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Systematic Framework toward a Highly Reliable Approach in Metal Accounting

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ABSTRACT
Metal accounting is becoming an area of growing focus because of the requirement for the resulting data to feed directly into financial reports. It is vital in the fulfillment of best corporate governance practices and to provide assurance on metallurgical processes. The current metal accounting practices deliver a number of important measures, but an essential change in the approach toward data integrated and auditable metal accounting system is an indispensable need. This work aims to present a systematic framework toward a highly reliable method in metal accounting. The proposed approach introduces a novel mining to product metal accounting scheme and conceptualization of an intelligent metallurgical and metal accounting information management system (MMAIMS). An open cast gold mine in South Africa is presented as a case study. Based on the results and discussions that we have presented in this study, it has been shown that the proposed intelligent MMAIMS will result in improved plant process control, transparent financial reporting, and a suitable understanding of interrelationships between different process activities. The intelligent MMAIMS approach will eradicate data security risks related to multiple-user environment spreadsheets, create reliability in data used for decision-making and operation data synchronization. End to end metal accounting process visibility across the whole process will advance the audibility and transparency of metal accounting from mine to product, and enable good corporate governance and financial reporting of the salable metal product concerning smart mining and mineral processing concept.

KEYWORDS
AMIRA; auditing; gold; metal accounting; salable metal

1. Introduction

Metal accounting is a progressively significant governance matter in all mining operations. It is required from a risk management perspective, indicating that the company is in control of its product through the whole mining value chain. Metal accounting is defined as the system by which designated process data (relating to metals of economic interest), including mass measurement and analysis, are collected from several sources and distorted into an intelligible report format that is provided in a timely fashion with the aim of meeting specified reporting requirements (Johnston, Johns and Sterk 2015; Lothian 2013; Macfarlane 2015). As presented in Figure 1, metal accounting is a component of the general enterprise accounting that creates a powerful tool to determine and manage the real performances of a metallurgical installation for the gold, base metal or other commodities and achieving operational excellence at their various stages (i.e. mining and comminution, concentrator, smelter or hydrometallurgical plant, refinery, or a combination of these stages) (Drzymala, Luszczkiewicz and Foszcz 2010; Johnston, Johns and Sterk 2015). As shown in Figure 2, the metallurgical accounting system can be decomposed into its four main components: mass flow rate measurement (Cargill, Freeman and Gilbertson 2002; Wortley 2009); stream sampling (Brochot 2011; Holmes 2004, 2008; Ketata and Rockwell 2006, 2008; Morrison 2008a, 2008b); mass balancing; and data handling and reporting methods (Gaylard et al. 2009). Nevertheless, the most important changes often happen around mass balancing, data handling and reporting methods. Metal accounting starts with the metal balance, either on an annual, quarterly, monthly, weekly or even daily basis (Lachance et al. 2017, 2013; Seke 2014). It is worth noting that the mineralogical composition of ores and processing samples is of substantial use for the evaluation of comprehensive metal balance and plant performance. A comprehensive study involving mass balancing and quantitative mineralogy is necessary to improve plant performance and to recommend suitable adjustments in the plant flowsheet (Can et al. 2013; Whiten 2007). Whereas it is possible to measure the mineral composition of process samples, these measurements tend to be costly and slow compared with chemical assays. Elemental assays of samples are readily available and comparatively cheap can be converted into mineral composition (Whiten 2007).

The specification of the metal accounting system must be based on quantifying the impact of the accuracy of process stream and process stock measurement on the accuracy of the overall metal balances (Connelly 2009; Gaylard, Randolph and Wortley 2014; Johnston, Johns and Sterk 2015; Kowalczuk and Drzymala 2011). The design and specification of the system must include the definition of all risks or consequences of degradation of the accuracy of the metal/commodity balance process and it must

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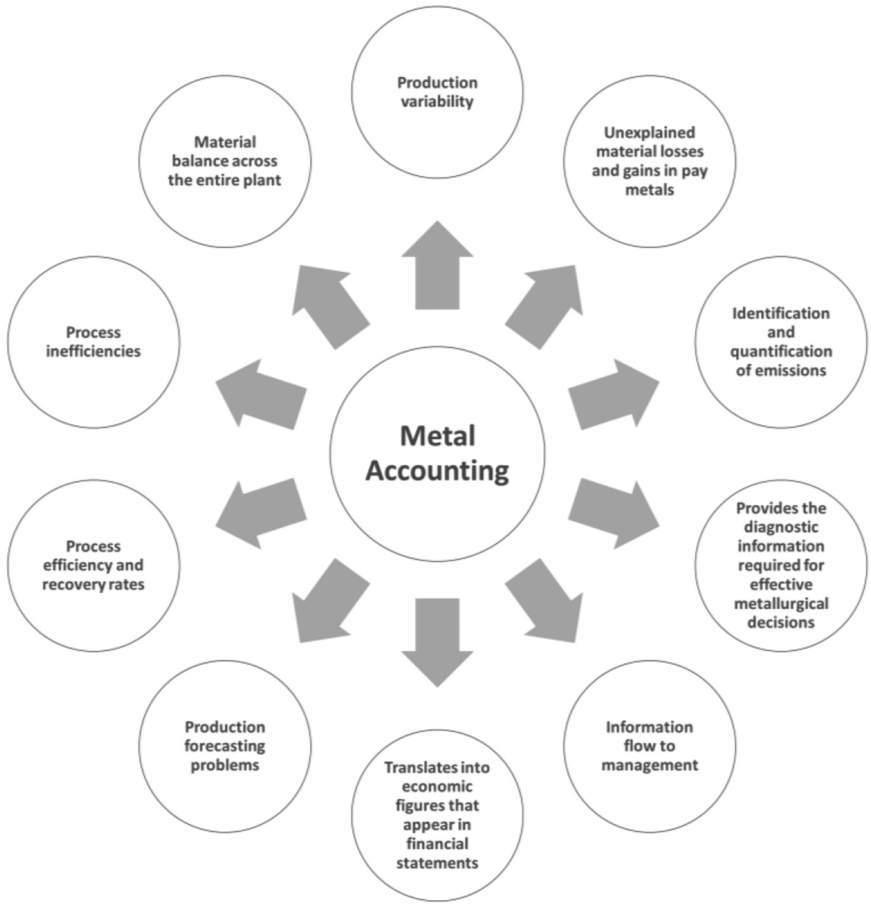

Figure 1. Key parameters and aspects, which can be monitored, and addressed with corrective measures using an accurately designed metal accounting procedure.

