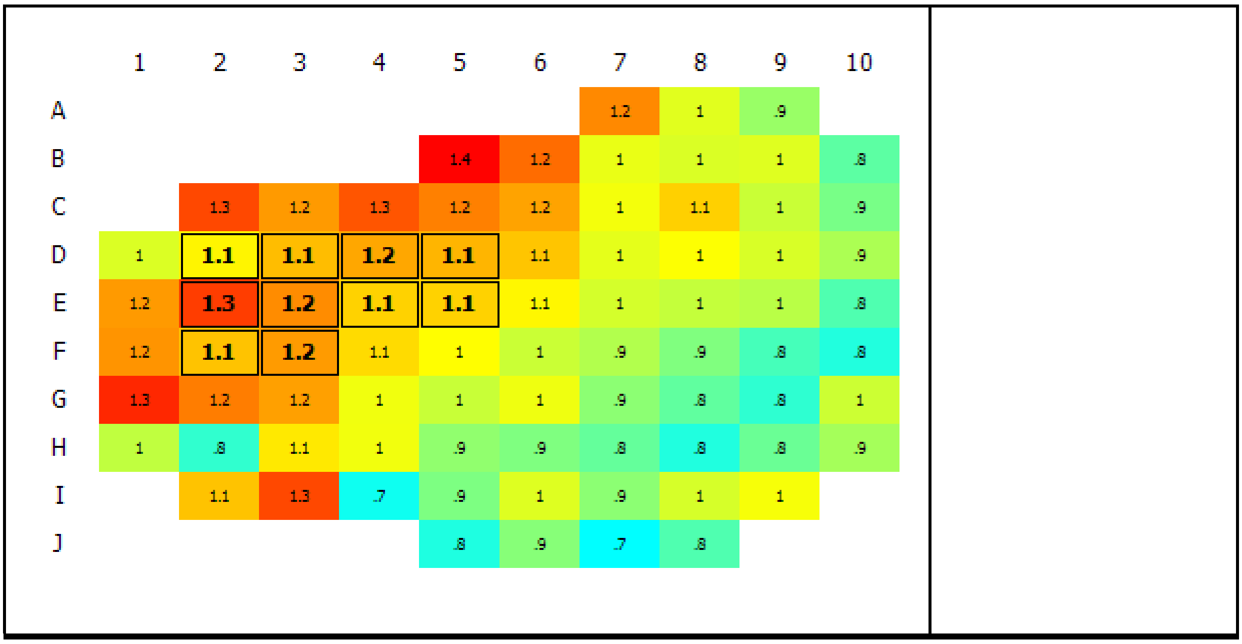


	1	2	3	4	5	6	7	8	9	10
A							16.4	17.5	19.4	
B					15.9	17.8	19.6	17.8	14.6	18
C		12.1	20.8	18.8	18.9	17.6	16.8	14.5	17.6	17.6
D	29.9	**28.9**	**24.8**	**20.3**	**18.7**	16.3	17.8	17.7	17	17.9
E	24.1	**21.2**	**21.3**	**20.1**	**19.1**	17.6	17.4	15.8	16.3	18.6
F	23	**20**	**19.4**	19.4	18.4	18.7	17.9	18	17.9	18
G	17.7	17.8	18.5	20.6	20.5	17.2	18	17.8	17.9	15.1
H	28.6	28.5	18	18	18.7	18.6	17	17.6	14.5	16
I		13.9	10.3	25.4	20.6	15	16.9	12.6	12	
J					15.6	16.8	20.9	16.3		

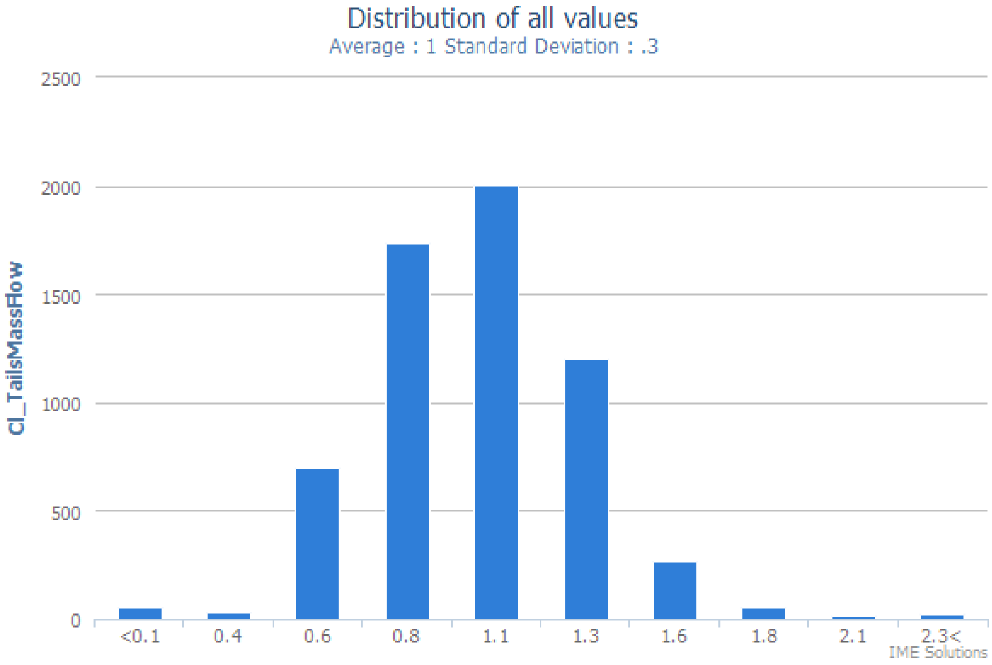


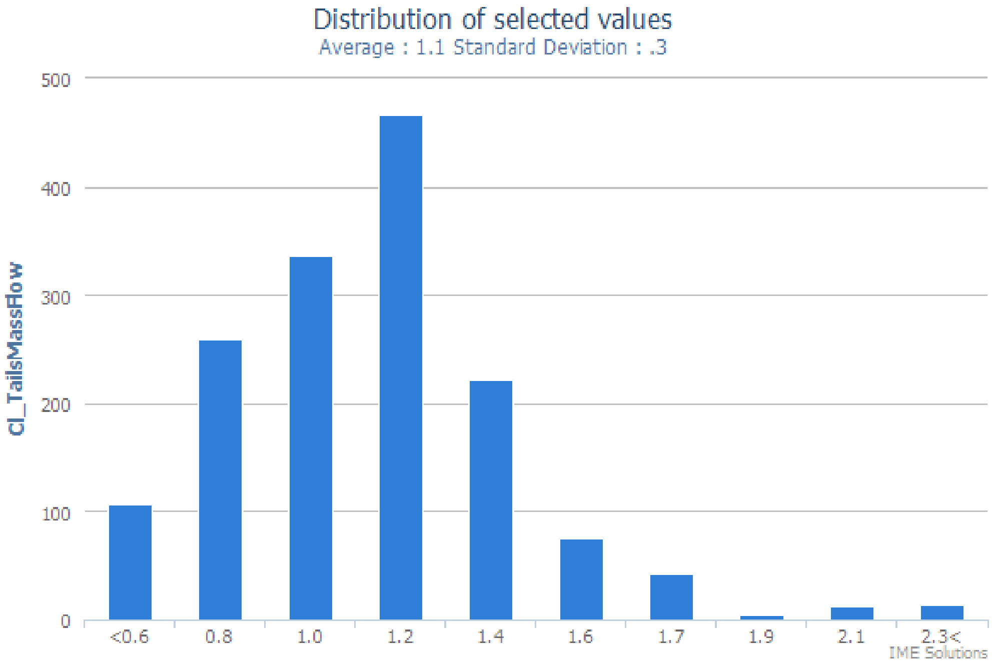

Distribution of selected values
Average : 20.6 Standard Deviation : 6.8
Cl_RecMasspull
500
400
300
200
100
0
<9.3
13.0
16.7
20.5
24.2
27.9
31.6
35.4
39.1
42.8<
IME Solutions

Cleaner Tails Mass Flow



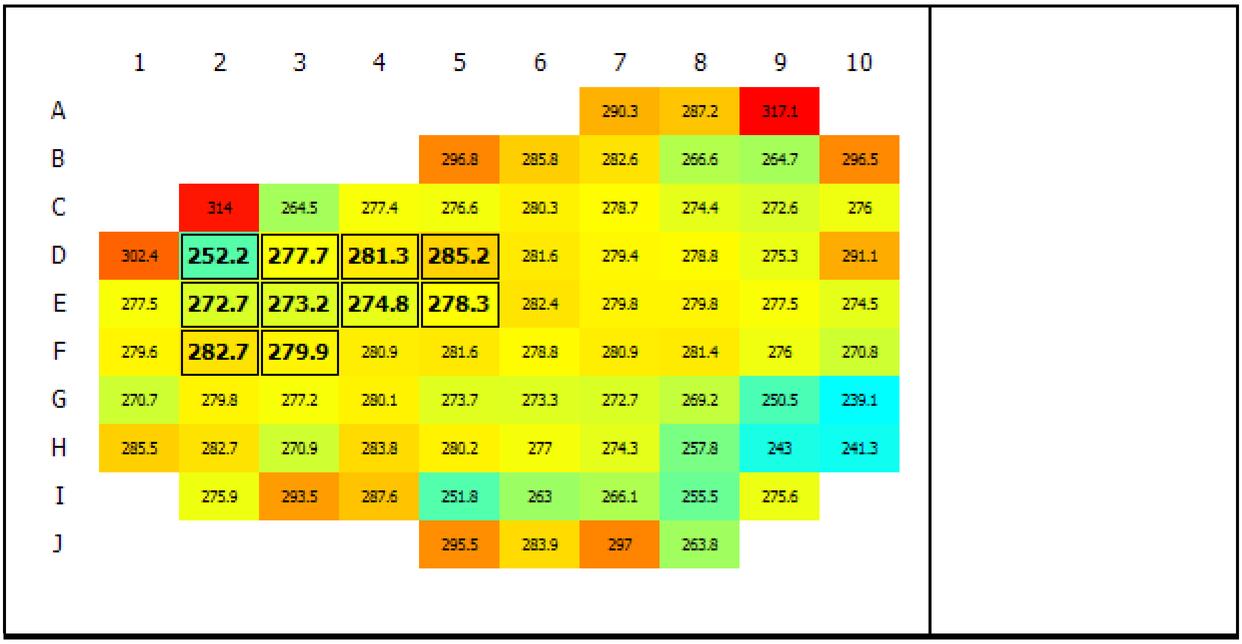
	1	2	3	4	5	6	7	8	9	10
A							1.2	1	.9	
B					1.4	1.2	1	1	1	.8
C		1.3	1.2	1.3	1.2	1.2	1	1.1	1	.9
D	1	**1.1**	**1.1**	**1.2**	**1.1**	1.1	1	1	1	.9
E	1.2	**1.3**	**1.2**	**1.1**	**1.1**	1.1	1	1	1	.8
F	1.2	**1.1**	**1.2**	1.1	1	1	.9	.9	.8	.8
G	1.3	1.2	1.2	1	1	1	.9	.8	.8	1
H	1	.8	1.1	1	.9	.9	.8	.8	.8	.9
I		1.1	1.3	.7	.9	1	.9	1	1	
J					.8	.9	.7	.8		



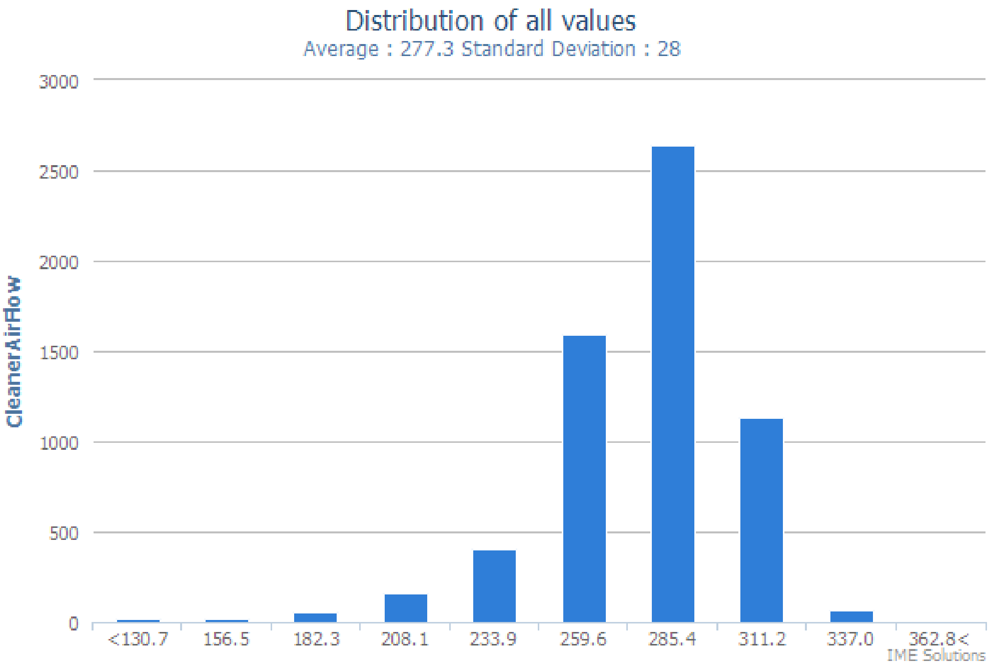

Distribution of selected values
Average : 1.1 Standard Deviation : .3
Cl_TailsMassFlow
500
400
300
200
100
0
<0.6
0.8
1.0
1.2
1.4
1.6
1.7
1.9
2.1
2.3<
IME Solutions

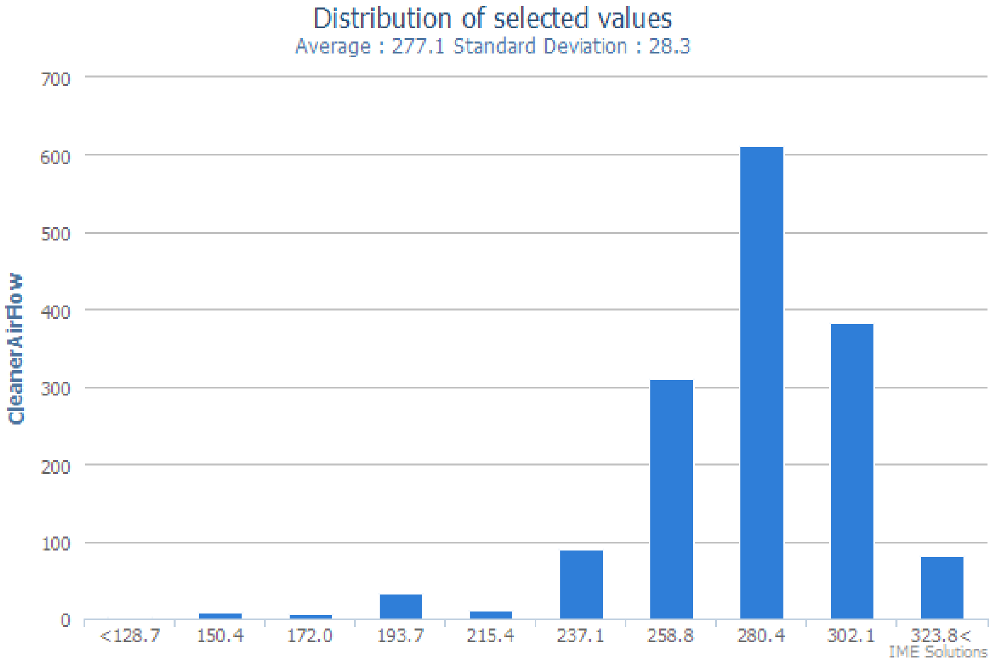
Cleaner Air Flow

Sum of all air flows to the cleaner circuit



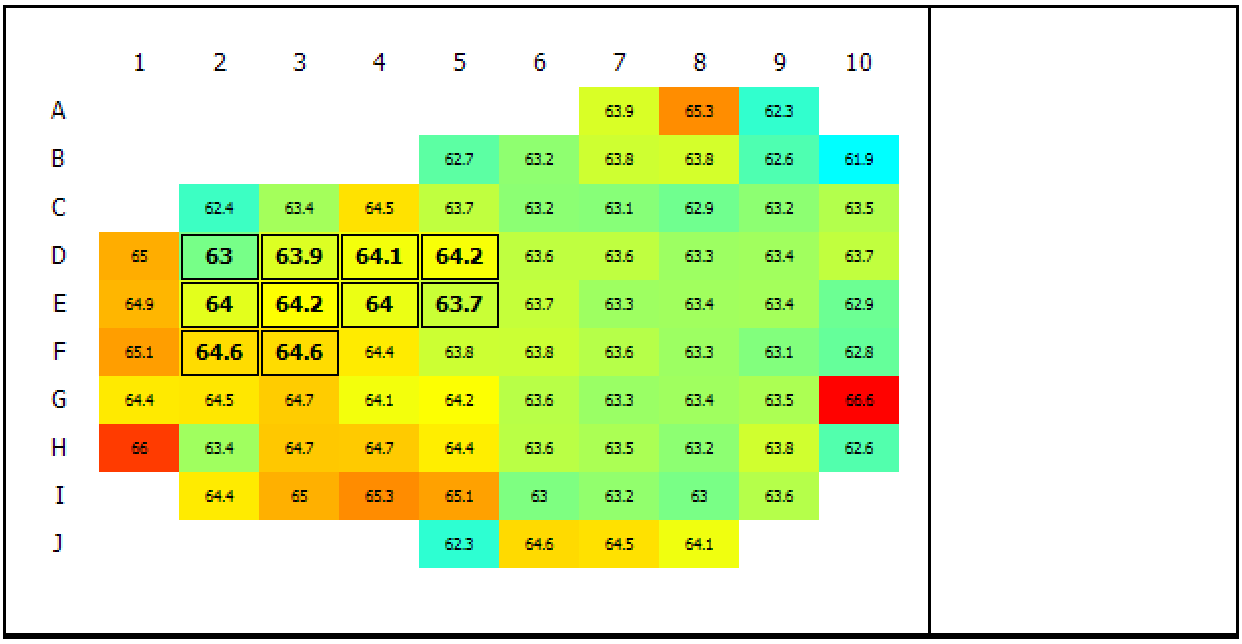
	1	2	3	4	5	6	7	8	9	10
A							290.3	287.2	317.1	
B					296.8	285.8	282.6	266.6	264.7	296.5
C		314	264.5	277.4	276.6	280.3	278.7	274.4	272.6	276
D	302.4	**252.2**	**277.7**	**281.3**	**285.2**	281.6	279.4	278.8	275.3	291.1
E	277.5	**272.7**	**273.2**	**274.8**	**278.3**	282.4	279.8	279.8	277.5	274.5
F	279.6	**282.7**	**279.9**	280.9	281.6	278.8	280.9	281.4	276	270.8
G	270.7	279.8	277.2	280.1	273.7	273.3	272.7	269.2	250.5	239.1
H	285.5	282.7	270.9	283.8	280.2	277	274.3	257.8	243	241.3
I		275.9	293.5	287.6	251.8	263	266.1	255.5	275.6	
J					295.5	283.9	297	263.8		



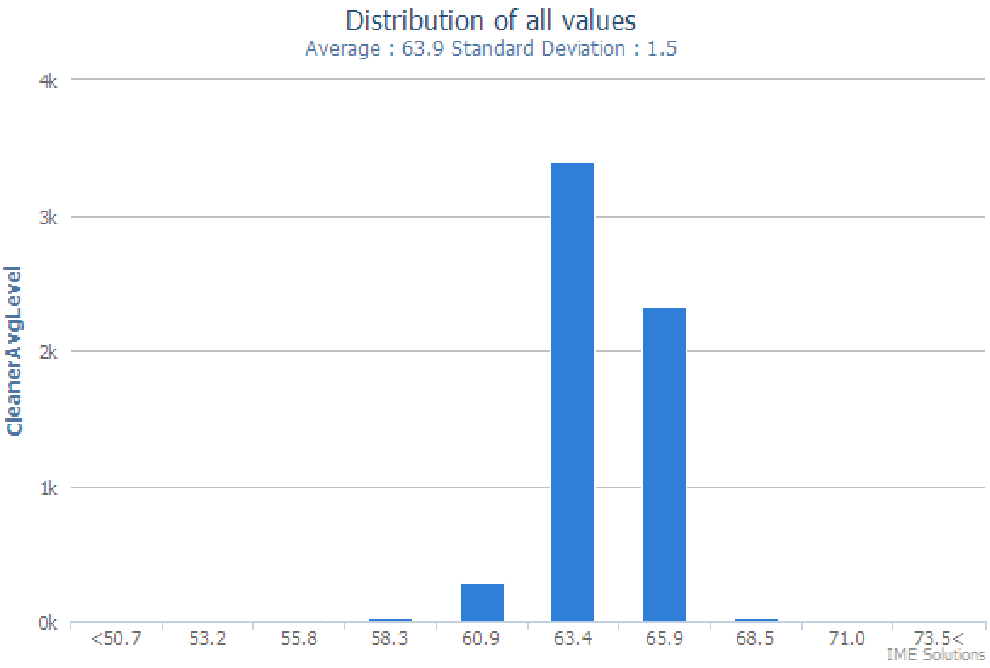

Distribution of selected values
Average : 277.1 Standard Deviation : 28.3
CleanerAirFlow
700
600
500
400
300
200
100
0
<128.7
150.4
172.0
193.7
215.4
237.1
258.8
280.4
302.1
323.8<
IME Solutions

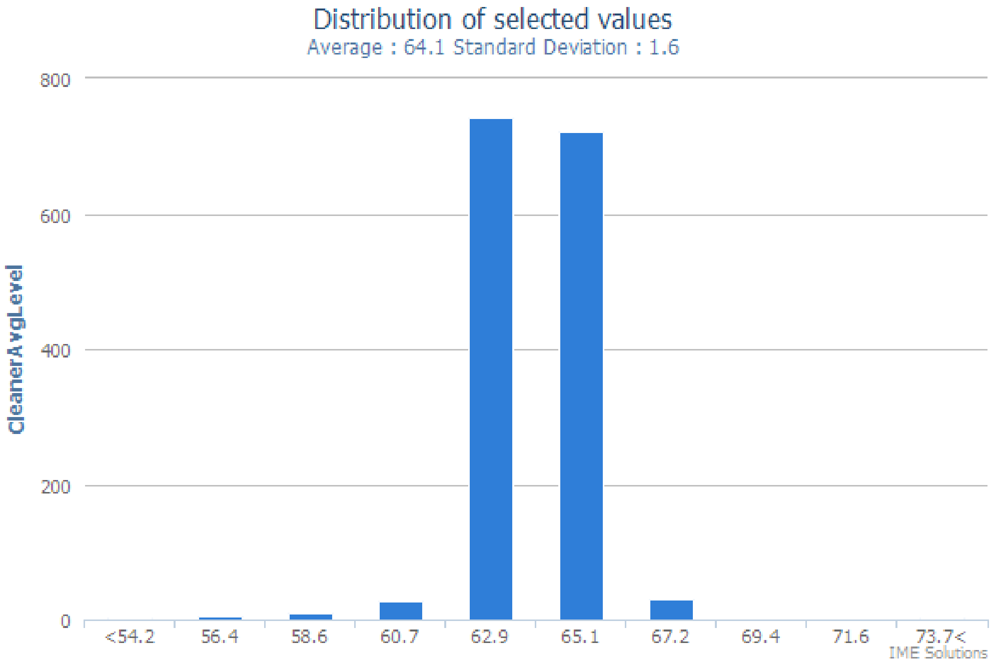
Cleaner Average Level

Average level of all cleaner cells

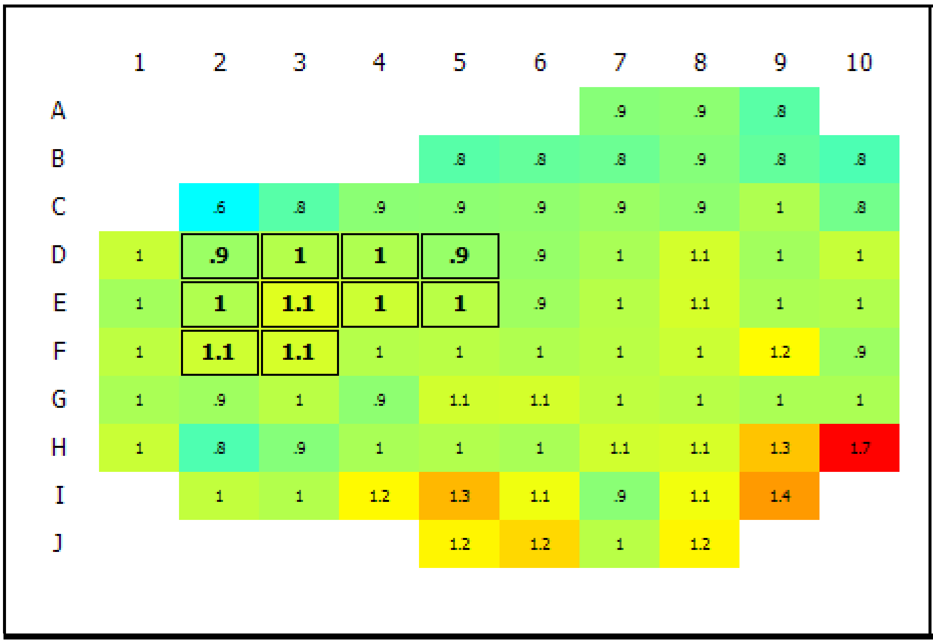


	1	2	3	4	5	6	7	8	9	10
A							63.9	65.3	62.3	
B					62.7	63.2	63.8	63.8	62.6	61.9
C		62.4	63.4	64.5	63.7	63.2	63.1	62.9	63.2	63.5
D	65	**63**	**63.9**	**64.1**	**64.2**	63.6	63.6	63.3	63.4	63.7
E	64.9	**64**	**64.2**	**64**	**63.7**	63.7	63.3	63.4	63.4	62.9
F	65.1	**64.6**	**64.6**	64.4	63.8	63.8	63.6	63.3	63.1	62.8
G	64.4	64.5	64.7	64.1	64.2	63.6	63.3	63.4	63.5	66.6
H	66	63.4	64.7	64.7	64.4	63.6	63.5	63.2	63.8	62.6
I		64.4	65	65.3	65.1	63	63.2	63	63.6	
J					62.3	64.6	64.5	64.1		

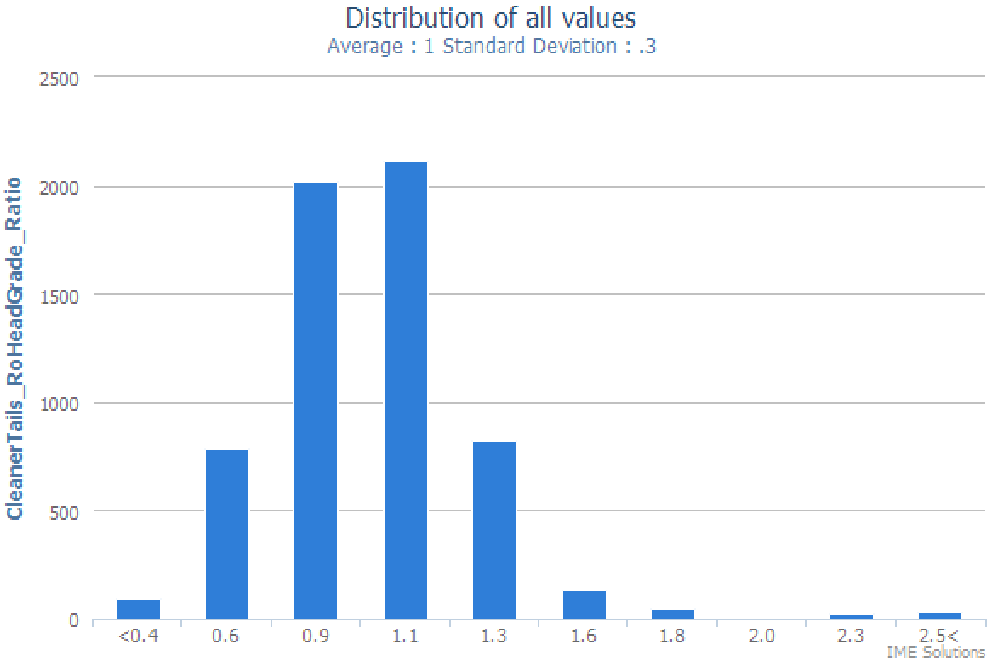


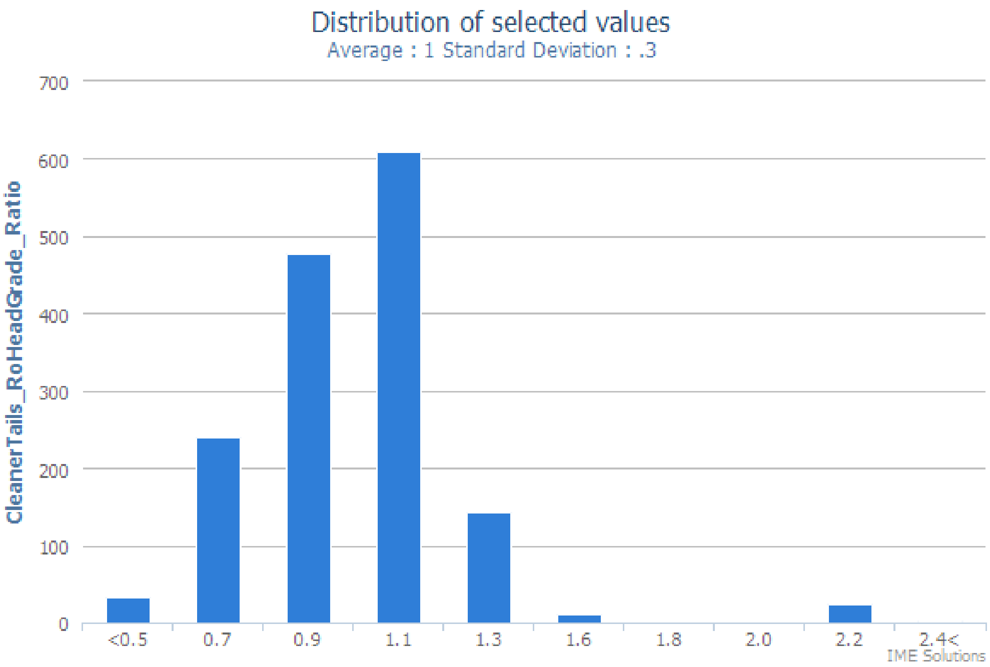

Distribution of selected values
Average : 64.1 Standard Deviation : 1.6
CleanerAvgLevel
800
600
400
200
0
<54.2
56.4
58.6
60.7
62.9
65.1
67.2
69.4
71.6
73.7<
IME Solutions

Cleaner Tails Nickel Grade versus Head Grade Ratio

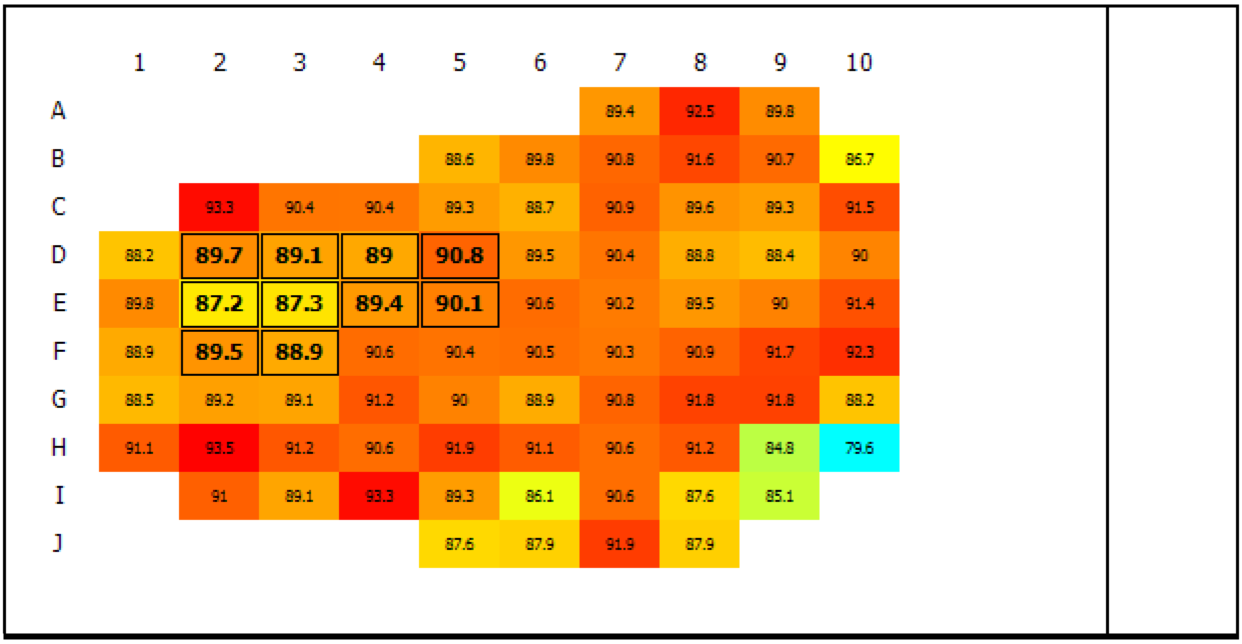


	1	2	3	4	5	6	7	8	9	10
A							.9	.9	.8	
B					.8	.8	.8	.9	.8	.8
C		.6	.8	.9	.9	.9	.9	.9	1	.8
D	1	**.9**	**1**	**1**	**.9**	.9	1	1.1	1	1
E	1	**1**	**1.1**	**1**	**1**	.9	1	1.1	1	1
F	1	**1.1**	**1.1**	1	1	1	1	1	1.2	.9
G	1	.9	1	.9	1.1	1.1	1	1	1	1
H	1	.8	.9	1	1	1	1.1	1.1	1.3	1.7
I		1	1	1.2	1.3	1.1	.9	1.1	1.4	
J					1.2	1.2	1	1.2		

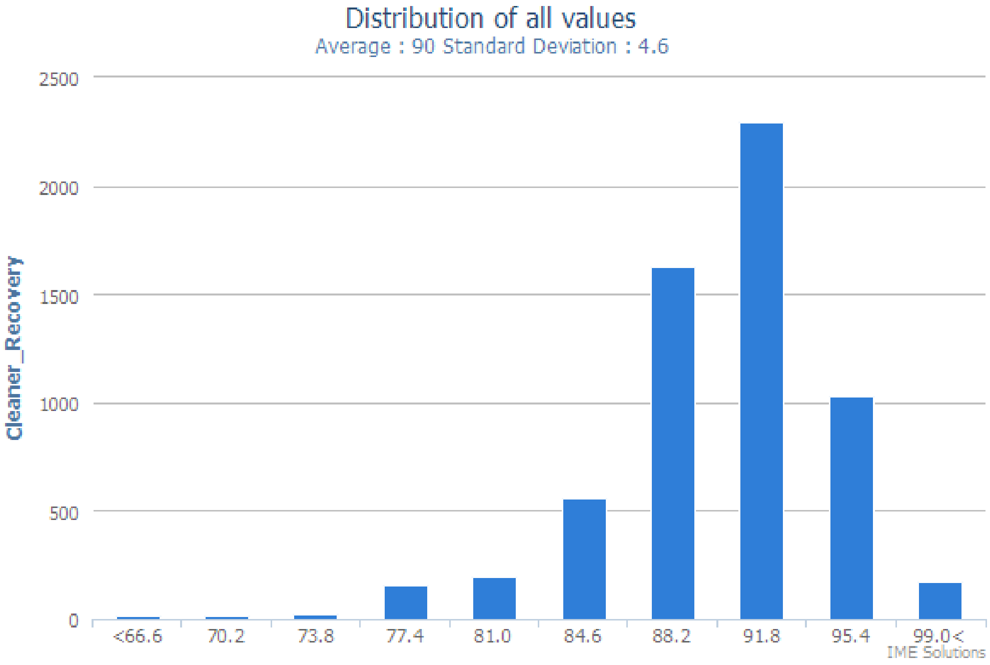


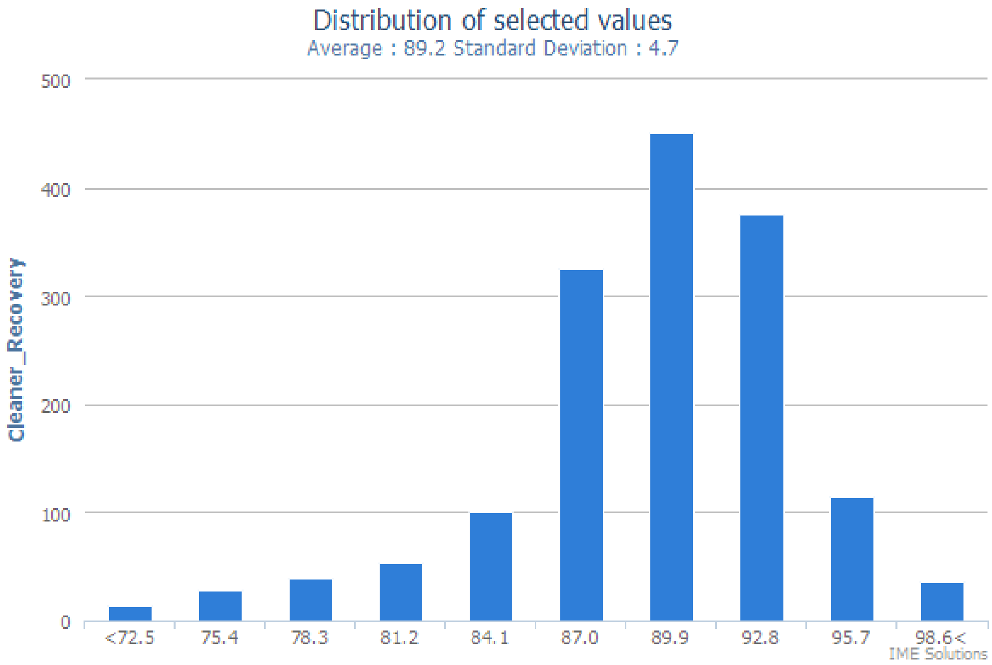

Distribution of selected values
Average : 1 Standard Deviation : .3
CleanerTails_RoHeadGrade_Ratio
700
600
500
400
300
200
100
0
<0.5
0.7
0.9
1.1
1.3
1.6
1.8
2.0
2.2
2.4<
IME Solutions

Cleaner Recovery



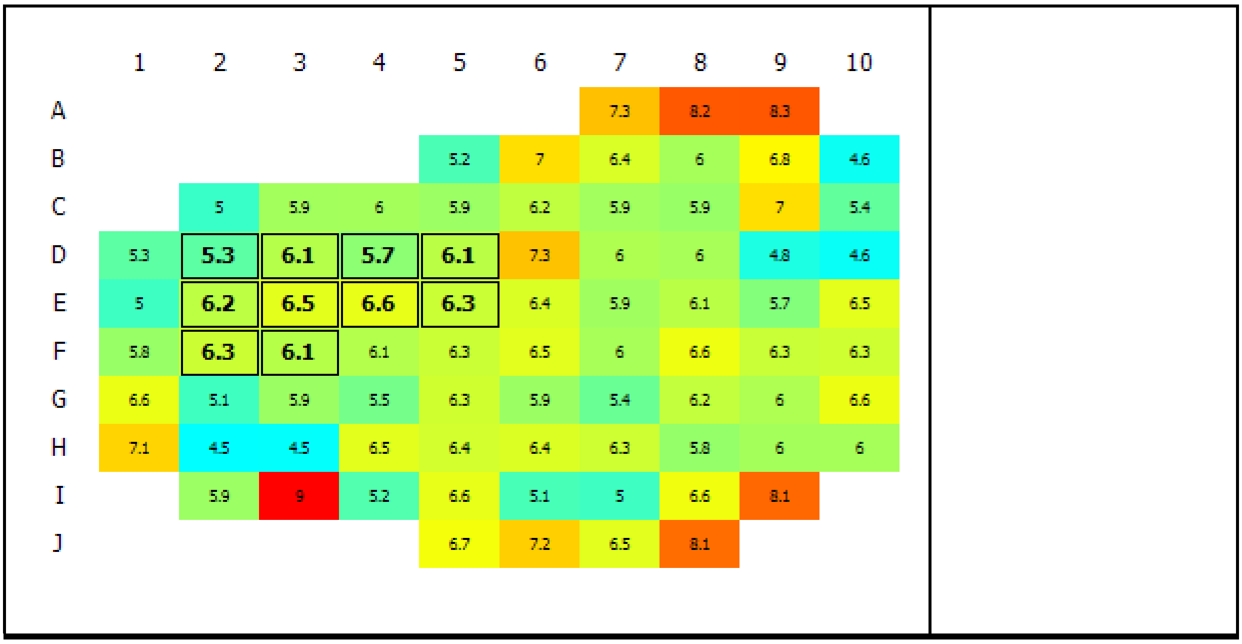
	1	2	3	4	5	6	7	8	9	10
A							89.4	92.5	89.8	
B					88.6	89.8	90.8	91.6	90.7	86.7
C		93.3	90.4	90.4	89.3	88.7	90.9	89.6	89.3	91.5
D	88.2	**89.7**	**89.1**	**89**	**90.8**	89.5	90.4	88.8	88.4	90
E	89.8	**87.2**	**87.3**	**89.4**	**90.1**	90.6	90.2	89.5	90	91.4
F	88.9	**89.5**	**88.9**	90.6	90.4	90.5	90.3	90.9	91.7	92.3
G	88.5	89.2	89.1	91.2	90	88.9	90.8	91.8	91.8	88.2
H	91.1	93.5	91.2	90.6	91.9	91.1	90.6	91.2	84.8	79.6
I		91	89.1	93.3	89.3	86.1	90.6	87.6	85.1	
J					87.6	87.9	91.9	87.9		



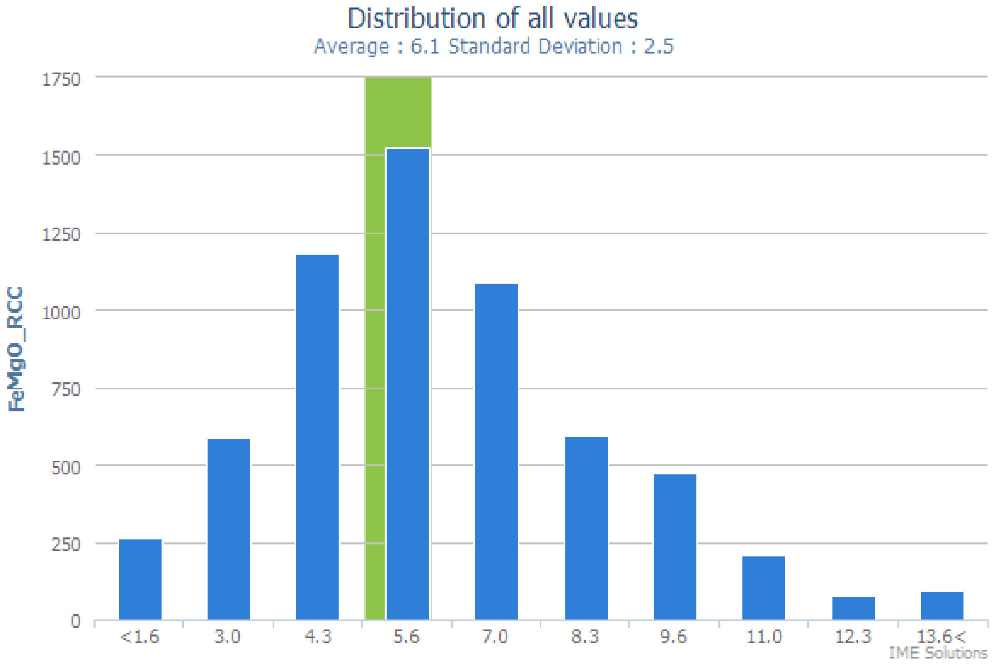


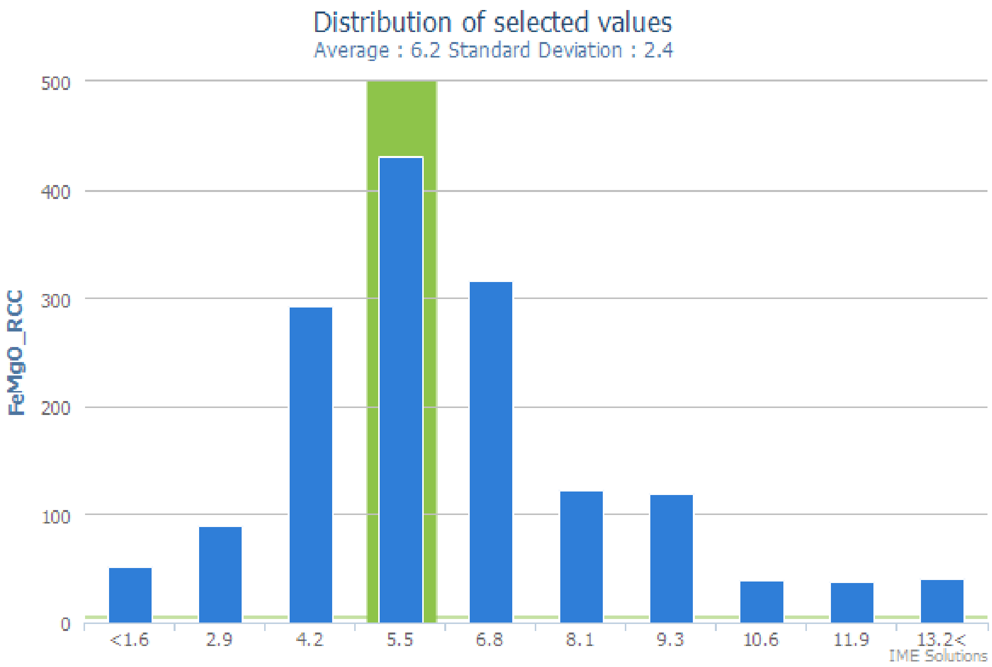
Distribution of selected values
Average : 89.2 Standard Deviation : 4.7
Cleaner_Recovery
500
400
300
200
100
0
<72.5
75.4
78.3
81.2
84.1
87.0
89.9
92.8
95.7
98.6<
IME Solutions

Final Concentrate Fe:MgO Ratio

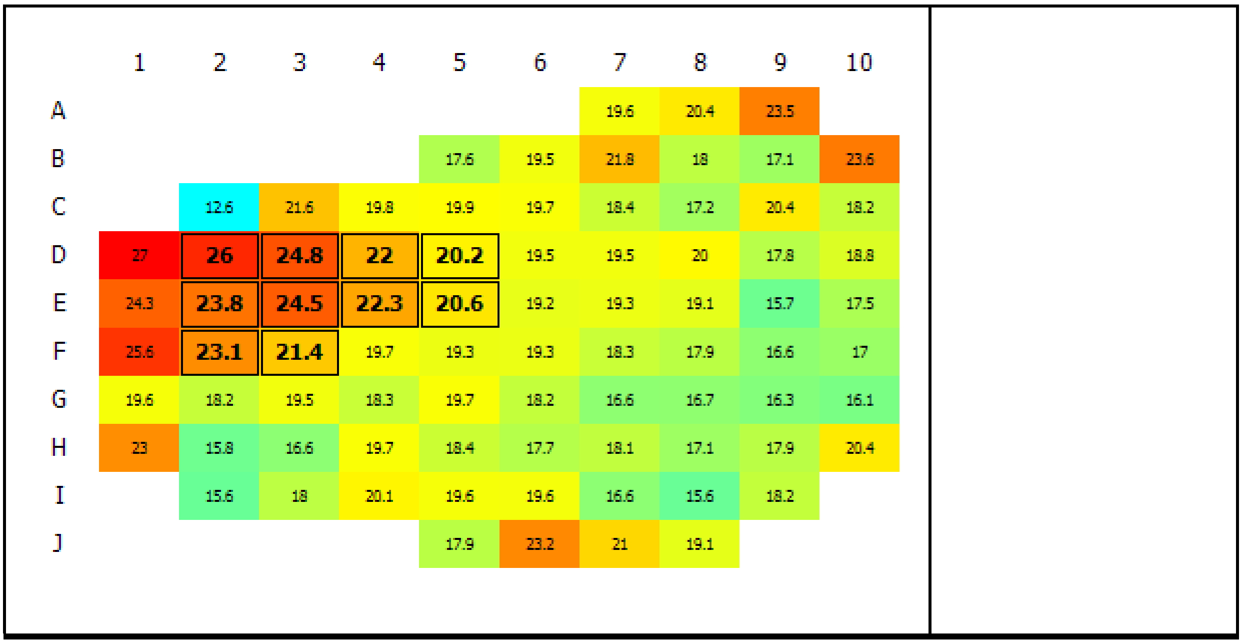


	1	2	3	4	5	6	7	8	9	10
A							7.3	8.2	8.3	
B					5.2	7	6.4	6	6.8	4.6
C		5	5.9	6	5.9	6.2	5.9	5.9	7	5.4
D	5.3	**5.3**	**6.1**	**5.7**	**6.1**	7.3	6	6	4.8	4.6
E	5	**6.2**	**6.5**	**6.6**	**6.3**	6.4	5.9	6.1	5.7	6.5
F	5.8	**6.3**	**6.1**	6.1	6.3	6.5	6	6.6	6.3	6.3
G	6.6	5.1	5.9	5.5	6.3	5.9	5.4	6.2	6	6.6
H	7.1	4.5	4.5	6.5	6.4	6.4	6.3	5.8	6	6
I		5.9	9	5.2	6.6	5.1	5	6.6	8.1	
J					6.7	7.2	6.5	8.1		