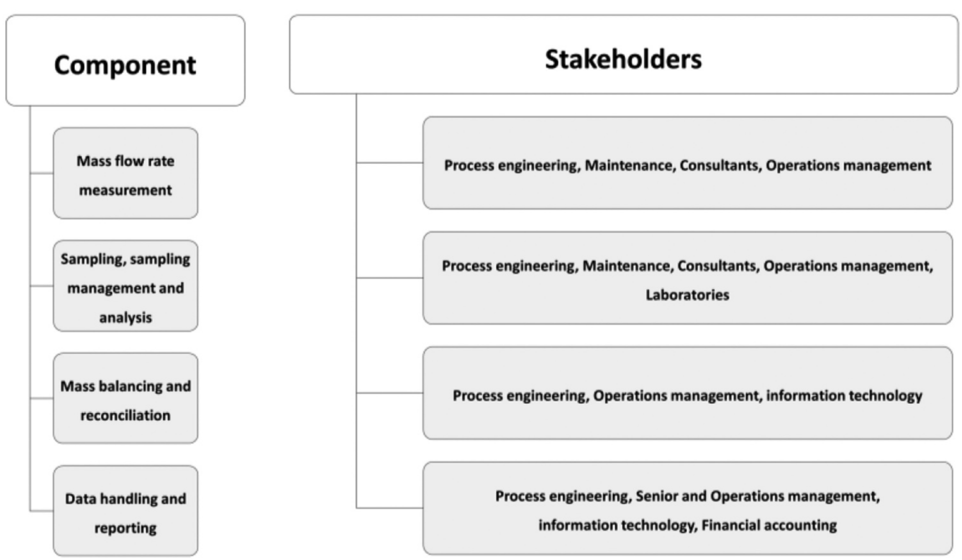

Figure 2. Main components of metal accounting systems (modified after Gaylard et al. 2009).

specify the means by which these risks can be quantified (Gaylard, Randolph and Wortley 2012). The design of the accounting system must form part of the design scope for new plants and it must include aspects, principles and approaches as presented in Figure 3. Although the importance of coherent material balance results has long been recognized, various stakeholders are increasingly inquisitive about how the reported numbers were obtained and how much accuracy can be attributed to them (Morrison and Gaylard 2008; Sahai 1992). In the modern mineral processing industry, much attention must be given to maximum productivity in a sustainable manner rather than only maximum production.

Traditionally, metal accounting and reconciliation have entailed of (Drzymala, Luszczkiewicz and Foszcz 2010; Macfarlane 2015)

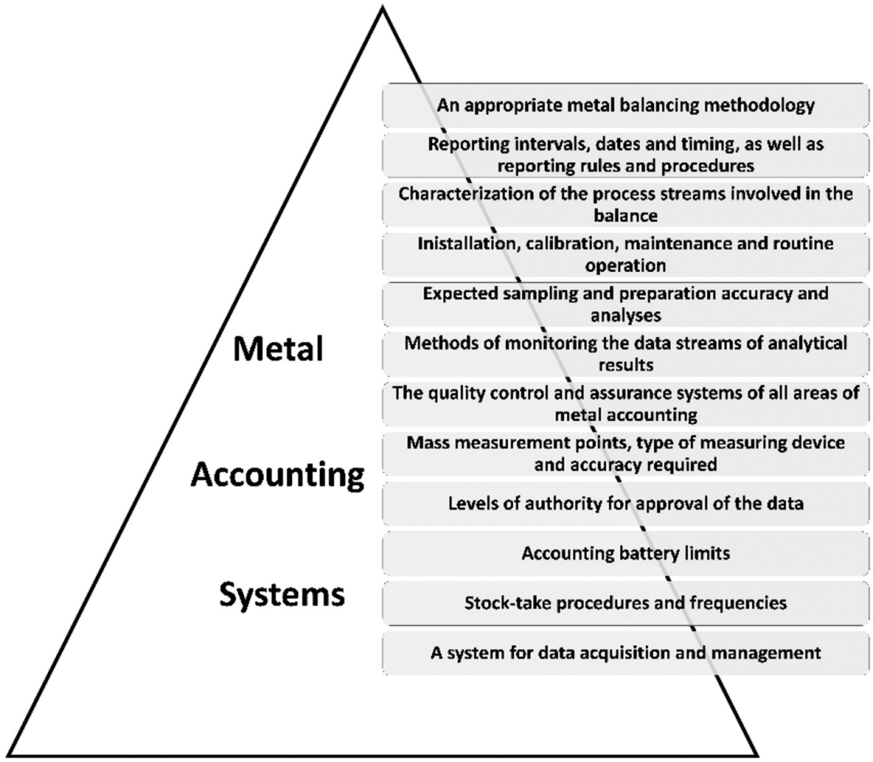

Figure 3. Aspects and principles, which needs to be included in the metal accounting system.

- Geological reconciliations of mineral resource to mineral reserve conversion;
- Mine planning reconciliation associated with the reconciliation of long-term to short-term plans;
- Grade control reconciliation of head grades from samples or block grades;
- Mine survey reconciliation of tonnage inconsistencies and mine call factors;
- Metallurgical reconciliation was based on metal balancing, followed by some commercial metal accounting that connects shipped product to sales quality, quantities, and revenues; and
- Reconciliations were all done for the specific departmental purpose at hand, and to varying levels of quality and effectiveness, but rarely cohesive into an end-to-end process.

The lack of an accepted set of standard procedures for metallurgical accounting was explicitly recognized as an industry-wide problem only in August 2001 during an SAIMM workshop held in Cape Town, South Africa. A group of six companies including BHP Billiton and Anglo American developed a set of rigorous yet practical metal accounting guidelines. Discussions that followed this workshop led to the initiation of the AMIRA Project P754, "Metal Accounting and Reconciliation," in 2003 (Morrison and Gaylard 2008). The AMIRA P754 project was launched in 2004 and as described by Morrison and Gaylard (2008) the main aim of the project was to develop a code of practice for metal accounting with the following key objectives:

- Development leading to an agreed industry standard at corporate governance level;
- Vital improvement of the trustworthiness of metal accounting from deposit to salable product;
- Development of procedures for data collection, data analysis, reporting and audit;
- A data analysis toolbox, which offers go/no go testing for metal balance data;
- Upgrade of industry adoption of these guidelines to advance transparency and financial credibility. Over time, these guidelines may progress into a code and eventually into a standard; and
- Develop and train engineers to become experts in metal balancing and reporting.

The first version of the resulting Code of Practice was released the following year (Jansen, Morrison and Dunn 2007). Since then, the Code was reviewed twice and revised releases were issued (Connelly 2009; Jansen, Morrison and Dunn 2007; Morrison 2008a, 2008b; Morrison and Gaylard 2008; Power 2010; Wortley 2009). The Code for Metal Accounting was published in its current version in 2007 (Morrison and Gaylard 2008). The main thrust of the code is to assimilate commercial and technical act to a much higher degree. The Check in-Check out (CI-CO) method has been chosen as the vehicle for this combined approach. In this approach, measurement of mass and metal flows becomes the critical element of the process. A quantitative knowledge of measurement precision and accuracy is also vital (Morrison and Gaylard 2008). Further description of the AMIRA Project P754 code is given in Table 1.

AMIRA (2007) divided metallurgical balance into primary accounting and secondary accounting (Table 2). The design of the metal accounting system should make adequate

Table 1. Description of the AMIRA Project P754 code.