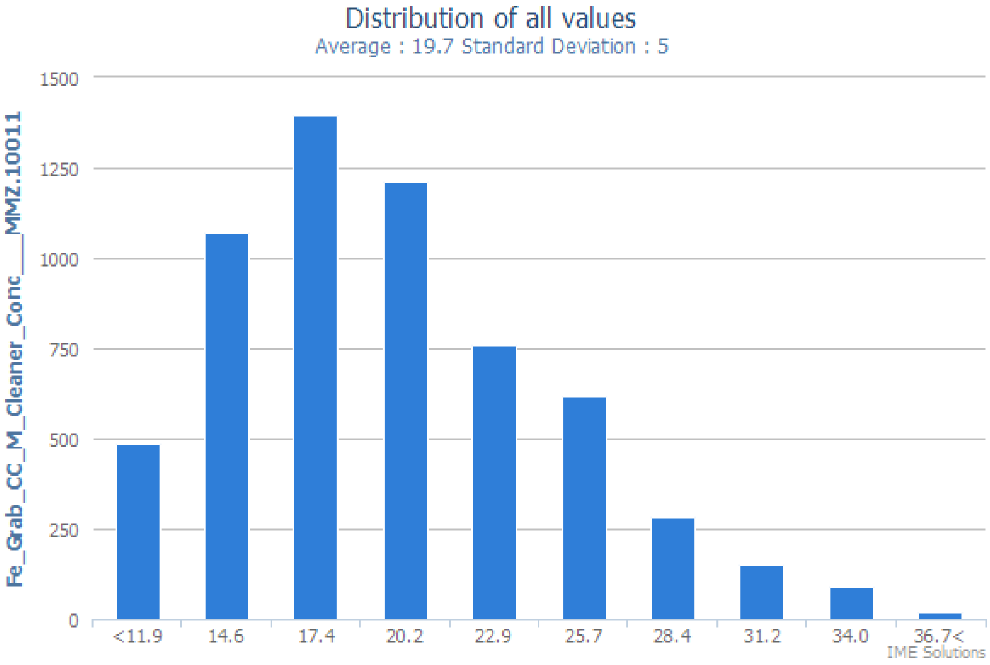


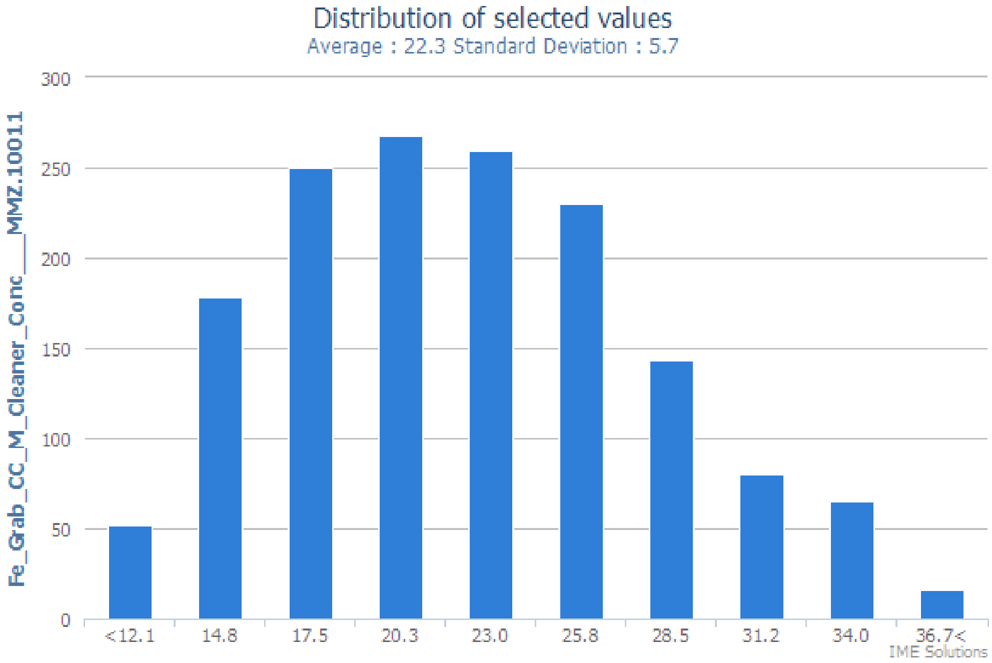

Distribution of selected values
Average : 6.2 Standard Deviation : 2.4
FeMgO_RCC
500
400
300
200
100
0
<1.6
2.9
4.2
5.5
6.8
8.1
9.3
10.6
11.9
13.2<
IME Solutions

Re-Cleaner Concentrate Fe Grade

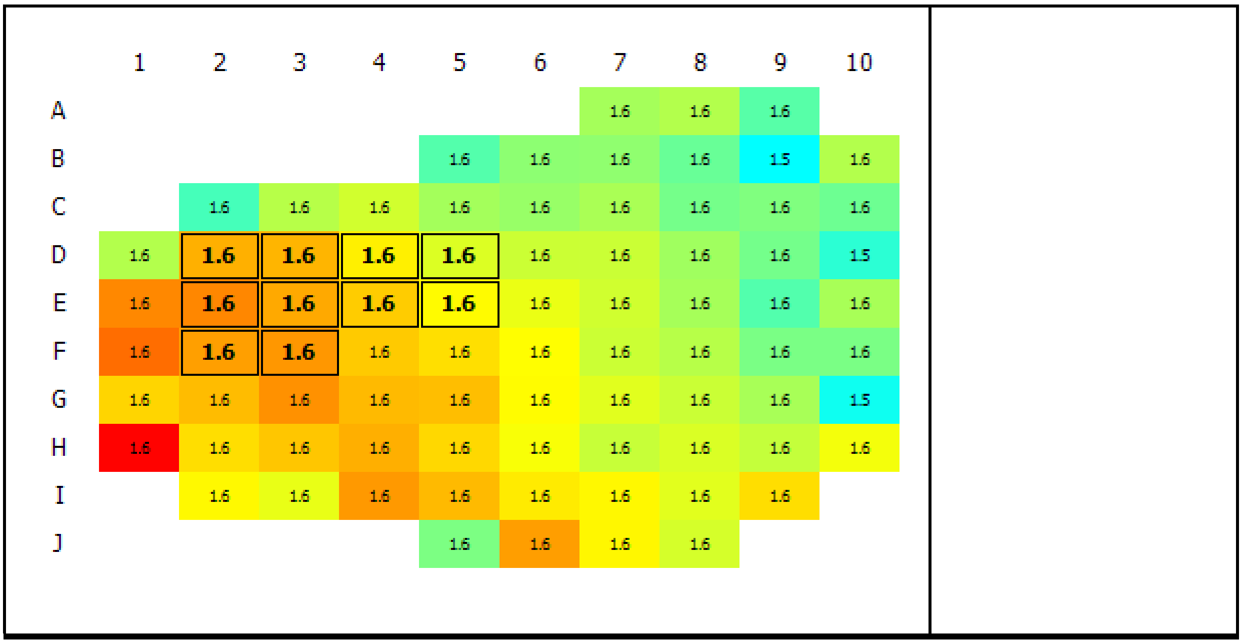


	1	2	3	4	5	6	7	8	9	10
A							19.6	20.4	23.5	
B					17.6	19.5	21.8	18	17.1	23.6
C		12.6	21.6	19.8	19.9	19.7	18.4	17.2	20.4	18.2
D	27	**26**	**24.8**	**22**	**20.2**	19.5	19.5	20	17.8	18.8
E	24.3	**23.8**	**24.5**	**22.3**	**20.6**	19.2	19.3	19.1	15.7	17.5
F	25.6	**23.1**	**21.4**	19.7	19.3	19.3	18.3	17.9	16.6	17
G	19.6	18.2	19.5	18.3	19.7	18.2	16.6	16.7	16.3	16.1
H	23	15.8	16.6	19.7	18.4	17.7	18.1	17.1	17.9	20.4
I		15.6	18	20.1	19.6	19.6	16.6	15.6	18.2	
J					17.9	23.2	21	19.1		

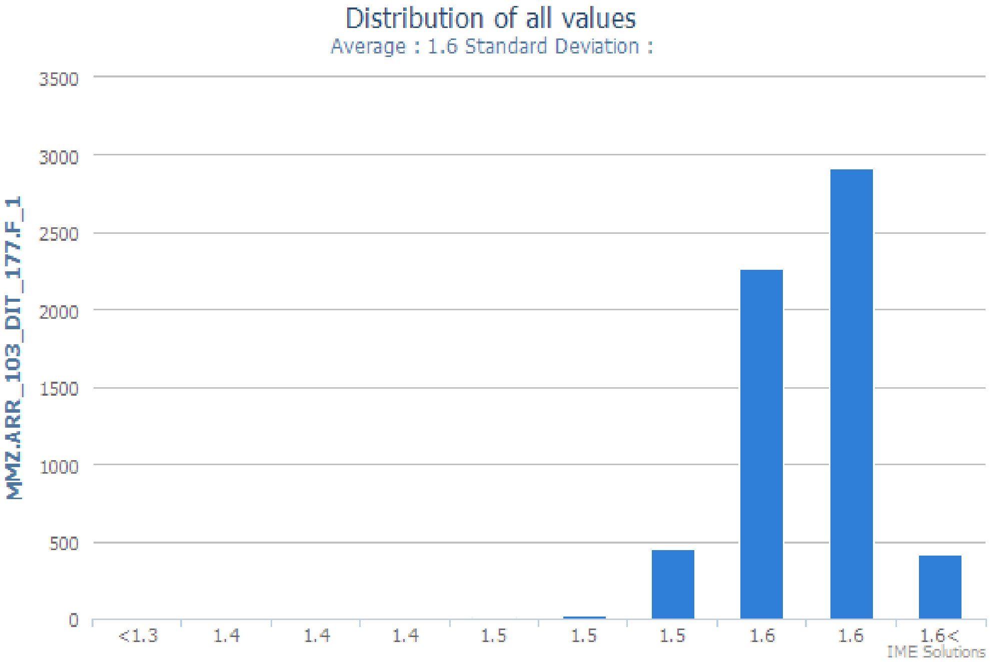


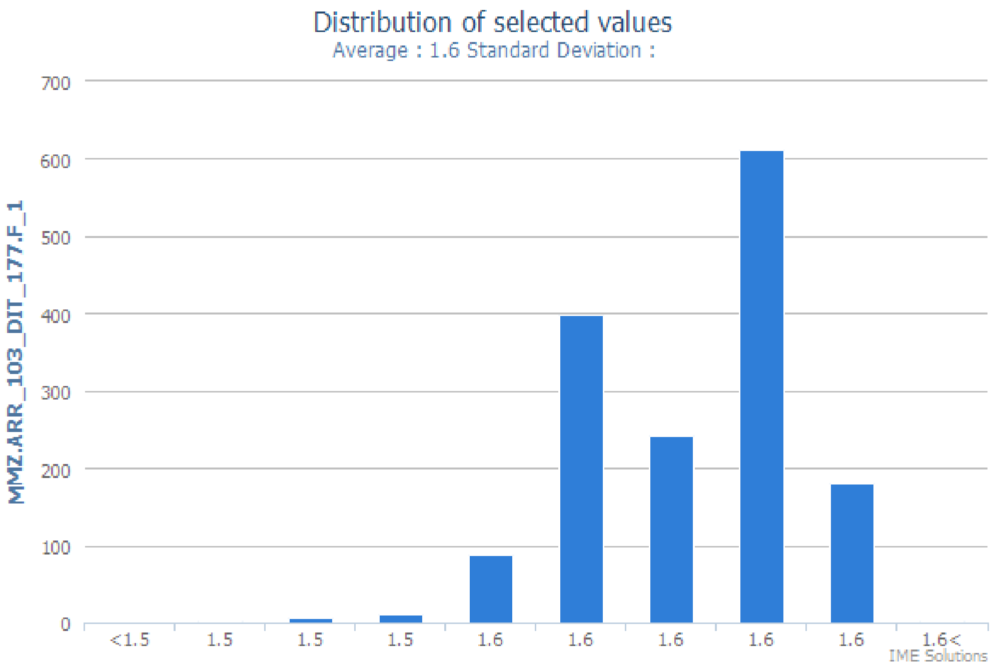

Distribution of selected values
Average : 22.3 Standard Deviation : 5.7
Fe_Grab_CC_M_Cleaner_Conc___MMZ.10011
300
250
200
150
100
50
0
<12.1
14.8
17.5
20.3
23.0
25.8
28.5
31.2
34.0
36.7<
IME Solutions

Cyclone Feed Density (SG)

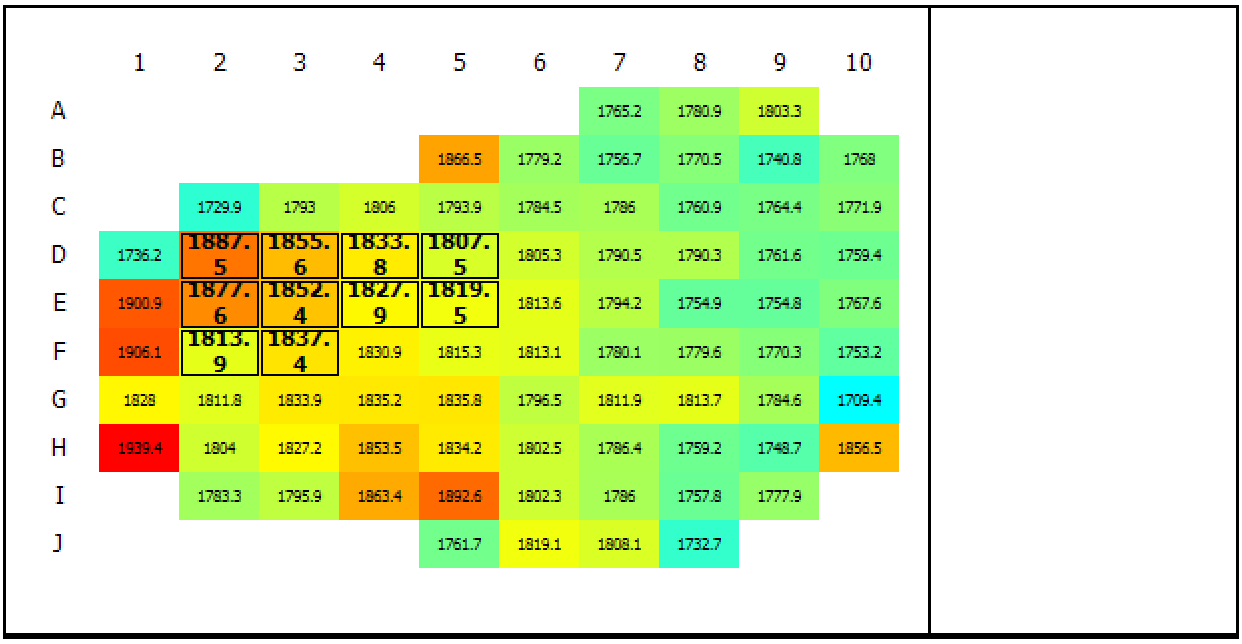


	1	2	3	4	5	6	7	8	9	10
A							1.6	1.6	1.6	
B					1.6	1.6	1.6	1.6	1.5	1.6
C		1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
D	1.6	**1.6**	**1.6**	**1.6**	**1.6**	1.6	1.6	1.6	1.6	1.5
E	1.6	**1.6**	**1.6**	**1.6**	**1.6**	1.6	1.6	1.6	1.6	1.6
F	1.6	**1.6**	**1.6**	1.6	1.6	1.6	1.6	1.6	1.6	1.6
G	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.5
H	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
I		1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	
J					1.6	1.6	1.6	1.6		

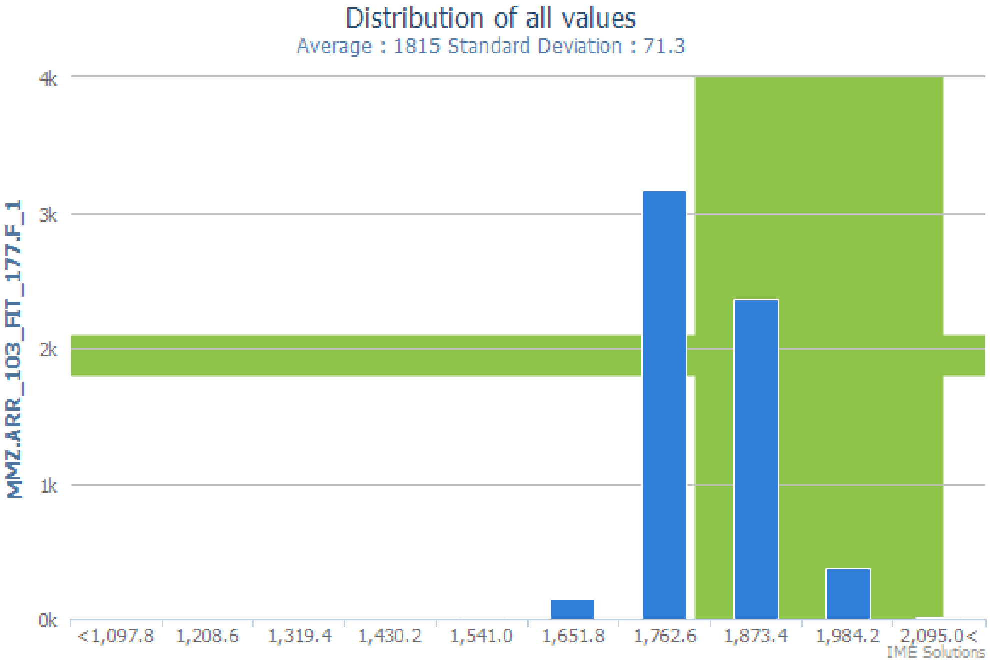


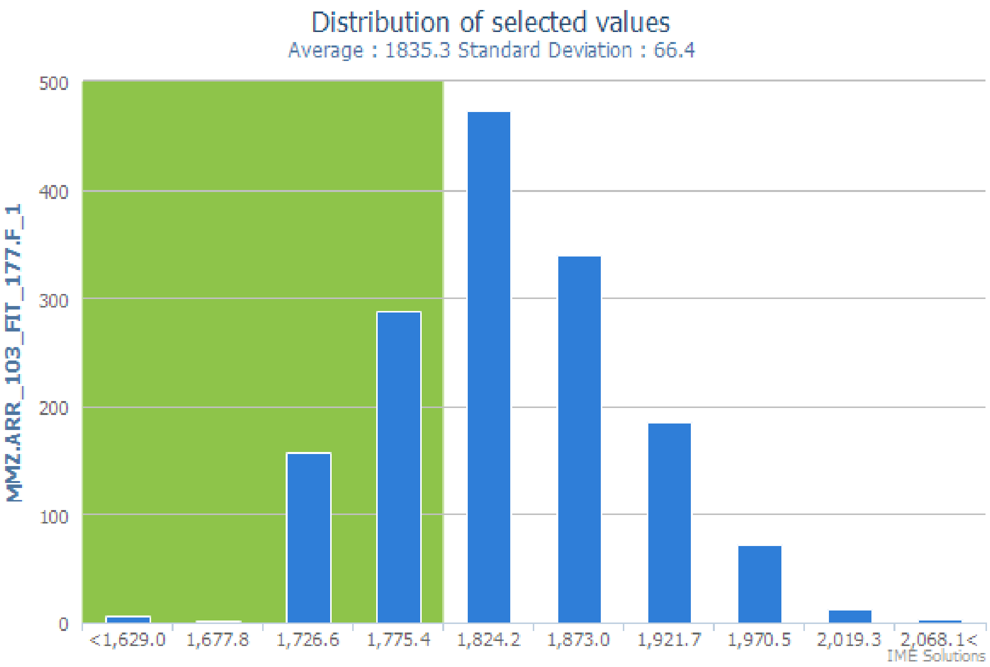

Distribution of selected values
Average : 1.6 Standard Deviation :
MMZ.ARR_103_DIT_177.F_1
700
600
500
400
300
200
100
0
<1.5
1.5
1.5
1.5
1.6
1.6
1.6
1.6
1.6
1.6<
IME Solutions

Cyclone Feed Flow (m^3/h)

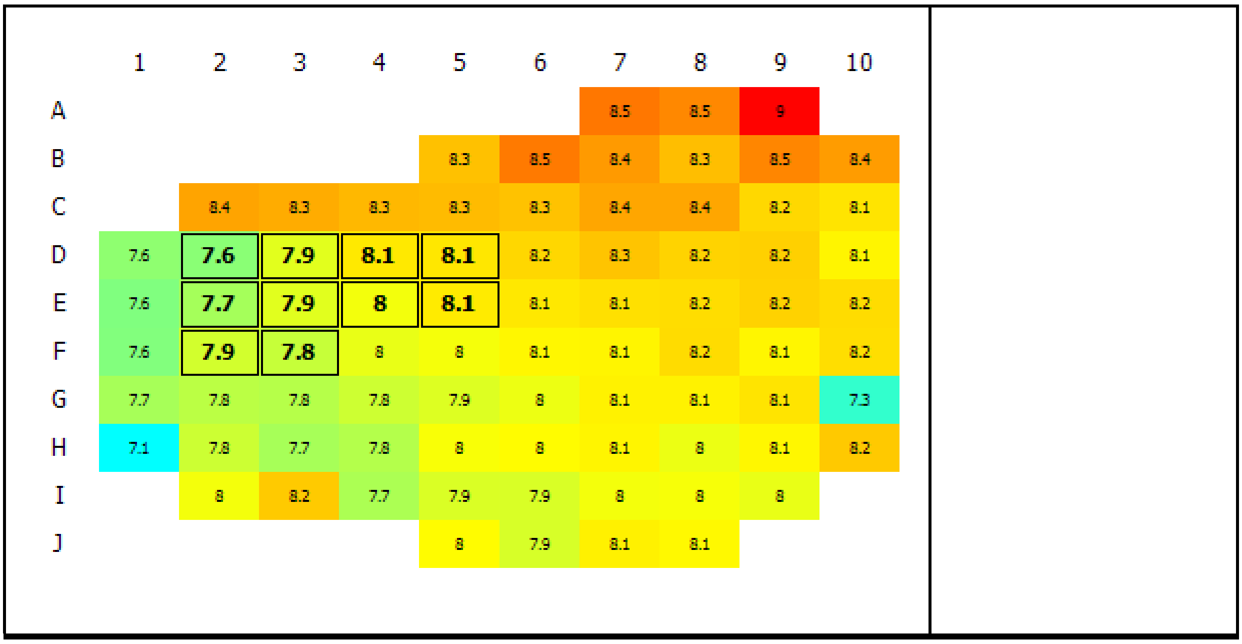


	1	2	3	4	5	6	7	8	9	10
A							1765.2	1780.9	1803.3	
B					1866.5	1779.2	1756.7	1770.5	1740.8	1768
C		1729.9	1793	1806	1793.9	1784.5	1786	1760.9	1764.4	1771.9
D	1736.2	1887.5	1855.6	1833.8	1807.5	1805.3	1790.5	1790.3	1761.6	1759.4
E	1900.9	1877.6	1852.4	1827.9	1819.5	1813.6	1794.2	1754.9	1754.8	1767.6
F	1906.1	1813.9	1837.4	1830.9	1815.3	1813.1	1780.1	1779.6	1770.3	1753.2
G	1828	1811.8	1833.9	1835.2	1835.8	1796.5	1811.9	1813.7	1784.6	1709.4
H	1939.4	1804	1827.2	1853.5	1834.2	1802.5	1786.4	1759.2	1748.7	1856.5
I		1783.3	1795.9	1863.4	1892.6	1802.3	1786	1757.8	1777.9	
J					1761.7	1819.1	1808.1	1732.7		

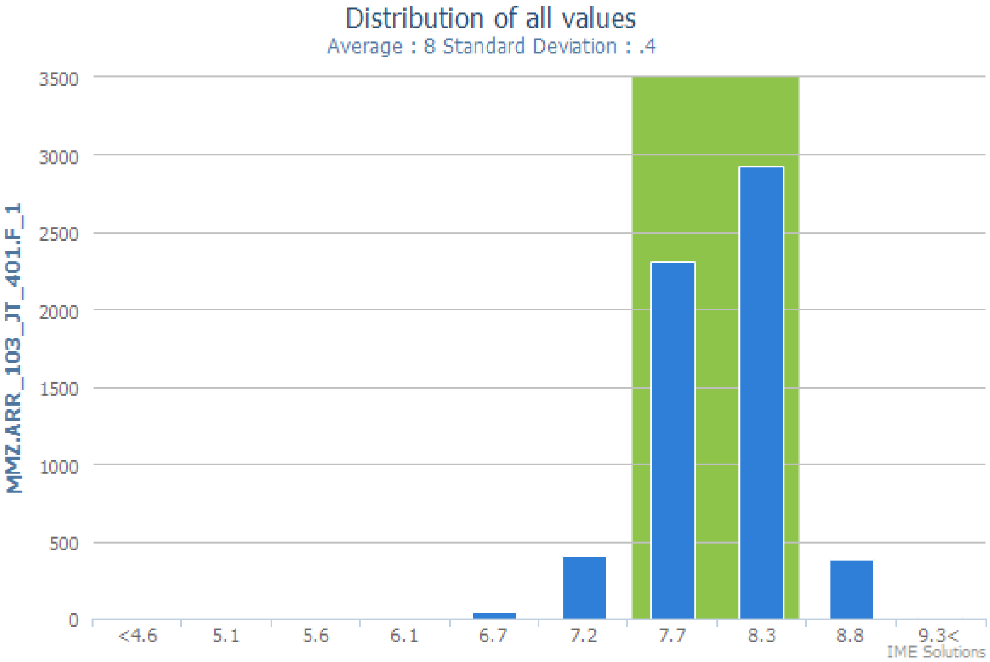


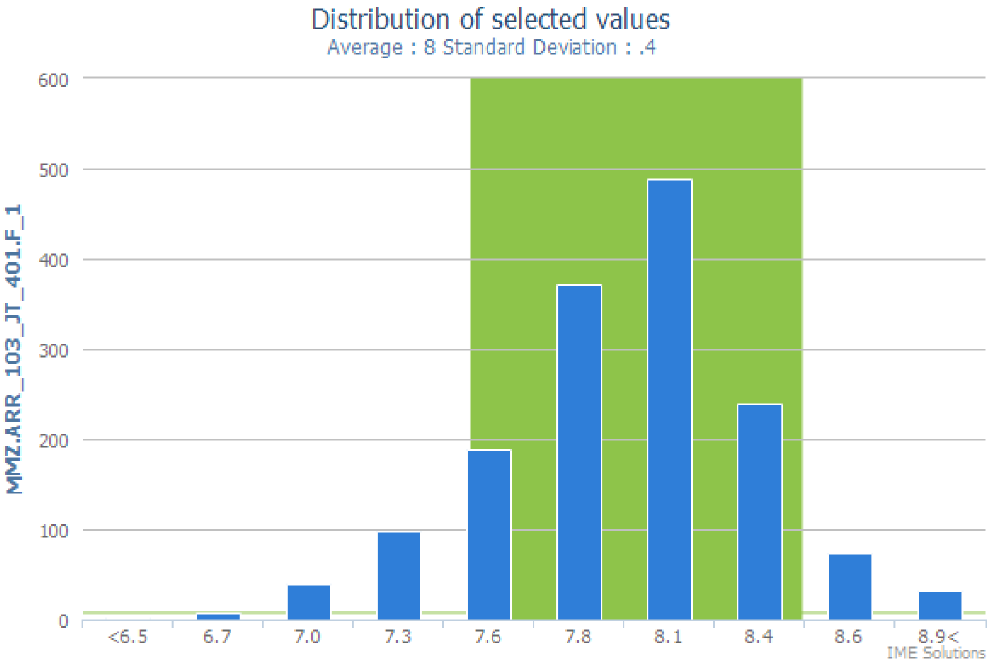

Distribution of selected values
Average : 1835.3 Standard Deviation : 66.4
MMZ.ARR_103_FIT_177.F_1
500
400
300
200
100
0
<1,629.0
1,677.8
1,726.6
1,775.4
1,824.2
1,873.0
1,921.7
1,970.5
2,019.3
2,068.1<
IME Solutions

FAG Mill Power (MW)

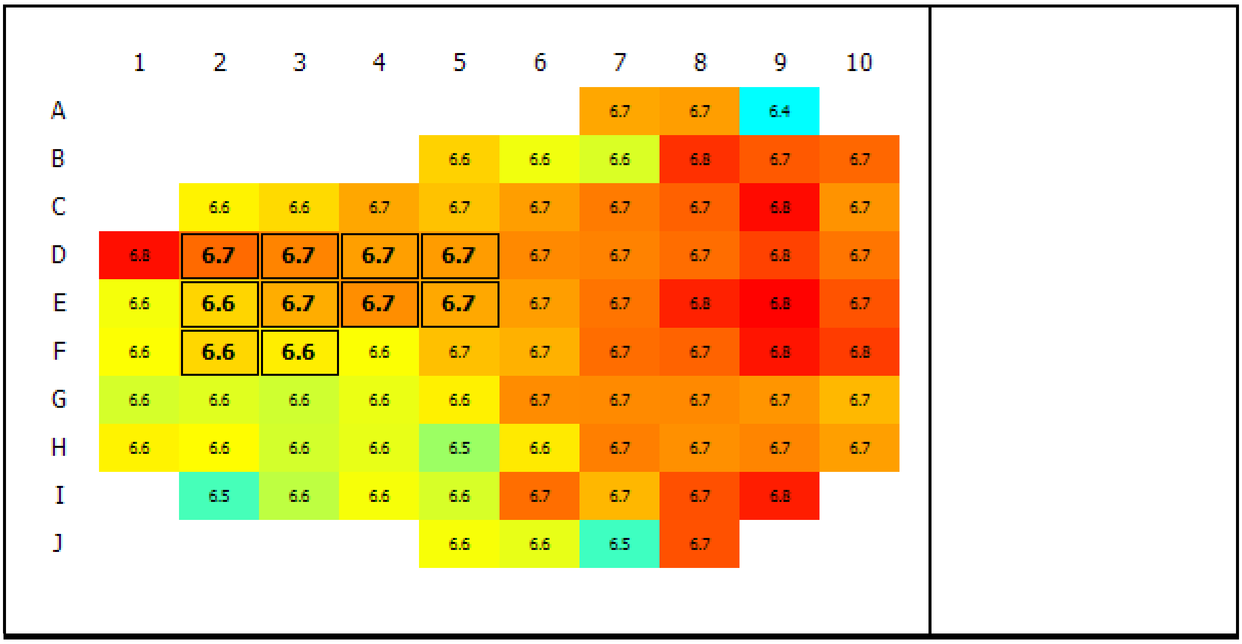


	1	2	3	4	5	6	7	8	9	10
A							8.5	8.5	9	
B					8.3	8.5	8.4	8.3	8.5	8.4
C		8.4	8.3	8.3	8.3	8.3	8.4	8.4	8.2	8.1
D	7.6	**7.6**	**7.9**	**8.1**	**8.1**	8.2	8.3	8.2	8.2	8.1
E	7.6	**7.7**	**7.9**	**8**	**8.1**	8.1	8.1	8.2	8.2	8.2
F	7.6	**7.9**	**7.8**	8	8	8.1	8.1	8.2	8.1	8.2
G	7.7	7.8	7.8	7.8	7.9	8	8.1	8.1	8.1	7.3
H	7.1	7.8	7.7	7.8	8	8	8.1	8	8.1	8.2
I		8	8.2	7.7	7.9	7.9	8	8	8	
J					8	7.9	8.1	8.1		

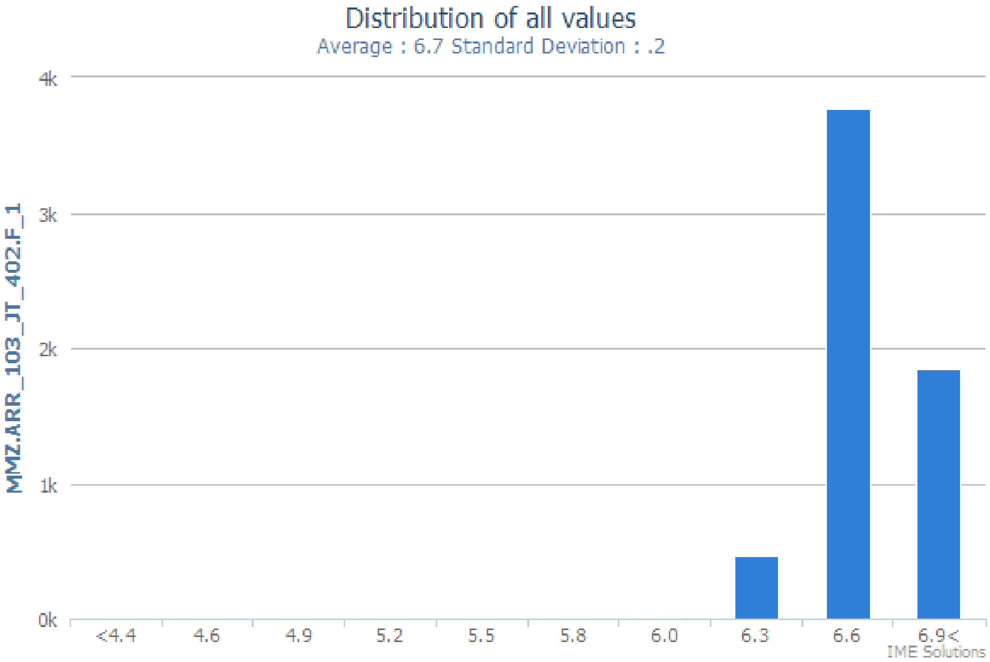


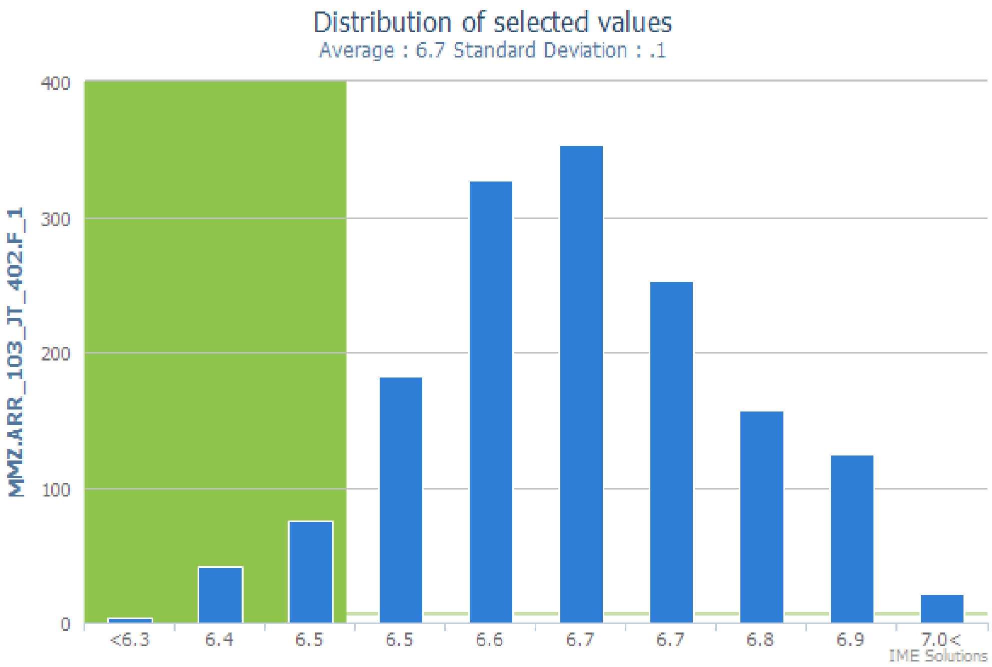

Distribution of selected values
Average : 8 Standard Deviation : .4
MMZ.ARR_103_JT_401.F_1
600
500
400
300
200
100
0
<6.5
6.7
7.0
7.3
7.6
7.8
8.1
8.4
8.6
8.9<
IME Solutions

Ball Mill Power (MW)

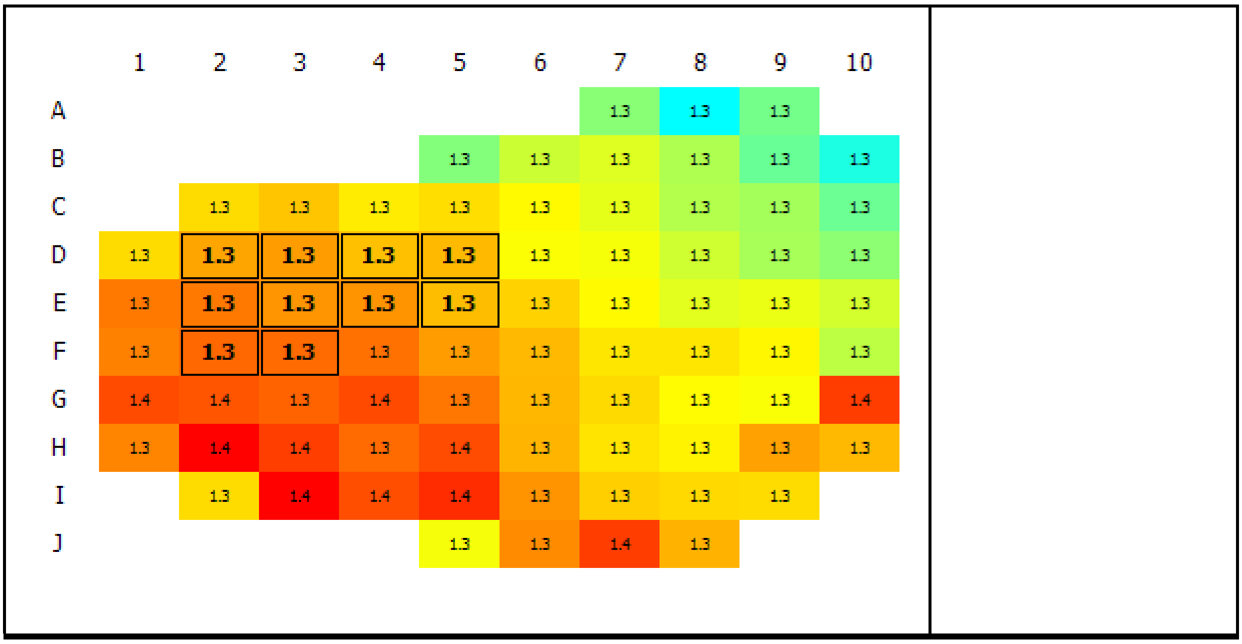


	1	2	3	4	5	6	7	8	9	10
A							6.7	6.7	6.4	
B					6.6	6.6	6.6	6.8	6.7	6.7
C		6.6	6.6	6.7	6.7	6.7	6.7	6.7	6.8	6.7
D	6.8	6.7	6.7	6.7	6.7	6.7	6.7	6.7	6.8	6.7
E	6.6	6.6	6.7	6.7	6.7	6.7	6.7	6.8	6.8	6.7
F	6.6	6.6	6.6	6.6	6.7	6.7	6.7	6.7	6.8	6.8
G	6.6	6.6	6.6	6.6	6.6	6.7	6.7	6.7	6.7	6.7
H	6.6	6.6	6.6	6.6	6.5	6.6	6.7	6.7	6.7	6.7
I		6.5	6.6	6.6	6.6	6.7	6.7	6.7	6.8	
J					6.6	6.6	6.5	6.7		

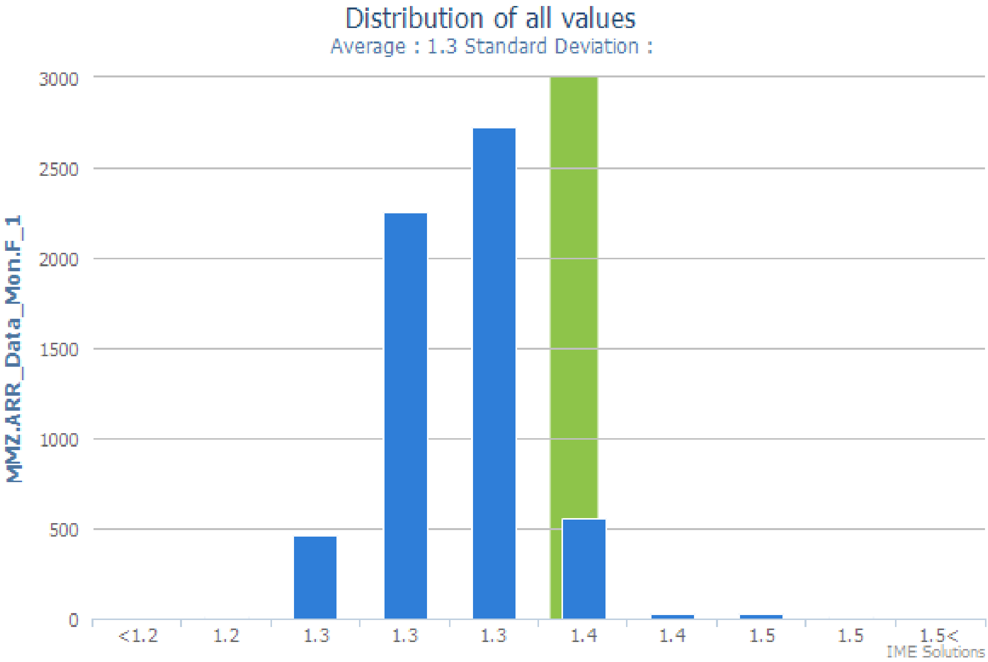


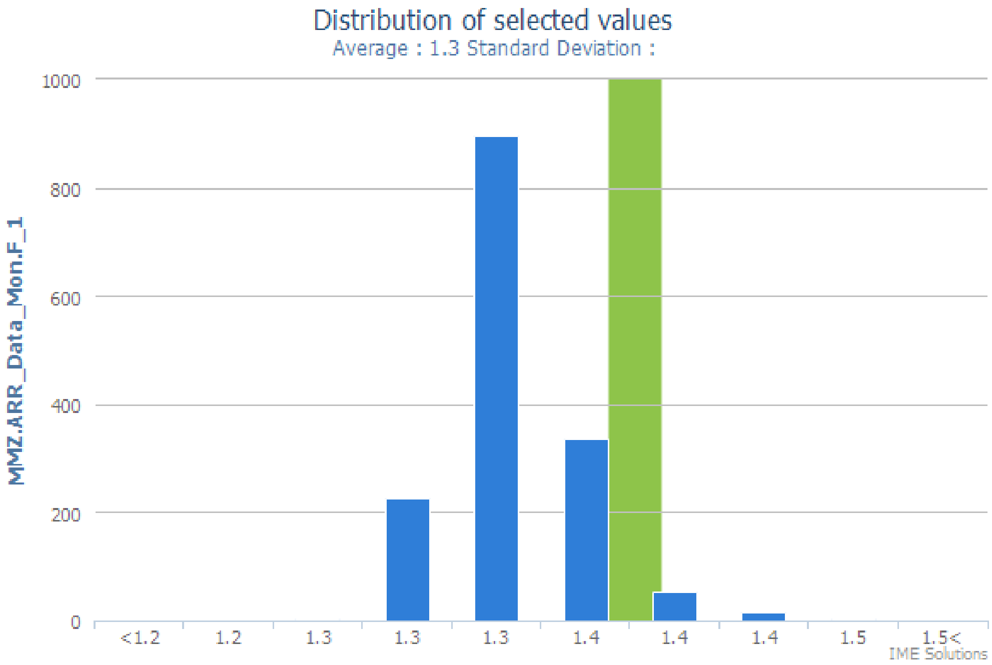

Distribution of selected values
Average : 6.7 Standard Deviation : .1
MMZ.ARR_103_JT_402.F_1
400
300
200
100
0
<6.3
6.4
6.5
6.5
6.6
6.7
6.7
6.8
6.9
7.0<
IME Solutions

Flotation Feed Density (SG)

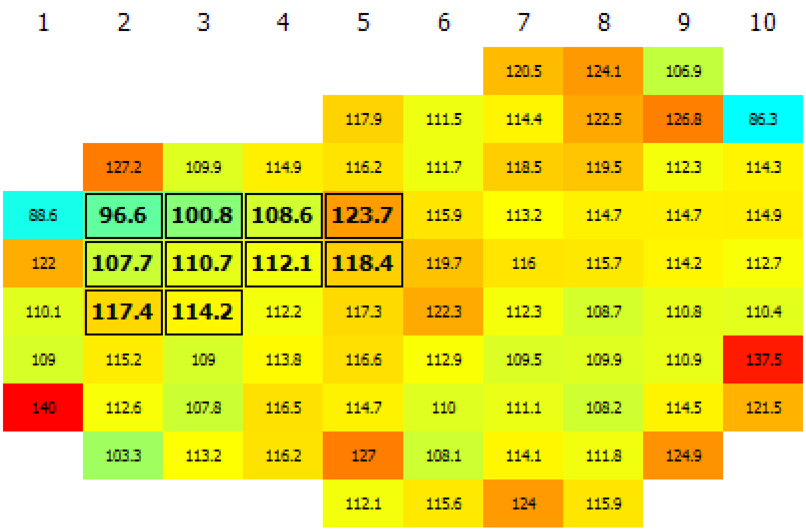


	1	2	3	4	5	6	7	8	9	10
A							1.3	1.3	1.3	
B					1.3	1.3	1.3	1.3	1.3	1.3
C		1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3
D	1.3	**1.3**	**1.3**	**1.3**	**1.3**	1.3	1.3	1.3	1.3	1.3
E	1.3	**1.3**	**1.3**	**1.3**	**1.3**	1.3	1.3	1.3	1.3	1.3
F	1.3	**1.3**	**1.3**	1.3	1.3	1.3	1.3	1.3	1.3	1.3
G	1.4	1.4	1.3	1.4	1.3	1.3	1.3	1.3	1.3	1.4
H	1.3	1.4	1.4	1.3	1.4	1.3	1.3	1.3	1.3	1.3
I		1.3	1.4	1.4	1.4	1.3	1.3	1.3	1.3	
J					1.3	1.3	1.4	1.3		

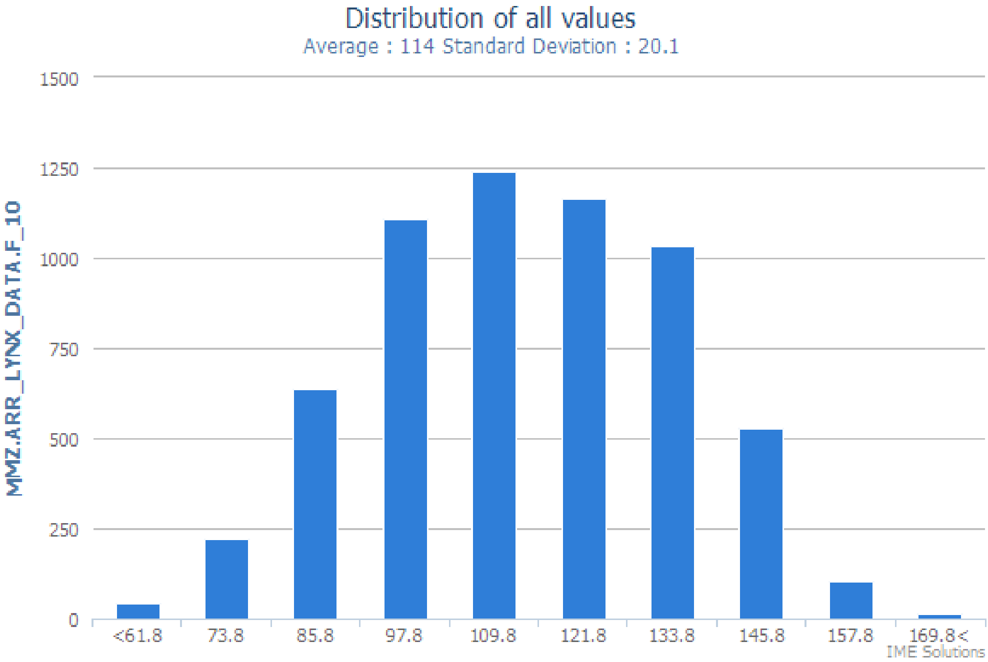


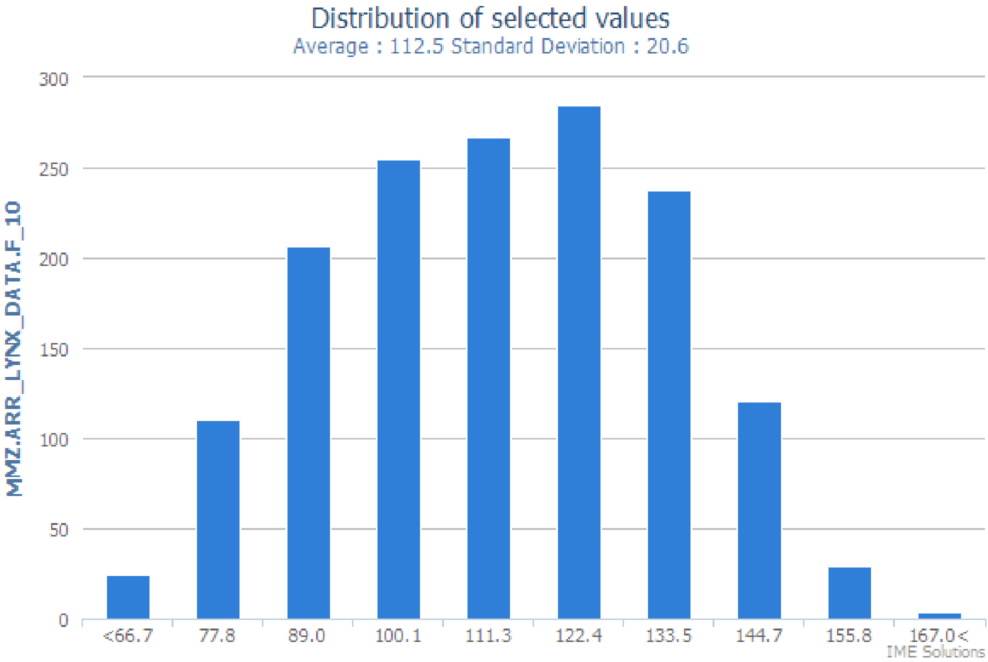

Distribution of selected values
Average : 1.3 Standard Deviation :
MMZ.ARR_Data_Mon.F_1
1000
800
600
400
200
0
<1.2
1.2
1.3
1.3
1.3
1.4
1.4
1.4
1.5
1.5<
IME Solutions