The code is based on	Recommended strategy for gold and base metal plants	The primary objective	The second objective
The "Check in-Check out (CI-CO)" concept. The mass and metal values used for CI-CO are "absolute" and provide the basis of financial transfers. The CI-CO process happens at each transmission of custody – whether between divisions within a company, or between companies.	To reconcile based on tailings, feed rate, and production (gold) or feed, concentrate and tailings assays (base metals).	To provide a set of standard generic procedures and guidelines for all aspects of metal accounting, from measurement and sampling to data handling and reconciliation and reporting of results.	To facilitate risk management by enabling plant management to quantify, manage, and minimize the level of risk to which it could be exposed through failures and shortcomings of a metal accounting system

Table 2. Description of primary accounting and secondary accounting.

Metallurgical balance	
Primary accounting	Secondary accounting
• It means determination, through measurement, analysis, and computation, of the magnitude of each component of interest across an entire plant. • It allows for a material balance across the entire plant and is the objective of any metal accounting system.	• It means determination; across each section of a process flow sheet in the plant. • It includes mass balances over specific circuits within a plant. • It provides information that can be used to help identify where process inventory is located, where time lags are involved, or where any measurement problems exist, thereby improving primary accounting.

provision for secondary accounting measurements to reinforce the primary accounting data. While some parts of these guidelines are in endurance with current routine practices, other parts applaud changes to congenital practices that could be substantial such as the importance of data redundancy (Lachance et al. 2017; Lachance, Leroux and Gariépy 2015). Within the Mineral processing phase, metallurgical accounting (primary accounting) and metal accounting (secondary accounting) information are generally stored in different systems and are often not incorporated. This provides challenges when forecasting metal production outputs from a particular operation and introduces unknown variation in plant performance, thus affecting productivity and profitability (Holmes 2004; Lachance et al. 2014; Morrison, Gu and McCallum 2002; Wortley 2009). Even with AMIRA P754 coder, it is recommended that the application of the code for most companies should be more evolutionary than revolutionary, but with considerably more stress on measurement and definition of measurement error (Morrison and Gaylard 2008).

Besides the initial endeavor to integrate the geological and mining components into the code, in order to generate an end-to-end accounting system, however, partial support for this was coming from mining companies at the time (Macfarlane 2015). This has led the Code to be tended to concentrate on the mineral processing part of the value chain only. Therefore, the traditional obstacle, the reconciliation of the plant metal balancing system and the mine accounting system at the point of delivery from the mine to the processing plant remnants in place. This study aims to introduce a systematic framework toward a highly reliable approach in metal accounting. The original contribution of these research roots from the introduction of a novel mining to product metal accounting scheme and conceptualization of an intelligent metallurgical and metal accounting information management system (MMAIMS). Moreover, the advancements in predictive and forecasting techniques such as machine learning will be included in a follow-up paper focusing on simulations and utilization of integrated MMAIMS data for cross-process metal accounting output forecasting. An open cast gold mine in South Africa is presented as a case study. Due to complex interrelationship between various variables in metal flow from different units of the precious metals such as gold accounting envelope, metal accounting systems through modeling a metal accounting nerve system as will be explained further are applied. The proposed approach ponders procedures followed by the gold mine in measuring gold in Closing Stock (inventory counts), gold in Intake (plant feed weighing, sampling, and assaying) and gold in Output (weighing, sampling, and assaying of products, waste streams). Successful implementation of the proposed framework will contribute to the global smart mining campaign where data is one of the most valuable assets and the growth in the technological developments provides visible reporting of salable metals and acceleration of process optimization (Jiang et al. 2017). It is worth noting that although the proposed metal accounting system caters for various stakeholders (e.g. technical, financial and non-financial capitals, including external parties), emphasis is placed on operational activities, as this is where the roots of the process begin.

2. Case study – gold-producing mine from South Africa

An open cast gold mine in South Africa was selected as a case study. Due to confidentiality reasons, we are not allowed to disclose the exact name of the case study mine nor the company and therefore we will simply refer to it as a 'gold mine.' Metal accounting activities for this gold mine involve (a) mining, incorporating drilling, blasting, loading and hauling, (b) stockpiling, where the material from the pits is deposited, (c) mineral processing, incorporating crushing, milling, leaching, elution, electrowinning (EW) to produce gold sludge, smelting to produce gold doré bar and waste disposal, and

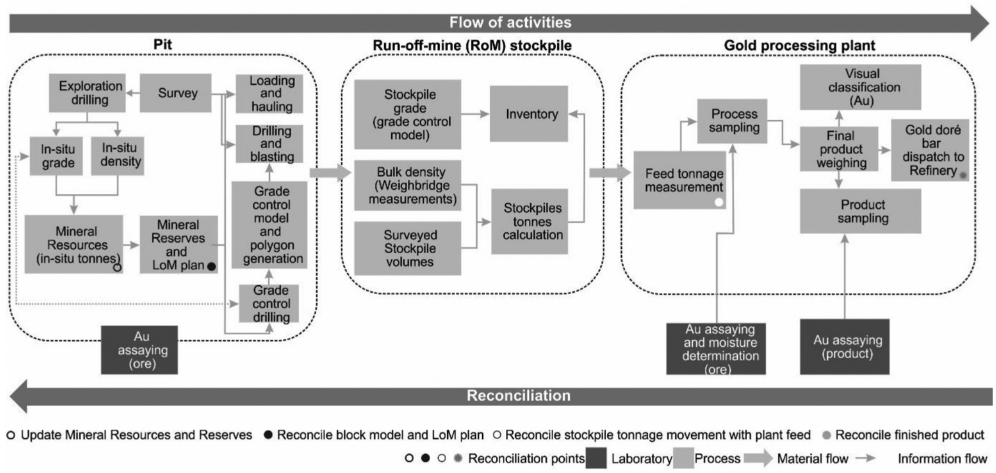

Figure 4. Metal accounting flow of activities and material reconciliation.

(d) support functions such as the laboratory, survey, engineering and maintenance. Since metal accounting activities in this gold mine follow that of multiple point sampling (MPS) and multiple point analysis (MPA), we have classified the business processes into three broad units, namely pit, stockpile and the gold plant (Figure 4). Within each unit, most of the mining companies have started incorporating online analysis on conveyed feed flows. In the Pit unit (i.e. mining activities) and run-off-mine (ROM) stockpiles, grade control software such as "Pitram" (Micromine 2017) utilizes mine design, survey and production data to provide real-time stockpile balances and metal stocks throughout the mining operation to assist with the accuracy of grade control. A similar approach has been adopted in the mineral processing industry, e.g. Metal Management Services (MMS) Group cloud-based software system known as "WIRE" collects process plant operation data into a central database, model processes and relationships and reports results via web interface. In commodities that are mainly monomineralic, on-line analysis has been used for elemental balancing which helps with the overall metal accounting balancing. Elemental balancing has been successfully applied in iron ore operations since 2011 (Kowalczuk and Drzymala 2011; Matthews and Du Toit 2011) and in copper operations (Balzan et al., 2016). However, successful application of elemental balancing is yet to be tested in polymetallic ores such as base metal sulfide ores, gold-uranium-pyrite deposits such as those of the Witwatersrand Supergroup and platinum group metals (PGM) of the Bushveld Complex (South Africa).

The input and output from each unit are weighed, sampled, analyzed and quantified using acceptable principles of mass balance (Berger and Benedict 2011). Mass balance involves the laws of conservation of mass (Equation 1), thus

$$\sum_{1}^{n}(\text{ClosingStock} + \text{Output}) = \sum_{1}^{n}(\text{OpeningStock} + \text{Intake})$$

where

n = total number of sections in the metal accounting envelope considered a unit,

Opening Stock = Closing Stock from the previous reporting period, as measured through a stock count,

Intake = amount of gold ore received into the metal accounting envelope, and

Output = amount of gold exiting the Metal Accounting envelope (as the final product or in a waste stream or in a by-product).

For precious metals such as gold, we recognize that tracking of metal flow from different units within the metal accounting envelope requires a clear understanding of the complex inter-relationship between various variables. We, therefore, approach metal accounting through modeling a metal accounting nerve system (Figure 5). The metal accounting nerve system can be defined as a complex system whereby material exists in various forms, and continuously moving between a wide variety of units (i.e. pit, stockpile and the gold plant). This allows accounting for all gold content independent of commercial considerations and origin or destination of flow (Chirisa, 2017).

In general, metal accounting encompasses multiple points and scales; for example, in large corporation operations such as Anglo American Platinum where ore is sourced from different operations/mining complexes and the processing facilities are either centralized or divided based on regions with the ultimate refinery of products streamlined to a single destination, assays-based accounting per operation/mining complex would be considered. However, batch and stockpile accounting will be more appropriate in the central facilities or designated short-term and long-term ore storage facilities. The same applies for gold mining complexes such as the Sibanye Stillwater Driefontein Mining Complex in South Africa where ore comes from multiple shafts (e.g. requires assays-based accounting at ore source/shaft), but processed in a central metallurgical facility (e.g. requires batch accounting or single point sampling of feed material, but multiple point sampling downstream). In this regard, it is important to ensure that the metal accounting system is designed to take inputs from the varying processing destinations in alignment to both mining and metallurgical plant facility configurations.

Our proposed approach to metal accounting reflects procedures followed by the gold mine in measuring gold in Closing

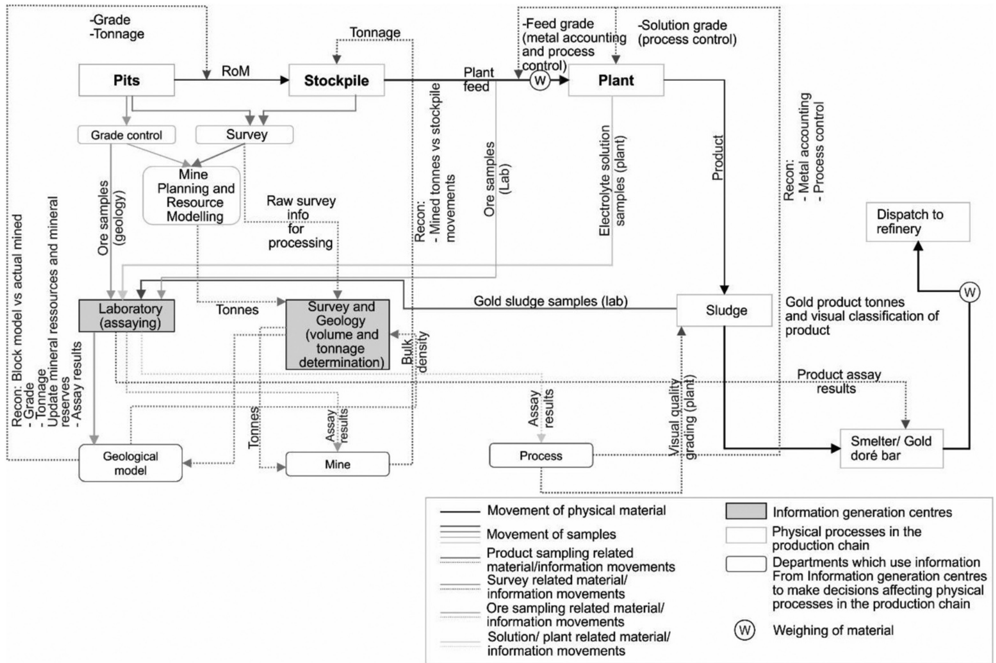

Figure 5. An illustration of activity-based interrelationships in the metal accounting nerve system.

Stock (inventory counts), gold in Intake (plant feed weighing, sampling and assaying) and gold in Output (weighing, sampling and assaying of products, waste streams). As per the mine metal accounting nerve system (Figure 2), the laboratory generates the metal assays, density measurement and optimum milling index and, as such, it is a key entity in ensuring that the metal accounting performs correctly. All material weighing equipment and their ability to generate correct and reliable results are key to the auditable metal accounting system. Where volume measurements are conducted, the manner in which this is conducted, and subsequently converted to mass (through the application of density) is also key to metal accounting processes. Therefore, it is recommended that the laboratory, be it internal or external must be ISO/IEC 17025 accredited (ISO 2017). ISO/IEC 17025 accreditation and protocols provide a baseline to operate competently and generate valid results, which in turn ensure accuracy and precision of the results, thus improving stakeholder confidence (ISO 2017). All the laboratory analytical procedures must be formally documented in a form of standard operating procedures (SOPs) including quality control and quality assurance system. As part of ISO/IEC 17025 accreditation, all analytical results must be stored in a credible laboratory information management system (LIMS) that is auditable with a transparent chain of custody.

2.1. Metal accounting unit 1: pit (the gold mine)

The Pit consists of 10 broad activities of which each directly or indirectly contributes to metal accounting accuracy and precision of metal accounting results (Figure 4). Although this paper does not discuss all activities in detail, we provide some insights on those that are primary to the process such as grade control and in-pit survey.

2.1.1. Grade control

During the drilling and blasting phase, the mine use of blast monitoring technology (BMT) to monitor the movement of the ore. This is aimed at minimizing dilution. Fleet movement carrying ore is monitored and recorded by mine geologists. As identified in the metal accounting nerve system (Figure 5), grade control is the first activity undertaken at the mine to evaluate and assign grades to material that is mined from the pit and eventually fed to the mineral processing plant. Figure 6 illustrates the grade control practices adopted at the mine based on our metal accounting proposed practices. For quality control, modeling of the mineral resources and mineral reserves is done immediately after grade control drilling. Only assay data that have been vetted in the quality control and quality assurance (QAQC) system is utilized for the modeling of the mineral resource. If an area in the grade control model has not been updated, the area must not be mined. The modeling process also involves updating of mineralized domains, geological structures that define the ore body, and facies classification. The model is validated before it is handed over to grade control for polygon demarcation and mine planning. Planners responsible for short-term (12 months) mine planning rely on this updated model.