Mill Feed P_{80}

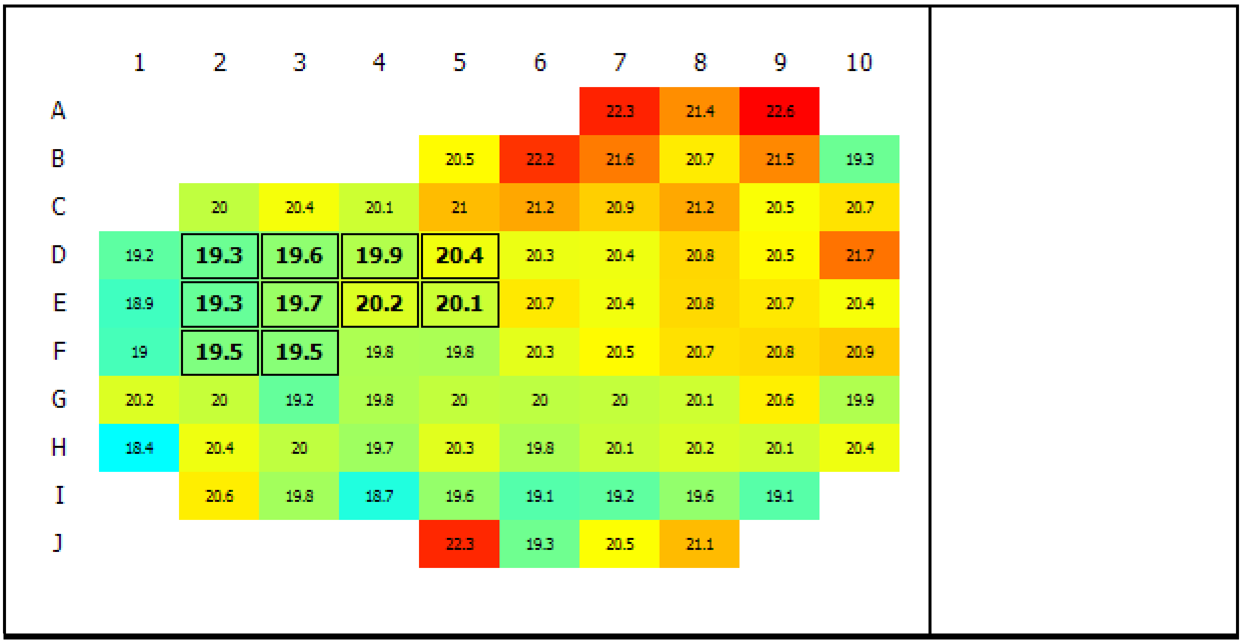


	1	2	3	4	5	6	7	8	9	10
A							120.5	124.1	106.9	
B					117.9	111.5	114.4	122.5	126.8	86.3
C		127.2	109.9	114.9	116.2	111.7	118.5	119.5	112.3	114.3
D	88.6	**96.6**	**100.8**	**108.6**	**123.7**	115.9	113.2	114.7	114.7	114.9
E	122	**107.7**	**110.7**	**112.1**	**118.4**	119.7	116	115.7	114.2	112.7
F	110.1	**117.4**	**114.2**	112.2	117.3	122.3	112.3	108.7	110.8	110.4
G	109	115.2	109	113.8	116.6	112.9	109.5	109.9	110.9	137.5
H	140	112.6	107.8	116.5	114.7	110	111.1	108.2	114.5	121.5
I		103.3	113.2	116.2	127	108.1	114.1	111.8	124.9	
J					112.1	115.6	124	115.9		

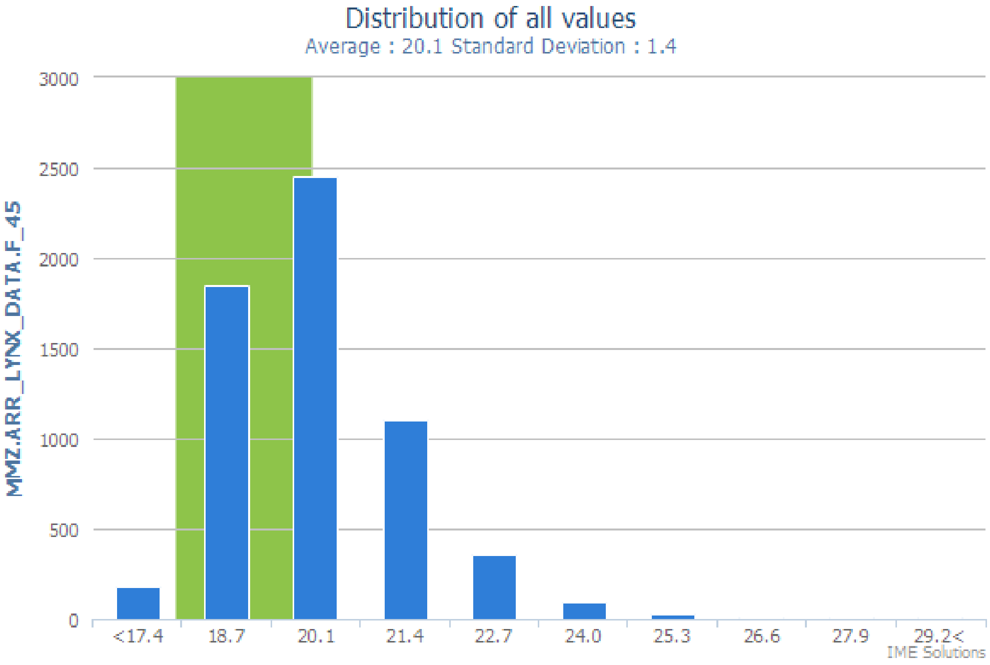


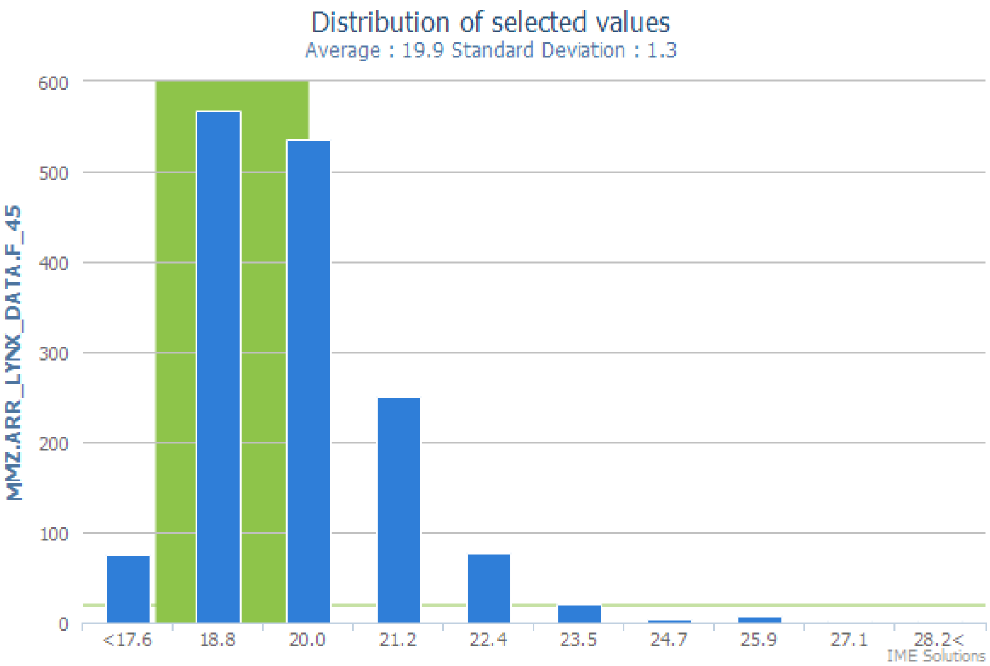

Distribution of selected values
Average : 112.5 Standard Deviation : 20.6
MMZ.ARR_LYNX_DATA.F_10
300
250
200
150
100
50
0
<66.7
77.8
89.0
100.1
111.3
122.4
133.5
144.7
155.8
167.0<
IME Solutions

Pebble Crusher P_{80}

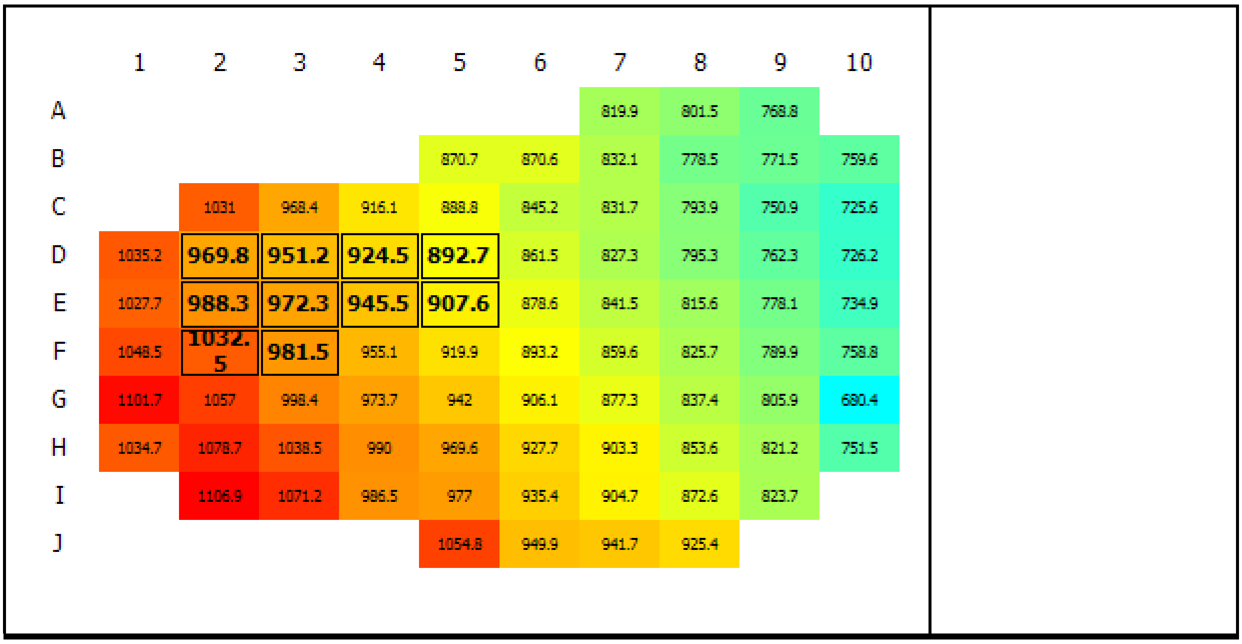


	1	2	3	4	5	6	7	8	9	10
A							22.3	21.4	22.6	
B					20.5	22.2	21.6	20.7	21.5	19.3
C		20	20.4	20.1	21	21.2	20.9	21.2	20.5	20.7
D	19.2	**19.3**	**19.6**	**19.9**	**20.4**	20.3	20.4	20.8	20.5	21.7
E	18.9	**19.3**	**19.7**	**20.2**	**20.1**	20.7	20.4	20.8	20.7	20.4
F	19	**19.5**	**19.5**	19.8	19.8	20.3	20.5	20.7	20.8	20.9
G	20.2	20	19.2	19.8	20	20	20	20.1	20.6	19.9
H	18.4	20.4	20	19.7	20.3	19.8	20.1	20.2	20.1	20.4
I		20.6	19.8	18.7	19.6	19.1	19.2	19.6	19.1	
J					22.3	19.3	20.5	21.1		

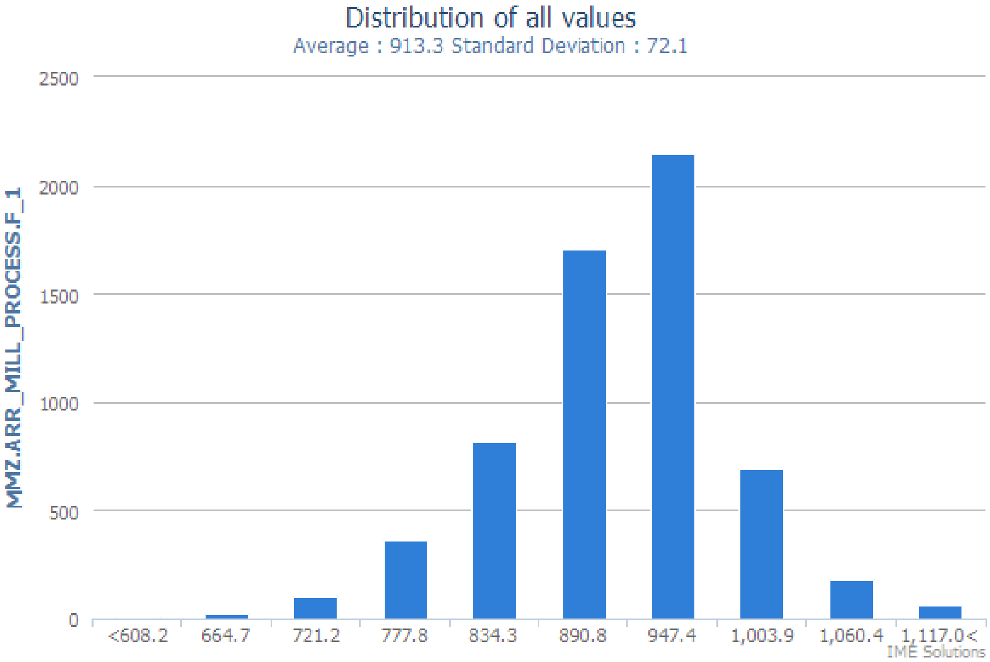


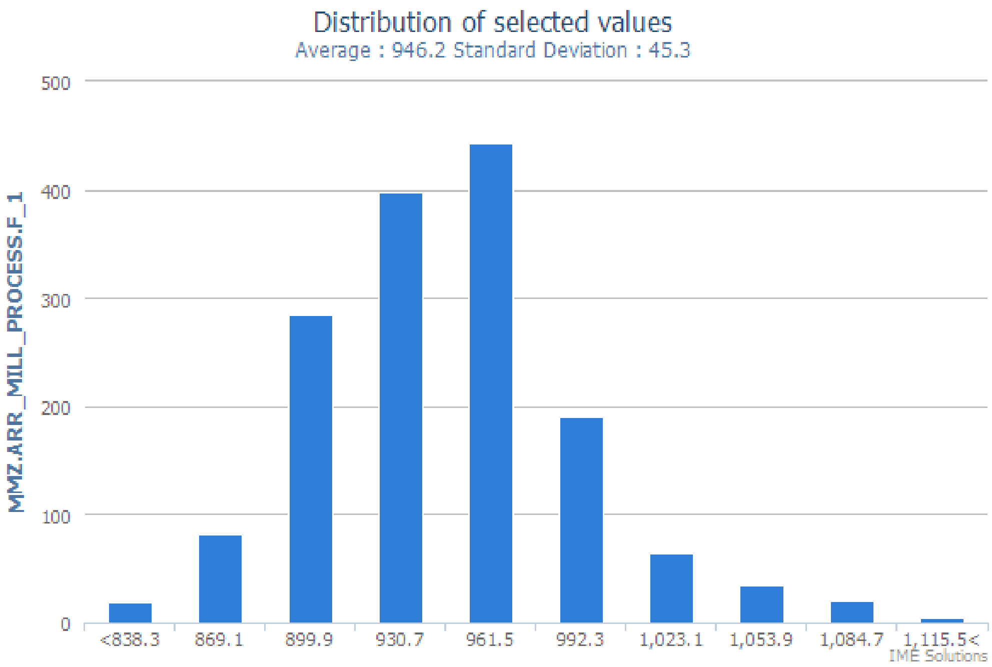

Distribution of selected values
Average : 19.9 Standard Deviation : 1.3
MMZ.ARR_LYNX_DATA.F_45
600
500
400
300
200
100
0
<17.6
18.8
20.0
21.2
22.4
23.5
24.7
25.9
27.1
28.2<
IME Solutions

Total Mill Feed Rate (tons/hour)

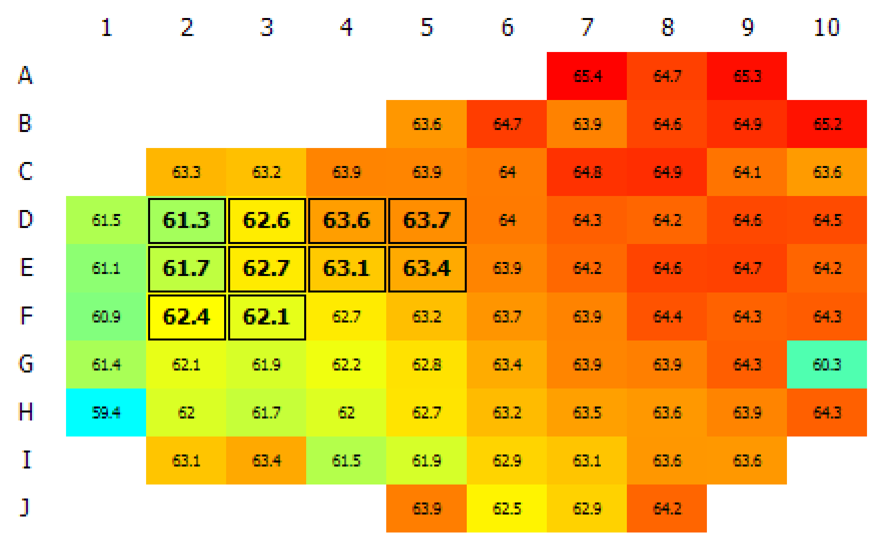


	1	2	3	4	5	6	7	8	9	10
A							819.9	801.5	768.8	
B					870.7	870.6	832.1	778.5	771.5	759.6
C		1031	968.4	916.1	888.8	845.2	831.7	793.9	750.9	725.6
D	1035.2	**969.8**	**951.2**	**924.5**	**892.7**	861.5	827.3	795.3	762.3	726.2
E	1027.7	**988.3**	**972.3**	**945.5**	**907.6**	878.6	841.5	815.6	778.1	734.9
F	1048.5	**1032.5**	**981.5**	955.1	919.9	893.2	859.6	825.7	789.9	758.8
G	1101.7	1057	998.4	973.7	942	906.1	877.3	837.4	805.9	680.4
H	1034.7	1078.7	1038.5	990	969.6	927.7	903.3	853.6	821.2	751.5
I		1106.9	1071.2	986.5	977	935.4	904.7	872.6	823.7	
J					1054.8	949.9	941.7	925.4		

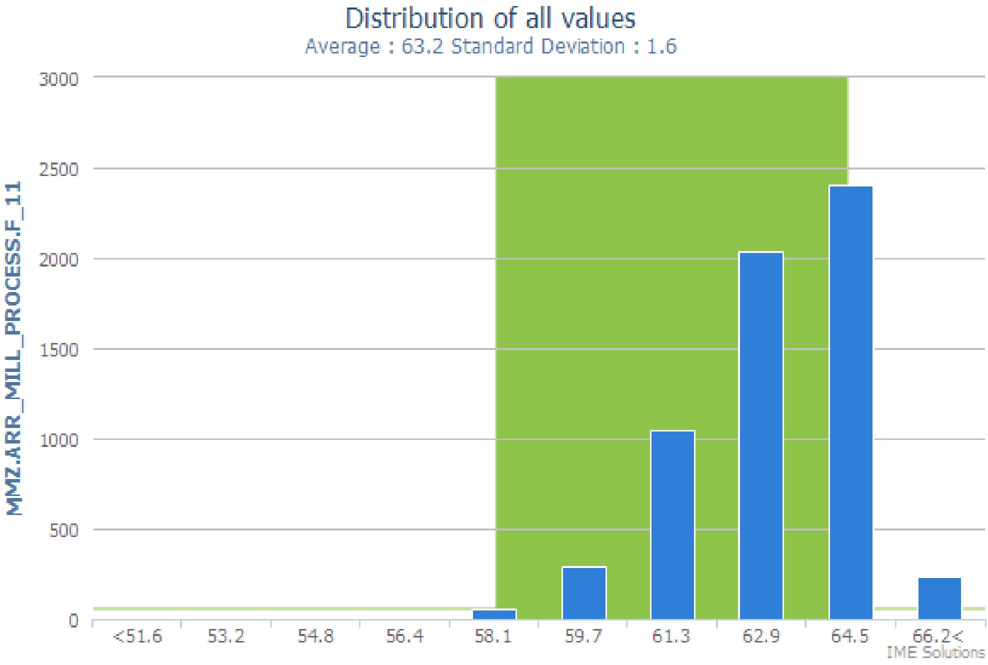


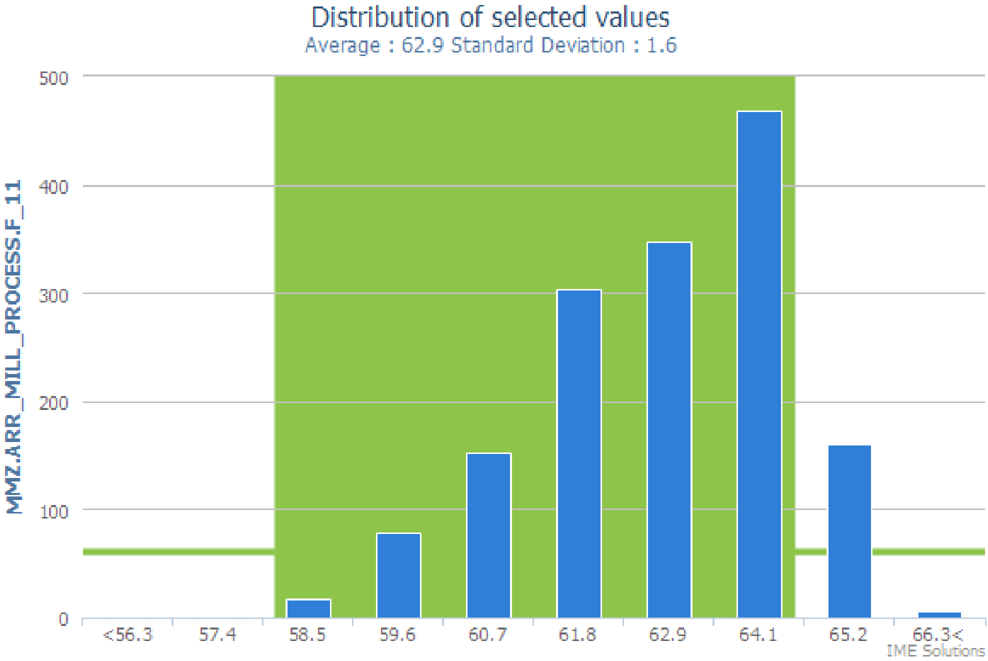

Distribution of selected values
Average : 946.2 Standard Deviation : 45.3
MMZ.ARR_MILL_PROCESS.F_1
500
400
300
200
100
0
<838.3
869.1
899.9
930.7
961.5
992.3
1,023.1
1,053.9
1,084.7
1,115.5<
IME Solutions

FAG Mill Average Bearing Pressure (bar)

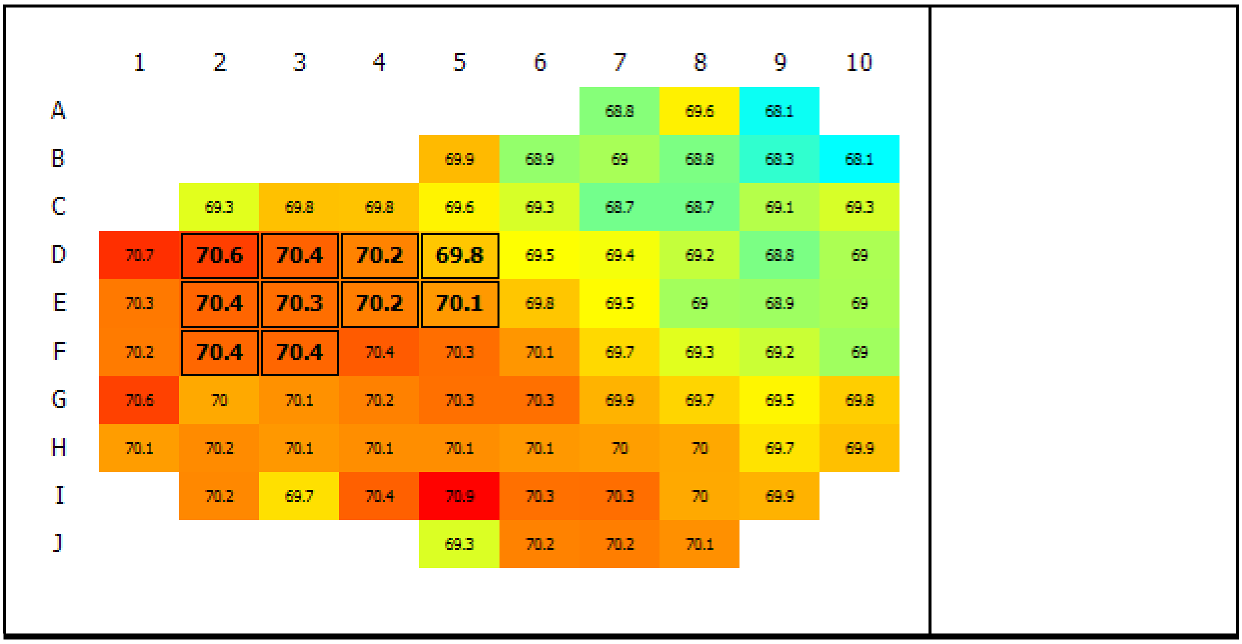


	1	2	3	4	5	6	7	8	9	10
A							65.4	64.7	65.3	
B					63.6	64.7	63.9	64.6	64.9	65.2
C		63.3	63.2	63.9	63.9	64	64.8	64.9	64.1	63.6
D	61.5	**61.3**	**62.6**	**63.6**	**63.7**	64	64.3	64.2	64.6	64.5
E	61.1	**61.7**	**62.7**	**63.1**	**63.4**	63.9	64.2	64.6	64.7	64.2
F	60.9	**62.4**	**62.1**	62.7	63.2	63.7	63.9	64.4	64.3	64.3
G	61.4	62.1	61.9	62.2	62.8	63.4	63.9	63.9	64.3	60.3
H	59.4	62	61.7	62	62.7	63.2	63.5	63.6	63.9	64.3
I		63.1	63.4	61.5	61.9	62.9	63.1	63.6	63.6	
J					63.9	62.5	62.9	64.2		

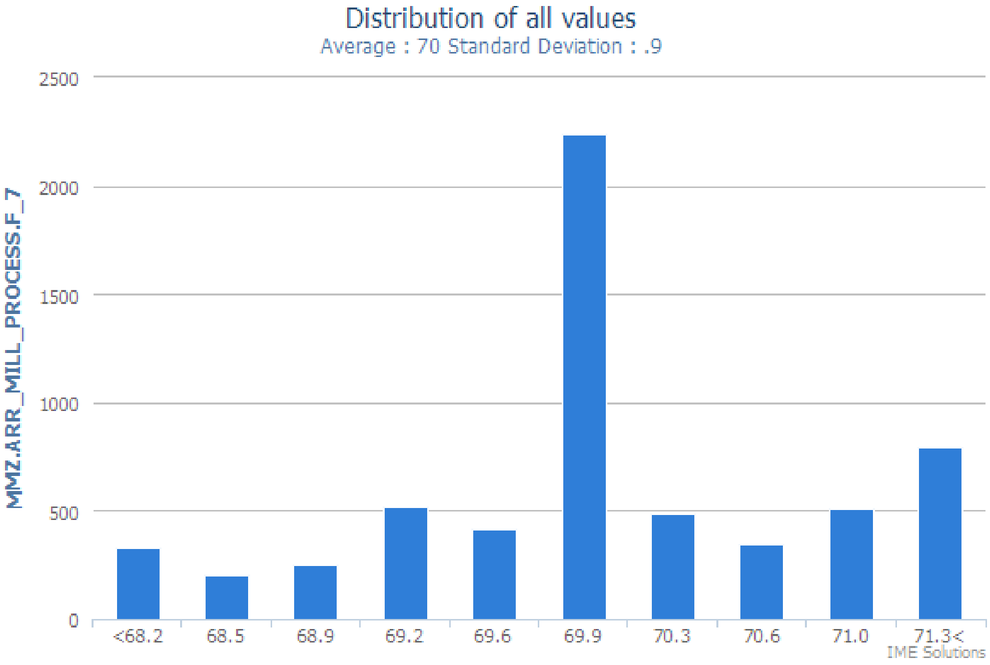


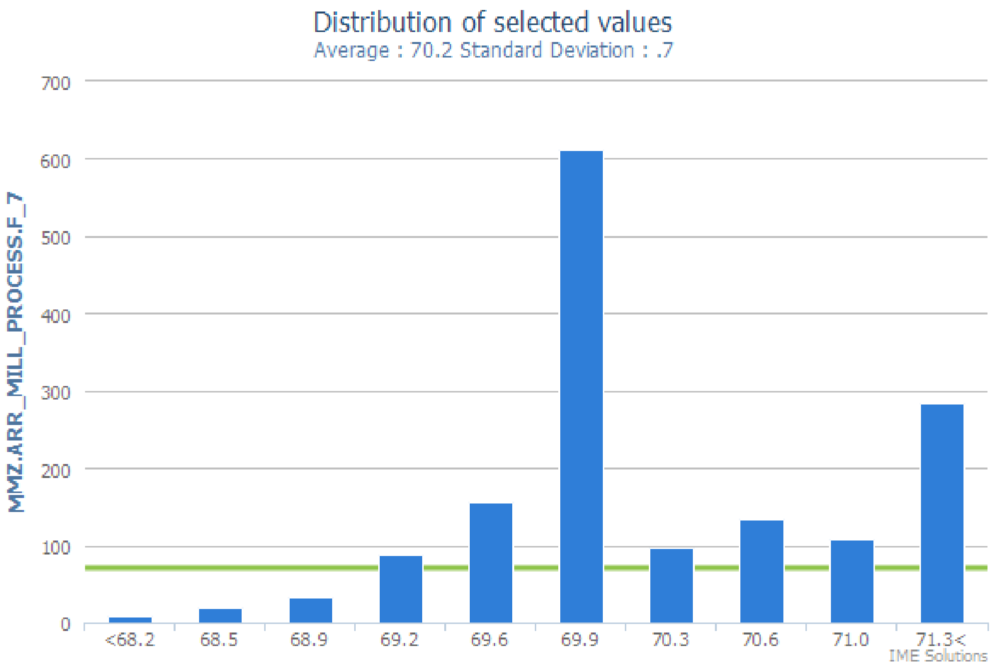

Distribution of selected values
Average : 62.9 Standard Deviation : 1.6
MMZ.ARR_MILL_PROCESS.F_11
500
400
300
200
100
0
<56.3
57.4
58.5
59.6
60.7
61.8
62.9
64.1
65.2
66.3<
IME Solutions

FAG Mill In-Mill Density (% solids)

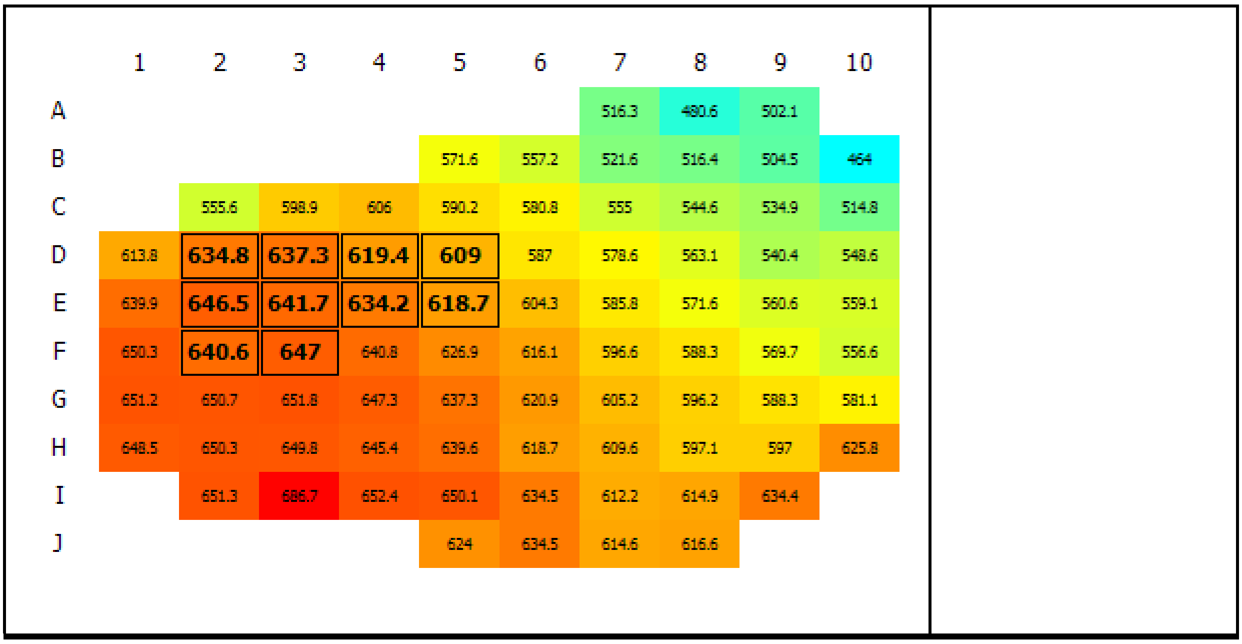


	1	2	3	4	5	6	7	8	9	10
A							68.8	69.6	68.1	
B					69.9	68.9	69	68.8	68.3	68.1
C		69.3	69.8	69.8	69.6	69.3	68.7	68.7	69.1	69.3
D	70.7	**70.6**	**70.4**	**70.2**	**69.8**	69.5	69.4	69.2	68.8	69
E	70.3	**70.4**	**70.3**	**70.2**	**70.1**	69.8	69.5	69	68.9	69
F	70.2	**70.4**	**70.4**	70.4	70.3	70.1	69.7	69.3	69.2	69
G	70.6	70	70.1	70.2	70.3	70.3	69.9	69.7	69.5	69.8
H	70.1	70.2	70.1	70.1	70.1	70.1	70	70	69.7	69.9
I		70.2	69.7	70.4	70.9	70.3	70.3	70	69.9	
J					69.3	70.2	70.2	70.1		

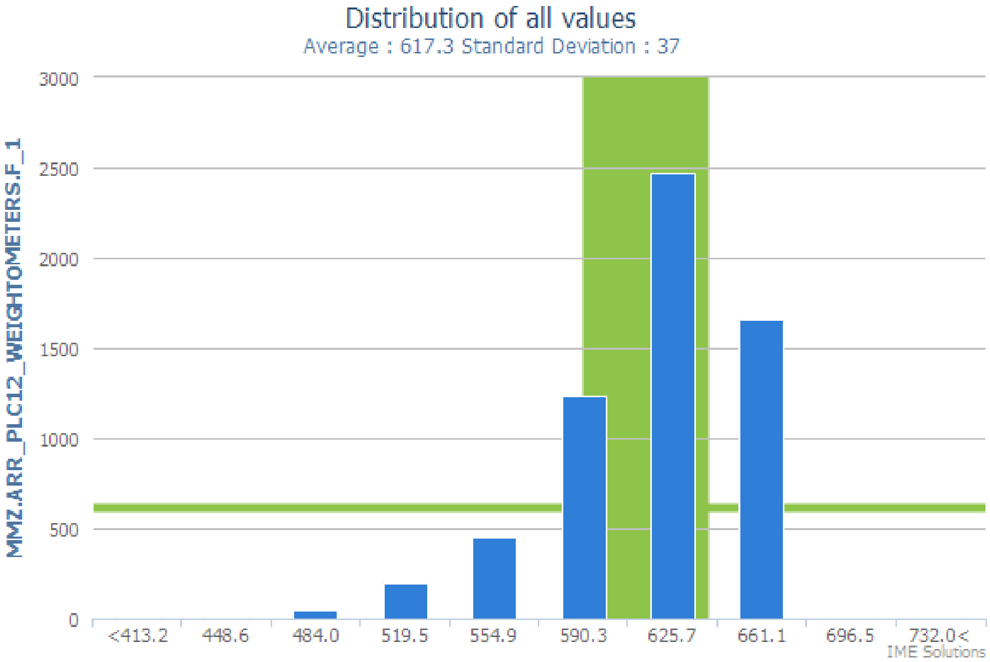


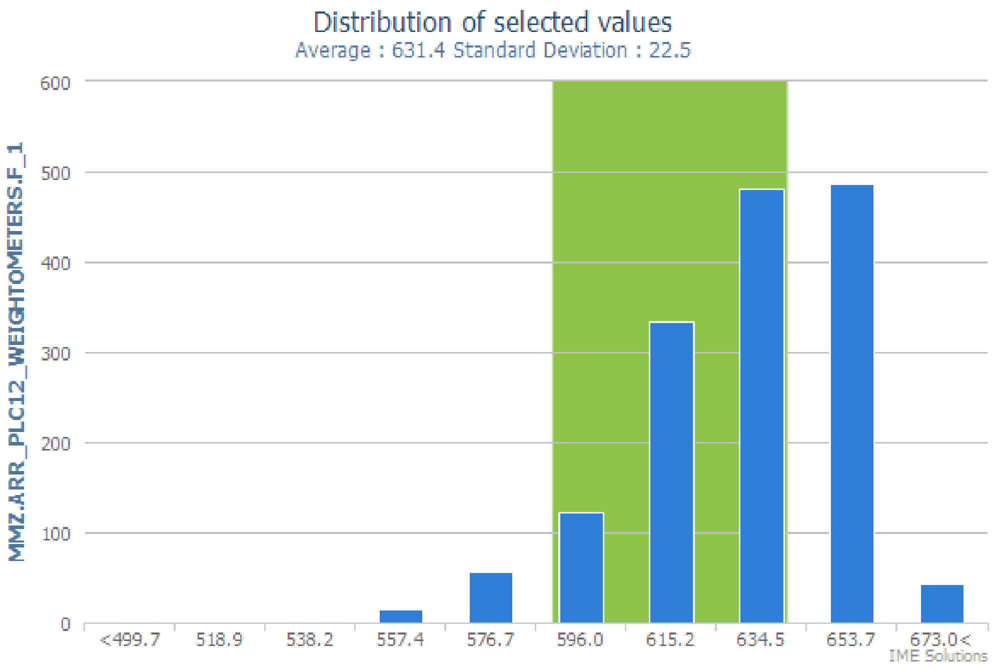

Distribution of selected values
Average : 70.2 Standard Deviation : .7
MMZ.ARR_MILL_PROCESS.F_7
700
600
500
400
300
200
100
0
<68.2
68.5
68.9
69.2
69.6
69.9
70.3
70.6
71.0
71.3<
IME Solutions

FAG Mill Feed Rate [Tons/hour]

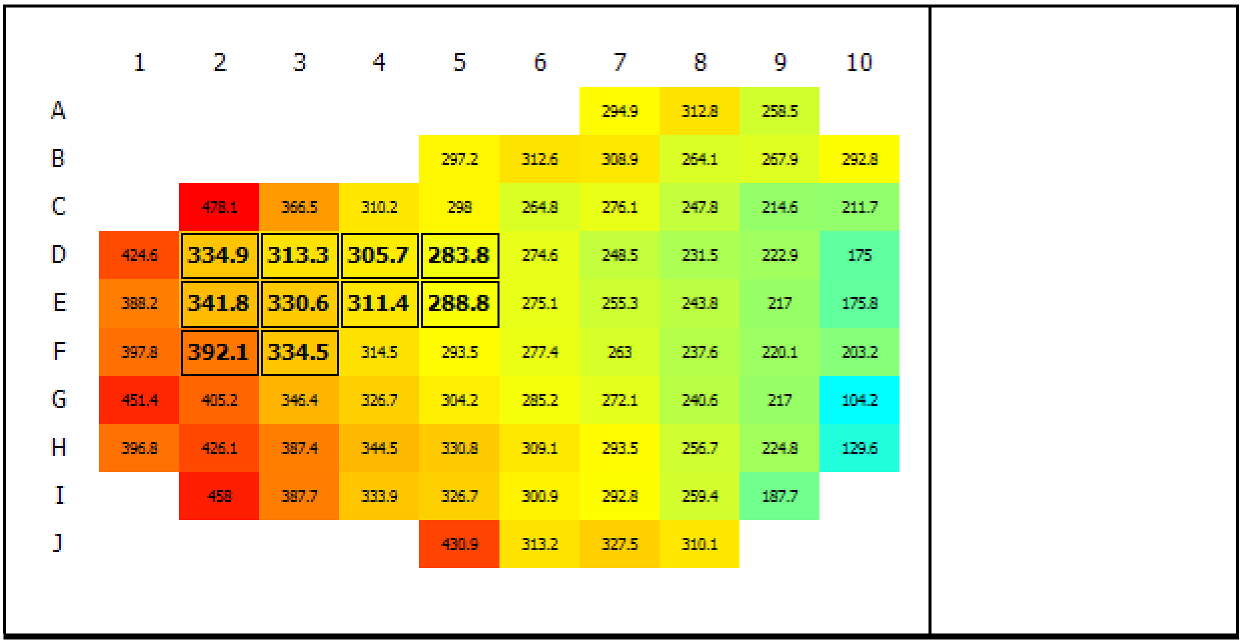


	1	2	3	4	5	6	7	8	9	10
A							516.3	480.6	502.1	
B					571.6	557.2	521.6	516.4	504.5	464
C		555.6	598.9	606	590.2	580.8	555	544.6	534.9	514.8
D	613.8	**634.8**	**637.3**	**619.4**	**609**	587	578.6	563.1	540.4	548.6
E	639.9	**646.5**	**641.7**	**634.2**	**618.7**	604.3	585.8	571.6	560.6	559.1
F	650.3	**640.6**	**647**	640.8	626.9	616.1	596.6	588.3	569.7	556.6
G	651.2	650.7	651.8	647.3	637.3	620.9	605.2	596.2	588.3	581.1
H	648.5	650.3	649.8	645.4	639.6	618.7	609.6	597.1	597	625.8
I		651.3	686.7	652.4	650.1	634.5	612.2	614.9	634.4	
J					624	634.5	614.6	616.6		

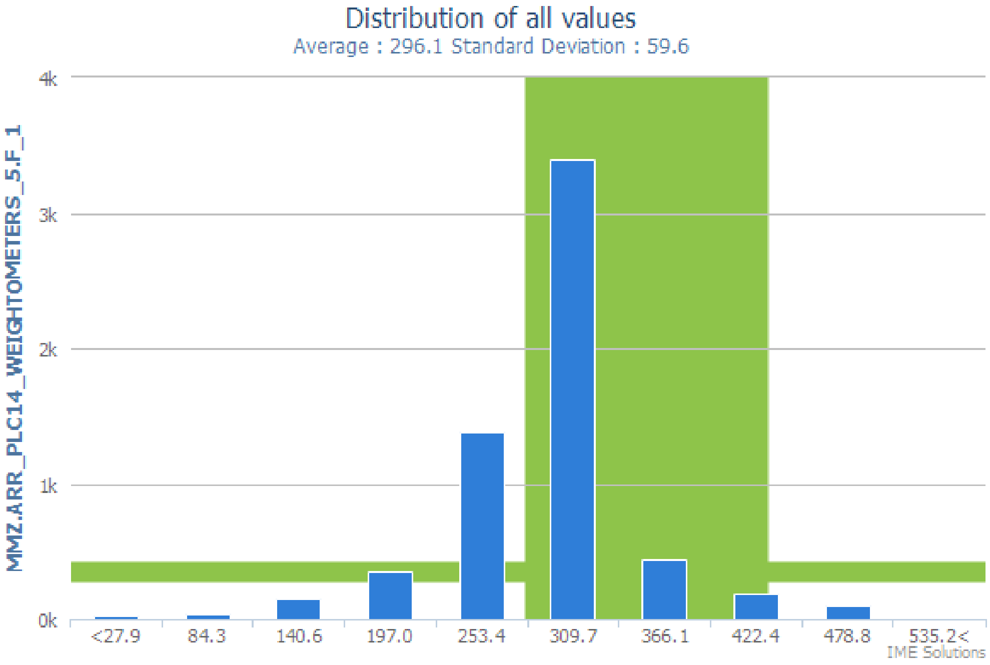


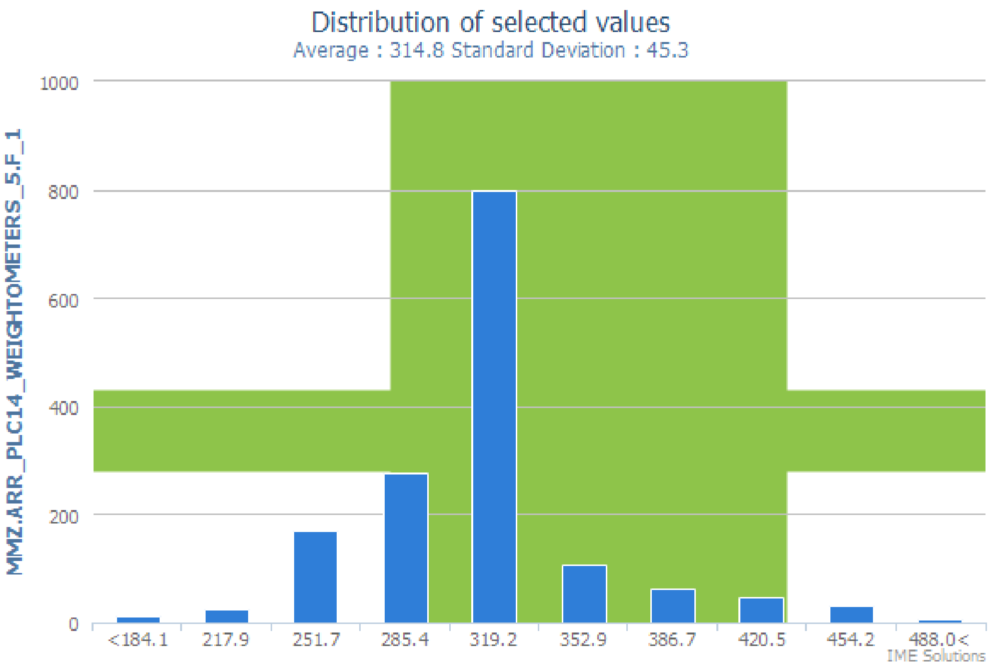

Distribution of selected values
Average : 631.4 Standard Deviation : 22.5
MMZ.ARR_PLC12_WEIGHTOMETERS.F_1
600
500
400
300
200
100
0
<499.7
518.9
538.2
557.4
576.7
596.0
615.2
634.5
653.7
673.0<
IME Solutions

Pebble Crusher Feed Rate [Tons/hour]

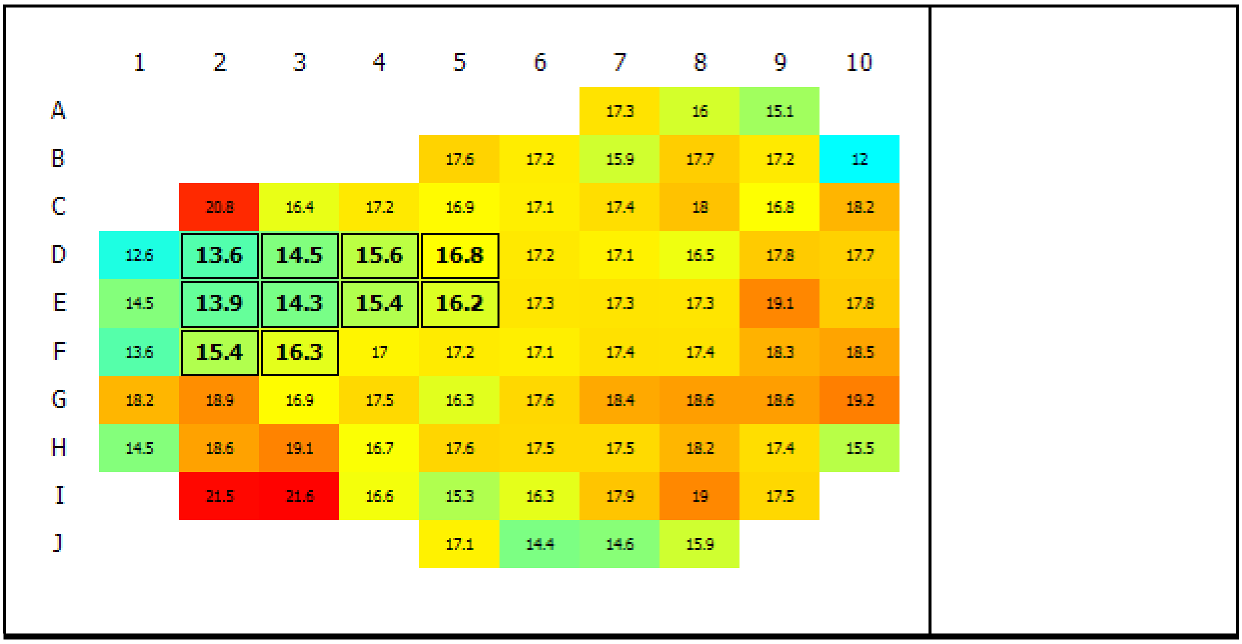


	1	2	3	4	5	6	7	8	9	10
A							294.9	312.8	258.5	
B					297.2	312.6	308.9	264.1	267.9	292.8
C		478.1	366.5	310.2	298	264.8	276.1	247.8	214.6	211.7
D	424.6	**334.9**	**313.3**	**305.7**	**283.8**	274.6	248.5	231.5	222.9	175
E	388.2	**341.8**	**330.6**	**311.4**	**288.8**	275.1	255.3	243.8	217	175.8
F	397.8	**392.1**	**334.5**	314.5	293.5	277.4	263	237.6	220.1	203.2
G	451.4	405.2	346.4	326.7	304.2	285.2	272.1	240.6	217	104.2
H	396.8	426.1	387.4	344.5	330.8	309.1	293.5	256.7	224.8	129.6
I		458	387.7	333.9	326.7	300.9	292.8	259.4	187.7	
J					430.9	313.2	327.5	310.1		