2.1.2. Mine survey

We considered the following pit surveying activities performed at the mine, which is essential for monitoring tonnages and grades of stockpiles:

- In-pit surveying: mining floors are surveyed to ensure that mining is taking place according to design elevations. This is also undertaken to monitor tonnage movements and dilution;

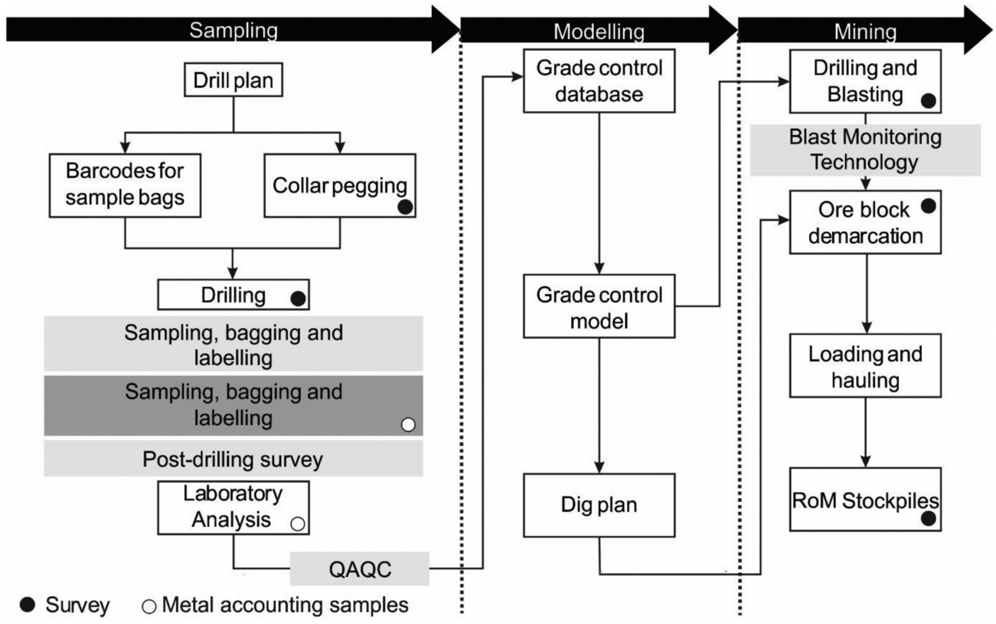

Figure 6. Protocol for metal accounting grade control processes.

- Grade control pattern: the surveyors set out the drilling pattern in the pit as per the drill plan provided by the Geology Department. In addition, drill hole collars are surveyed at the completion of drilling. Planned drill hole positions are sometimes moved to the alternative nearest location as a result of factors such as floor instability; and
- Ore block demarcation: surveyors demarcate grade polygons on the ground post-blasting as per the dig plan provided. The geologists validate the polygons prior to loading and hauling.

The polygons are demarcated with pegs and are color coded. The equipment used for pit surveying includes the total station, which is calibrated every 6 months by a Global Positioning System (GPS) and scanners. The use of scanners during in-pit surveys has improved the accuracy of measurements, as each scanning cycle is able to produce millions of pit point cloud that is used for the production of pit digital terrane model and digital elevation models.

2.2. Metal accounting unit 2: stockpiles

Ore stockpiles are generated from pit activities as ROM and stored according to ore grade. Metal accounting activities in stockpiles cover aspects of ore classification based on the above-mentioned grades, bulk density measurements, moisture determination, stockpile volume measurements, calculation and quantification of ore tonnes, stock counts and reconciliation of stockpile data (Figure 7). For the subject gold mine, a total of four gold grade classifications based on value are applied to the ROM material and stockpiled accordingly. The gold grade categories are (a) high grade (>5 g/t), (b)

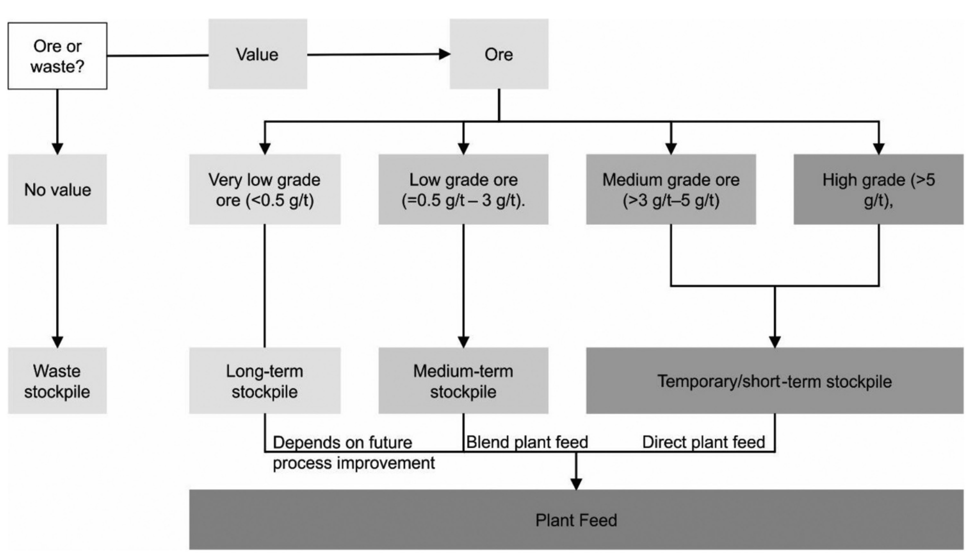

Figure 7. Ore classification and stockpiling decision tree metric.

medium grade ore (>3 g/t–5 g/t), (c) low-grade ore (≥0.5 g/t – 3 g/t), and very low grade (0.5 g/t). The very low-grade material is stored in long-term stockpiles with a possibility for reconversion to a future resource depending on economic feasibility and process improvement. Material with no value is classified and stockpiled as waste material (Figure 7). As part of the plant feed grade variation monitoring process, tracking changes in grade should be linked to the ore dispersion variance in order to assess how this affects mineral reserve classification, e.g. proven versus probable reserves.

The stockpiles are measured on a weekly basis by the Mine Surveyor and the results are stored in a survey database hosted on the local server. The stockpile measurement procedures are documented in a formal SOP that has version control and is reviewed by competent survey personnel. The stockpiles are measured by a laser scanner, by the internal mine survey team and the results are reported to the mining, mineral resource management and mineral processing teams. Ore flow measurements showing the start of the month stock (Opening Stock), addition (ROM) and depletion (plant feed) are performed daily and reconciled monthly. On a quarterly basis, drone surveys are conducted by a contractor and used for internal survey data validation. The contractor also helps with annual check surveys and stock quantification.

The bulk density of the different stockpile material is analyzed by the internal laboratory and results are reported to the Geology Department. The density is reported in accordance with the rock type and grade. The density determination exercise is conducted on a monthly basis. This is consistent with the frequency of the stockpile surveys and monthly data reconciliation. The Geoscience Department, which is the custodian of ore grades, and density measurements have a detailed SOP on how samples for density are taken and how density measurements are recorded. The total in-situ volume (m^3) as determined by the mine surveyors is multiplied by the respective ore density in order to calculate the total material (ore) tonnes. The reconciliation data are managed by the Chief Mine Surveyor and data security is prioritized. A complementary measurement weighbridge is used for the Tipper trucks, which haul the ore from the ore stockpiles to the plant. Moisture content is determined on ore that is taken from the stockpiles to the plant and reported on a dry basis. This minimizes the overestimation of the ore delivered to the plant, which may lead to metal content misstatement during metal accounting reporting stages. The grade reconciliation (Figure 7) is also useful for financial reporting purposes because items such as the expected product selling prices must be contrasted with estimated costs to complete refining. Any losses must be recorded and reported in the financial statements. A stratification of materials by grade will make this estimation of financial stock losses much more accurate.

2.3. Metal accounting unit 3: gold plant

The metal accounting components of the gold processing plant have been classified into six categories, namely:

2.3.1. Metal accounting in plant feed and comminution

Metal accounting in the gold processing plant starts with feed material and comminution. For the subject gold mine, there is one primary crusher (i.e. jaw crusher), one secondary crusher (i.e. cone crusher), and two milling circuits (i.e. 1x Ball Mill and 1x SAG Mill). The crushers and mill make up the comminution phase of the plant and are used to prepare the incoming feed, respectively. During comminution, feed material (+250 mm) size is reduced to <75 µm at 85% passing. Each of the circuits is equipped with a weightometer on the conveyor belts leading to their respective mill feed bins (Figure 8). Each of the weightometers is linked to the Supervisory Control and Data Acquisition (SCADA) system, from which the weight readings are read, displayed and data are automatically fed into the metal accounting system. SCADA is a well-understood system and widely used control system architecture that is used in numerous mineral processing plants globally. Moisture content on the mill feed sample is taken to be equivalent to the moisture of plant feed as measured through the samples collected from the belt cut. This requires the operator to physically take a cut sample at two hourly intervals and place it in a covered container or bag to avoid contamination. This sample is used to determine the gold and moisture content of the feed for metallurgical balancing. Physical sampling may be avoided by retrofitting an automated belt cutter. Belt cut samples are not used to infer plant head grade. Instead, the plant metallurgists construct a mass balance around the ball mill/cyclone sections. The plant head grade which is back-calculated from this exercise is used for metal accounting purposes.

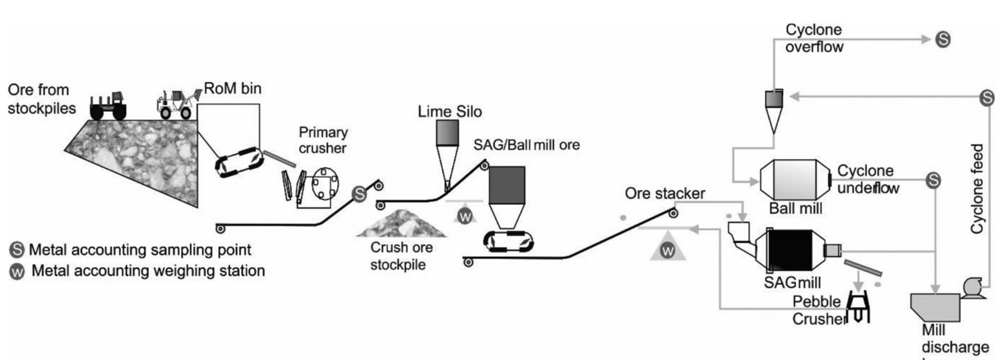

Figure 8. Illustration of metal accounting plant feed material flow and comminution circuit.

2.3.2. Metal accounting in gravity concentration circuit

Metal accounting in the gravity concentration circuit involves quantification of gold in (a) gravity concentrator, (b) InLine Leach Reactor (ILR) pregnant solution, and (c) electrowinning cells. Sampling for metal accounting takes place on the above multiple entries and output points (Figure 9). After electrowinning, the gravity concentration circuit gold sludge is combined with Carbon-in-leach (CIL) gold sludge in the calcine oven.

2.3.3. Metal accounting in carbon-in-leach circuit

Carbon-in-leach comprises several stages of metal accounting, namely leached solid and pregnant solution sampling, carbon sampling, and pulp density and volume measurements (Figure 9). Metal accounting samples in leached solid and pregnant leach solution are taken from all leach tanks at operation-specific intervals, which range between 1 and 2 hours. Gold in carbon commonly involves four sampling streams, that is, acid wash column, loaded carbon, elution column as barren carbon and reactivated carbon from Regen kiln hopper. Intervals for taking such samples also range between 1 and 2 hours and is operation specific. Within the CIL circuit, multiple points are used for pulp density and volume measurements. Volume measurements for the solution in tanks are read off the SCADA system and for the solution in elution column and EW cells, the volume of the equipment is used. Where automated solution volume is not available, volume measurements are conducted by using the rope measurement system to determine the depth of the solution.

2.3.4. Accounting for gold doré bar product

After electrowinning in the CIL and gravity concentration circuits, the gold sludge is treated in the calcine oven and smelting furnace in order to prepare the doré bar product for dispatch to refineries (Figure 9). The critical metal accounting factors for this stage are product quality and quantity, which must be measured by the operations daily. The factors are weighing, sampling, assaying, product shipment protocols and waste disposal protocols. In order to minimize human error, it is recommended that the weighing and sampling protocols should be automated and weigh directly into metal accounting system, which we have proposed in the discussion section. Book inventory records should be generated using the above information into a suitable and agile metal accounting system. Adjustments of material captured in metal accounting system must be signed off by security personnel, plant metallurgist and plant manager or head of metallurgical services.

2.3.5. Metal accounting in the leach residue

In both mining and processing units, multiple waste streams exist either in a solid form or liquid state. For example, waste from mining includes stripped overburden, contacts very low-grade material (Figure 7); whereas waste from process plant may include material discard flows from bulk and particle sorting systems, as well as any other pre-concentration processes and recovery of ore from waste dumps. Therefore, metal accounting does not only end in concentration and smelting circuits, but must also be done on each waste stream and in the tailings storage facility (TSF). Although each waste stream matters, for simplicity, we will only discuss the TSF waste stream in details, which is where most of the waste are channeled. A TSF sample must be taken to determine the amount of gold in solution and leach residues which is lost to the tailings dam points (Figure 9). Ideally, a composite sample should be collected from the overflow launder of the detox tank by the automatic sampler at 250 mm every 30 minutes and screened to remove carbon if present. This sample must be filtered promptly and after collecting the filtrate the cake should be washed with freshwater to stop leaching prior to assay.