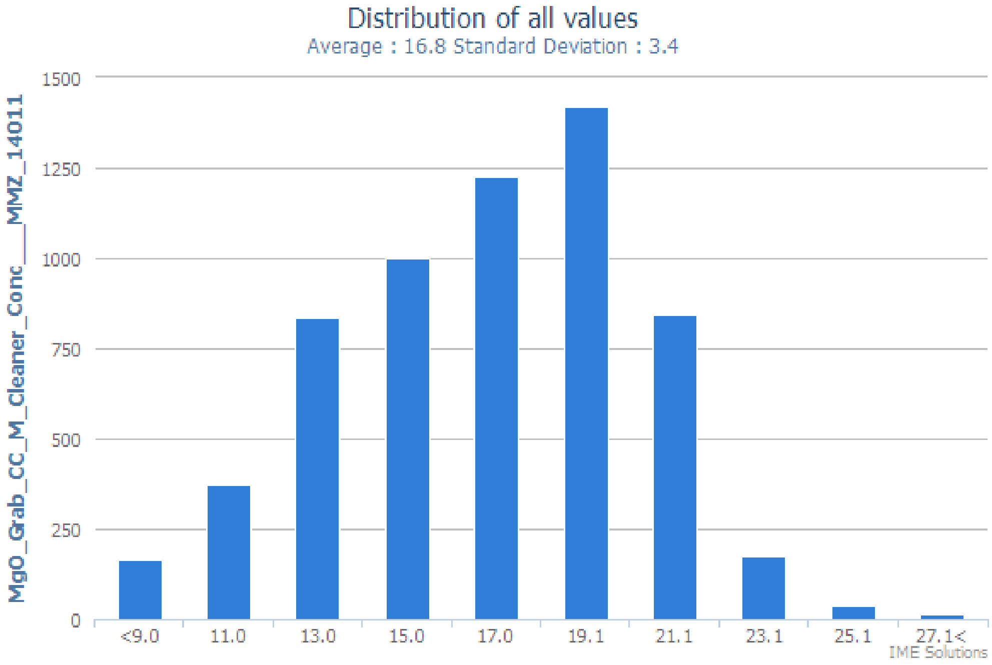


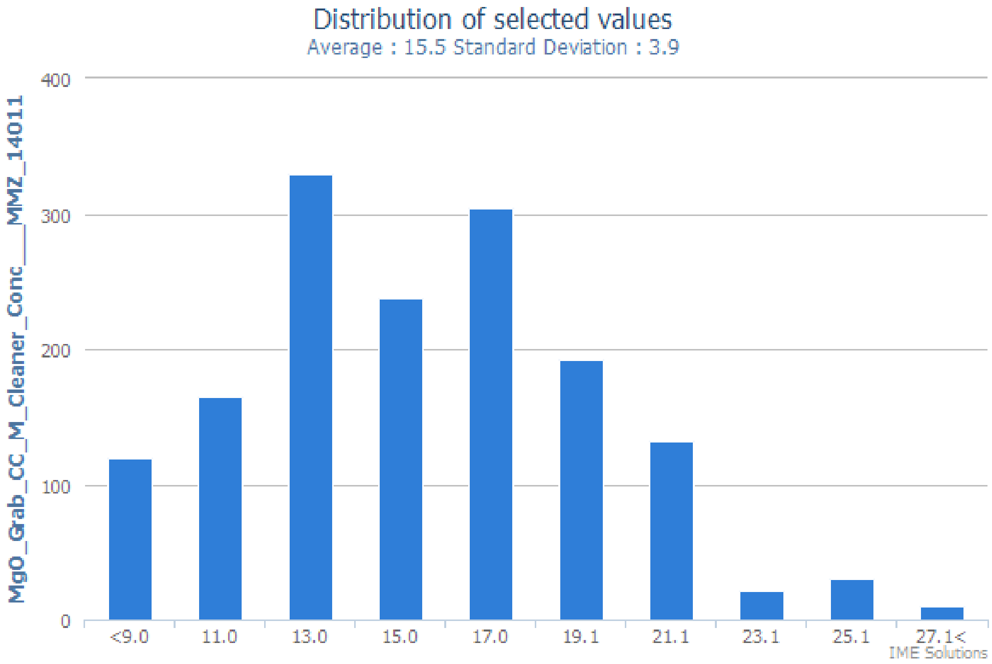

Distribution of selected values
Average : 314.8 Standard Deviation : 45.3
MMZ.ARR_PLC14_WEIGHTOMETERS_5.F_1
1000
800
600
400
200
0
<184.1
217.9
251.7
285.4
319.2
352.9
386.7
420.5
454.2
488.0<
IME Solutions

Cleaner Concentrate MgO Grade

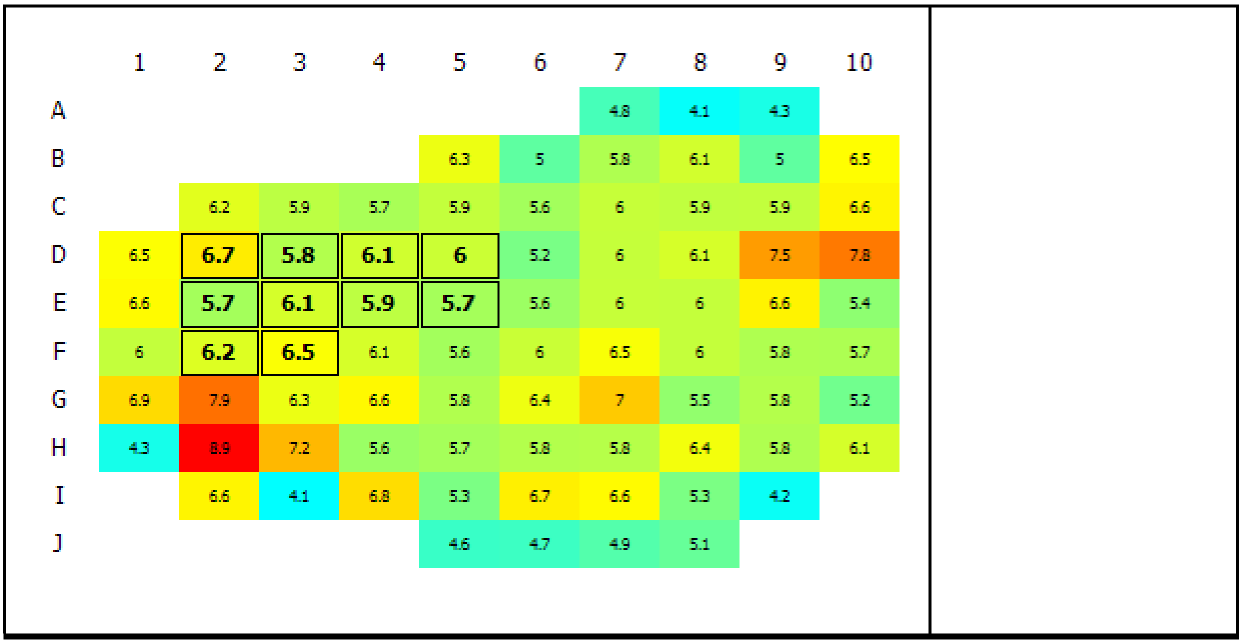


	1	2	3	4	5	6	7	8	9	10
A							17.3	16	15.1	
B					17.6	17.2	15.9	17.7	17.2	12
C		20.8	16.4	17.2	16.9	17.1	17.4	18	16.8	18.2
D	12.6	**13.6**	**14.5**	**15.6**	**16.8**	17.2	17.1	16.5	17.8	17.7
E	14.5	**13.9**	**14.3**	**15.4**	**16.2**	17.3	17.3	17.3	19.1	17.8
F	13.6	**15.4**	**16.3**	17	17.2	17.1	17.4	17.4	18.3	18.5
G	18.2	18.9	16.9	17.5	16.3	17.6	18.4	18.6	18.6	19.2
H	14.5	18.6	19.1	16.7	17.6	17.5	17.5	18.2	17.4	15.5
I		21.5	21.6	16.6	15.3	16.3	17.9	19	17.5	
J					17.1	14.4	14.6	15.9		

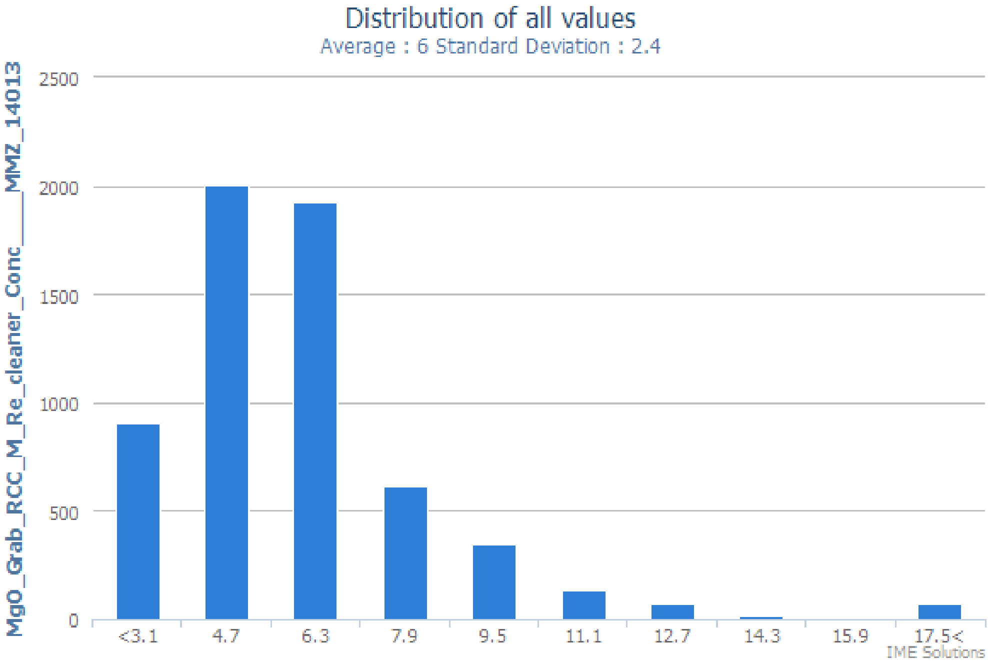


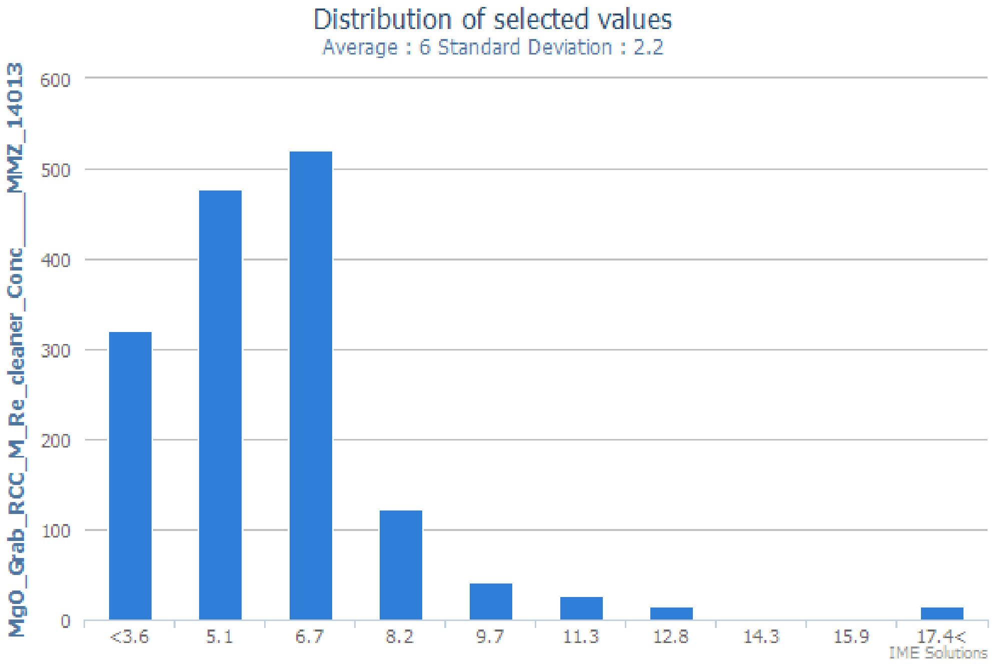

Distribution of selected values
Average : 15.5 Standard Deviation : 3.9
MgO_Grab_CC_M_Cleaner_Conc___MMZ_14011
400
300
200
100
0
<9.0
11.0
13.0
15.0
17.0
19.1
21.1
23.1
25.1
27.1<
IME Solutions

Re-Cleaner Concentrate MgO Grade (from grab samples)

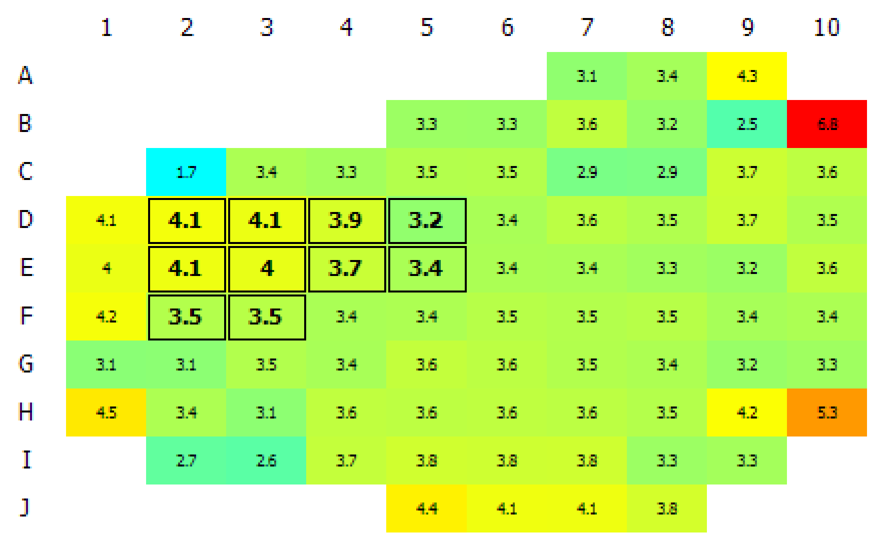


	1	2	3	4	5	6	7	8	9	10
A							4.8	4.1	4.3	
B					6.3	5	5.8	6.1	5	6.5
C		6.2	5.9	5.7	5.9	5.6	6	5.9	5.9	6.6
D	6.5	6.7	5.8	6.1	6	5.2	6	6.1	7.5	7.8
E	6.6	5.7	6.1	5.9	5.7	5.6	6	6	6.6	5.4
F	6	6.2	6.5	6.1	5.6	6	6.5	6	5.8	5.7
G	6.9	7.9	6.3	6.6	5.8	6.4	7	5.5	5.8	5.2
H	4.3	8.9	7.2	5.6	5.7	5.8	5.8	6.4	5.8	6.1
I		6.6	4.1	6.8	5.3	6.7	6.6	5.3	4.2	
J					4.6	4.7	4.9	5.1		

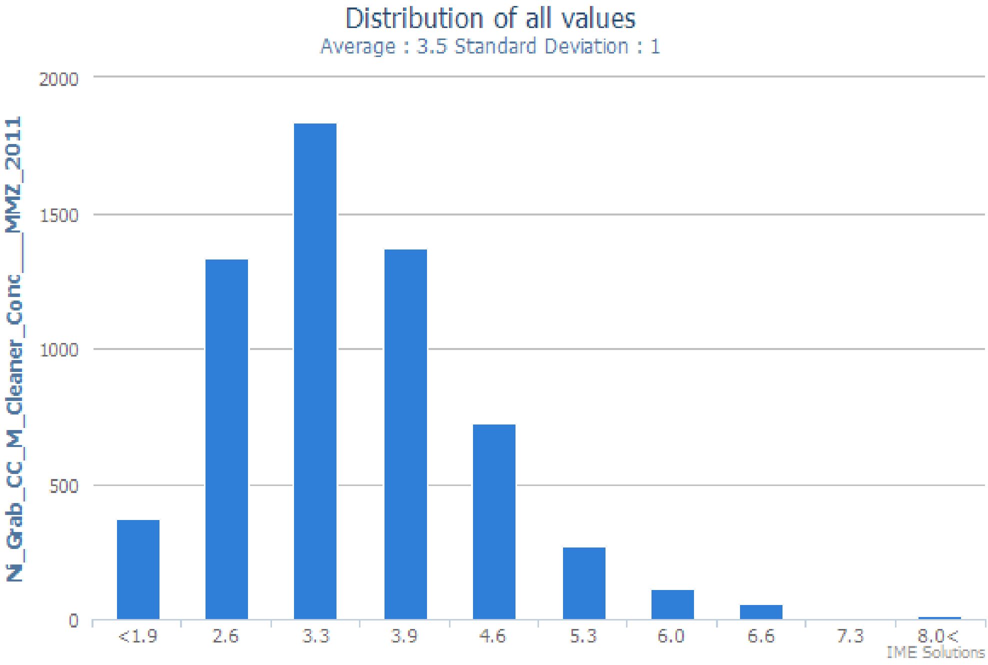


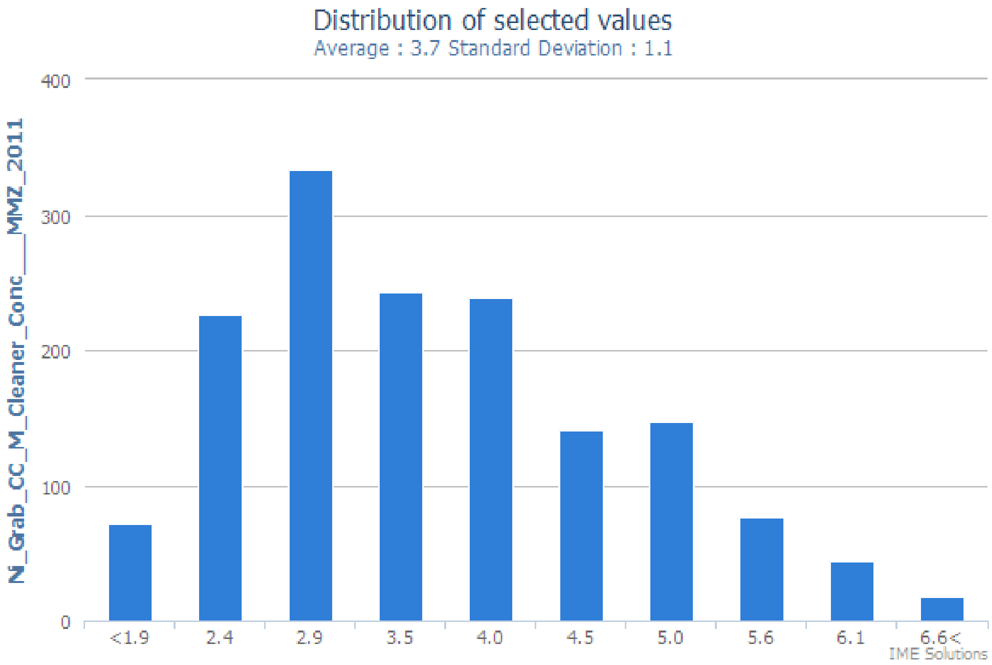

Distribution of selected values
Average : 6 Standard Deviation : 2.2
MgO_Grab_RCC_M_Re_cleaner_Conc____MMZ_14013
600
500
400
300
200
100
0
<3.6
5.1
6.7
8.2
9.7
11.3
12.8
14.3
15.9
17.4<
IME Solutions

Cleaner Concentrate Nickel Grade (from grab samples)

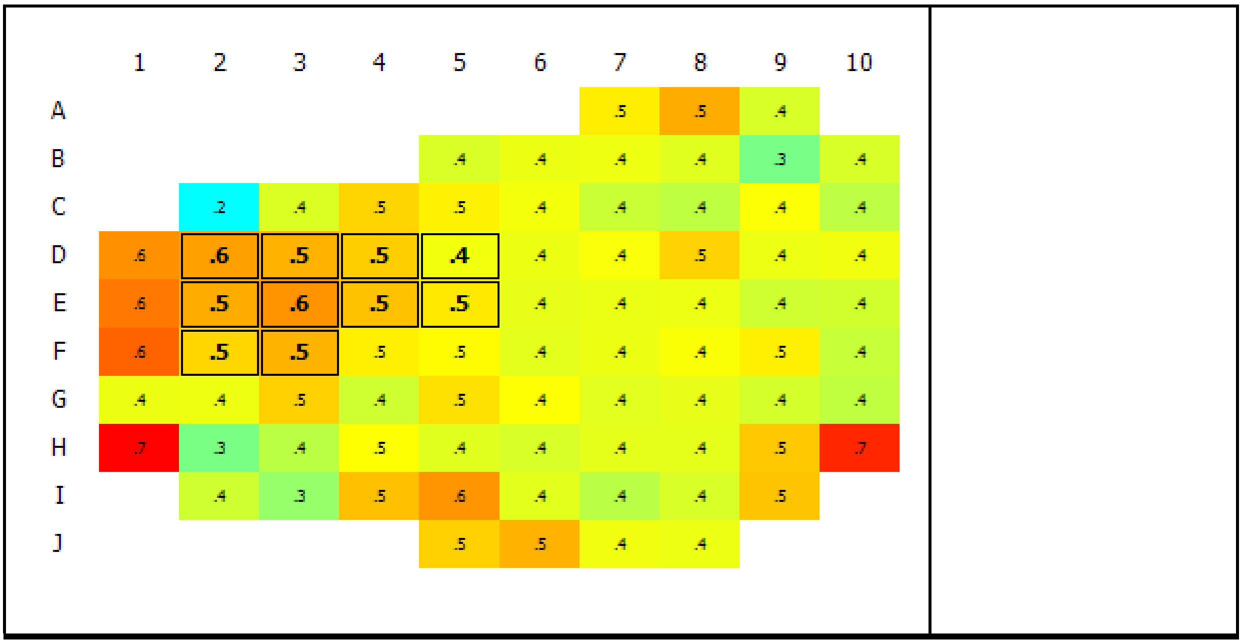


	1	2	3	4	5	6	7	8	9	10
A							3.1	3.4	4.3	
B					3.3	3.3	3.6	3.2	2.5	6.8
C		1.7	3.4	3.3	3.5	3.5	2.9	2.9	3.7	3.6
D	4.1	**4.1**	**4.1**	**3.9**	**3.2**	3.4	3.6	3.5	3.7	3.5
E	4	**4.1**	**4**	**3.7**	**3.4**	3.4	3.4	3.3	3.2	3.6
F	4.2	**3.5**	**3.5**	3.4	3.4	3.5	3.5	3.5	3.4	3.4
G	3.1	3.1	3.5	3.4	3.6	3.6	3.5	3.4	3.2	3.3
H	4.5	3.4	3.1	3.6	3.6	3.6	3.6	3.5	4.2	5.3
I		2.7	2.6	3.7	3.8	3.8	3.8	3.3	3.3	
J					4.4	4.1	4.1	3.8		

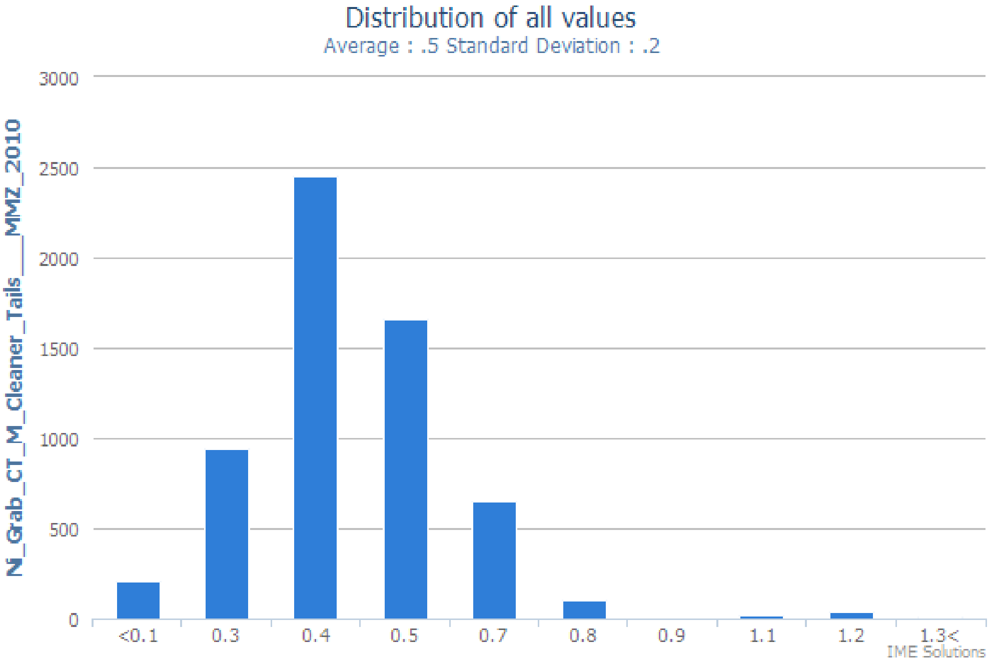


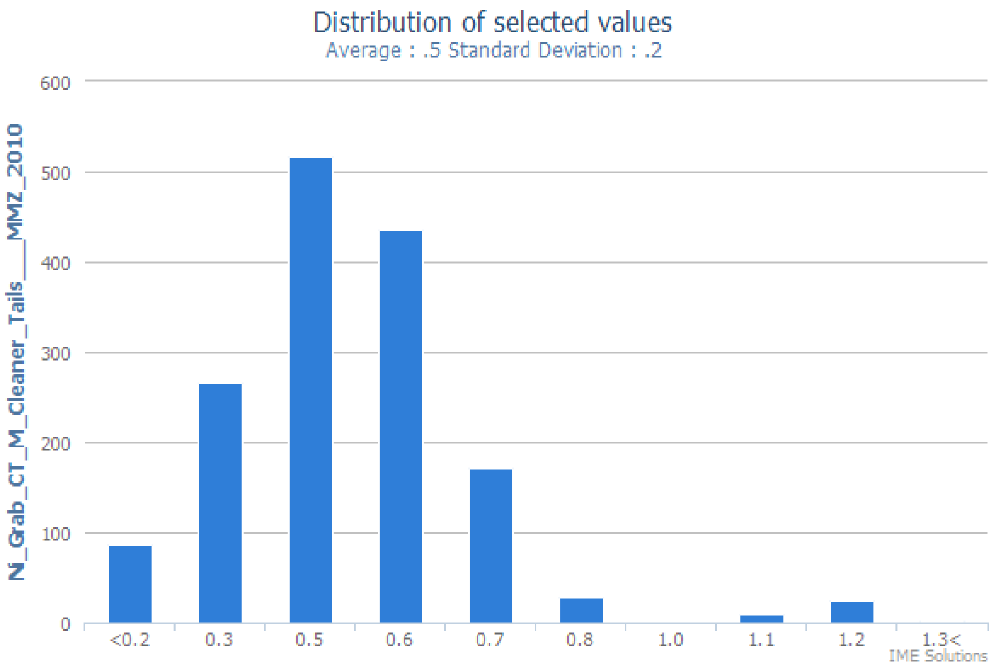

Distribution of selected values
Average : 3.7 Standard Deviation : 1.1
Ni_Grab_CC_M_Cleaner_Conc___MMZ_2011
400
300
200
100
0
<1.9
2.4
2.9
3.5
4.0
4.5
5.0
5.6
6.1
6.6<
IME Solutions

Cleaner Tails Nickel Grade

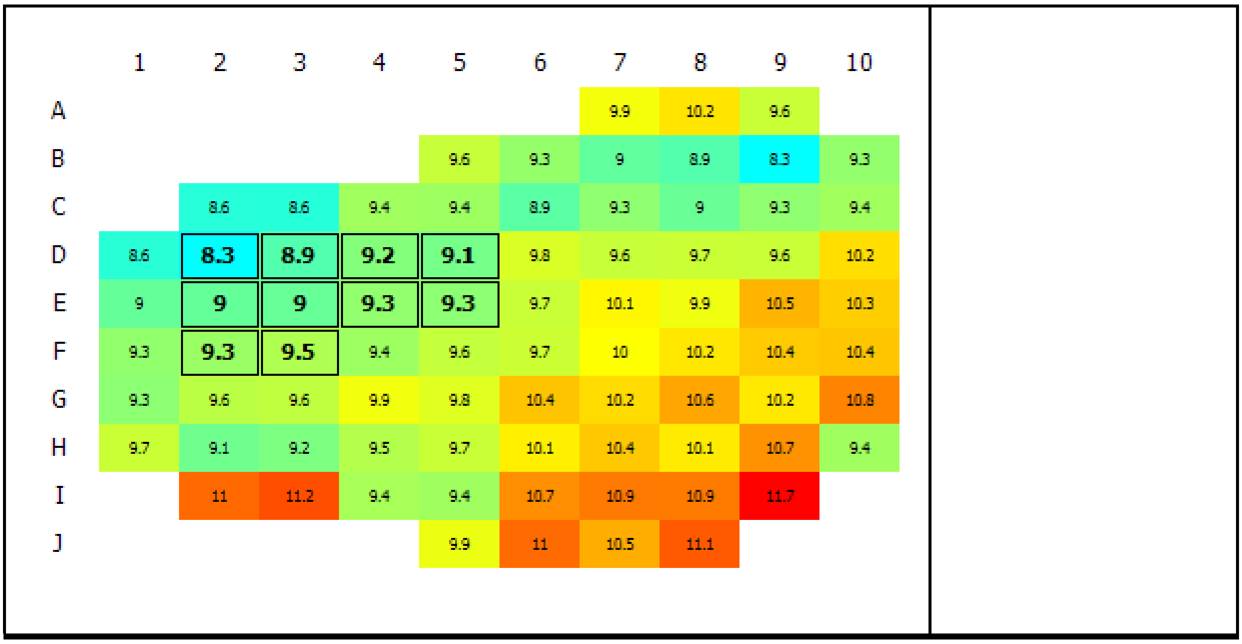


	1	2	3	4	5	6	7	8	9	10
A							.5	.5	.4	
B					.4	.4	.4	.4	.3	.4
C		.2	.4	.5	.5	.4	.4	.4	.4	.4
D	.6	.6	.5	.5	.4	.4	.4	.5	.4	.4
E	.6	.5	.6	.5	.5	.4	.4	.4	.4	.4
F	.6	.5	.5	.5	.5	.4	.4	.4	.5	.4
G	.4	.4	.5	.4	.5	.4	.4	.4	.4	.4
H	.7	.3	.4	.5	.4	.4	.4	.4	.5	.7
I		.4	.3	.5	.6	.4	.4	.4	.5	
J					.5	.5	.4	.4		

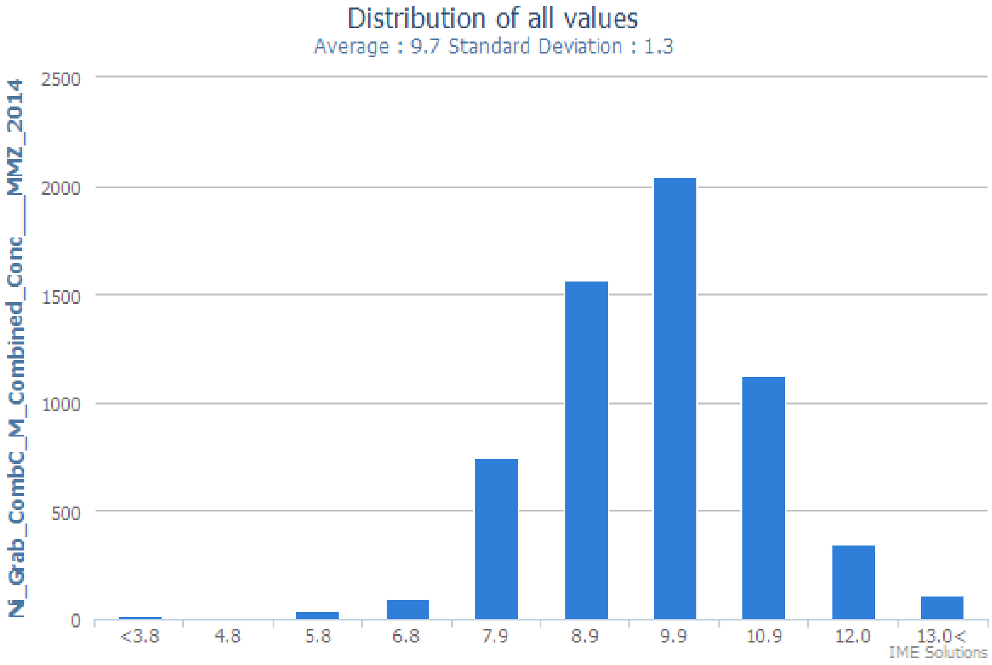


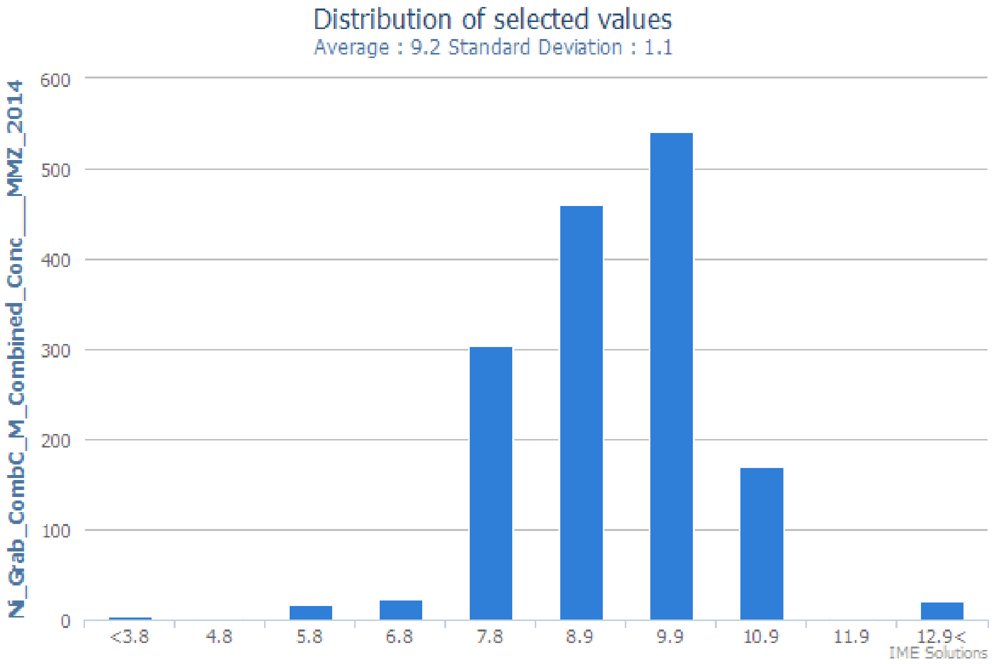

Distribution of selected values
Average : .5 Standard Deviation : .2
N_Grab_CT_M_Cleaner_Tails__MMZ_2010
600
500
400
300
200
100
0
<0.2
0.3
0.5
0.6
0.7
0.8
1.0
1.1
1.2
1.3<
IME Solutions

Combined Concentrate Nickel Grade

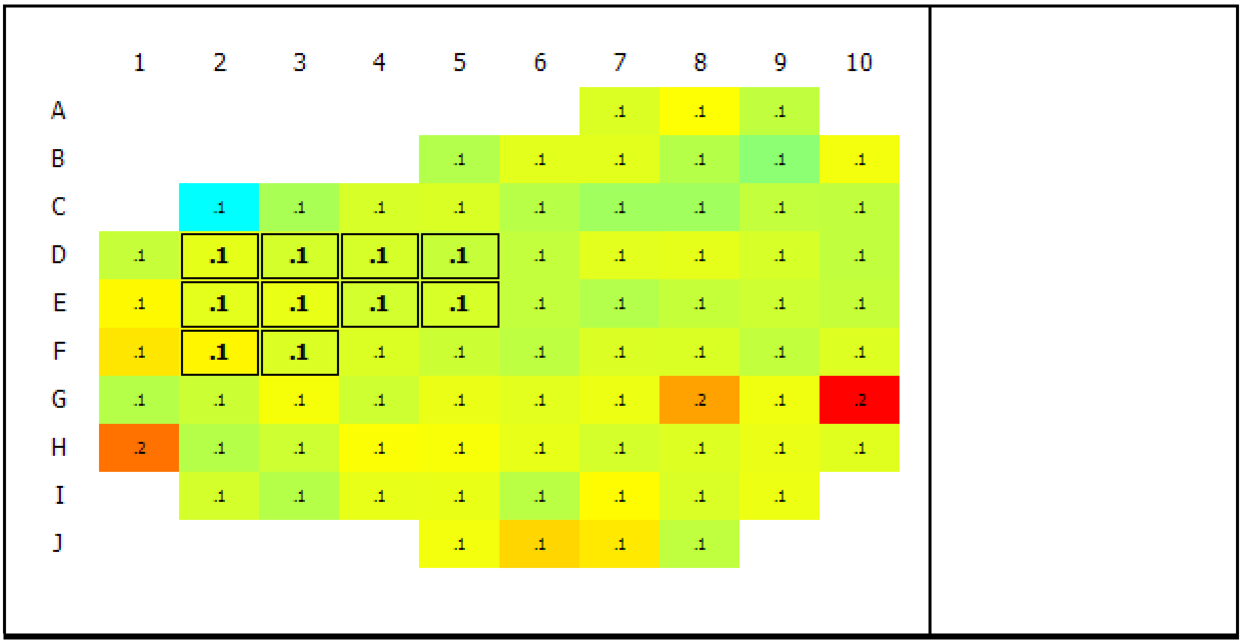


	1	2	3	4	5	6	7	8	9	10
A							9.9	10.2	9.6	
B					9.6	9.3	9	8.9	8.3	9.3
C		8.6	8.6	9.4	9.4	8.9	9.3	9	9.3	9.4
D	8.6	**8.3**	**8.9**	**9.2**	**9.1**	9.8	9.6	9.7	9.6	10.2
E	9	**9**	**9**	**9.3**	**9.3**	9.7	10.1	9.9	10.5	10.3
F	9.3	**9.3**	**9.5**	9.4	9.6	9.7	10	10.2	10.4	10.4
G	9.3	9.6	9.6	9.9	9.8	10.4	10.2	10.6	10.2	10.8
H	9.7	9.1	9.2	9.5	9.7	10.1	10.4	10.1	10.7	9.4
I		11	11.2	9.4	9.4	10.7	10.9	10.9	11.7	
J					9.9	11	10.5	11.1		

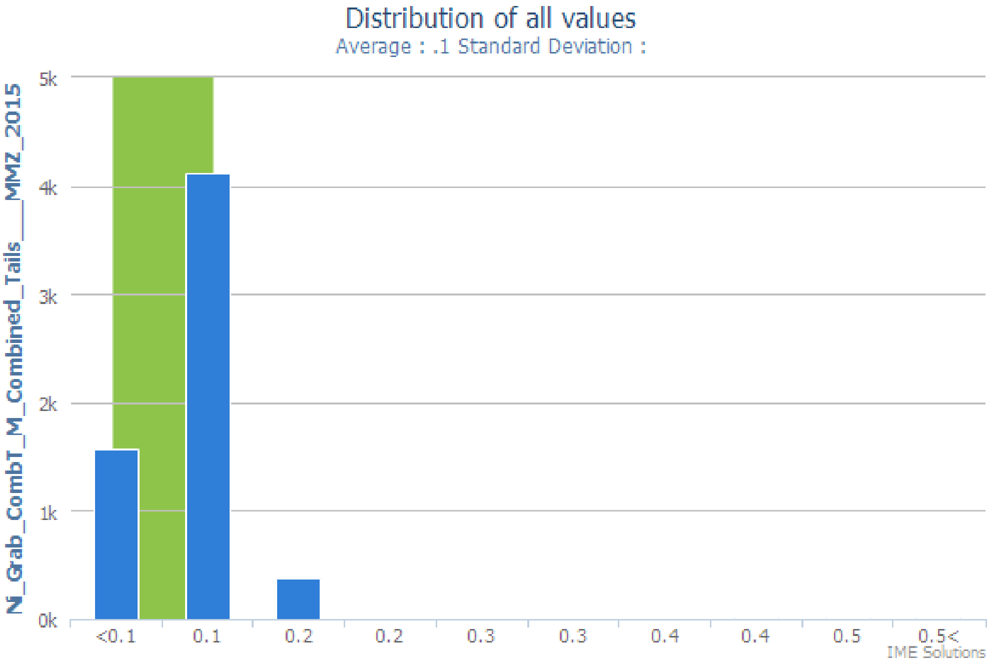


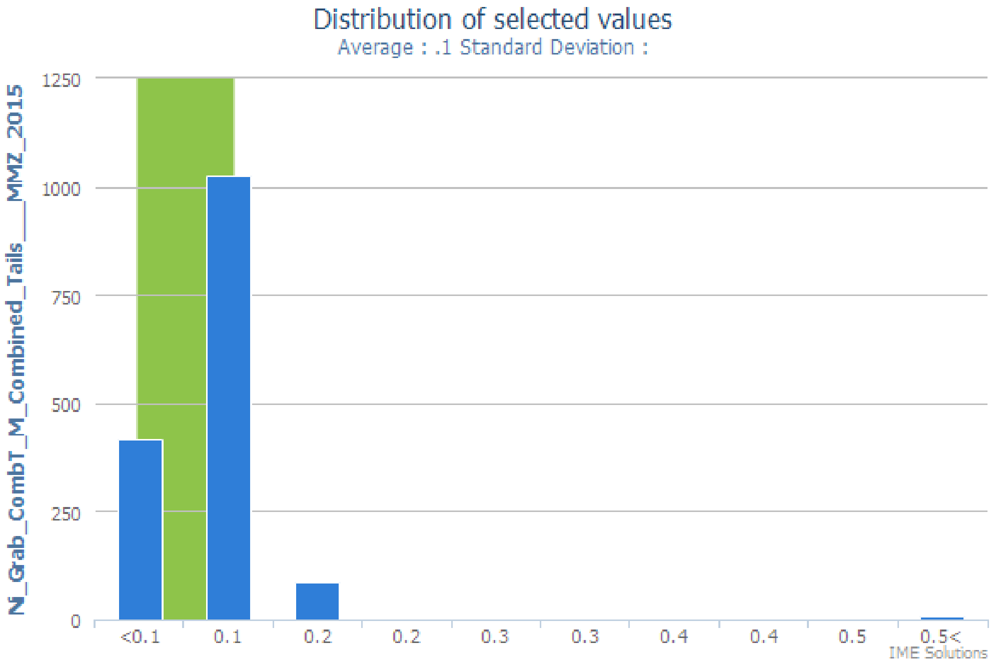

Distribution of selected values
Average : 9.2 Standard Deviation : 1.1
N_Grab_CombC_M_Combined_Conc___MMZ_2014
600
500
400
300
200
100
0
<3.8
4.8
5.8
6.8
7.8
8.9
9.9
10.9
11.9
12.9<
IME Solutions

Final Tailings Nickel Grade

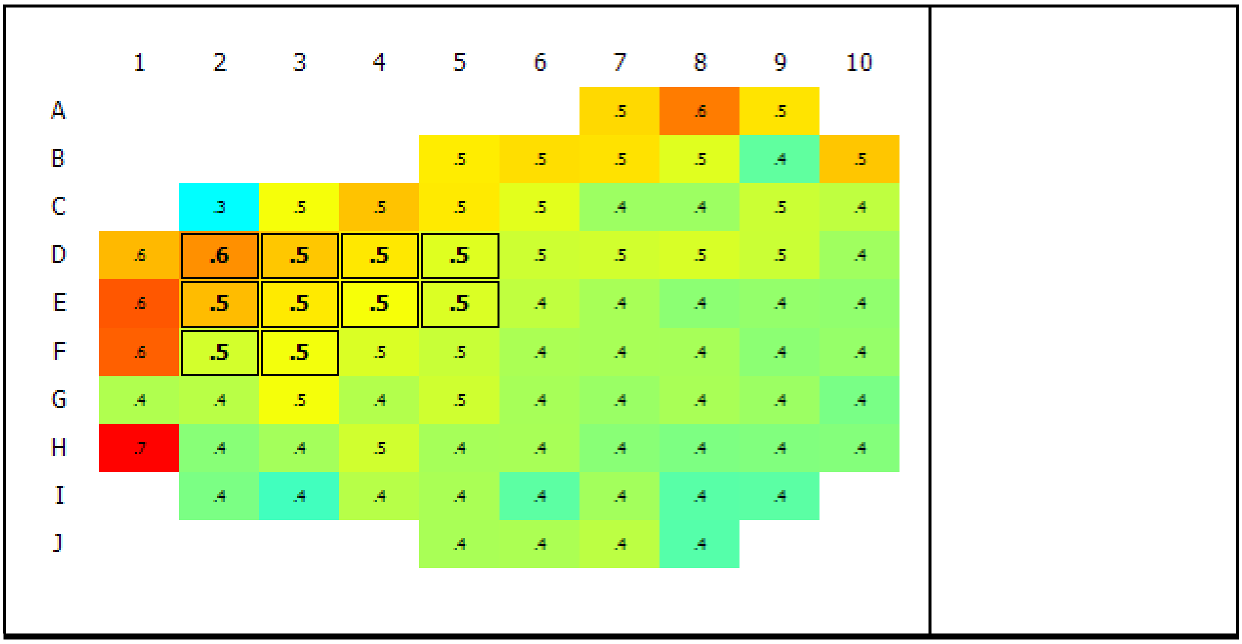


	1	2	3	4	5	6	7	8	9	10
A							.1	.1	.1	
B					.1	.1	.1	.1	.1	.1
C		.1	.1	.1	.1	.1	.1	.1	.1	.1
D	.1	**.1**	**.1**	**.1**	**.1**	.1	.1	.1	.1	.1
E	.1	**.1**	**.1**	**.1**	**.1**	.1	.1	.1	.1	.1
F	.1	**.1**	**.1**	.1	.1	.1	.1	.1	.1	.1
G	.1	.1	.1	.1	.1	.1	.1	.2	.1	.2
H	.2	.1	.1	.1	.1	.1	.1	.1	.1	.1
I		.1	.1	.1	.1	.1	.1	.1	.1	
J					.1	.1	.1	.1		

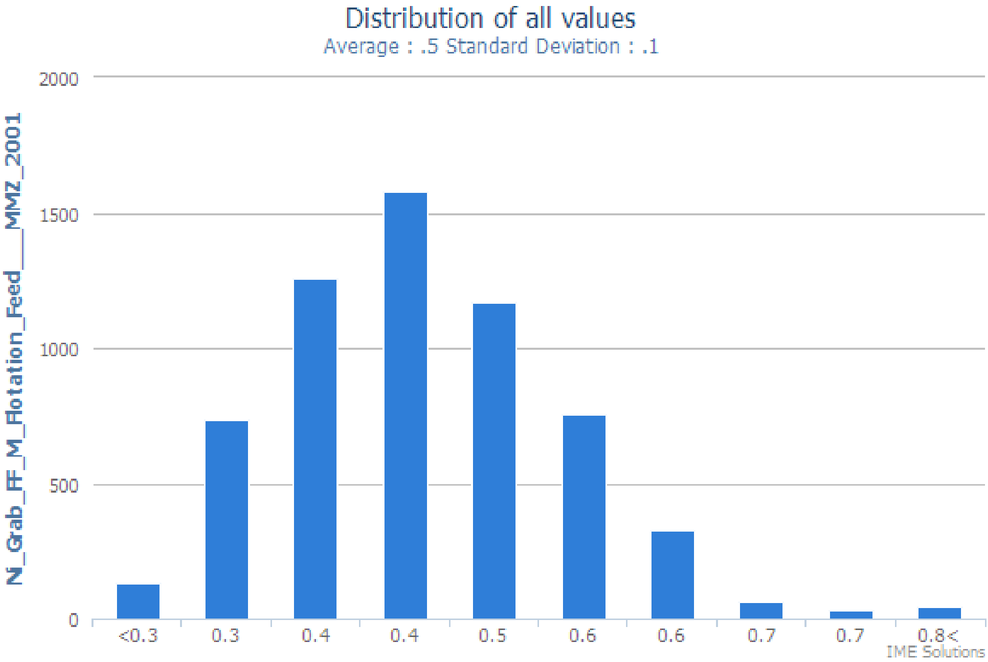


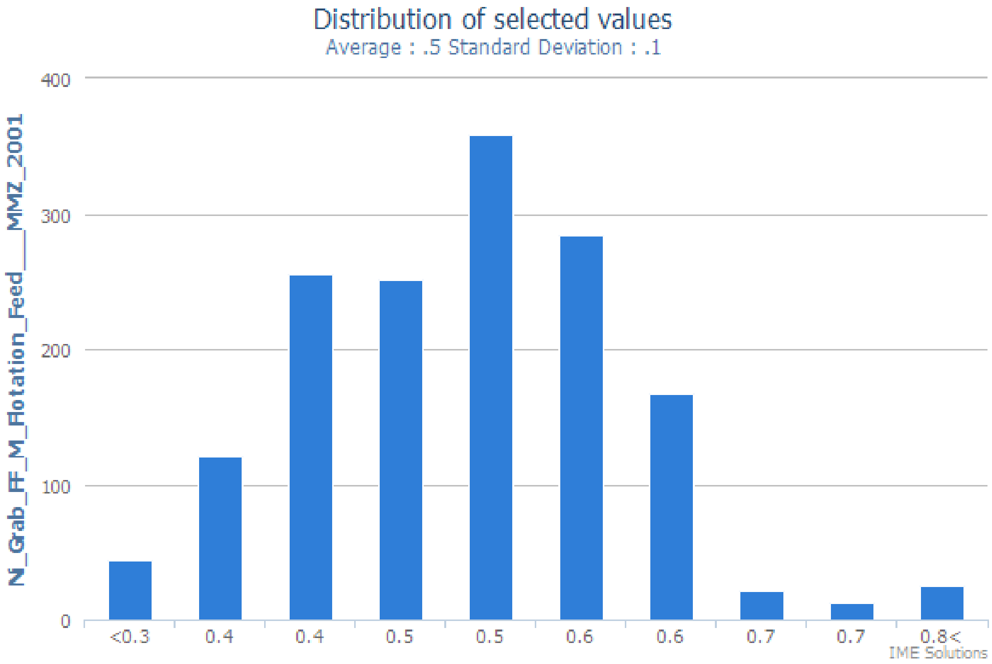

Distribution of selected values
Average : .1 Standard Deviation :
Ni_Grab_CombT_M_Combined_Tails___MMZ_2015
1250
1000
750
500
250
0
<0.1
0.1
0.2
0.2
0.3
0.3
0.4
0.4
0.5
0.5<
IME Solutions

Flotation Feed Nickel Grade (from grab samples)

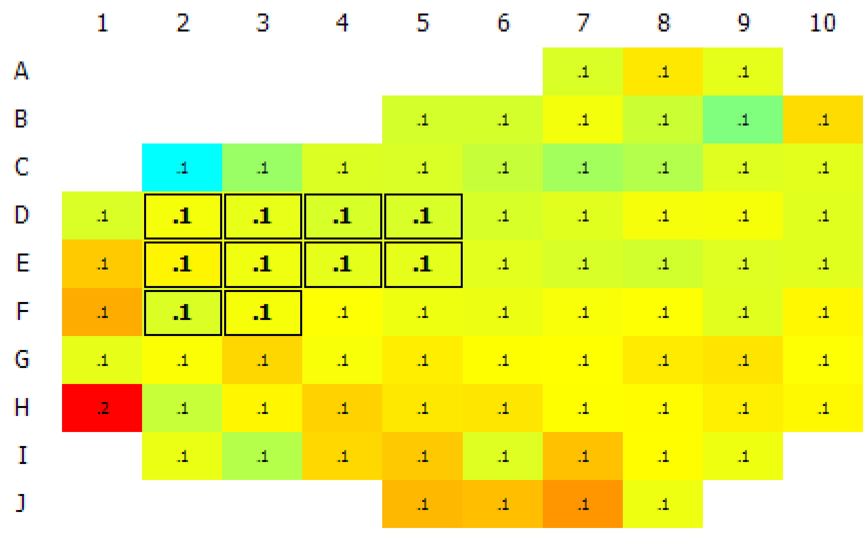


	1	2	3	4	5	6	7	8	9	10
A							.5	.6	.5	
B					.5	.5	.5	.5	.4	.5
C		.3	.5	.5	.5	.5	.4	.4	.5	.4
D	.6	.6	.5	.5	.5	.5	.5	.5	.5	.4
E	.6	.5	.5	.5	.5	.4	.4	.4	.4	.4
F	.6	.5	.5	.5	.5	.4	.4	.4	.4	.4
G	.4	.4	.5	.4	.5	.4	.4	.4	.4	.4
H	.7	.4	.4	.5	.4	.4	.4	.4	.4	.4
I		.4	.4	.4	.4	.4	.4	.4	.4	
J					.4	.4	.4	.4		

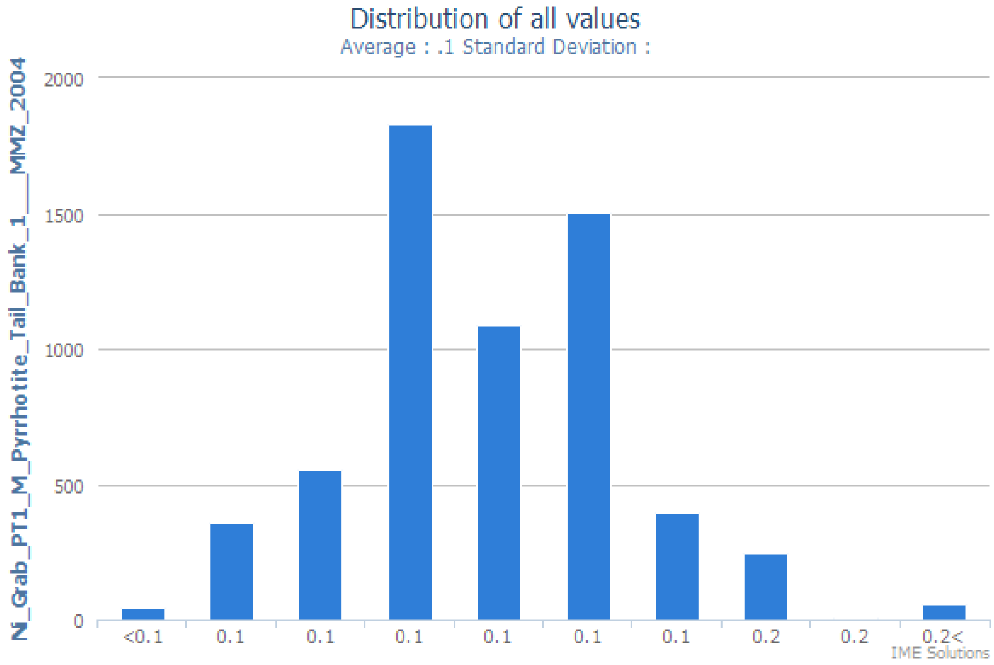


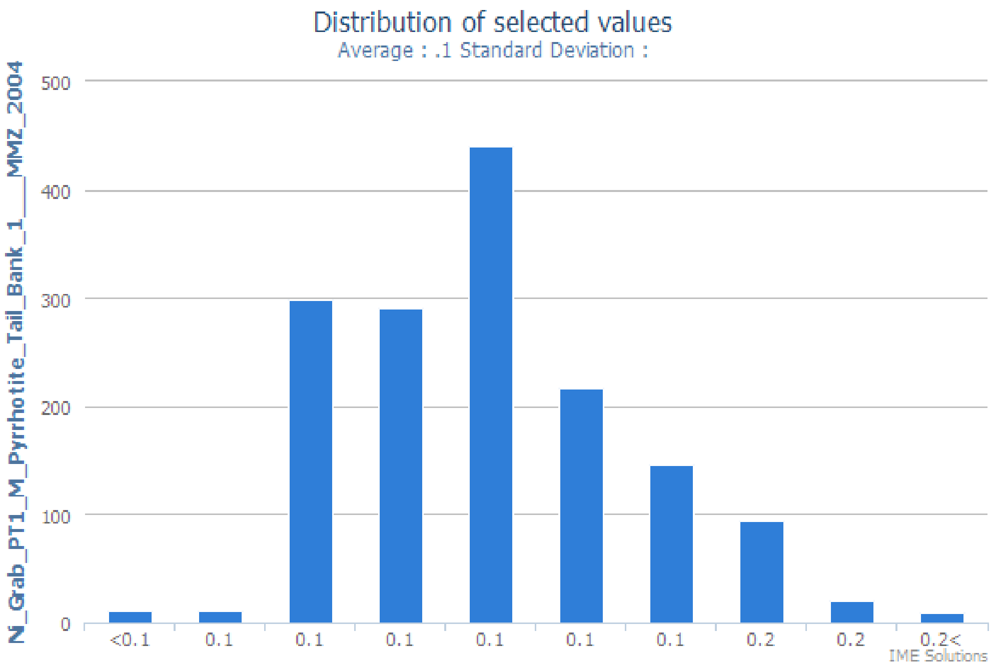

Distribution of selected values
Average : .5 Standard Deviation : .1
Ni_Grab_FF_M_Flotation_Feed___MMZ_2001
400
300
200
100
0
<0.3
0.4
0.4
0.5
0.5
0.6
0.6
0.7
0.7
0.8<
IME Solutions

Rougher Bank #1 Tailings Nickel Grade

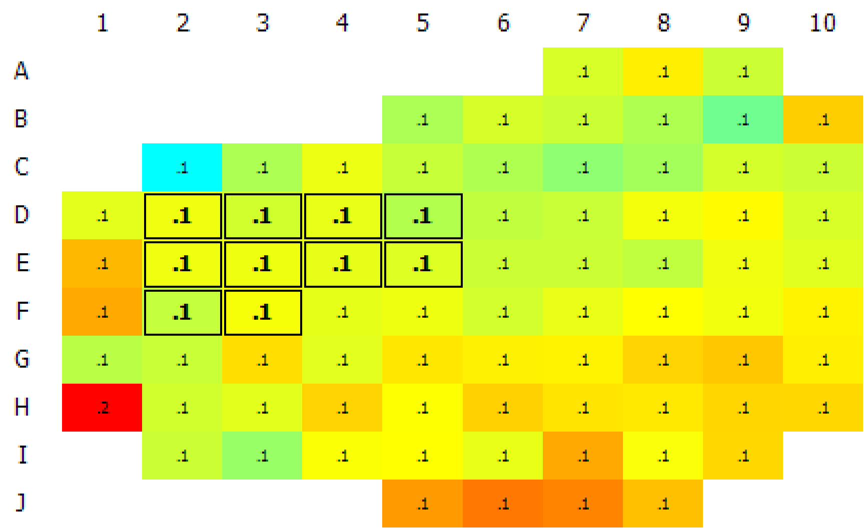


	1	2	3	4	5	6	7	8	9	10
A							.1	.1	.1	
B					.1	.1	.1	.1	.1	.1
C		.1	.1	.1	.1	.1	.1	.1	.1	.1
D	.1	**.1**	**.1**	**.1**	**.1**	.1	.1	.1	.1	.1
E	.1	**.1**	**.1**	**.1**	**.1**	.1	.1	.1	.1	.1
F	.1	**.1**	**.1**	.1	.1	.1	.1	.1	.1	.1
G	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1
H	.2	.1	.1	.1	.1	.1	.1	.1	.1	.1
I		.1	.1	.1	.1	.1	.1	.1	.1	
J					.1	.1	.1	.1		

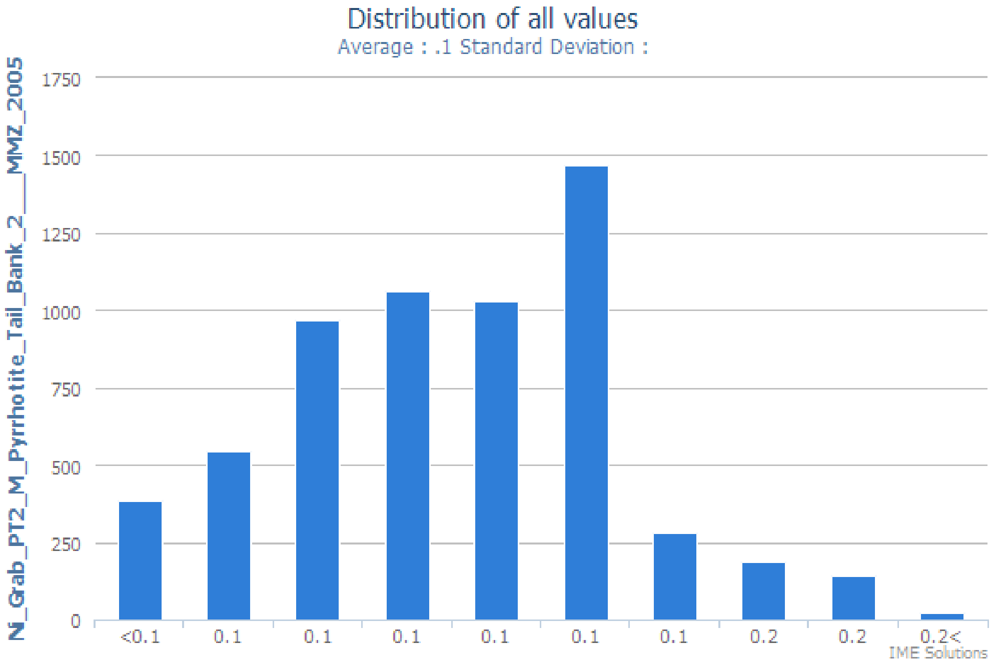


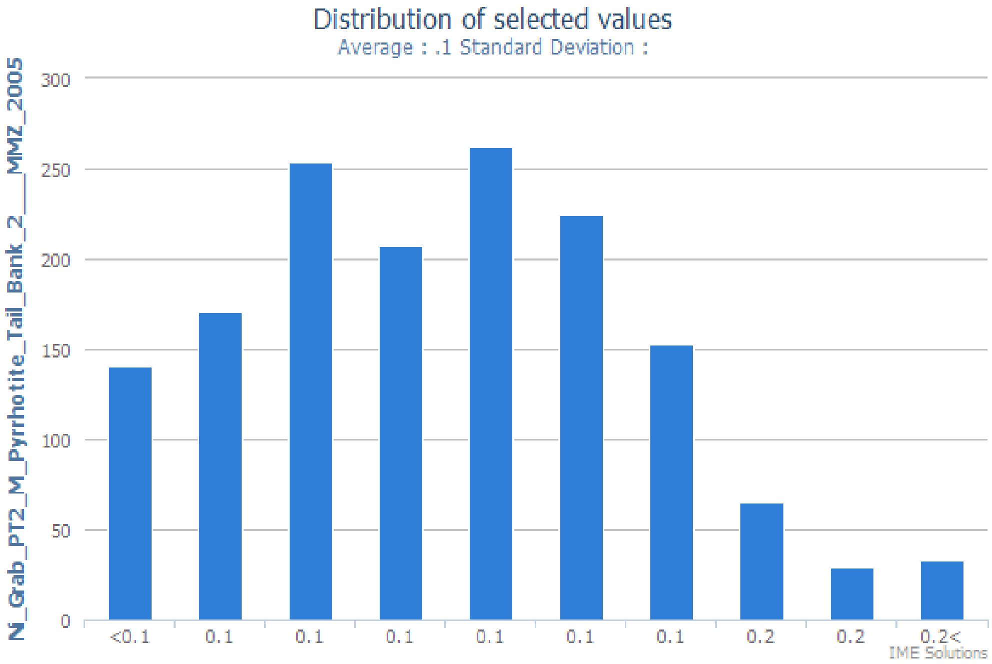

Distribution of selected values
Average : .1 Standard Deviation :
Ni_Grab_PT1_M_Pyrrhotite_Tail_Bank_1___MMZ_2004
500
400
300
200
100
0
<0.1
0.1
0.1
0.1
0.1
0.1
0.1
0.2
0.2
0.2<
IME Solutions

Rougher Bank #2 Tailings Nickel Grade

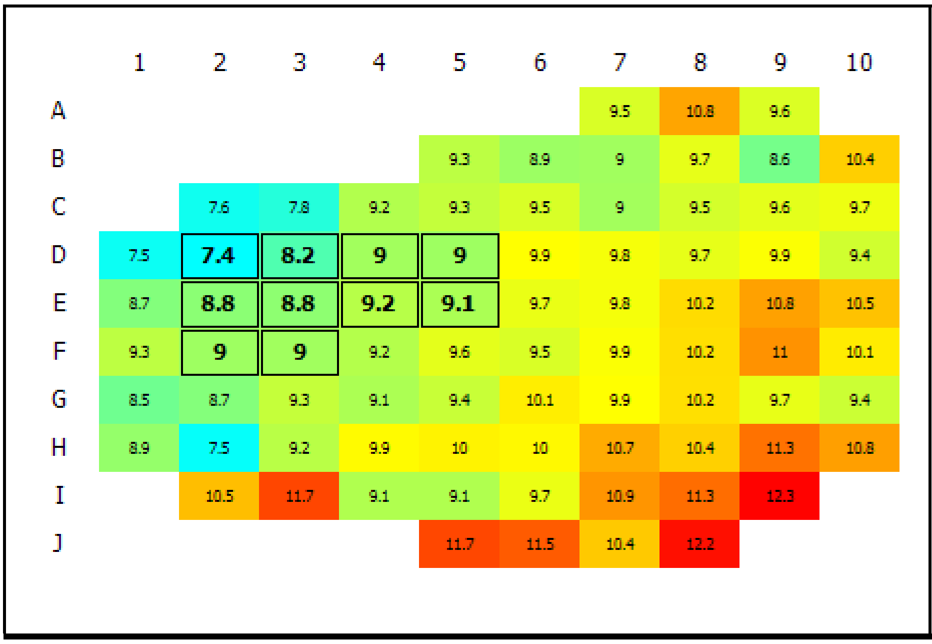


	1	2	3	4	5	6	7	8	9	10
A							.1	.1	.1	
B					.1	.1	.1	.1	.1	.1
C		.1	.1	.1	.1	.1	.1	.1	.1	.1
D	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1
E	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1
F	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1
G	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1
H	.2	.1	.1	.1	.1	.1	.1	.1	.1	.1
I		.1	.1	.1	.1	.1	.1	.1	.1	
J					.1	.1	.1	.1		

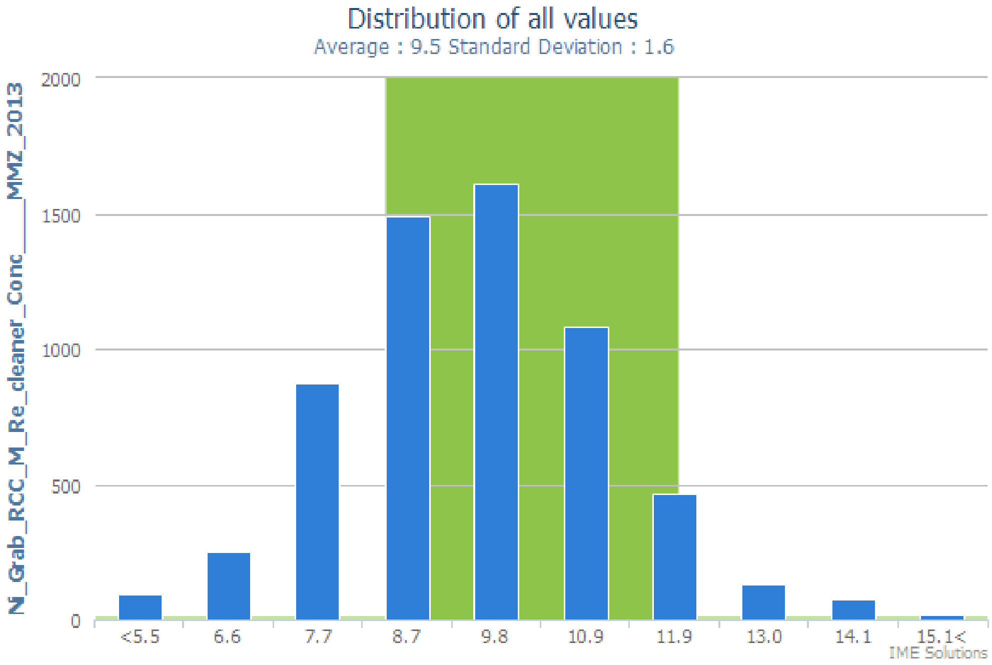


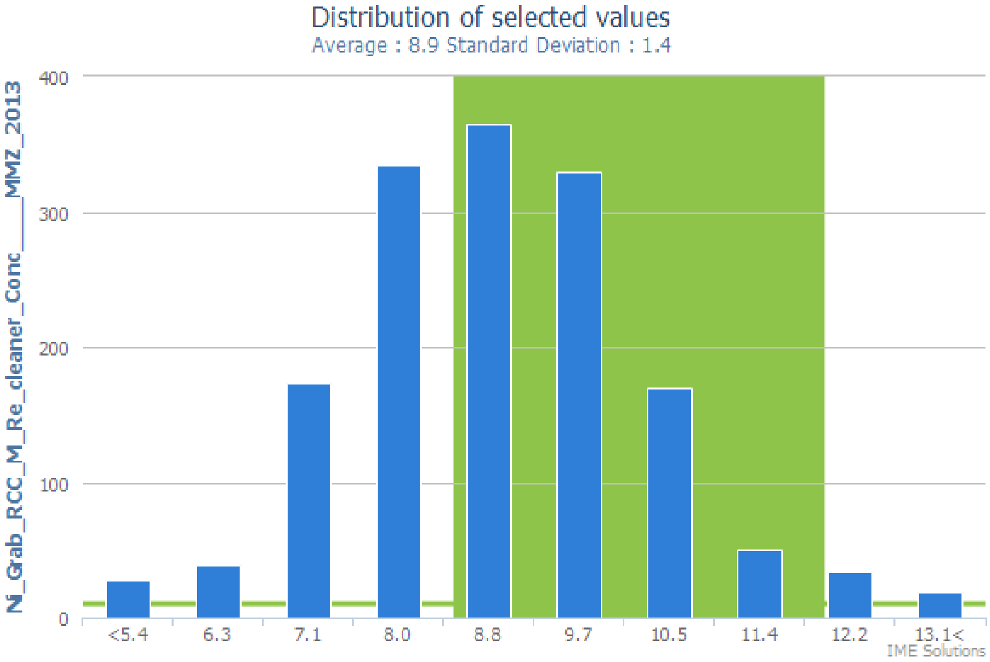

Distribution of selected values
Average : .1 Standard Deviation :
Ni_Grab_PT2_M_Pyrrhotite_Tail_Bank_2___MMZ_2005
300
250
200
150
100
50
0
<0.1
0.1
0.1
0.1
0.1
0.1
0.1
0.2
0.2
0.2<
IME Solutions

Re-Cleaner Concentrate Nickel Grade

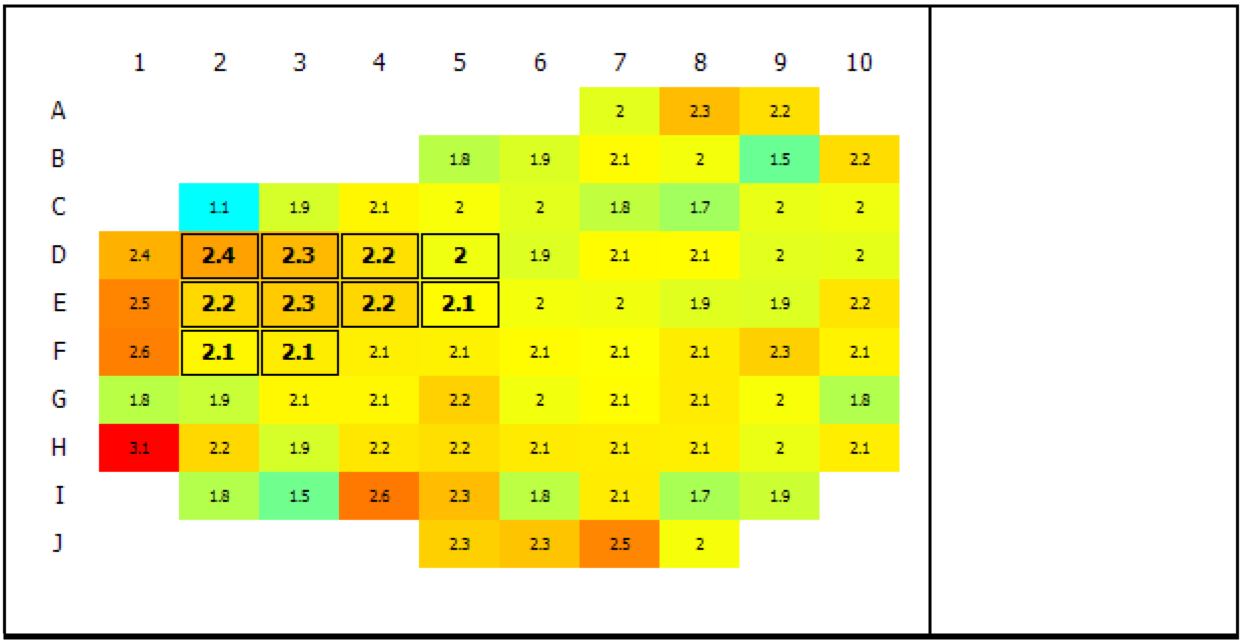


	1	2	3	4	5	6	7	8	9	10
A							9.5	10.8	9.6	
B					9.3	8.9	9	9.7	8.6	10.4
C		7.6	7.8	9.2	9.3	9.5	9	9.5	9.6	9.7
D	7.5	**7.4**	**8.2**	**9**	**9**	9.9	9.8	9.7	9.9	9.4
E	8.7	**8.8**	**8.8**	**9.2**	**9.1**	9.7	9.8	10.2	10.8	10.5
F	9.3	**9**	**9**	9.2	9.6	9.5	9.9	10.2	11	10.1
G	8.5	8.7	9.3	9.1	9.4	10.1	9.9	10.2	9.7	9.4
H	8.9	7.5	9.2	9.9	10	10	10.7	10.4	11.3	10.8
I		10.5	11.7	9.1	9.1	9.7	10.9	11.3	12.3	
J					11.7	11.5	10.4	12.2		

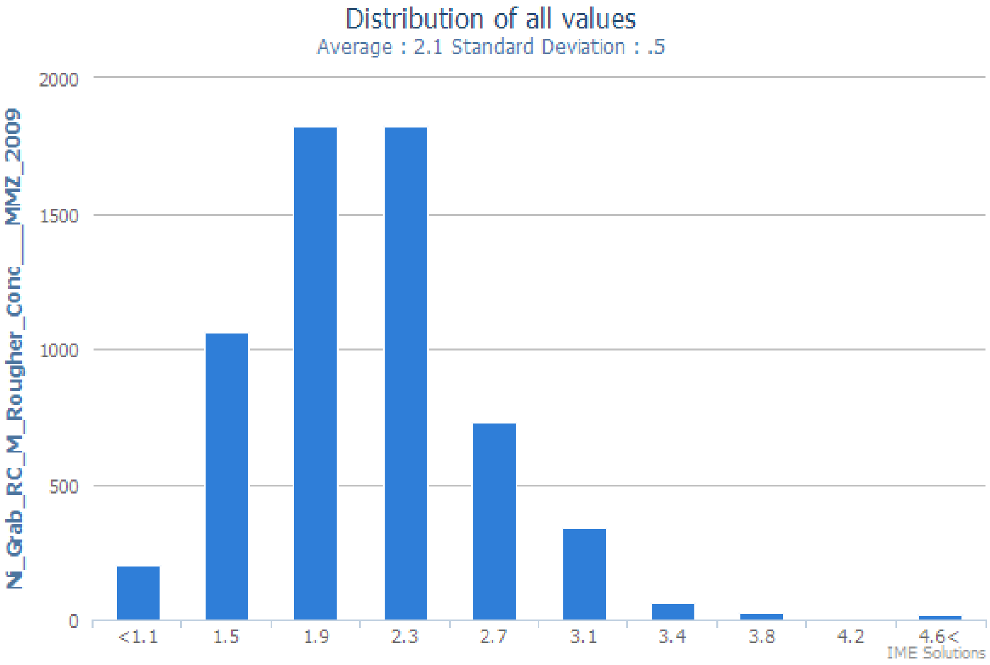


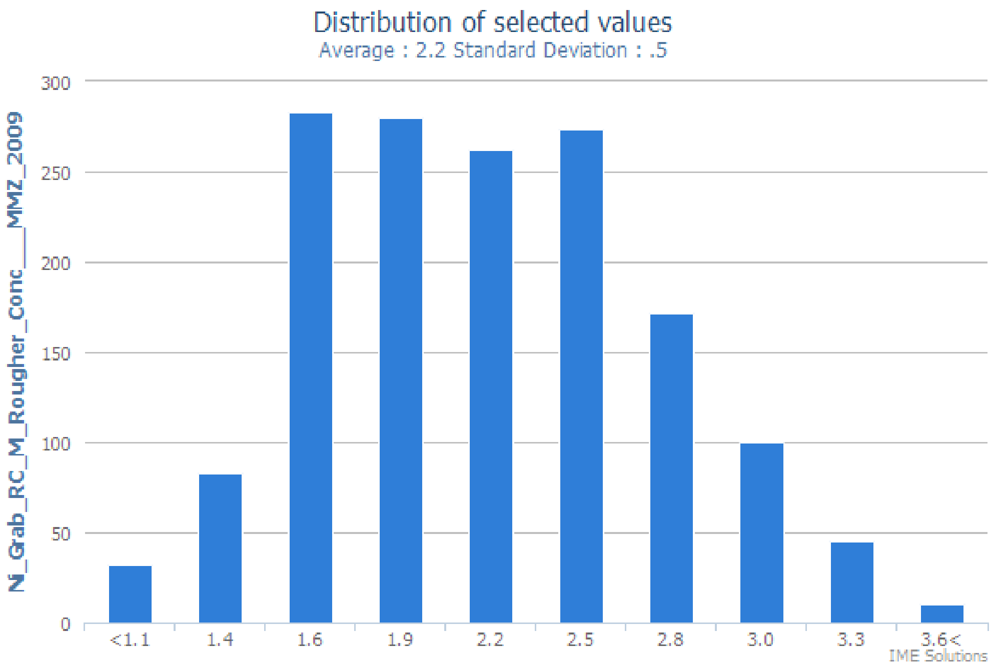

Distribution of selected values
Average : 8.9 Standard Deviation : 1.4
Ni_Grab_RCC_M_Re_cleaner_Conc___MMZ_2013
400
300
200
100
0
<5.4
6.3
7.1
8.0
8.8
9.7
10.5
11.4
12.2
13.1<
IME Solutions

Rougher Concentrate Nickel Grade (from grab samples)

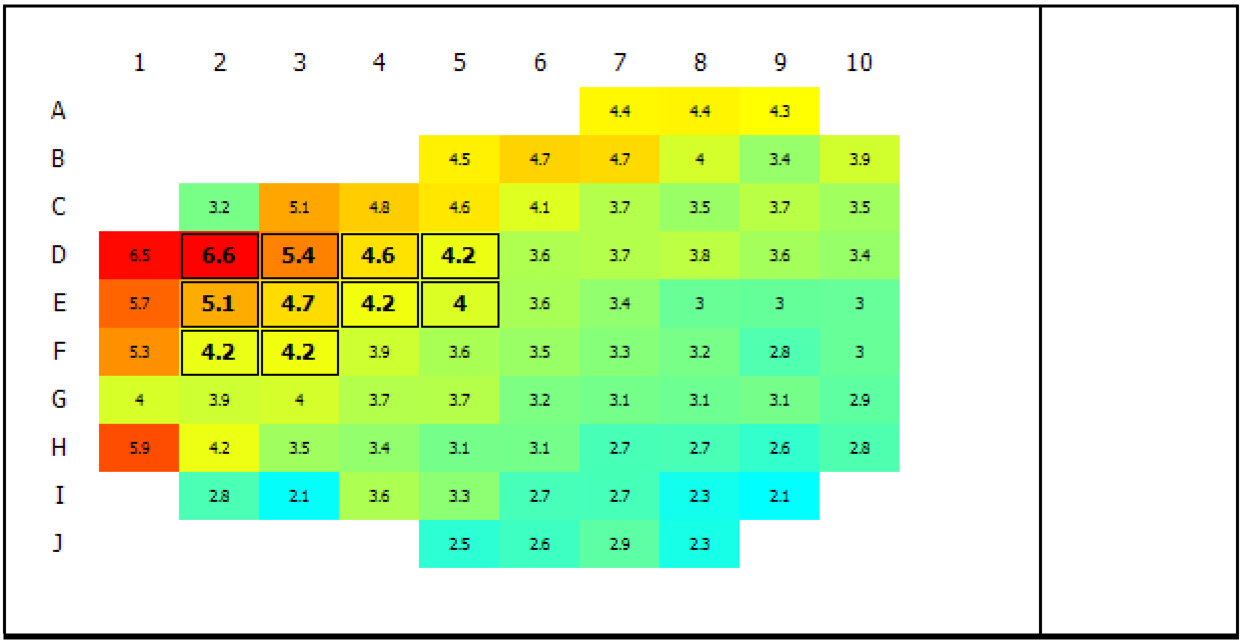


	1	2	3	4	5	6	7	8	9	10
A							2	2.3	2.2	
B					1.8	1.9	2.1	2	1.5	2.2
C		1.1	1.9	2.1	2	2	1.8	1.7	2	2
D	2.4	**2.4**	**2.3**	**2.2**	**2**	1.9	2.1	2.1	2	2
E	2.5	**2.2**	**2.3**	**2.2**	**2.1**	2	2	1.9	1.9	2.2
F	2.6	**2.1**	**2.1**	2.1	2.1	2.1	2.1	2.1	2.3	2.1
G	1.8	1.9	2.1	2.1	2.2	2	2.1	2.1	2	1.8
H	3.1	2.2	1.9	2.2	2.2	2.1	2.1	2.1	2	2.1
I		1.8	1.5	2.6	2.3	1.8	2.1	1.7	1.9	
J					2.3	2.3	2.5	2		

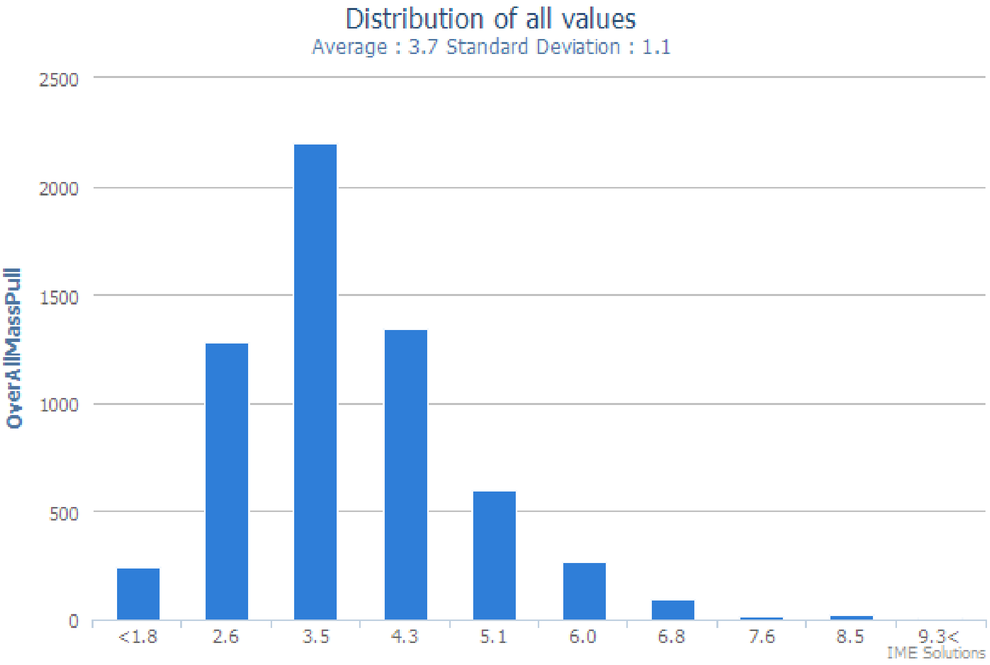


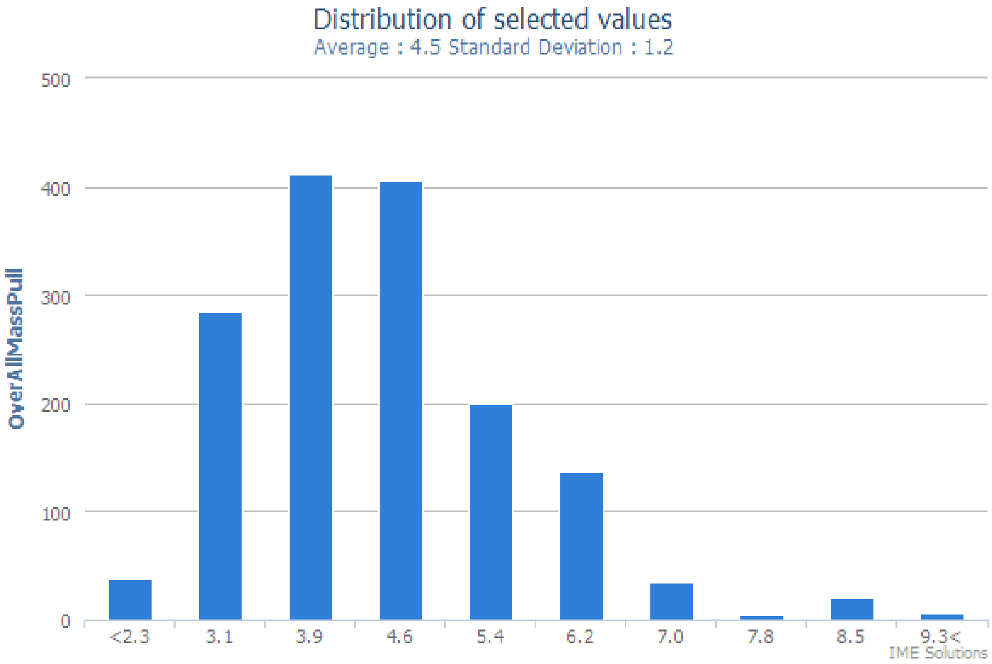

Distribution of selected values
Average : 2.2 Standard Deviation : .5
Ni_Grab_RC_M_Rougher_Conc___MMZ_2009
300
250
200
150
100
50
0
<1.1
1.4
1.6
1.9
2.2
2.5
2.8
3.0
3.3
3.6<
IME Solutions

Overall Mass Pull

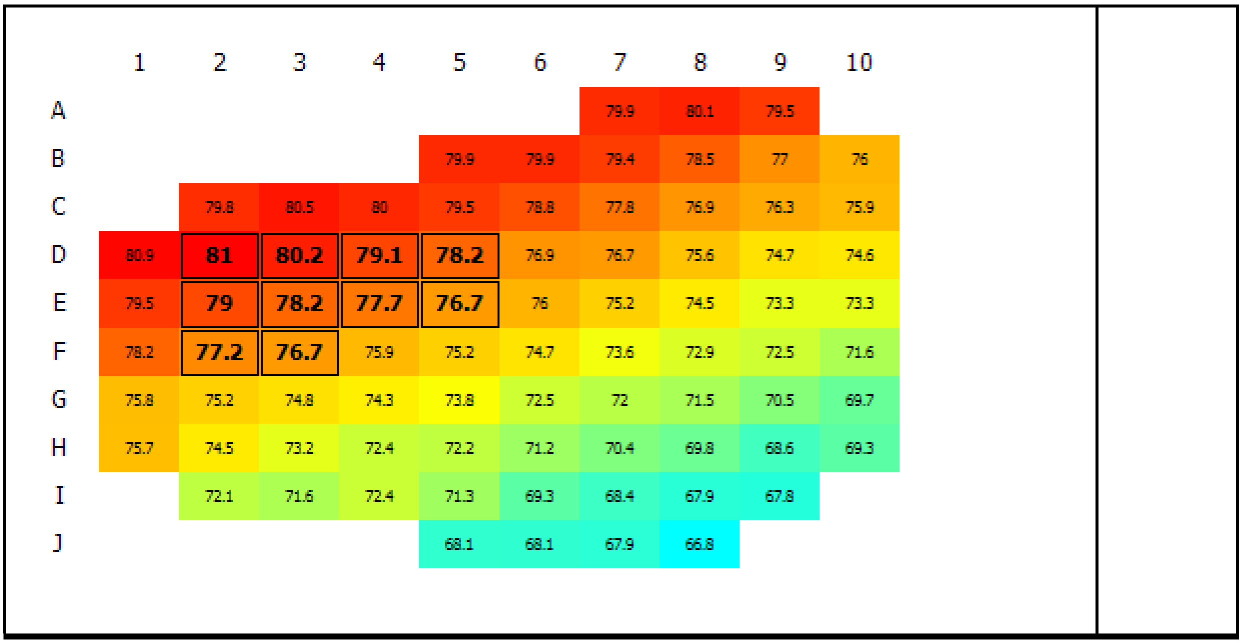


	1	2	3	4	5	6	7	8	9	10
A							4.4	4.4	4.3	
B					4.5	4.7	4.7	4	3.4	3.9
C		3.2	5.1	4.8	4.6	4.1	3.7	3.5	3.7	3.5
D	6.5	**6.6**	**5.4**	**4.6**	**4.2**	3.6	3.7	3.8	3.6	3.4
E	5.7	**5.1**	**4.7**	**4.2**	**4**	3.6	3.4	3	3	3
F	5.3	**4.2**	**4.2**	3.9	3.6	3.5	3.3	3.2	2.8	3
G	4	3.9	4	3.7	3.7	3.2	3.1	3.1	3.1	2.9
H	5.9	4.2	3.5	3.4	3.1	3.1	2.7	2.7	2.6	2.8
I		2.8	2.1	3.6	3.3	2.7	2.7	2.3	2.1	
J					2.5	2.6	2.9	2.3		

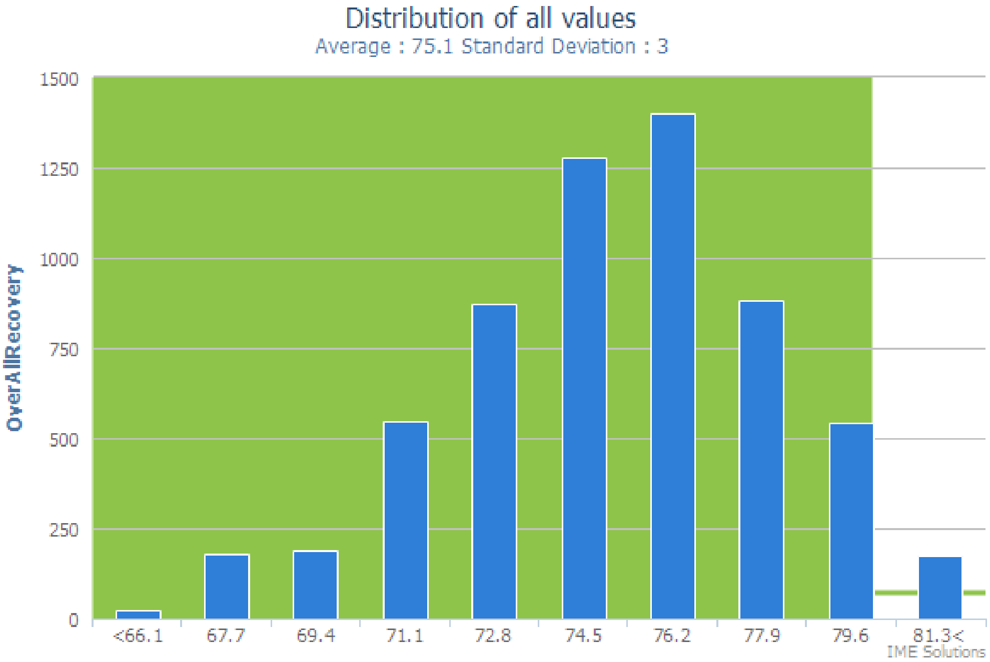


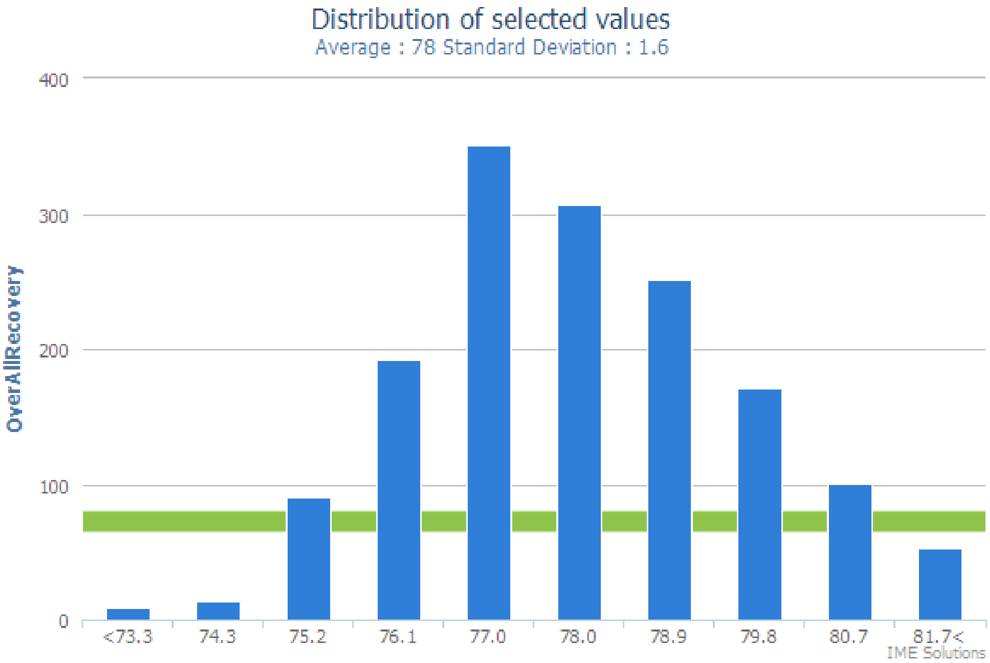

Distribution of selected values
Average : 4.5 Standard Deviation : 1.2
OverAllMassPull
500
400
300
200
100
0
<2.3
3.1
3.9
4.6
5.4
6.2
7.0
7.8
8.5
9.3<
IME Solutions

Overall Nickel Recovery



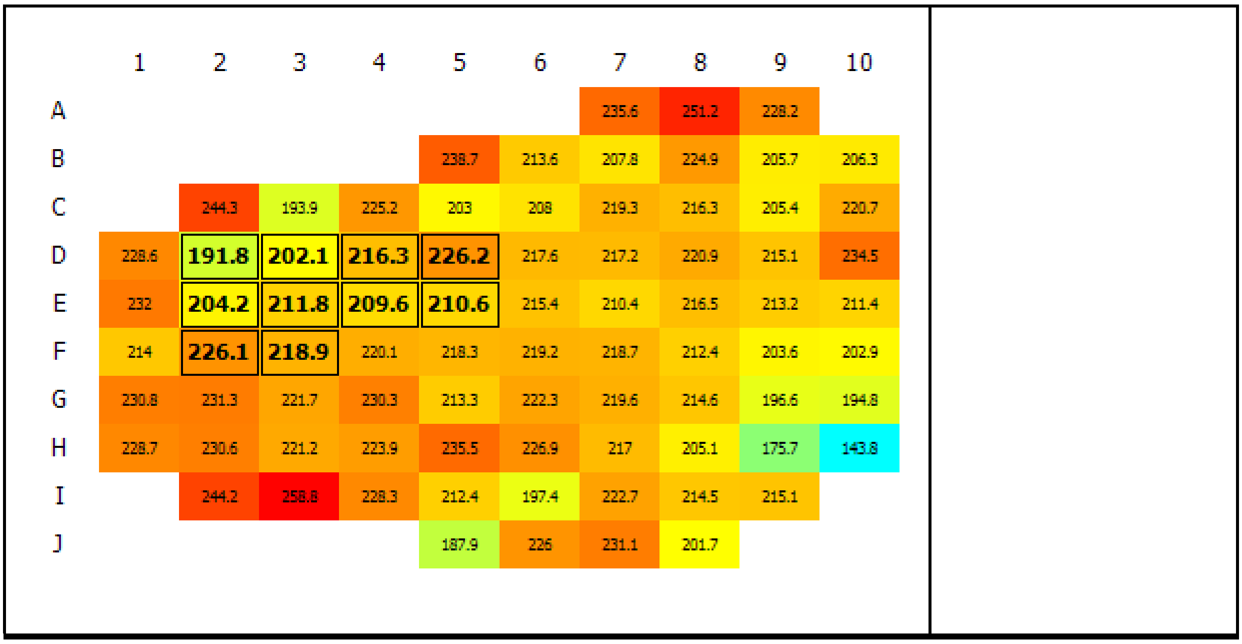
	1	2	3	4	5	6	7	8	9	10
A							79.9	80.1	79.5	
B					79.9	79.9	79.4	78.5	77	76
C		79.8	80.5	80	79.5	78.8	77.8	76.9	76.3	75.9
D	80.9	**81**	**80.2**	**79.1**	**78.2**	76.9	76.7	75.6	74.7	74.6
E	79.5	**79**	**78.2**	**77.7**	**76.7**	76	75.2	74.5	73.3	73.3
F	78.2	**77.2**	**76.7**	75.9	75.2	74.7	73.6	72.9	72.5	71.6
G	75.8	75.2	74.8	74.3	73.8	72.5	72	71.5	70.5	69.7
H	75.7	74.5	73.2	72.4	72.2	71.2	70.4	69.8	68.6	69.3
I		72.1	71.6	72.4	71.3	69.3	68.4	67.9	67.8	
J					68.1	68.1	67.9	66.8		