2.3.6. Reconciliation

Reconciliation at the mine is critical as many operations base their value on their resources and reserves, which may be poorly determined. These alone can determine the financial viability of an operation/company. The metal flow, its variability, its underlying loss potential, and its control points need to be fully understood before a systematic approach to reconciliation (Macfarlane 2015). The accounting processes related to metal valuation accounting are complex and are performed

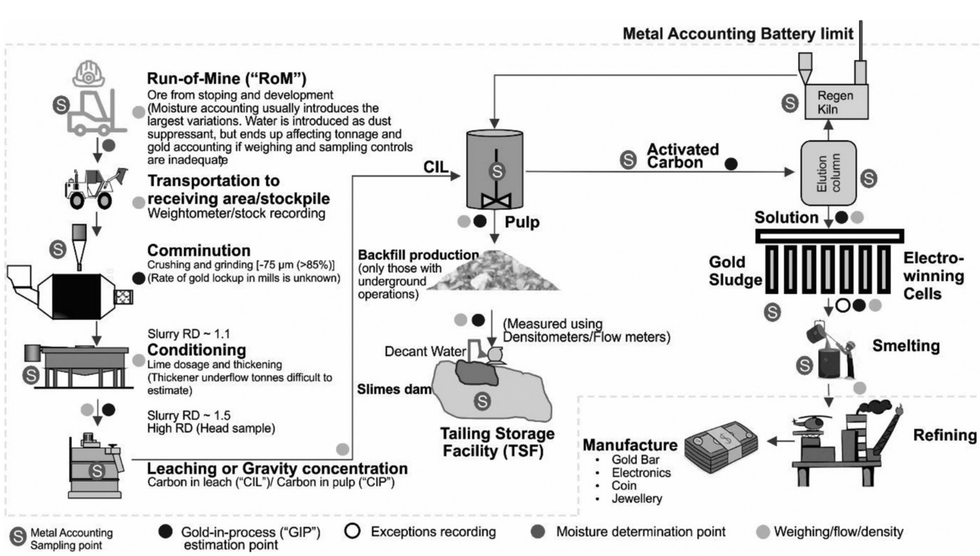

Figure 9. Gold accounting in the mineral processing plant.

monthly by the Plant Metallurgist and the Financial Controller in multiple Excel spreadsheets. Access to the metal accounting reconciliation data is restricted to the Plant metallurgist, Plant Manager and Head of technical Services. The reconciliation spreadsheets consist of a total of 20 active worksheets with each containing data from the three metal accounting units. This process consists of multiple steps with the various sources of data from different departments required for input, which makes it a complex process to follow. The complexity of the process makes it susceptible to risk of incorrect reconciliation of salable gold, which may result in misstatement during end of period declarations. A total of six SOPs are in place to explain the reconciliation procedures; however, they are not easy to follow through. In months where either the Plant Manager or the Financial Controller were off duty, metal accounting reconciliation was not done. This highlights the risk of using complex procedures and lack of proper training on personnel below the Plant Manager's level. The product recording system is a standalone spreadsheet and does not link to the main metal accounting reconciliation set of worksheets. In months where the metal inventories were adjusted post reconciliation, the product spreadsheet was not updated to match the general ledger records. This raises a risk of incorrect reporting of metals produced and may affect the company's reputation and financial standing. There is no risk and control matrix (RACM) for identification, raking and implementation of control measures to mitigate risks associated with the metal accounting processes. This implies that should specific inputs not balance with the expected output; the entire metal accounting system will need to be overhauled in order to locate and mitigate the issues.

3. Discussion

3.1. Systematic framework for metal accounting

In this contribution, we do not downplay the complexities for metal accounting that may be brought by mines that produce ore for toll treatment, plants that process ores from multiple mines, which may be owned by different companies, and ore-treatment requirements. We propose a framework that is governed by engineering design considerations, governance requirements and practicality through considering first principles and operational routine. We are cognizant that different ISO standards apply for sampling in different commodities and operations utilize different sampling protocols, many of which provide poor results in terms of metal content in process streams. Thus, it is important to establish a detailed metal accounting baseline that encompasses the entire value chain and not only to focus on downstream processing where potential value may have already been lost. The gold mine case study provided an ideal case in point where work has been done to align metal accounting processes to industry best practices. However, several sections of the metal accounting processes require attention due to several limitations and restrictions such as plant design limitations and lack of systematic framework. This manifest itself during mass balancing and reconciliation of salable metal product. Any mass balance is only as good as the input data used (Berger and Benedict 2011) and therefore, the sampling and assay procedures are crucial in obtaining a correct mass balance and consequently, the correct gold in circuit calculation (Chirisa 2017; Ketata and Rockwell 2008). A number of data recording processes in the plant and laboratory are not automated and automation would reduce the risk of error from manual processes. The lack of a software system capable of automatically sourcing data from various metal accounting equipment and units, performing automated data analysis and reconciliation poses a risk of material misstatement. In additional source of error is production variability and unexplained gains and losses, which highlights process inefficiencies. Our proposed systematic framework is presented in Figure 10 and builds up from a seminal work of presented by Chirisa (2017). The components of the proposed framework are aligned to metal accounting equation (Equation 1) which is linked to sustainable operational, governance, and financial reporting requirements. Each metal accounting unit contributes to the overall system auditability

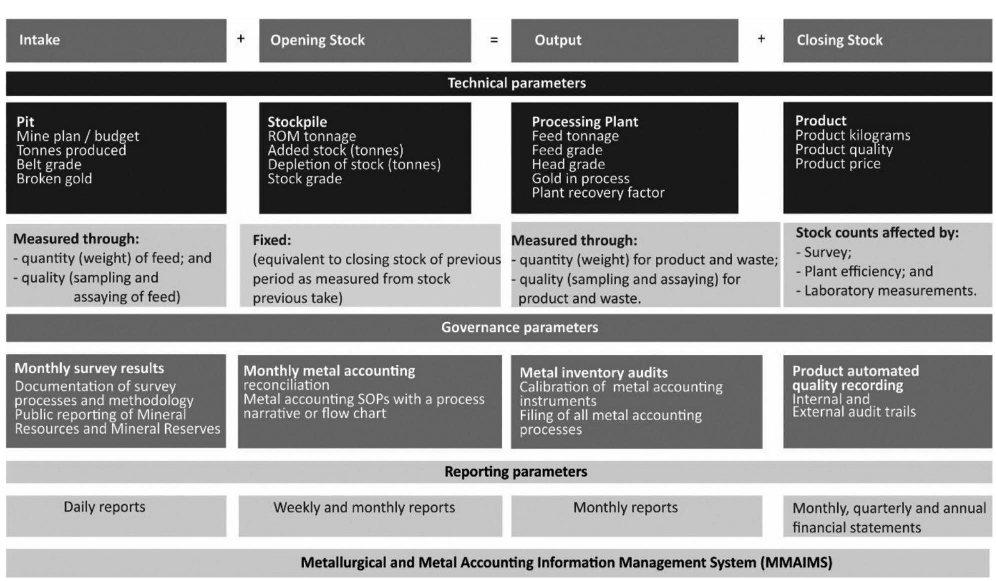

Figure 10. Intelligent Metallurgical and Metal Accounting Information Management System (MMAIMS).

using representative measurements and reasonable estimate of metal inventory. This will minimize or eliminate unrealized losses and ensure that metal accounting is dome to the utmost best protocols. In addition to the assurance issues, other limitations, e.g. contextual bias in some processing plants may occur in the proposed metal accounting model. Additional details to improve the current metal accounting practices are discussed in the subsequent sections.