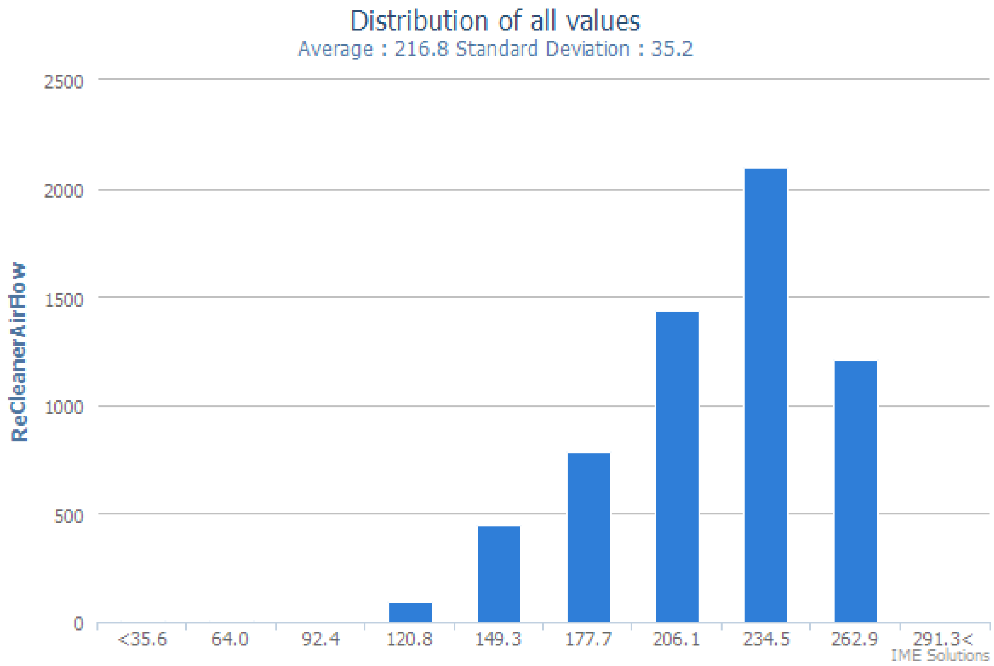

Distribution of selected values
Average : 78 Standard Deviation : 1.6
OverAllRecovery
400
300
200
100
0
<73.3
74.3
75.2
76.1
77.0
78.0
78.9
79.8
80.7
81.7<
IME Solutions

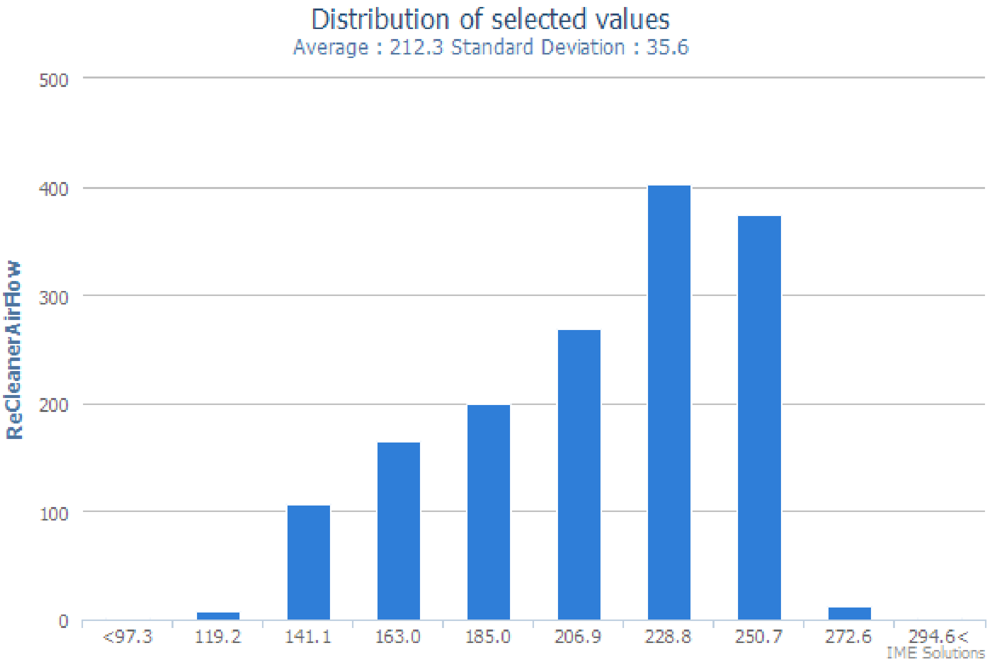
Re-Cleaner Air Flow

Total air flowrate to re-cleaners



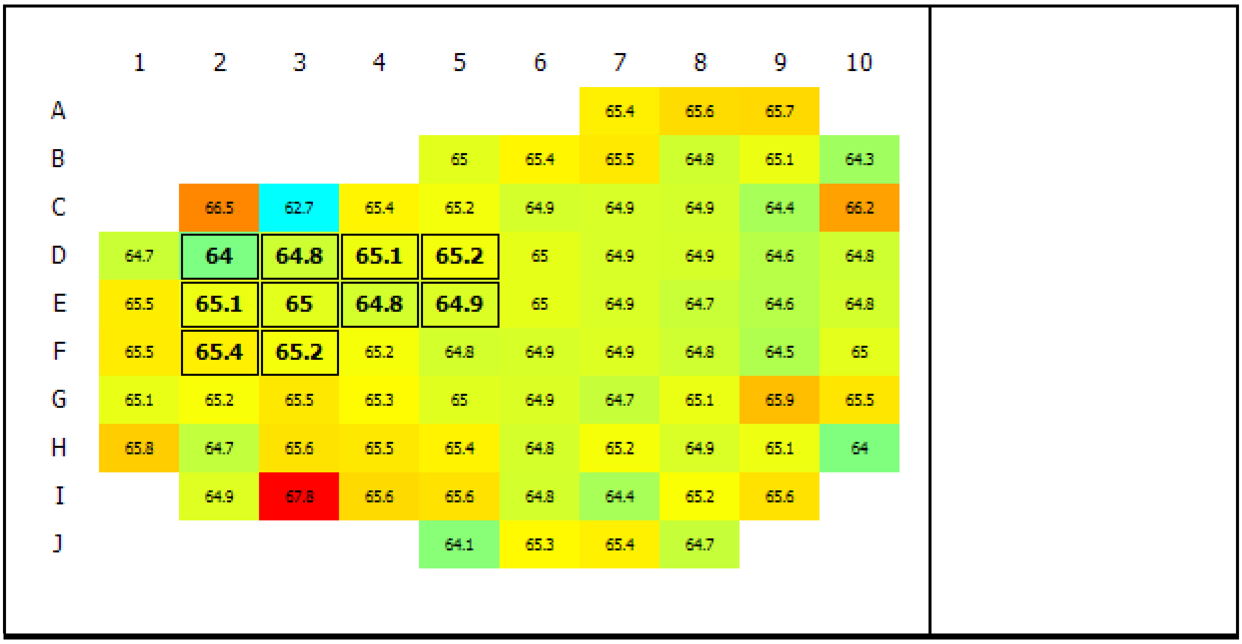
	1	2	3	4	5	6	7	8	9	10
A							235.6	251.2	228.2	
B					238.7	213.6	207.8	224.9	205.7	206.3
C		244.3	193.9	225.2	203	208	219.3	216.3	205.4	220.7
D	228.6	**191.8**	**202.1**	**216.3**	**226.2**	217.6	217.2	220.9	215.1	234.5
E	232	**204.2**	**211.8**	**209.6**	**210.6**	215.4	210.4	216.5	213.2	211.4
F	214	**226.1**	**218.9**	220.1	218.3	219.2	218.7	212.4	203.6	202.9
G	230.8	231.3	221.7	230.3	213.3	222.3	219.6	214.6	196.6	194.8
H	228.7	230.6	221.2	223.9	235.5	226.9	217	205.1	175.7	143.8
I		244.2	258.8	228.3	212.4	197.4	222.7	214.5	215.1	
J					187.9	226	231.1	201.7		



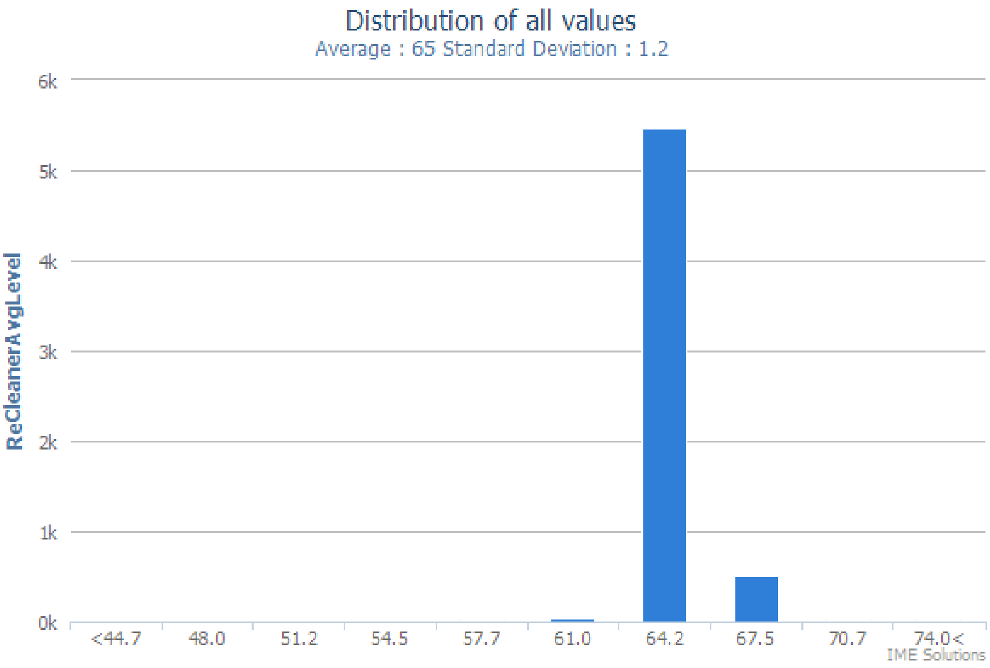

Distribution of selected values
Average : 212.3 Standard Deviation : 35.6
ReCleanerAirFlow
500
400
300
200
100
0
<97.3
119.2
141.1
163.0
185.0
206.9
228.8
250.7
272.6
294.6<
IME Solutions

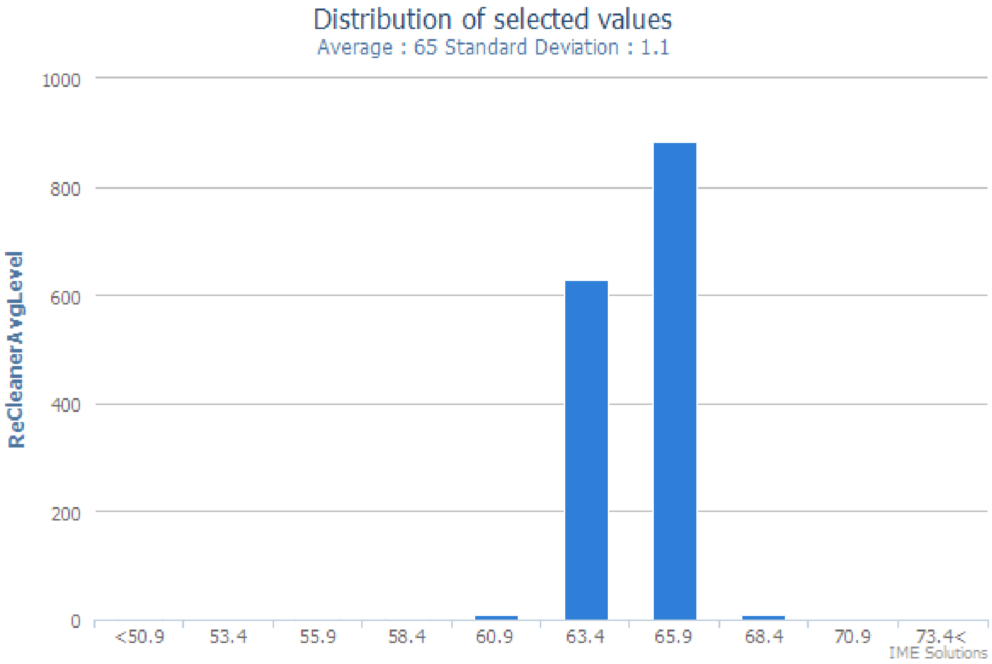
Re-Cleaners Average Level

Average level of all the cells in the re-cleaner circuit



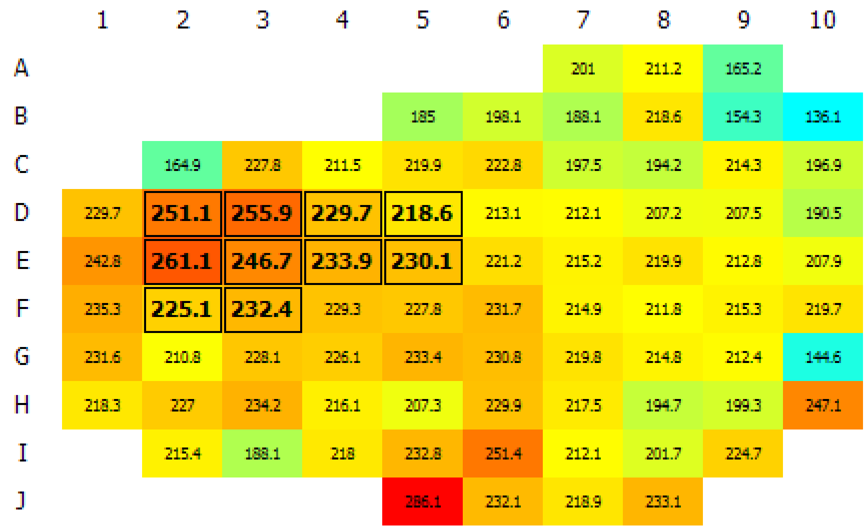
	1	2	3	4	5	6	7	8	9	10
A							65.4	65.6	65.7	
B					65	65.4	65.5	64.8	65.1	64.3
C		66.5	62.7	65.4	65.2	64.9	64.9	64.9	64.4	66.2
D	64.7	**64**	**64.8**	**65.1**	**65.2**	65	64.9	64.9	64.6	64.8
E	65.5	**65.1**	**65**	**64.8**	**64.9**	65	64.9	64.7	64.6	64.8
F	65.5	**65.4**	**65.2**	65.2	64.8	64.9	64.9	64.8	64.5	65
G	65.1	65.2	65.5	65.3	65	64.9	64.7	65.1	65.9	65.5
H	65.8	64.7	65.6	65.5	65.4	64.8	65.2	64.9	65.1	64
I		64.9	67.8	65.6	65.6	64.8	64.4	65.2	65.6	
J					64.1	65.3	65.4	64.7		



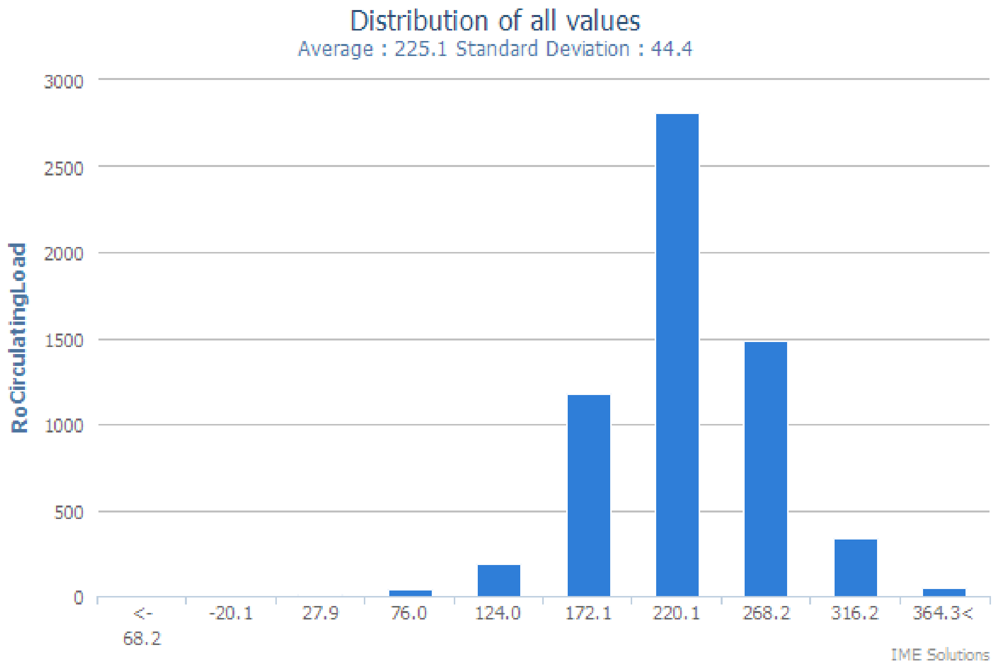

Distribution of selected values
Average : 65 Standard Deviation : 1.1
ReCleanerAvgLevel
1000
800
600
400
200
0
<50.9
53.4
55.9
58.4
60.9
63.4
65.9
68.4
70.9
73.4<
IME Solutions

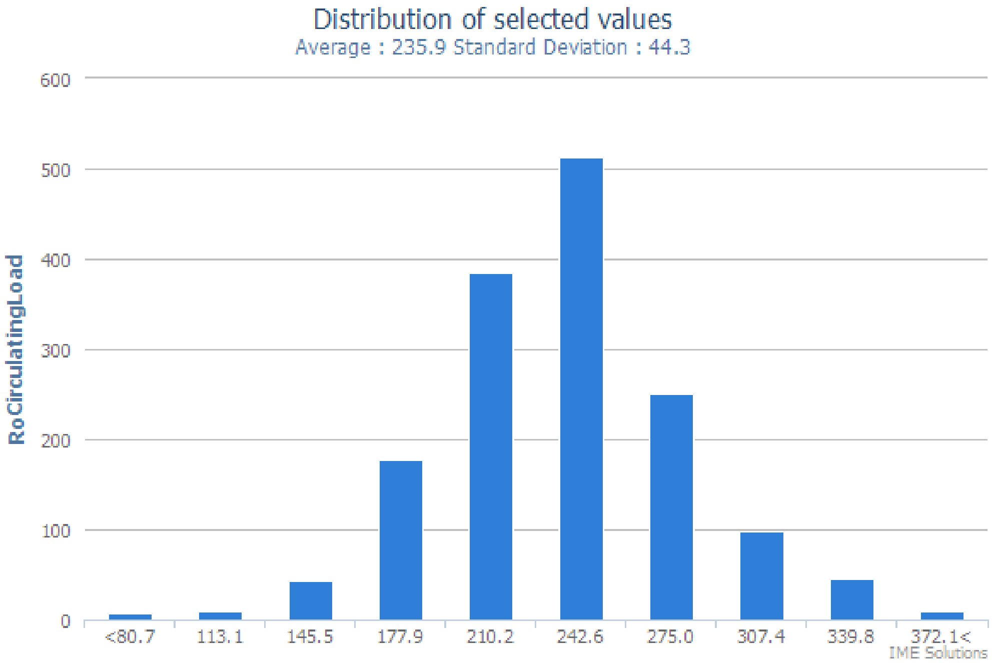
Rougher Circulating Load

Cleaner Tails to Rougher Flow

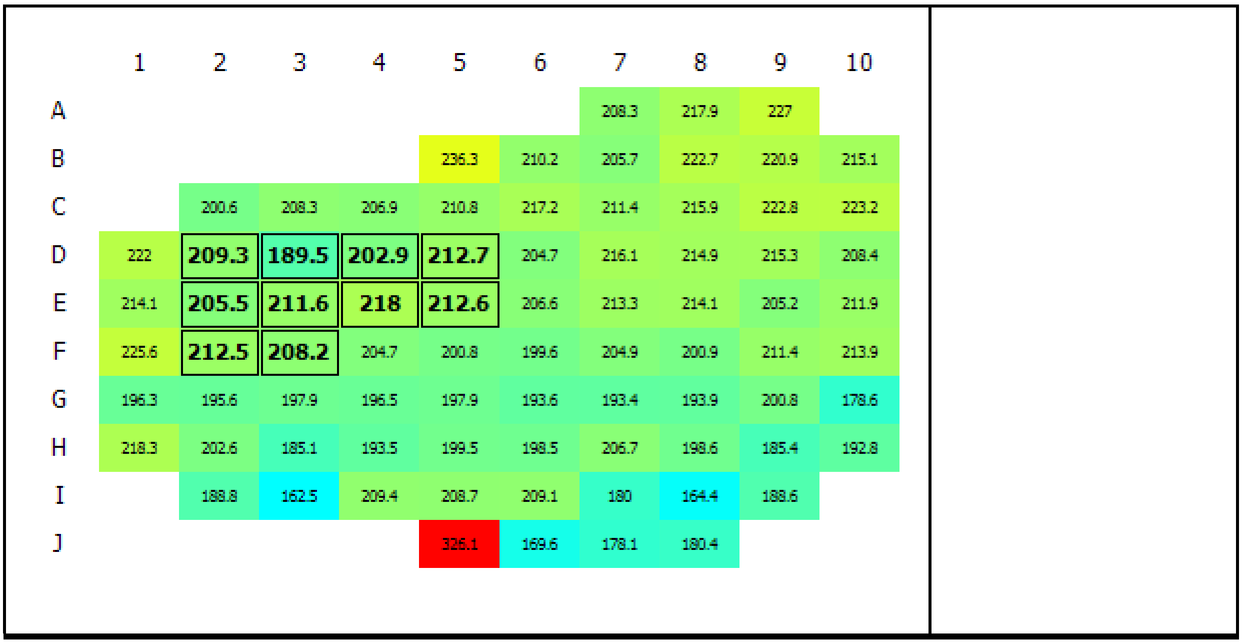


	1	2	3	4	5	6	7	8	9	10
A							201	211.2	165.2	
B					185	198.1	188.1	218.6	154.3	136.1
C		164.9	227.8	211.5	219.9	222.8	197.5	194.2	214.3	196.9
D	229.7	**251.1**	**255.9**	**229.7**	**218.6**	213.1	212.1	207.2	207.5	190.5
E	242.8	**261.1**	**246.7**	**233.9**	**230.1**	221.2	215.2	219.9	212.8	207.9
F	235.3	**225.1**	**232.4**	229.3	227.8	231.7	214.9	211.8	215.3	219.7
G	231.6	210.8	228.1	226.1	233.4	230.8	219.8	214.8	212.4	144.6
H	218.3	227	234.2	216.1	207.3	229.9	217.5	194.7	199.3	247.1
I		215.4	188.1	218	232.8	251.4	212.1	201.7	224.7	
J					286.1	232.1	218.9	233.1		

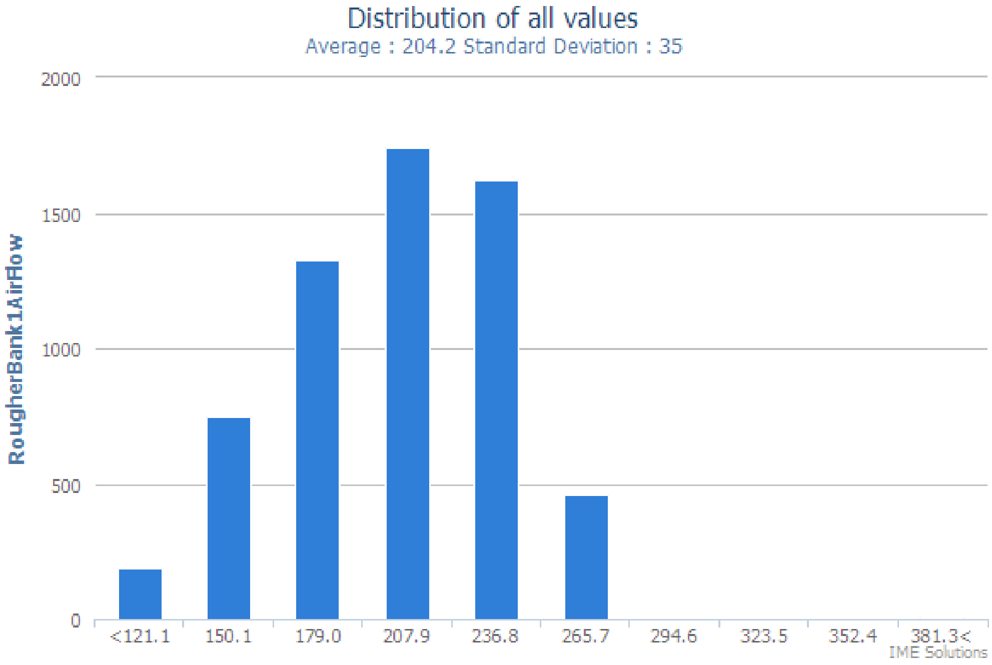


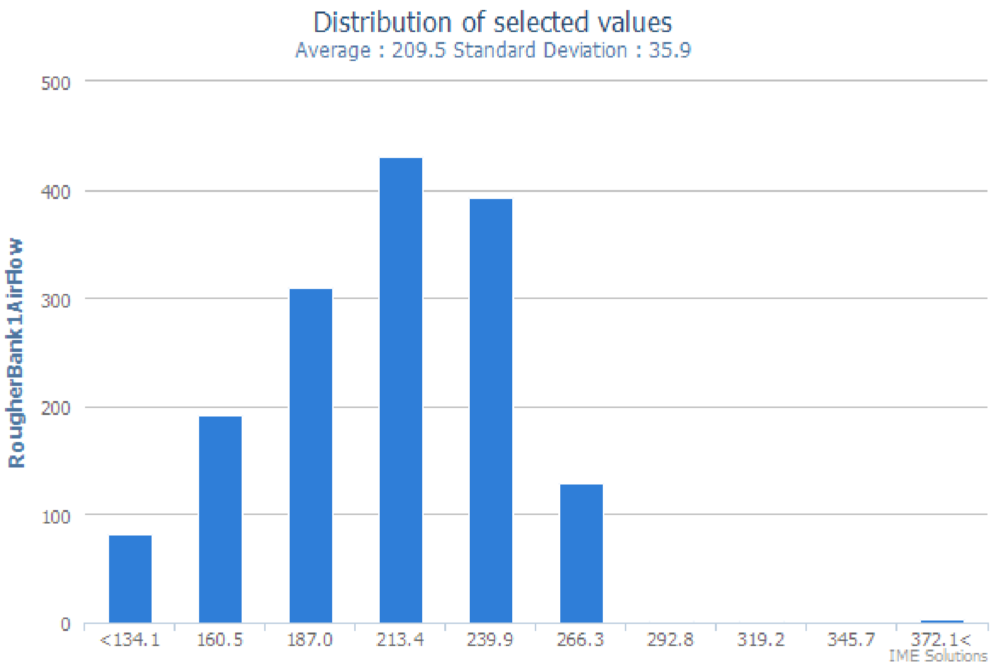

Distribution of selected values
Average : 235.9 Standard Deviation : 44.3
RoCirculatingLoad
600
500
400
300
200
100
0
<80.7
113.1
145.5
177.9
210.2
242.6
275.0
307.4
339.8
372.1<
IME Solutions

Rougher Bank #1 Air Flow

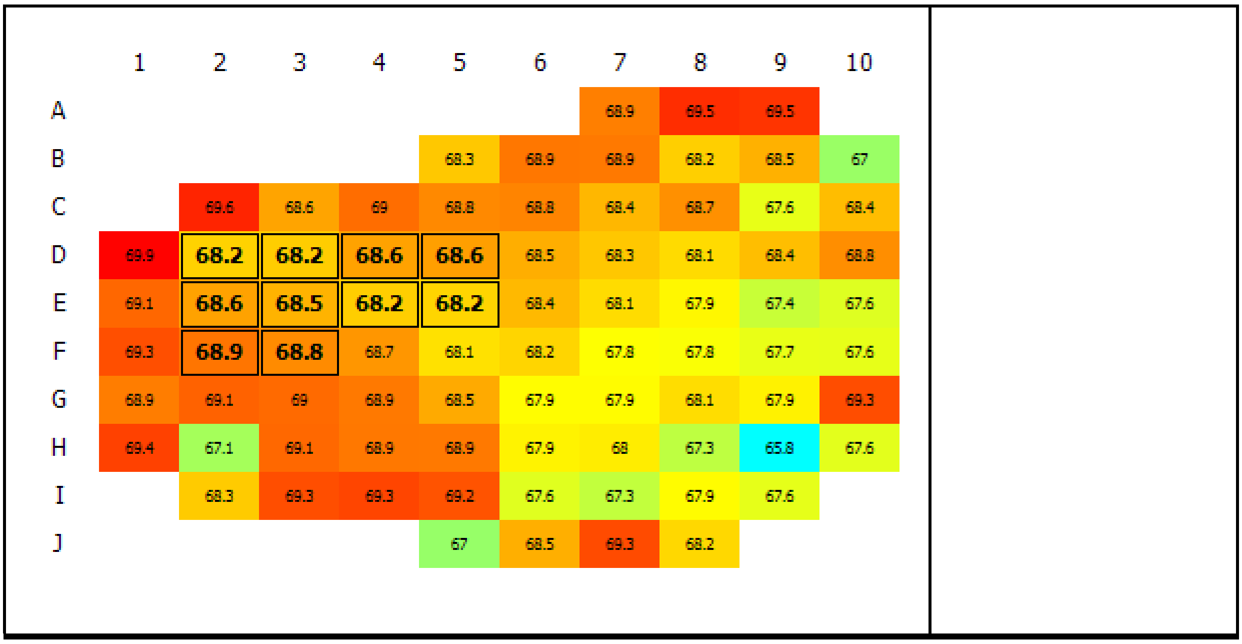


	1	2	3	4	5	6	7	8	9	10
A							208.3	217.9	227	
B					236.3	210.2	205.7	222.7	220.9	215.1
C		200.6	208.3	206.9	210.8	217.2	211.4	215.9	222.8	223.2
D	222	**209.3**	**189.5**	**202.9**	**212.7**	204.7	216.1	214.9	215.3	208.4
E	214.1	**205.5**	**211.6**	**218**	**212.6**	206.6	213.3	214.1	205.2	211.9
F	225.6	**212.5**	**208.2**	204.7	200.8	199.6	204.9	200.9	211.4	213.9
G	196.3	195.6	197.9	196.5	197.9	193.6	193.4	193.9	200.8	178.6
H	218.3	202.6	185.1	193.5	199.5	198.5	206.7	198.6	185.4	192.8
I		188.8	162.5	209.4	208.7	209.1	180	164.4	188.6	
J					326.1	169.6	178.1	180.4		

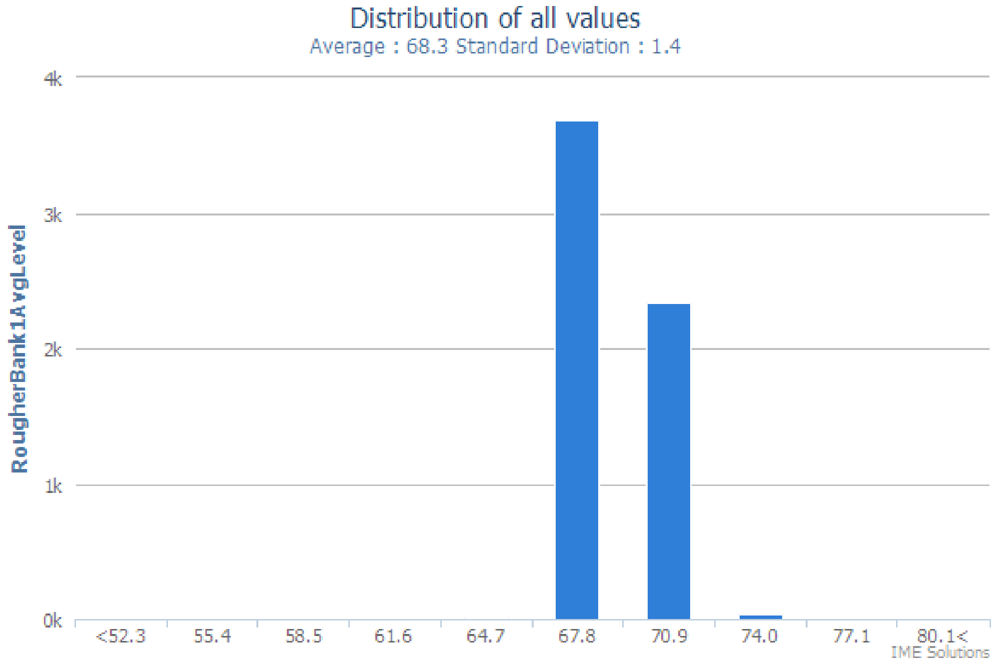


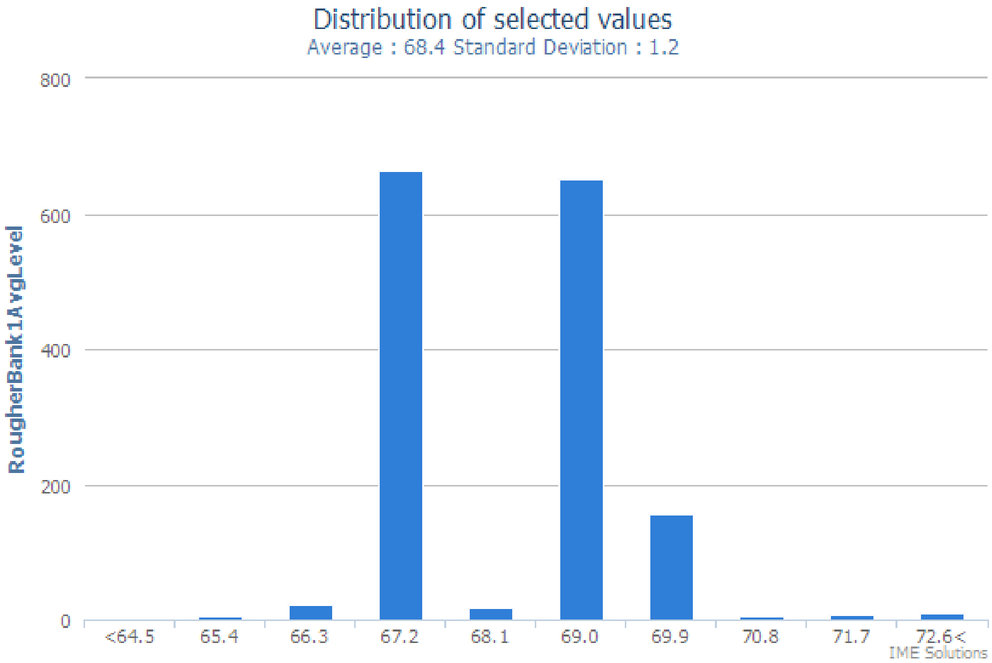

Distribution of selected values
Average : 209.5 Standard Deviation : 35.9
RougherBank1AirFlow
500
400
300
200
100
0
<134.1
160.5
187.0
213.4
239.9
266.3
292.8
319.2
345.7
372.1<
IME Solutions

Rougher Bank #1 Average Level

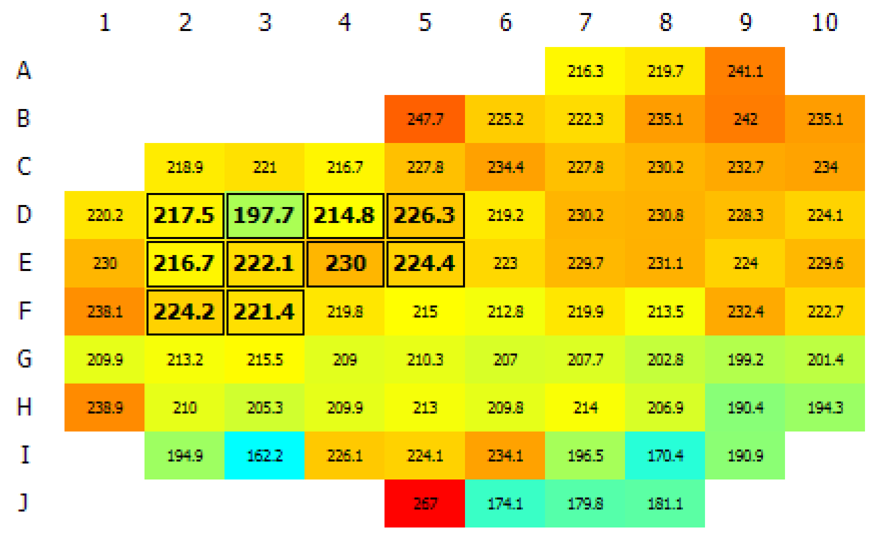


	1	2	3	4	5	6	7	8	9	10
A							68.9	69.5	69.5	
B					68.3	68.9	68.9	68.2	68.5	67
C		69.6	68.6	69	68.8	68.8	68.4	68.7	67.6	68.4
D	69.9	**68.2**	**68.2**	**68.6**	**68.6**	68.5	68.3	68.1	68.4	68.8
E	69.1	**68.6**	**68.5**	**68.2**	**68.2**	68.4	68.1	67.9	67.4	67.6
F	69.3	**68.9**	**68.8**	68.7	68.1	68.2	67.8	67.8	67.7	67.6
G	68.9	69.1	69	68.9	68.5	67.9	67.9	68.1	67.9	69.3
H	69.4	67.1	69.1	68.9	68.9	67.9	68	67.3	65.8	67.6
I		68.3	69.3	69.3	69.2	67.6	67.3	67.9	67.6	
J					67	68.5	69.3	68.2		

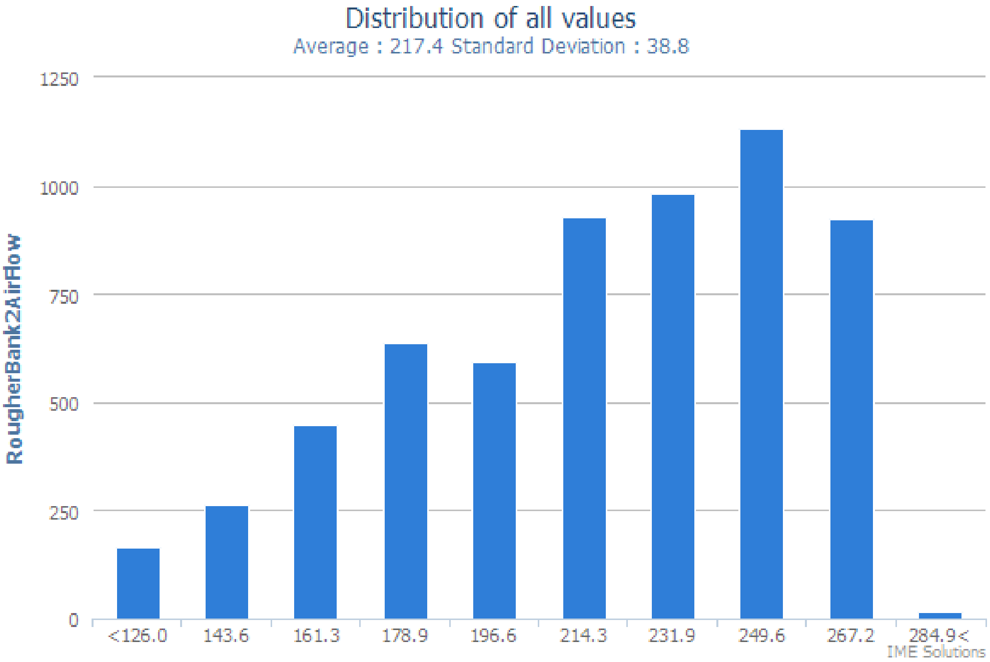


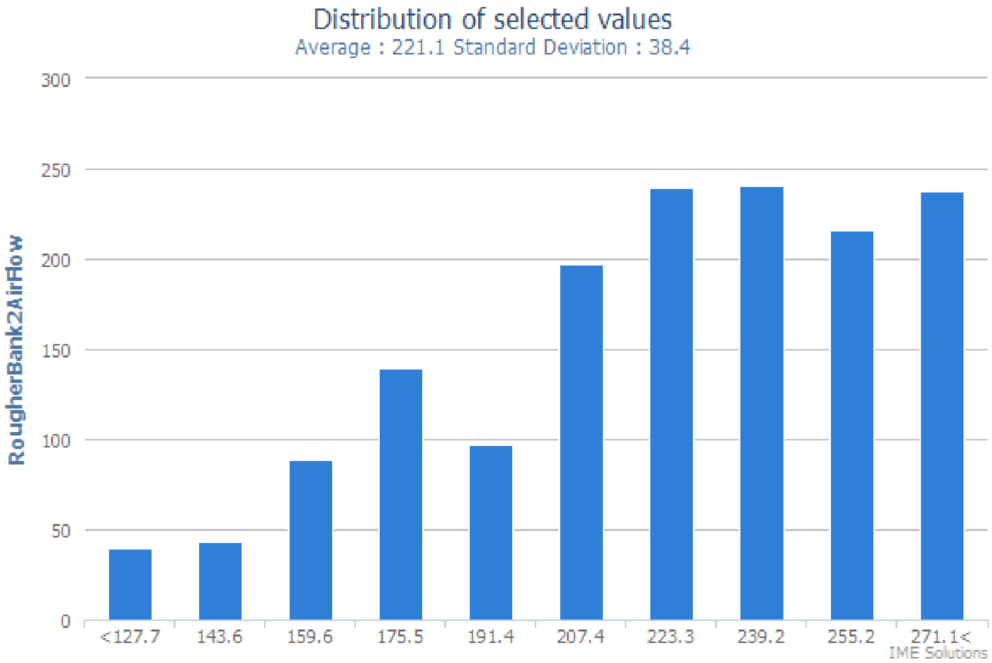

Distribution of selected values
Average : 68.4 Standard Deviation : 1.2
RougherBank1AvgLevel
800
600
400
200
0
<64.5
65.4
66.3
67.2
68.1
69.0
69.9
70.8
71.7
72.6<
IME Solutions

Rougher Bank #2 Air Flow

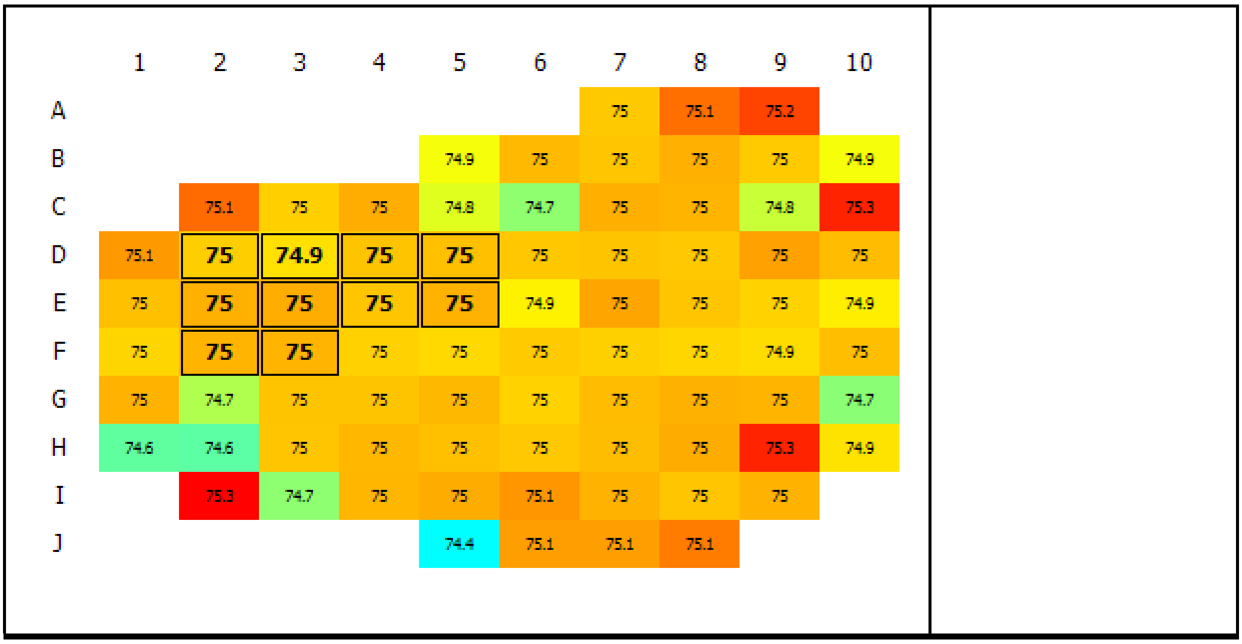


	1	2	3	4	5	6	7	8	9	10
A							216.3	219.7	241.1	
B					247.7	225.2	222.3	235.1	242	235.1
C		218.9	221	216.7	227.8	234.4	227.8	230.2	232.7	234
D	220.2	**217.5**	**197.7**	**214.8**	**226.3**	219.2	230.2	230.8	228.3	224.1
E	230	**216.7**	**222.1**	**230**	**224.4**	223	229.7	231.1	224	229.6
F	238.1	**224.2**	**221.4**	219.8	215	212.8	219.9	213.5	232.4	222.7
G	209.9	213.2	215.5	209	210.3	207	207.7	202.8	199.2	201.4
H	238.9	210	205.3	209.9	213	209.8	214	206.9	190.4	194.3
I		194.9	162.2	226.1	224.1	234.1	196.5	170.4	190.9	
J					267	174.1	179.8	181.1		

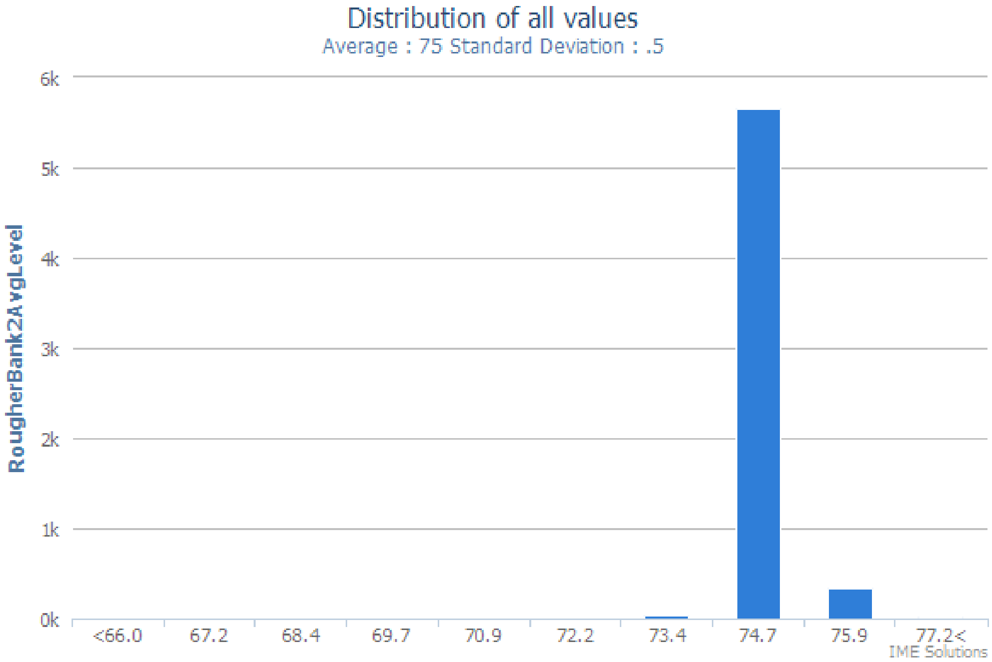


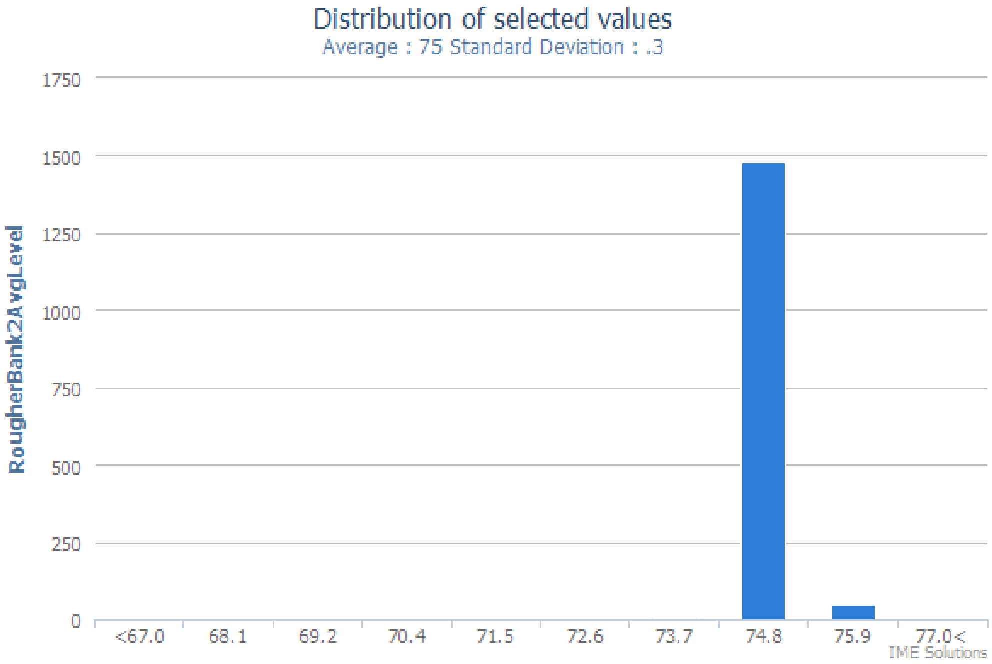

Distribution of selected values
Average : 221.1 Standard Deviation : 38.4
RougherBank2AirFlow
300
250
200
150
100
50
0
<127.7
143.6
159.6
175.5
191.4
207.4
223.3
239.2
255.2
271.1<
IME Solutions

Rougher Bank #2 Average Level

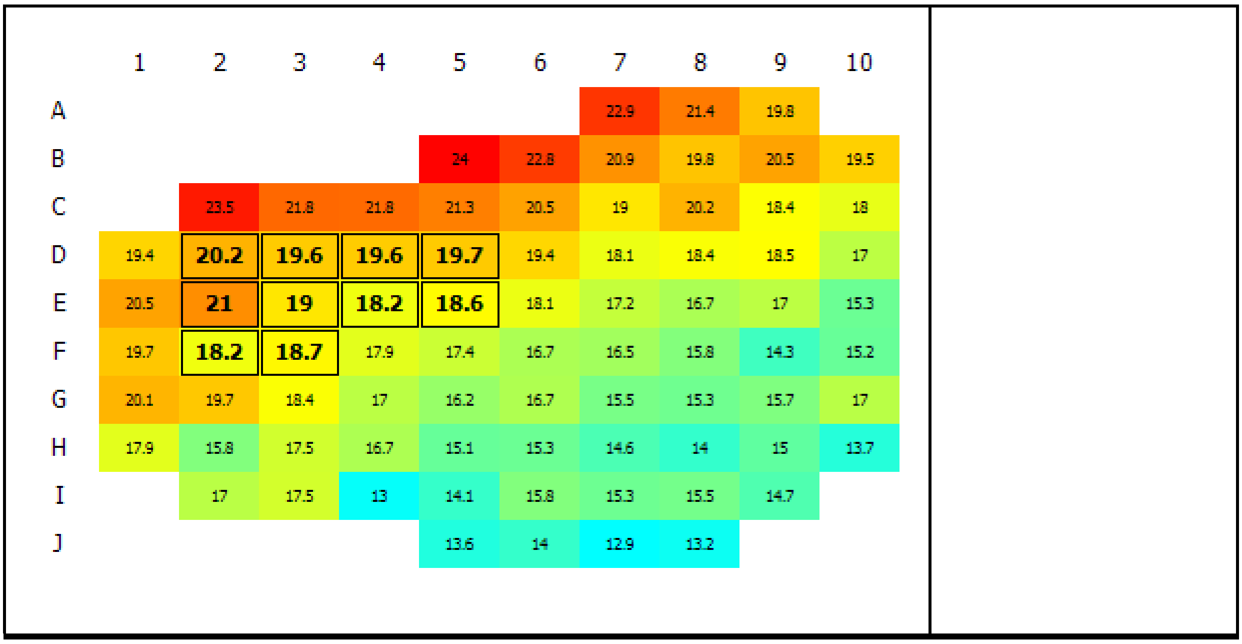


	1	2	3	4	5	6	7	8	9	10
A							75	75.1	75.2	
B					74.9	75	75	75	75	74.9
C		75.1	75	75	74.8	74.7	75	75	74.8	75.3
D	75.1	**75**	**74.9**	**75**	**75**	75	75	75	75	75
E	75	**75**	**75**	**75**	**75**	74.9	75	75	75	74.9
F	75	**75**	**75**	75	75	75	75	75	74.9	75
G	75	74.7	75	75	75	75	75	75	75	74.7
H	74.6	74.6	75	75	75	75	75	75	75.3	74.9
I		75.3	74.7	75	75	75.1	75	75	75	
J					74.4	75.1	75.1	75.1		

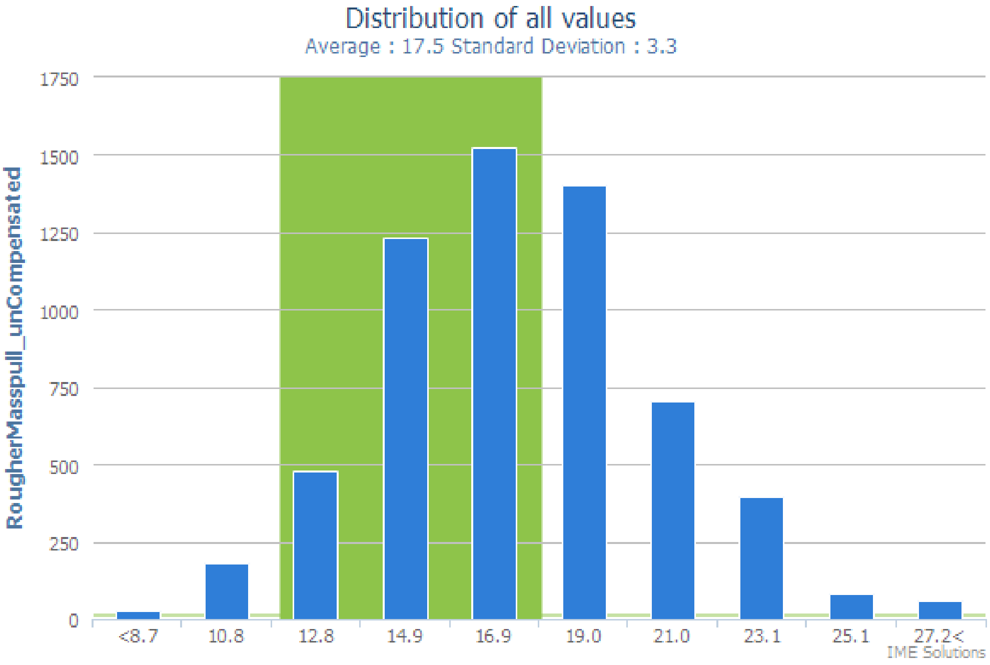


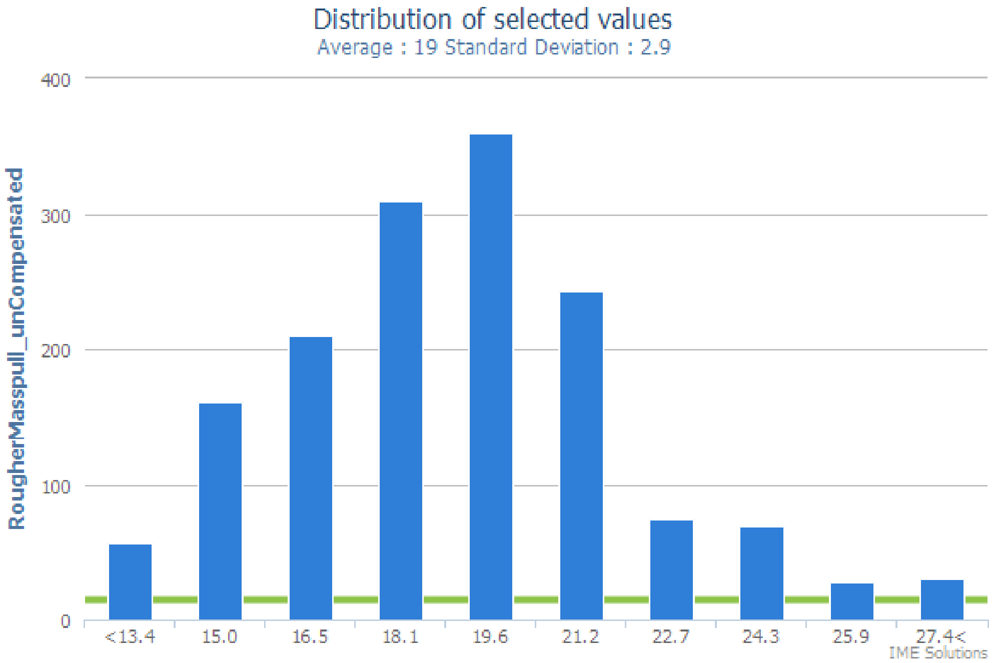

Distribution of selected values
Average : 75 Standard Deviation : .3
RougherBank2AvgLevel
1750
1500
1250
1000
750
500
250
0
<67.0
68.1
69.2
70.4
71.5
72.6
73.7
74.8
75.9
77.0<
IME Solutions

Rougher Mass Pull (Uncompenated)

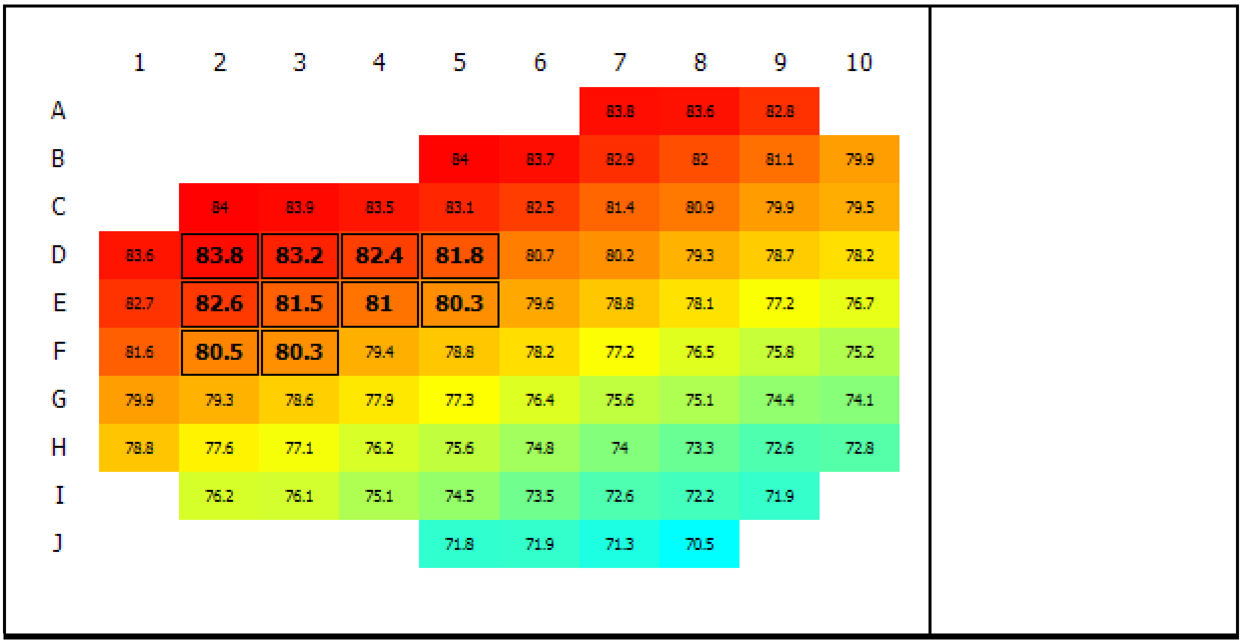


	1	2	3	4	5	6	7	8	9	10
A							22.9	21.4	19.8	
B					24	22.8	20.9	19.8	20.5	19.5
C		23.5	21.8	21.8	21.3	20.5	19	20.2	18.4	18
D	19.4	**20.2**	**19.6**	**19.6**	**19.7**	19.4	18.1	18.4	18.5	17
E	20.5	**21**	**19**	**18.2**	**18.6**	18.1	17.2	16.7	17	15.3
F	19.7	**18.2**	**18.7**	17.9	17.4	16.7	16.5	15.8	14.3	15.2
G	20.1	19.7	18.4	17	16.2	16.7	15.5	15.3	15.7	17
H	17.9	15.8	17.5	16.7	15.1	15.3	14.6	14	15	13.7
I		17	17.5	13	14.1	15.8	15.3	15.5	14.7	
J					13.6	14	12.9	13.2		

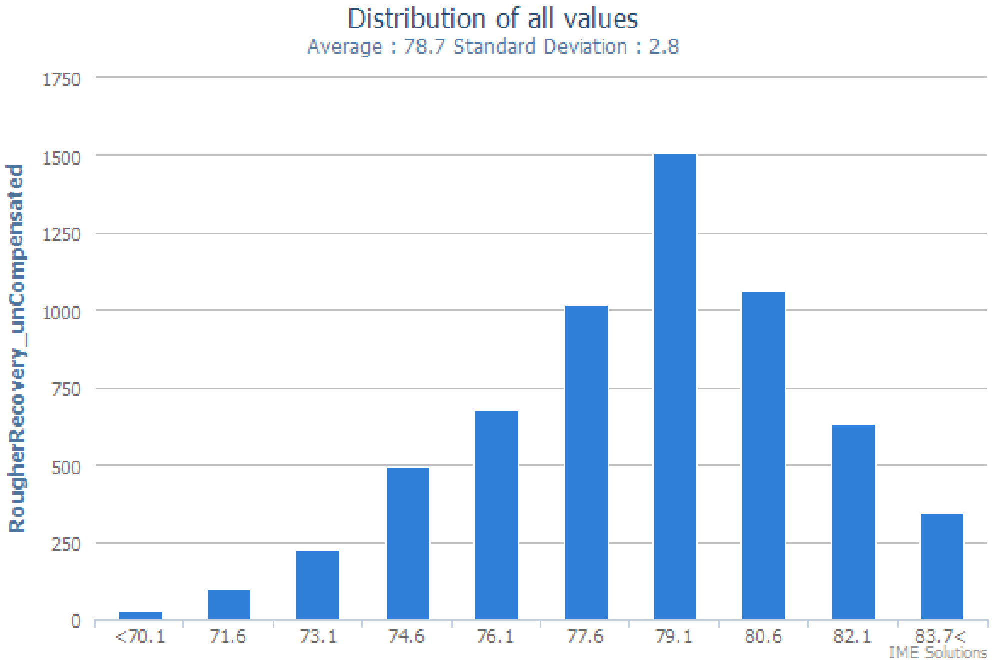


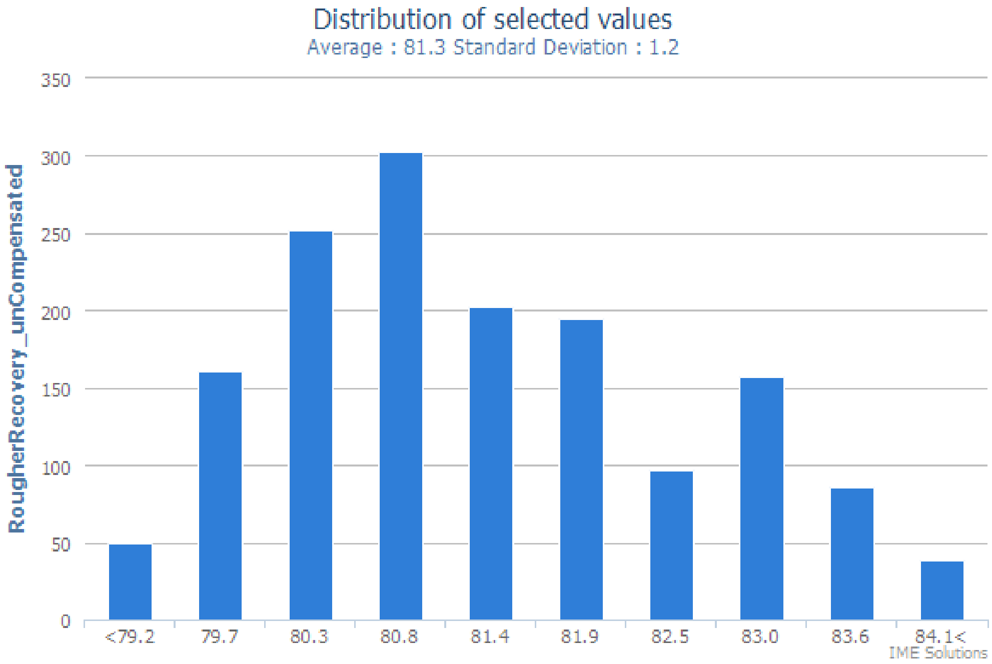

Distribution of selected values
Average : 19 Standard Deviation : 2.9
RougherMasspull_unCompensated
400
300
200
100
0
<13.4
15.0
16.5
18.1
19.6
21.2
22.7
24.3
25.9
27.4<
IME Solutions

Rougher Recovery

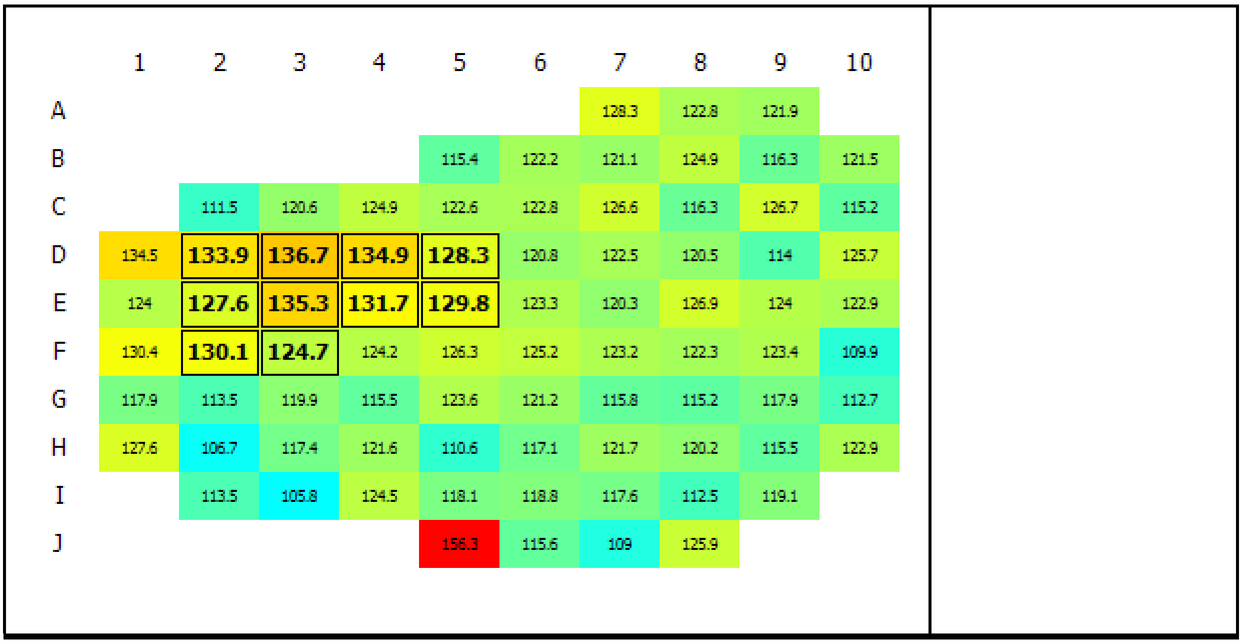


	1	2	3	4	5	6	7	8	9	10
A							83.8	83.6	82.8	
B					84	83.7	82.9	82	81.1	79.9
C		84	83.9	83.5	83.1	82.5	81.4	80.9	79.9	79.5
D	83.6	**83.8**	**83.2**	**82.4**	**81.8**	80.7	80.2	79.3	78.7	78.2
E	82.7	**82.6**	**81.5**	**81**	**80.3**	79.6	78.8	78.1	77.2	76.7
F	81.6	**80.5**	**80.3**	79.4	78.8	78.2	77.2	76.5	75.8	75.2
G	79.9	79.3	78.6	77.9	77.3	76.4	75.6	75.1	74.4	74.1
H	78.8	77.6	77.1	76.2	75.6	74.8	74	73.3	72.6	72.8
I		76.2	76.1	75.1	74.5	73.5	72.6	72.2	71.9	
J					71.8	71.9	71.3	70.5		

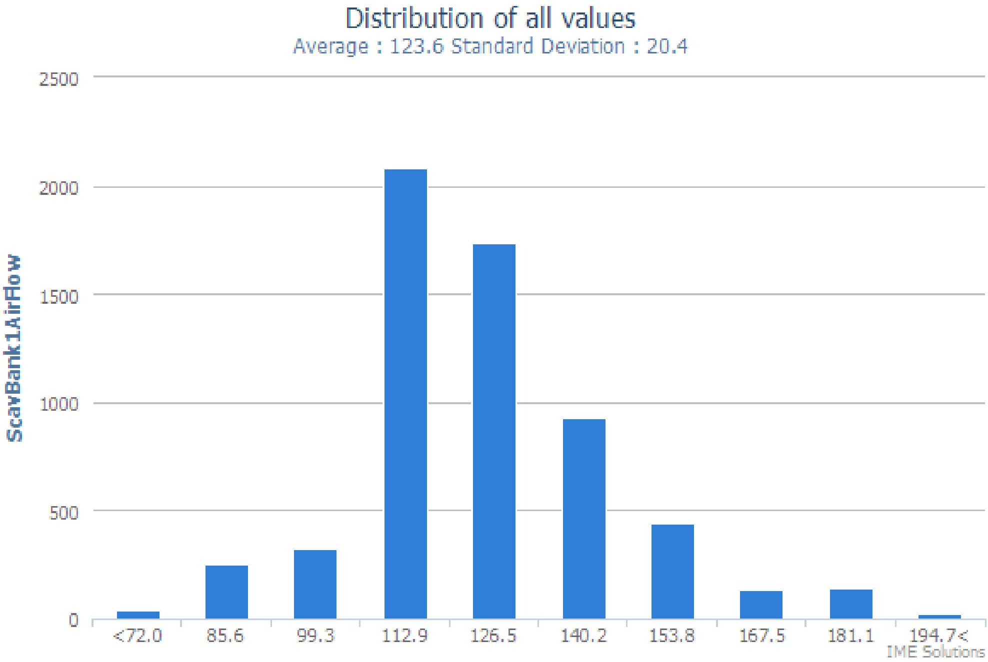


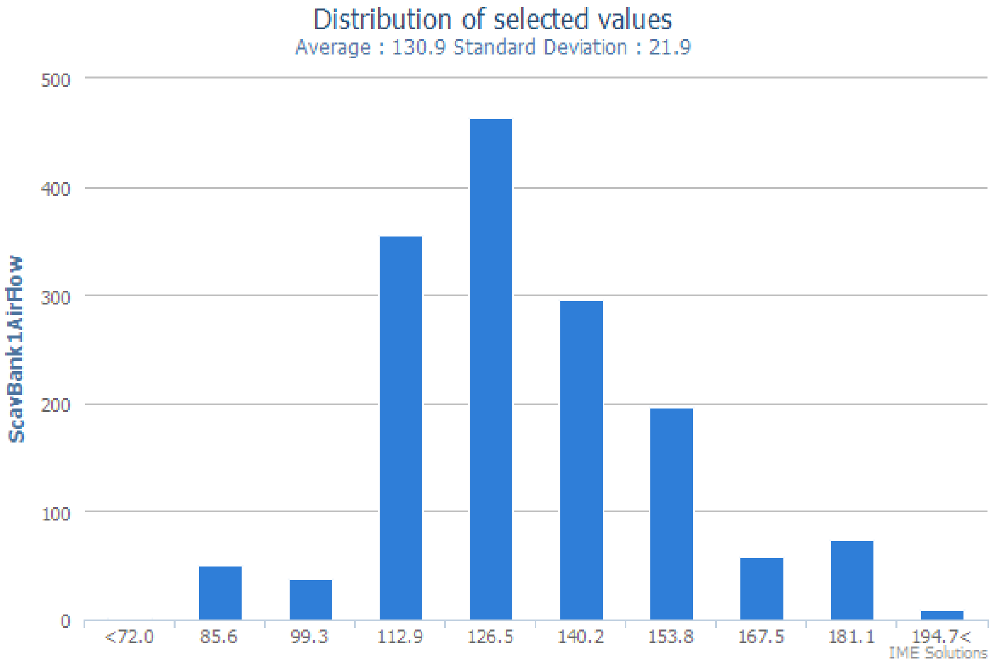

Distribution of selected values
Average : 81.3 Standard Deviation : 1.2
RougherRecovery_unCompensated
350
300
250
200
150
100
50
0
<79.2
79.7
80.3
80.8
81.4
81.9
82.5
83.0
83.6
84.1<
IME Solutions

Scavenger Bank #1 Air Flow

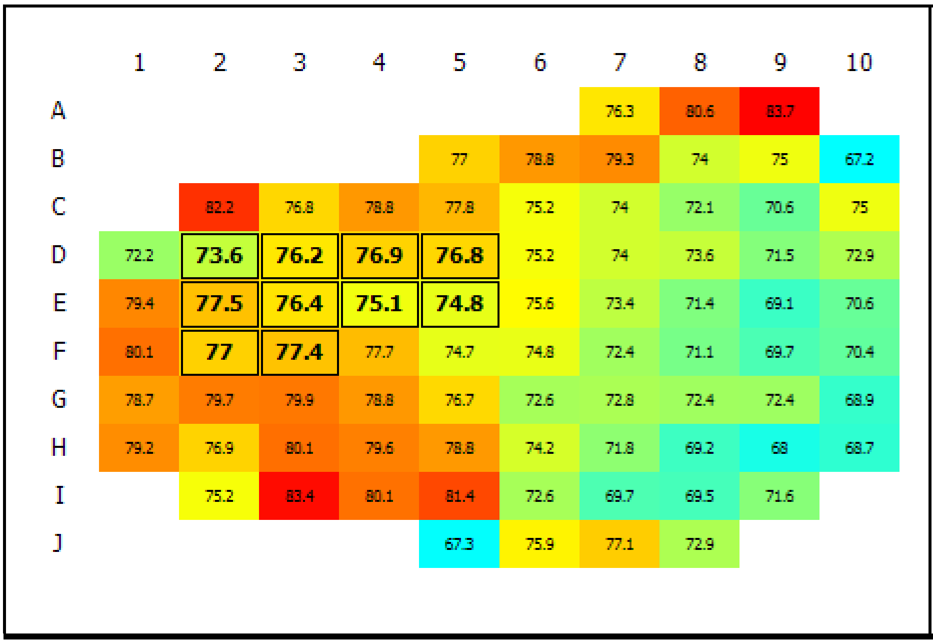


	1	2	3	4	5	6	7	8	9	10
A							128.3	122.8	121.9	
B					115.4	122.2	121.1	124.9	116.3	121.5
C		111.5	120.6	124.9	122.6	122.8	126.6	116.3	126.7	115.2
D	134.5	**133.9**	**136.7**	**134.9**	**128.3**	120.8	122.5	120.5	114	125.7
E	124	**127.6**	**135.3**	**131.7**	**129.8**	123.3	120.3	126.9	124	122.9
F	130.4	**130.1**	**124.7**	124.2	126.3	125.2	123.2	122.3	123.4	109.9
G	117.9	113.5	119.9	115.5	123.6	121.2	115.8	115.2	117.9	112.7
H	127.6	106.7	117.4	121.6	110.6	117.1	121.7	120.2	115.5	122.9
I		113.5	105.8	124.5	118.1	118.8	117.6	112.5	119.1	
J					156.3	115.6	109	125.9		

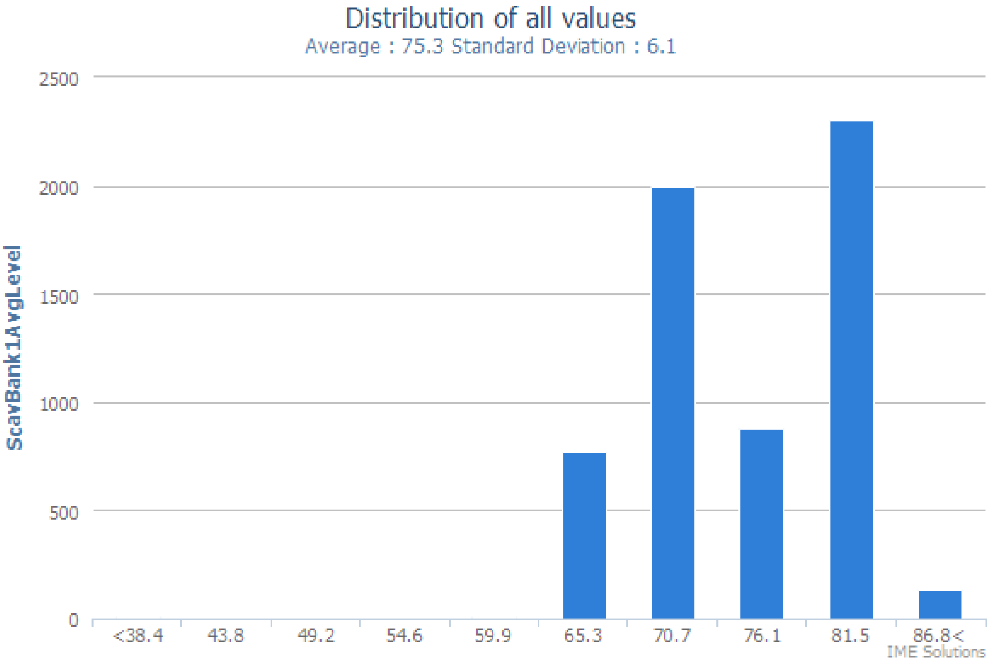


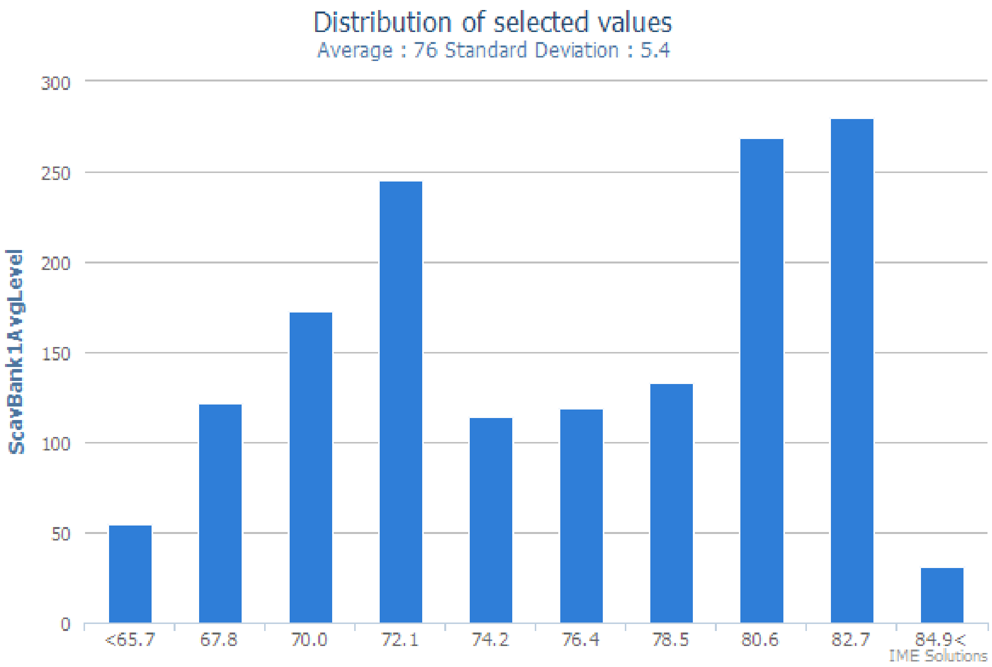

Distribution of selected values
Average : 130.9 Standard Deviation : 21.9
ScavBank1AirFlow
500
400
300
200
100
0
<72.0
85.6
99.3
112.9
126.5
140.2
153.8
167.5
181.1
194.7<
IME Solutions

Average Bank #1 Average Level

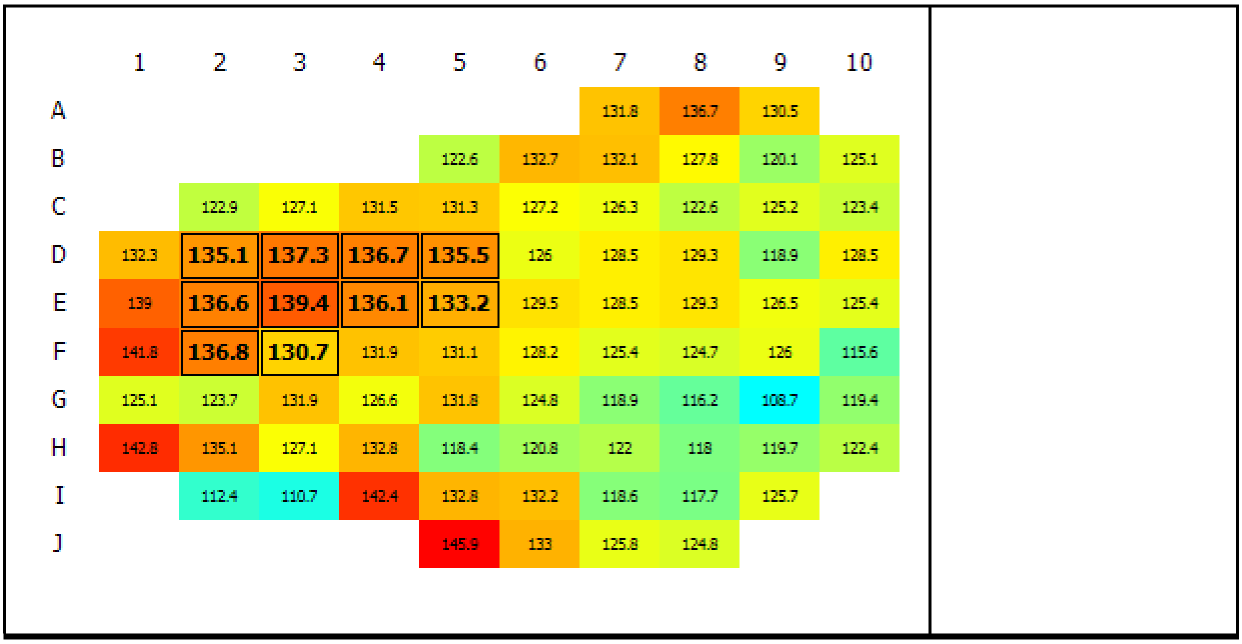


	1	2	3	4	5	6	7	8	9	10
A							76.3	80.6	83.7	
B					77	78.8	79.3	74	75	67.2
C		82.2	76.8	78.8	77.8	75.2	74	72.1	70.6	75
D	72.2	**73.6**	**76.2**	**76.9**	**76.8**	75.2	74	73.6	71.5	72.9
E	79.4	**77.5**	**76.4**	**75.1**	**74.8**	75.6	73.4	71.4	69.1	70.6
F	80.1	**77**	**77.4**	77.7	74.7	74.8	72.4	71.1	69.7	70.4
G	78.7	79.7	79.9	78.8	76.7	72.6	72.8	72.4	72.4	68.9
H	79.2	76.9	80.1	79.6	78.8	74.2	71.8	69.2	68	68.7
I		75.2	83.4	80.1	81.4	72.6	69.7	69.5	71.6	
J					67.3	75.9	77.1	72.9		

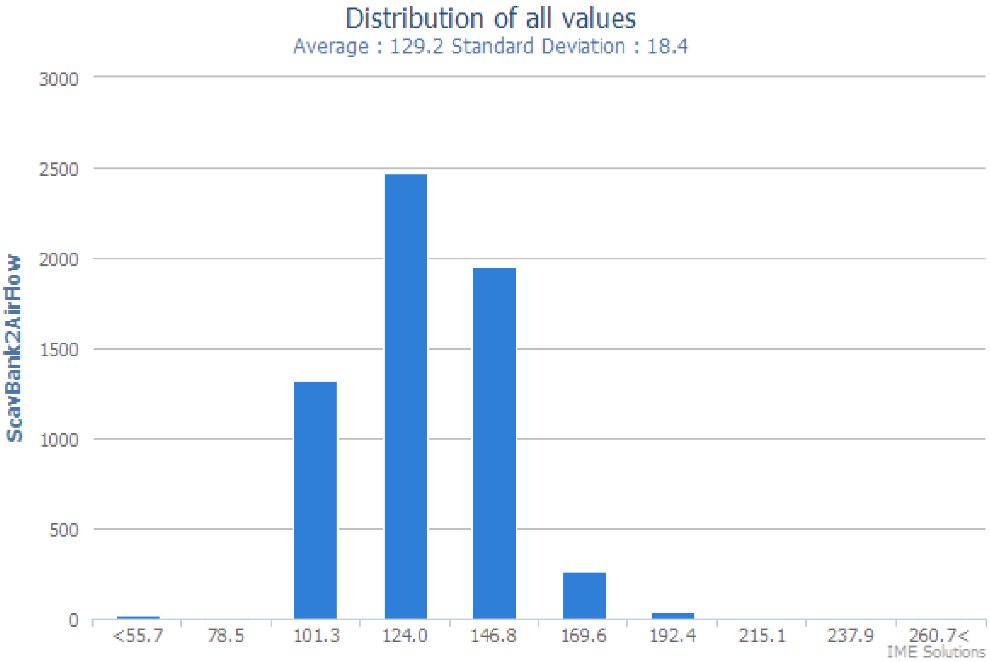


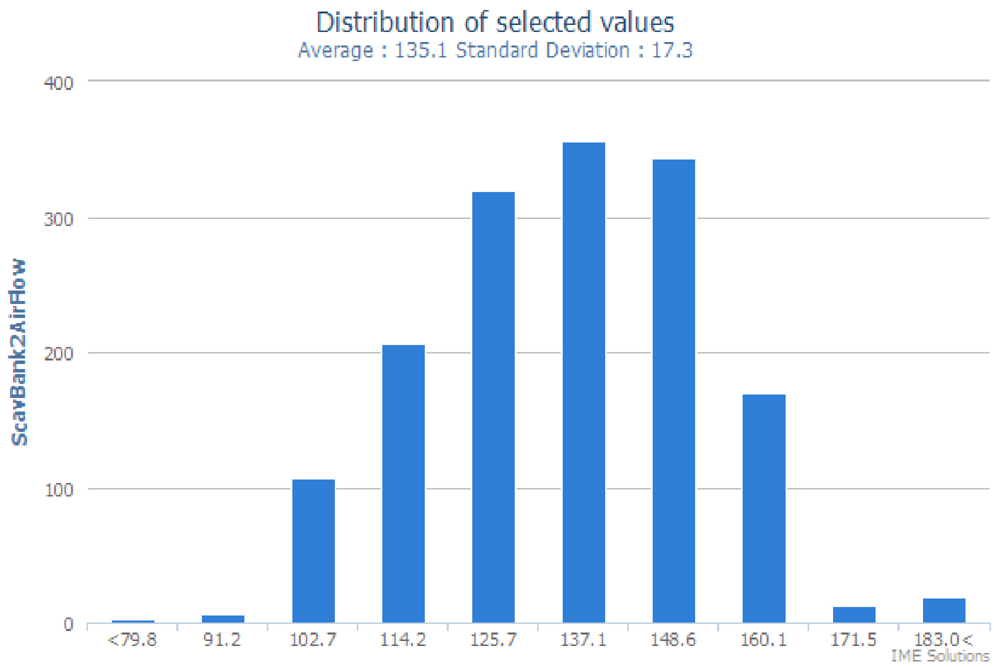

Distribution of selected values
Average : 76 Standard Deviation : 5.4
ScavBank1AvgLevel
300
250
200
150
100
50
0
<65.7
67.8
70.0
72.1
74.2
76.4
78.5
80.6
82.7
84.9<
IME Solutions

Scavenger Bank #2 Air Flow

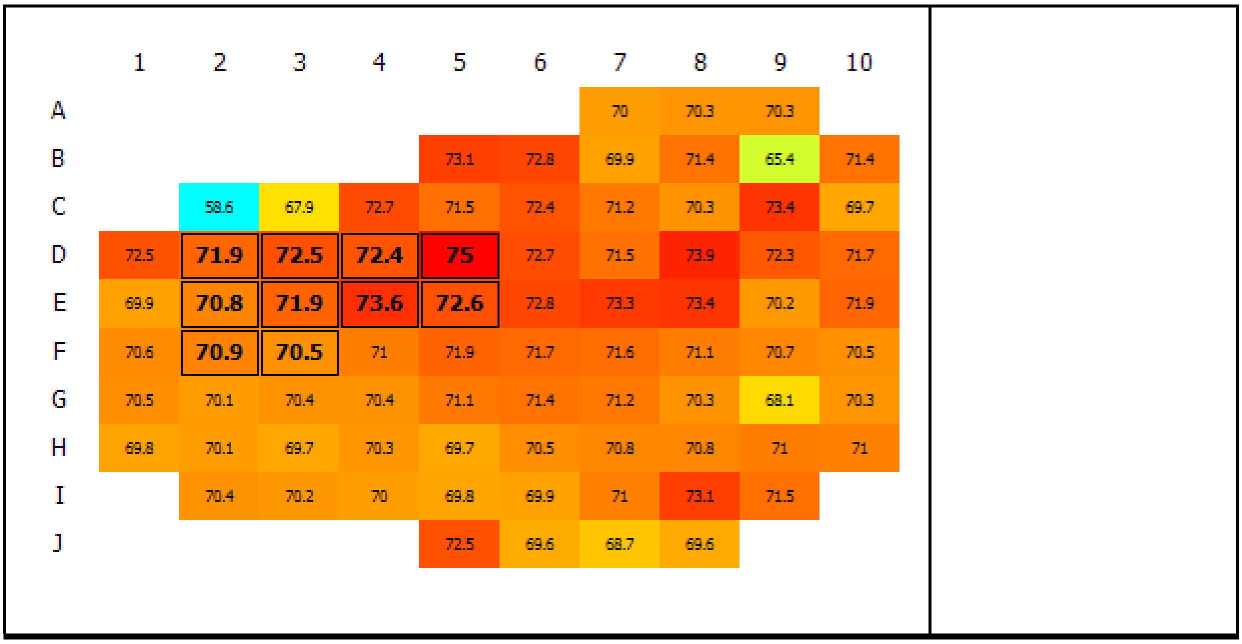


	1	2	3	4	5	6	7	8	9	10
A							131.8	136.7	130.5	
B					122.6	132.7	132.1	127.8	120.1	125.1
C		122.9	127.1	131.5	131.3	127.2	126.3	122.6	125.2	123.4
D	132.3	**135.1**	**137.3**	**136.7**	**135.5**	126	128.5	129.3	118.9	128.5
E	139	**136.6**	**139.4**	**136.1**	**133.2**	129.5	128.5	129.3	126.5	125.4
F	141.8	**136.8**	**130.7**	131.9	131.1	128.2	125.4	124.7	126	115.6
G	125.1	123.7	131.9	126.6	131.8	124.8	118.9	116.2	108.7	119.4
H	142.8	135.1	127.1	132.8	118.4	120.8	122	118	119.7	122.4
I		112.4	110.7	142.4	132.8	132.2	118.6	117.7	125.7	
J					145.9	133	125.8	124.8		

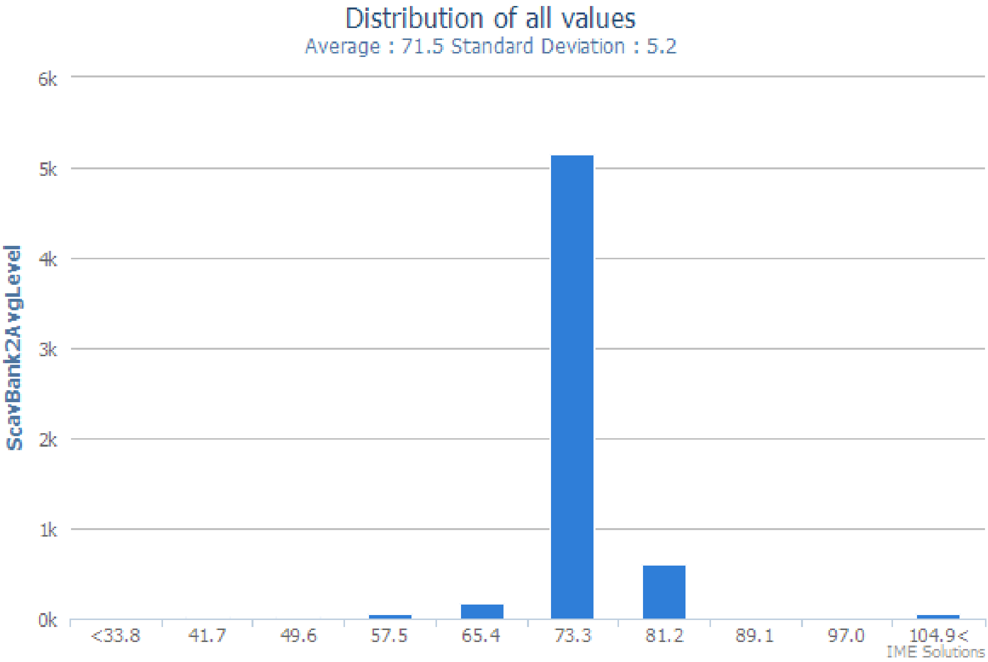


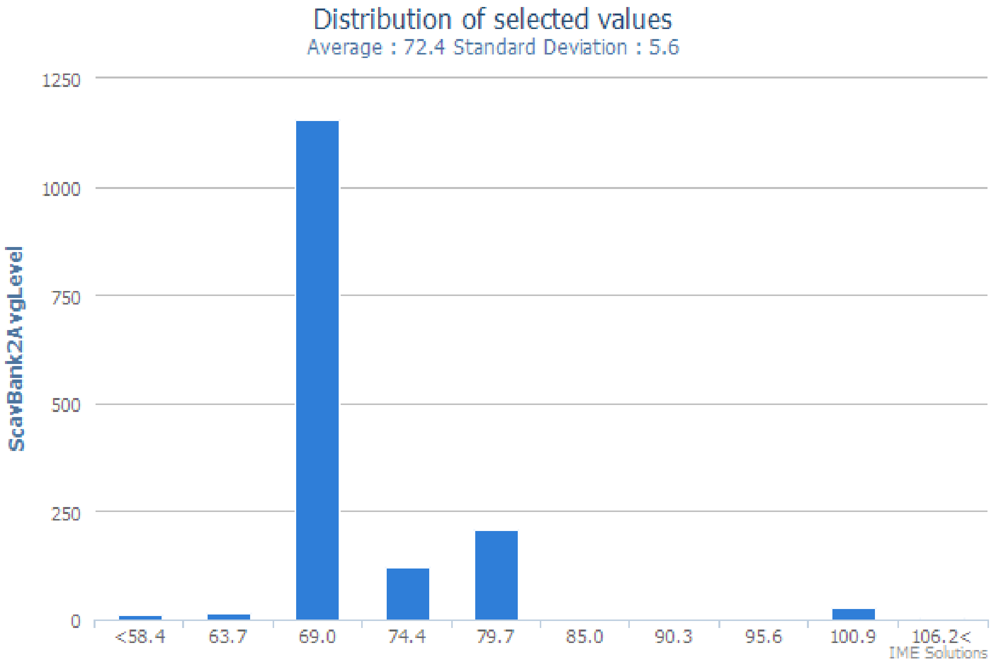

Distribution of selected values
Average : 135.1 Standard Deviation : 17.3
ScavBank2AirFlow
400
300
200
100
0
<79.8
91.2
102.7
114.2
125.7
137.1
148.6
160.1
171.5
183.0<
IME Solutions

Scavenger Bank #2 Average Level



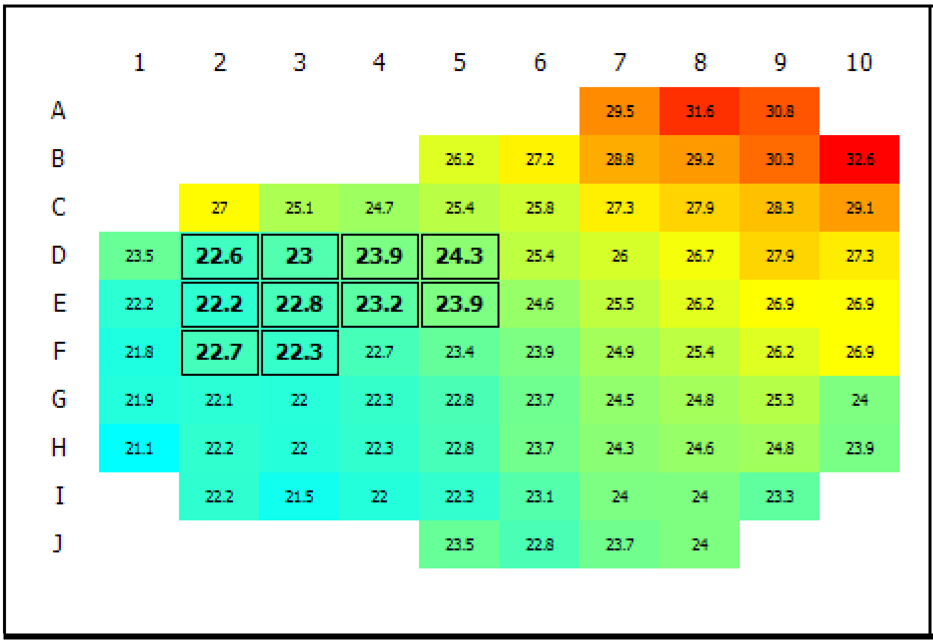
	1	2	3	4	5	6	7	8	9	10
A							70	70.3	70.3	
B					73.1	72.8	69.9	71.4	65.4	71.4
C		58.6	67.9	72.7	71.5	72.4	71.2	70.3	73.4	69.7
D	72.5	**71.9**	**72.5**	**72.4**	**75**	72.7	71.5	73.9	72.3	71.7
E	69.9	**70.8**	**71.9**	**73.6**	**72.6**	72.8	73.3	73.4	70.2	71.9
F	70.6	**70.9**	**70.5**	71	71.9	71.7	71.6	71.1	70.7	70.5
G	70.5	70.1	70.4	70.4	71.1	71.4	71.2	70.3	68.1	70.3
H	69.8	70.1	69.7	70.3	69.7	70.5	70.8	70.8	71	71
I		70.4	70.2	70	69.8	69.9	71	73.1	71.5	
J					72.5	69.6	68.7	69.6		



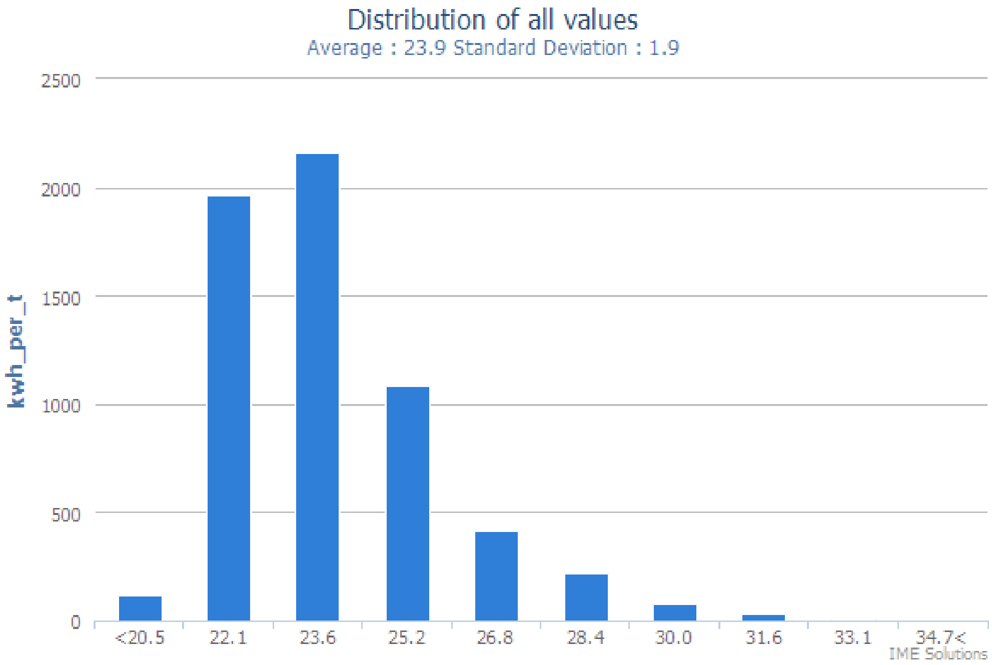

Distribution of selected values
Average : 72.4 Standard Deviation : 5.6
ScavBank2AvgLevel
1250
1000
750
500
250
0
<58.4
63.7
69.0
74.4
79.7
85.0
90.3
95.6
100.9
106.2<
IME Solutions

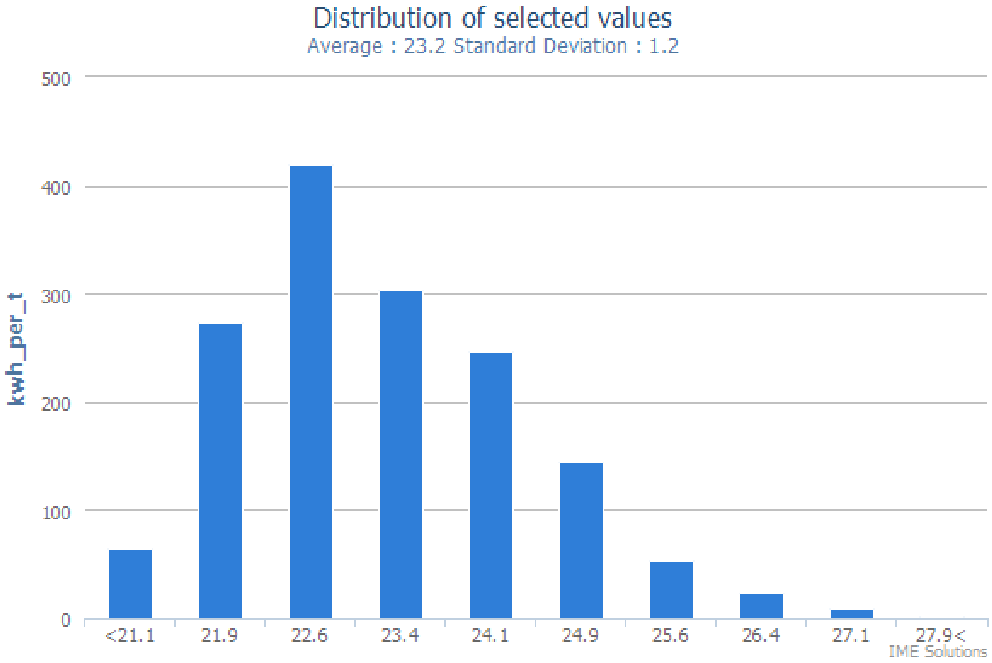
Power used per ton fed (kWh/t)

Using the Primary and Secondary Mill power as reference



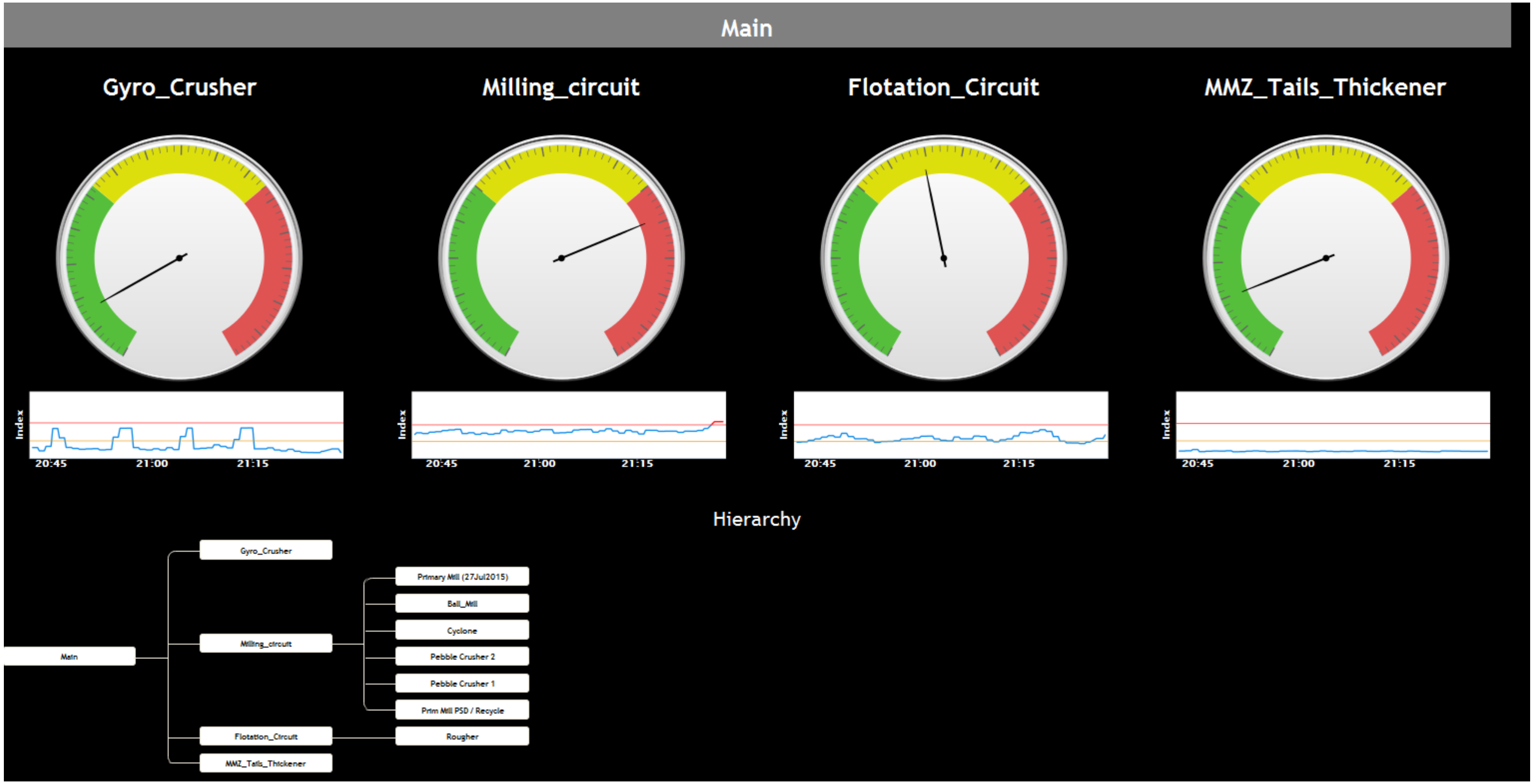
	1	2	3	4	5	6	7	8	9	10
A							29.5	31.6	30.8	
B					26.2	27.2	28.8	29.2	30.3	32.6
C		27	25.1	24.7	25.4	25.8	27.3	27.9	28.3	29.1
D	23.5	**22.6**	**23**	**23.9**	**24.3**	25.4	26	26.7	27.9	27.3
E	22.2	**22.2**	**22.8**	**23.2**	**23.9**	24.6	25.5	26.2	26.9	26.9
F	21.8	**22.7**	**22.3**	22.7	23.4	23.9	24.9	25.4	26.2	26.9
G	21.9	22.1	22	22.3	22.8	23.7	24.5	24.8	25.3	24
H	21.1	22.2	22	22.3	22.8	23.7	24.3	24.6	24.8	23.9
I		22.2	21.5	22	22.3	23.1	24	24	23.3	
J					23.5	22.8	23.7	24		

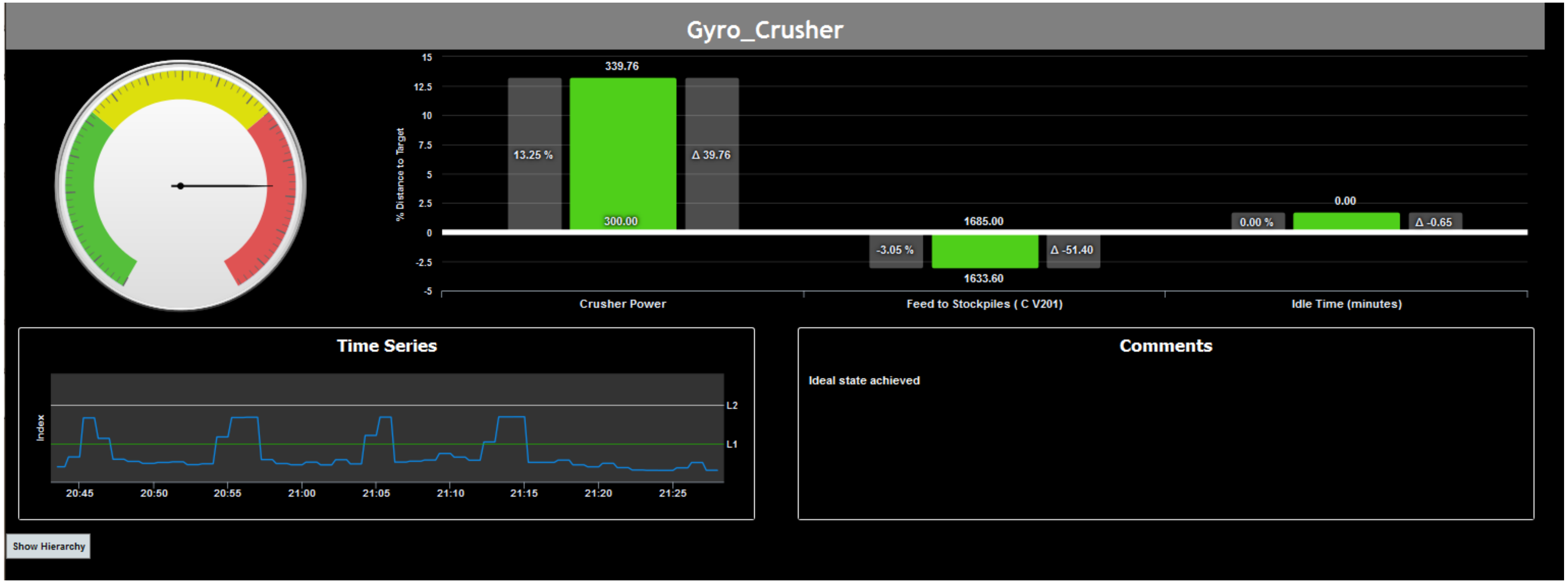



Distribution of selected values
Average : 23.2 Standard Deviation : 1.2
kwh_per_t
500
400
300
200
100
0
<21.1
21.9
22.6
23.4
24.1
24.9
25.6
26.4
27.1
27.9<
IME Solutions

Appendix C

Time-in-State Interface Developed for monitoring Process Performance at Nkomati Mine

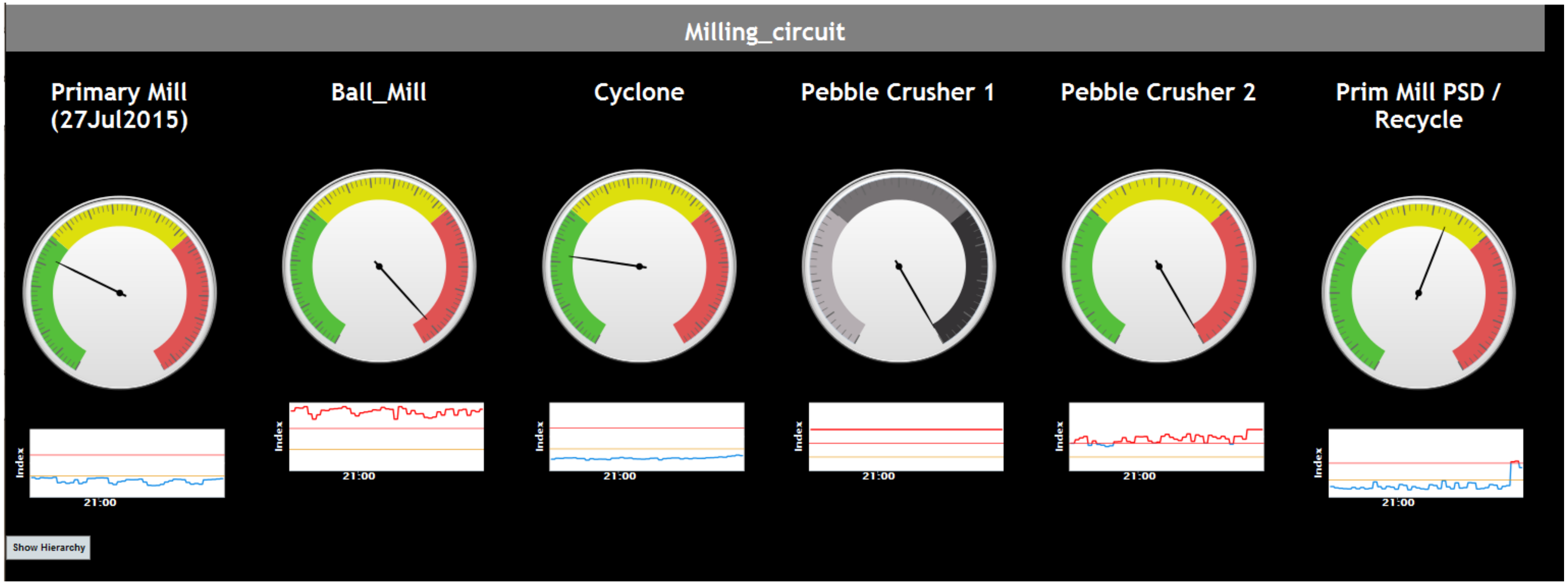

Main
Gyro_Crusher
Milling_circuit
Flotation_Circuit
MMZ_Tails_Thickener
Index
20:45
21:00
21:15
Hierarchy
Main
Gyro_Crusher
Milling_circuit
Flotation_Circuit
MMZ_Tails_Thickener
Primary Mill (27Jul2015)
Ball_Mill
Cyclone
Pebble Crusher 2
Pebble Crusher 1
Prim Mill PSD / Recycle
Rougher

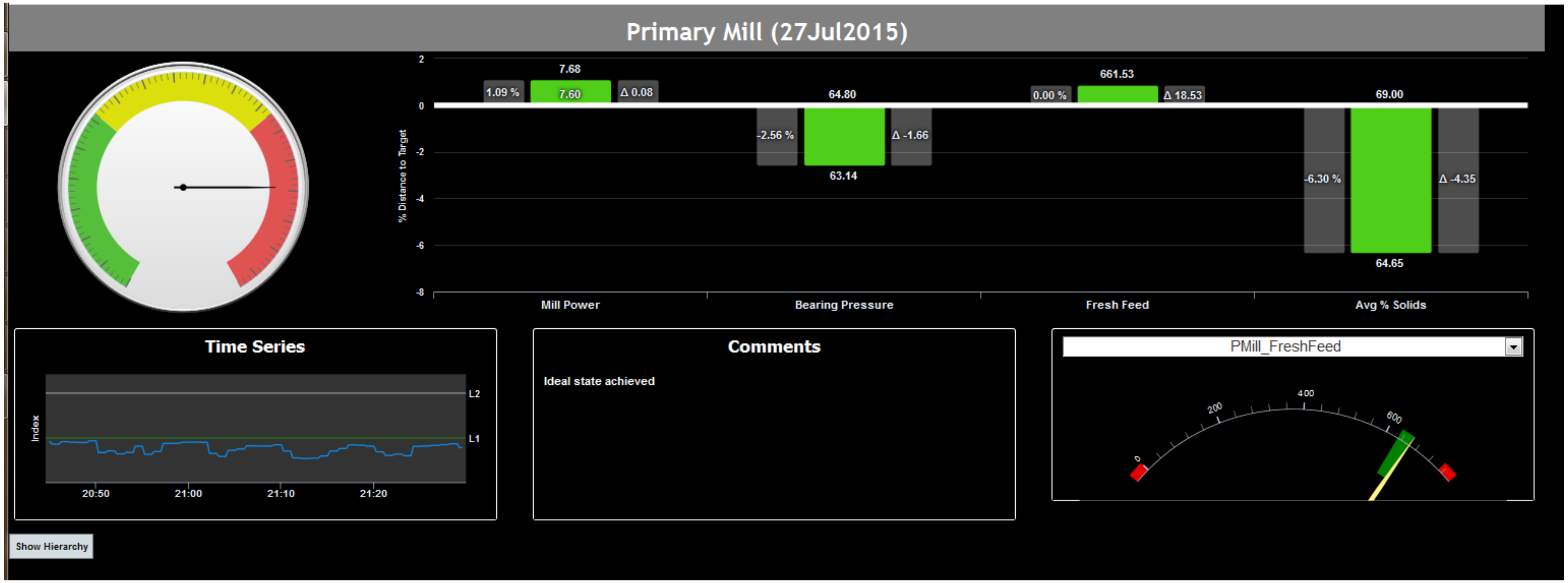


Gyro_Crusher

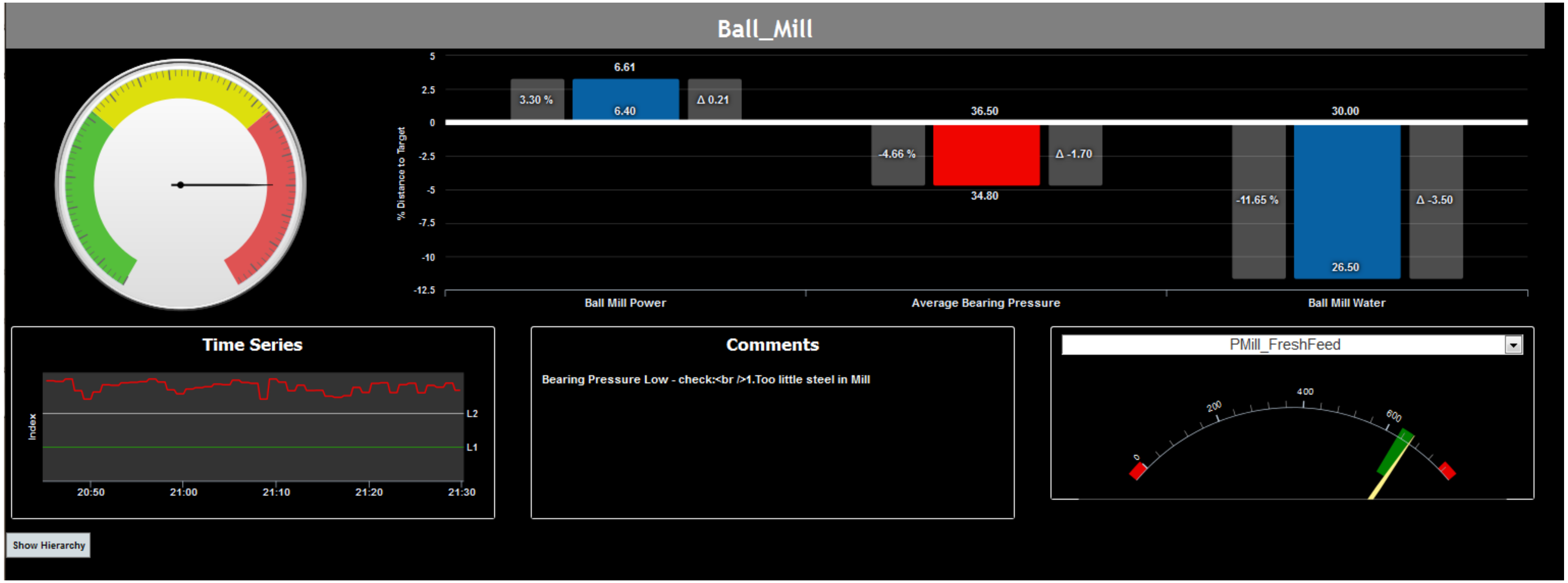
Comments

Ideal state achieved

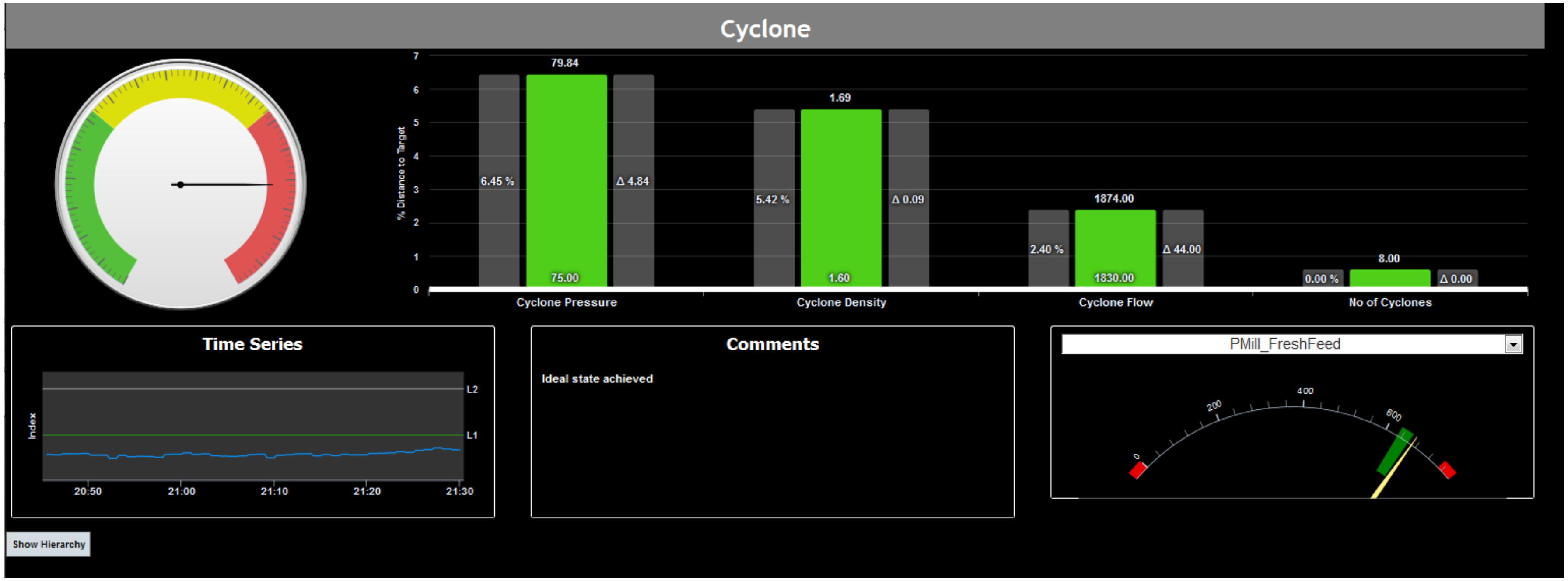

Milling_circuit
Primary Mill (27Jul2015)
Ball_Mill
Cyclone
Pebble Crusher 1
Pebble Crusher 2
Prim Mill PSD / Recycle
Index
21:00
Show Hierarchy



Ideal state achieved



Bearing Pressure Low - check:
1.Too little steel in Mill



Cyclone

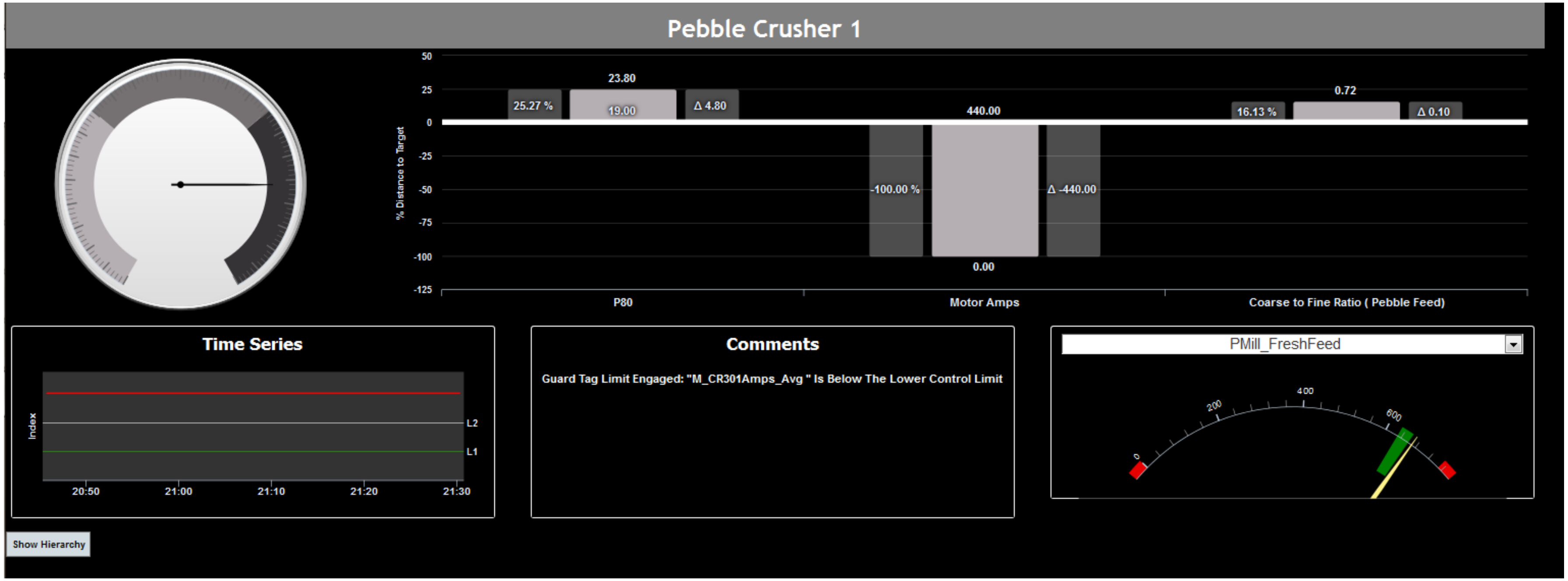
Time Series

Comments

Ideal state achieved

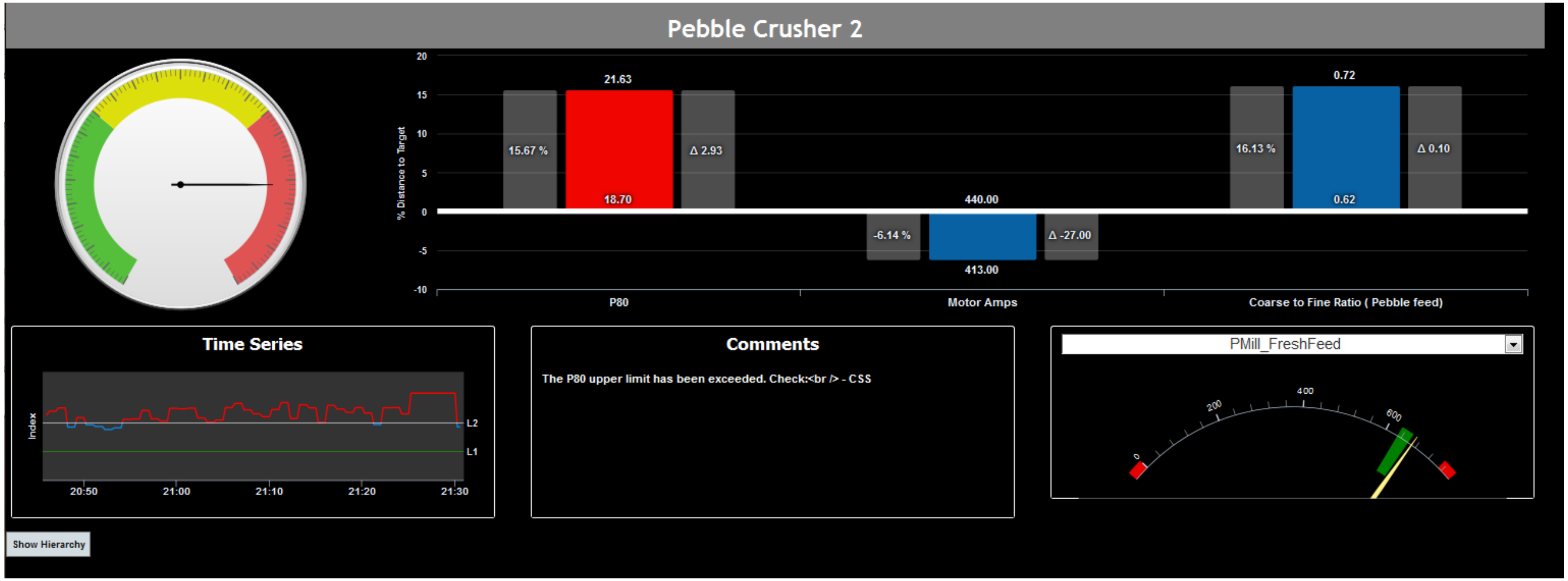
PMill_FreshFeed

Show Hierarchy

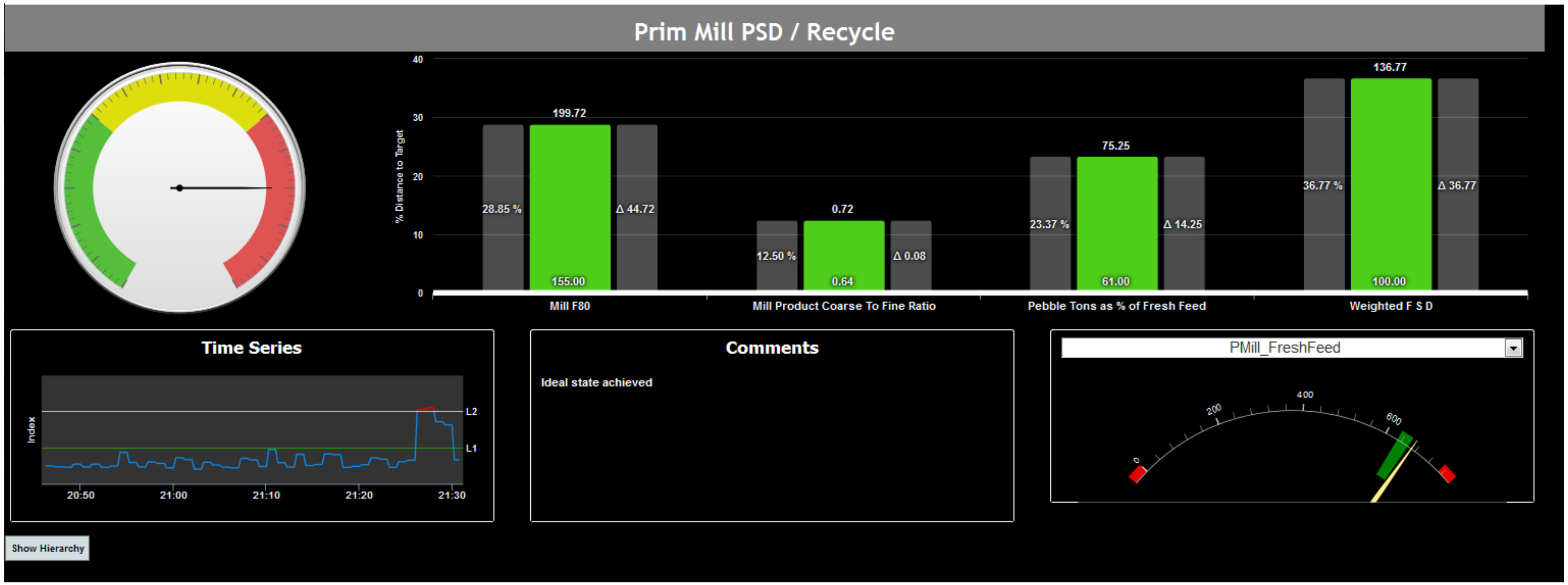


Guard Tag Limit Engaged: "M_CR301Amps_Avg " Is Below The Lower Control Limit

PMill_FreshFeed



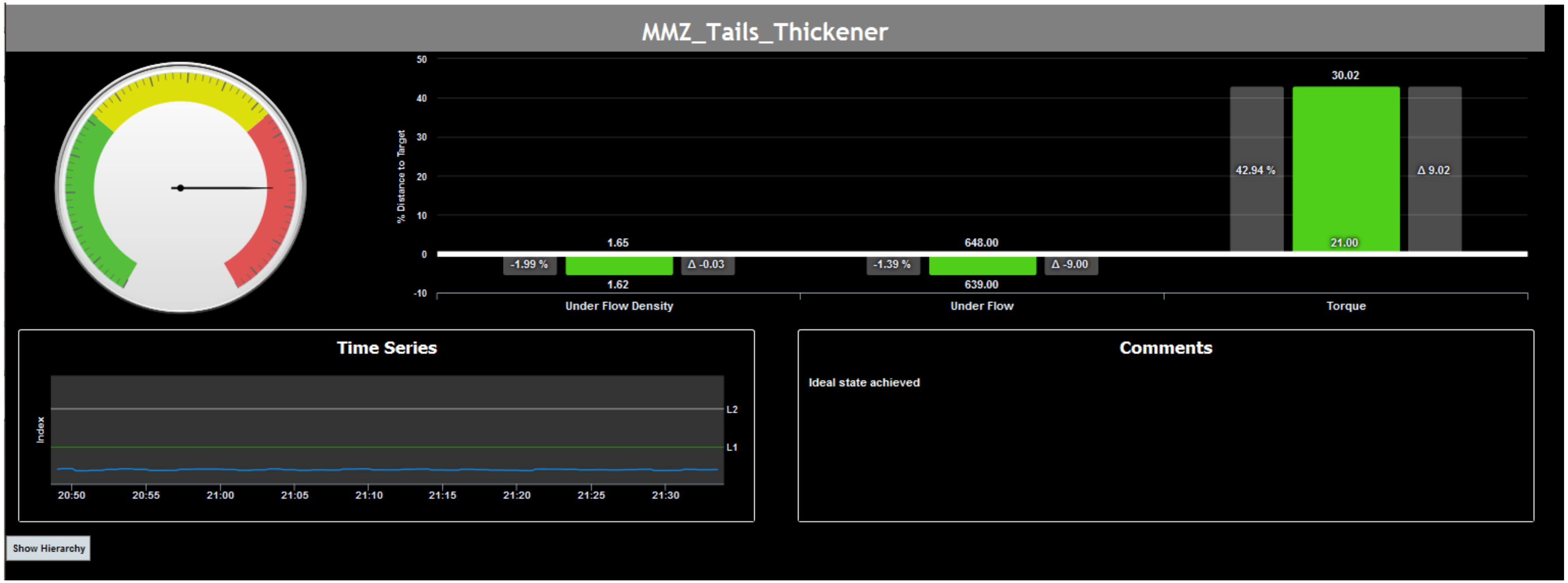
The P80 upper limit has been exceeded. Check:
 - CSS



Comments

Ideal state achieved

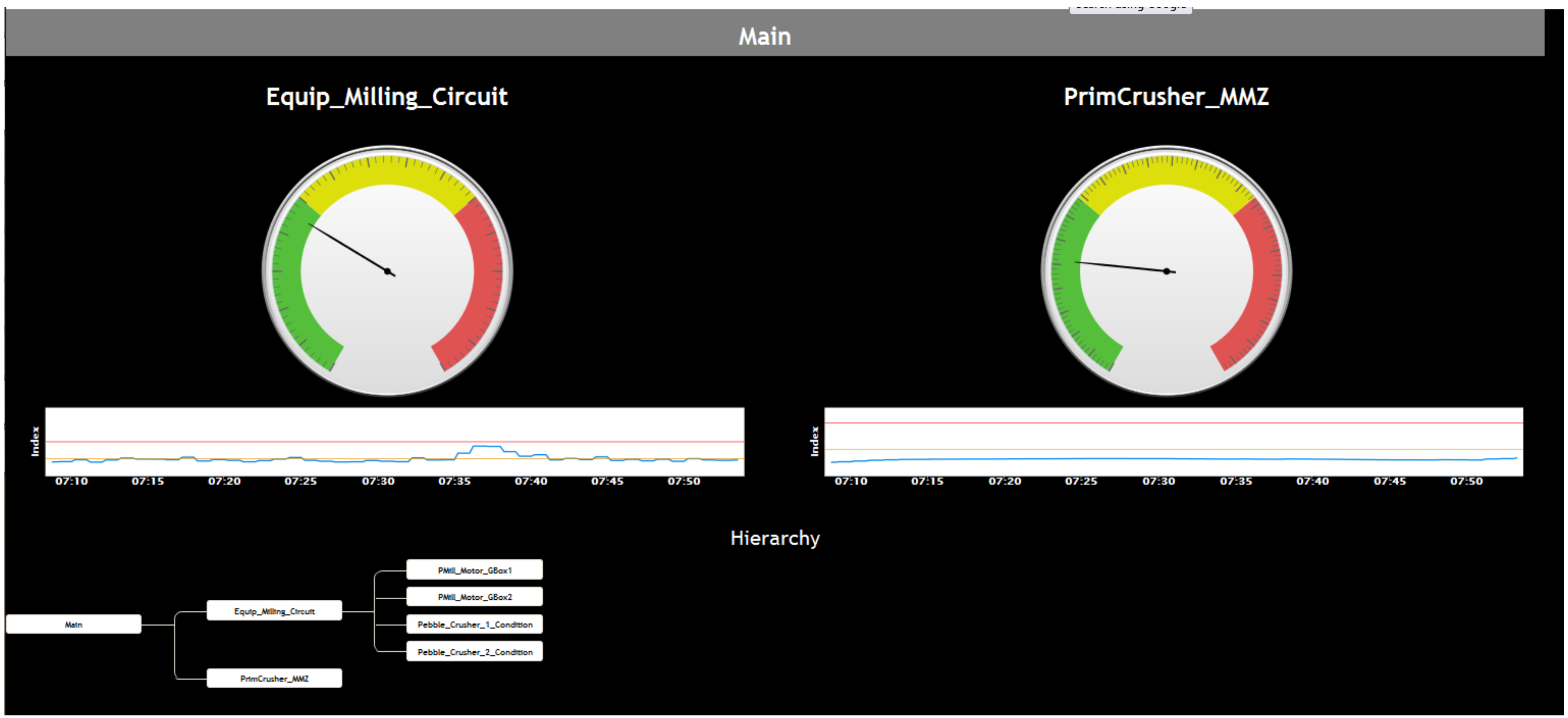
Ideal state achieved

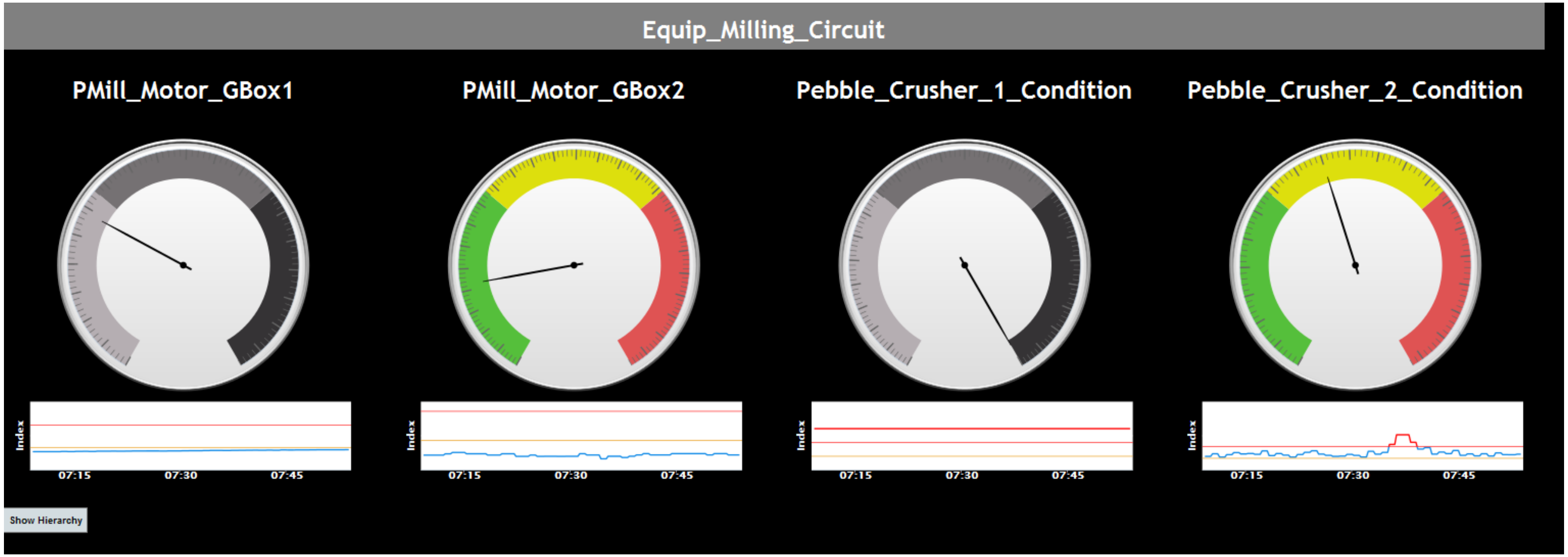


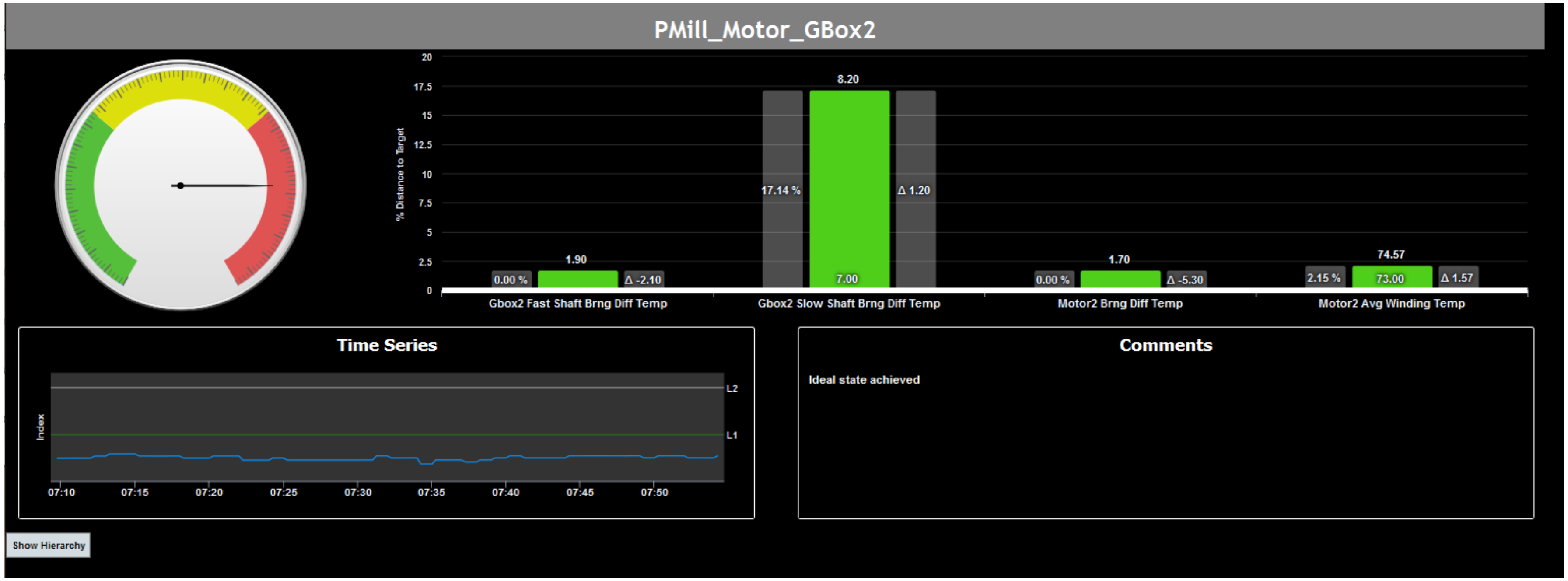
Ideal state achieved

Appendix D

Time-in-State Interface Developed for monitoring Engineering Performance of critical equipment at Nkomati Mine


Main
Equip_Milling_Circuit
PrimCrusher_MMZ
Index
07:10
07:15
07:20
07:25
07:30
07:35
07:40
07:45
07:50
Index
07:10
07:15
07:20
07:25
07:30
07:35
07:40
07:45
07:50
Hierarchy
PMill_Motor_GBox1
PMill_Motor_GBox2
Main
Equip_Milling_Circuit
Pebble_Crusher_1_Condition
Pebble_Crusher_2_Condition
PrimCrusher_MMZ

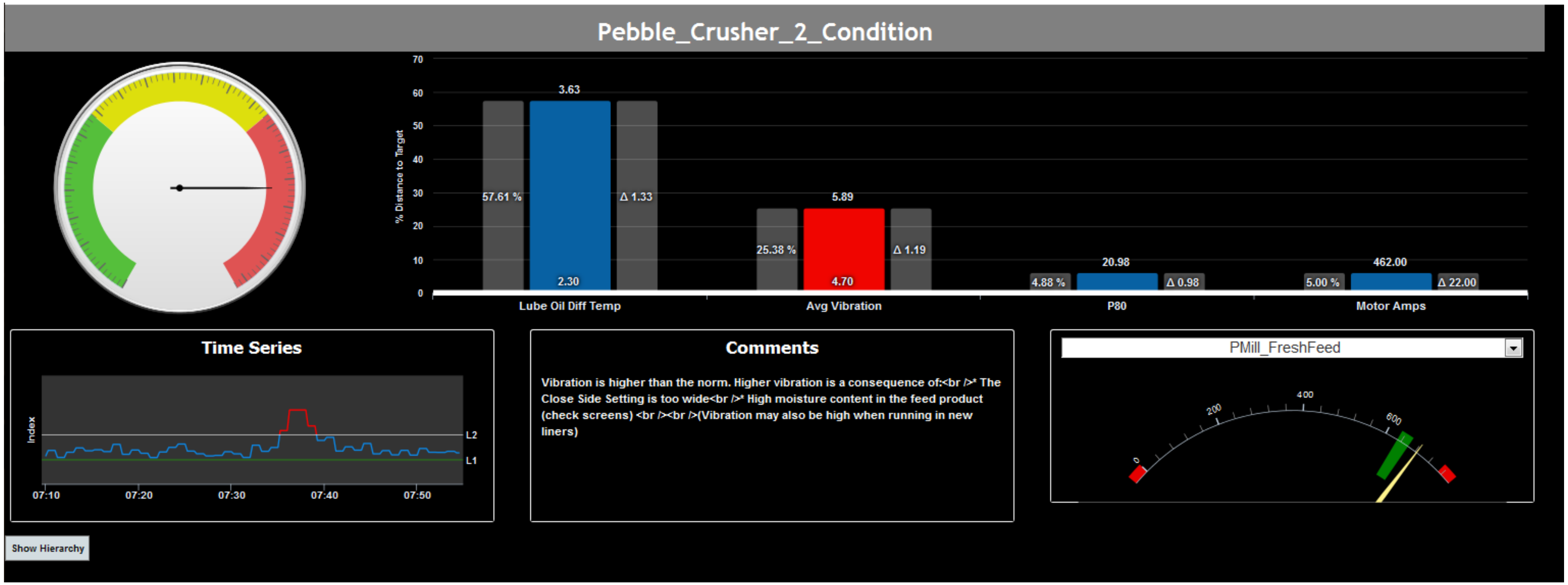

Equip_Milling_Circuit
PMill_Motor_GBox1
PMill_Motor_GBox2
Pebble_Crusher_1_Condition
Pebble_Crusher_2_Condition
Index
07:15
07:30
07:45
Show Hierarchy



PMill_Motor_GBox2

Comments

Ideal state achieved



Vibration is higher than the norm. Higher vibration is a consequence of:
* The Close Side Setting is too wide
* High moisture content in the feed product (check screens)

(Vibration may also be high when running in new liners)