3.2. Sampling for metal accounting

The majority of the mining companies have metallurgical and metal accounting processes either in place or in currently being implemented. Discussions on metallurgical and metal accounting sampling have often focused on the identification of suitable sampling points, sampling method and frequency, and the size of a sample. In the past decade, emphasis on metallurgical and metal accounting sampling has been on representativeness and preparation of the sample (Brochot 2011; Holmes 2004, 2008; Ketata and Rockwell 2006; Morrison 2008a, 2008b). The use of a combination of a network of samples and sensors to collect metal accounting data in the plant has also proved to be very useful (Holmes 2008; Brochot 2011). The application of an intelligent sampling controller system advances the quality of the sampling process. Thus, it increases the mineral processing plant productivity and assurances the mineral project's viability (Ketata and Rockwell 2008). All these aspects are very important to ensure that metallurgical and metal accounting processes are functional and effective. Notwithstanding the technological advancements for online sampling and analysis of many commodities that made process control and metal accounting more efficient (Aldrich et al. 2010; Goncharov and Struzhkin 2003; Khajehzadeh, Haavisto and Koresaar 2017; Popli et al. 2018), there are still methodological and practical challenges. It is worthy to note that most of these processes including sampling points are usually retrofitted once the mineral processing plant has been designed and/or implemented. To date, insufficient attention has been given on incorporating sampling during the design stages of the plant, especially for metal accounting processes. This is evident from the post-implementation consideration of sampling points and the retrofitting of sampling mechanisms.

We have also observed in our case study that the mine has a mixture of automated and manual metal accounting sampling techniques of which most of them were thought after the plant was already operating. Post-implementation sampling strategy has a number of limitations and may compromise the quality of metal accounting. Examples of such challenges include lack of sampling points in milling equipment, positioning of weightometers next to equipment with higher vibration pulses and using dip-stick methods to measure volumes in process tanks. In certain instances, incorrect sampling procedures may lead to over-understatement of the target metal quantities. This is common in mineral processing plants that are accounting for multiple ores and variable grades. In such instances, the general assumption is that when these ores with highly variable grades are combined in blends, the metallurgical performance of the blend is additive and will not negatively affect the recoveries and subsequent estimation of salable metal. However, certain ores have non-additive effects and significantly affect plant performance (Nwaila et al. 2019). Therefore, metal accounting sampling should be considered as a primary future during the design phase of the equipment and metallurgical plants.

3.3. Auditing metal accounting processes

The value of metal accounting audits[1] is commonly realized during the reconciliation of the salable metal/product and reporting of financial statements. The focus of the audits tends to be on testing the reliability of the metal accounting process, quantifying the metal inventory, checking adherence to SOPs and consistency of meeting the acceptable company set tolerance limits. Except for operational requirements, much of this is done for compliance following rules and regulations set out in various acts and codes of practice such as the Sarbanes-Oxley Act of 2002 (SOX) (US Securities and Exchange Commission 2002), AMIRA P754 Metal Accounting Code of Practice and Guidelines (Connelly 2009; Jansen, Morrison and Dunn 2007; Morrison 2008a, 2008b; Morrison and Gaylard 2008; Power 2010; Wortley 2009), UK Corporate Governance Code (FRC 2018), the King IV Code of governance (IoDSA 2016), stock exchange trading platforms (SAMREC 2016), and public reporting of mineral resources and ore reserves (SAMREC 2016). In compliance with industry best practices, management of companies allocate resources for internal and external quarterly or annual audits for metal accounting processes in order to assess the effectiveness of internal controls over financial reporting. Although the AMIRA P754 code in combination with other statutory codes provides the premise of what to check during a metal accounting audit, the nature and components of the audit remain site- and company-specific. The scope of work tends to be divided into two categories, namely technical and financial reporting audit. These two audits are supposed to provide assurance over metallurgical and metal accounting processes, and reporting of the salable products. However, several gaps exist in the consolidation of the gathered information. The gaps include:

(a) Defining metal accounting battery limits – metal accounting processes tend to be restructured to metallurgical plant processes with mining and other technical inputs only used for high-level comparison of data during reconciliation stages.
(b) Assessment of the risks associated with inadequate verification of work in progress – Although some of the metals stay in process for periods up to 6 months, inadequate controls on management of the ore materials such as handling and recycling of spillages often result in a cumulative material misstatement that is only realized after longer periods of occurrence. In some cases, this may result in unrealized material losses especially when the variance between theoretical estimation widens when compared to the assumed in-situ stocks.
(c) The use of one size fits all sampling procedures – due to poor metal accounting sampling design, sample quantities tend to be standardized even where the commodity requires larger sample sizes. Composite of samples is

usually created and deemed to be representable even when the combined aliquots were taken in areas that do not encompass the total ore characteristics.

(d) Uncertainties on stocktake procedures and reporting – financial and technical audits of metal accounting procedures and salable metal quantities are conducted at various times for different purposes. This works well for small-scale companies but introduces several biases for medium and large-scale companies. Firstly, the company wise metal accounting procedures should only serve the purpose of guiding the site-specific metal accounting. Secondly, the overall metal accounting process should be assessed through rigorous statistical analysis that includes defining confidence levels, accuracy and precision of work in progress inventories and the information must be centralized in MMAIMS. A competent metallurgical/chemical engineer must be accompanied by a financial reporting, compliance and governance specialists when conducting metal accounting audits.

(e) As part of metal accounting inputs, considerations of multiple stakeholders and economic, environmental, and social capitals are some of the central factors that should be included and these have been described in detail in a number of corporate codes of governance as reported in De Villiers, Pei-Chi and Maroun (2017), IRCSA (2015) and Carels, Maroun and Padia (2013).

(f) Lastly, regardless of the assay laboratory good standing/ accreditation, primary accounting should ensure that controls over the quantify of material tracked by the system, water content and losses in shipping/transit should also be tracked. The system needs to incorporate a feature, which allows for independent review and track material losses at each stage of the metal accounting.

3.4. Intelligent metallurgical and metal accounting information management system

The gold mine case study presented in this paper has shown that metallurgical and metal accounting data is recorded in isolated databases or captured in operation-specific Microsoft Excel spreadsheets. In addition, certain measurements including those of salable metals are manually captured into these databases. In line with the modern computational capabilities and our metal accounting nerve system approach, we are proposing the development of MMAIMS. The intelligent MMAIMS will provide a real-time, visual demonstration of what is happening in the operation, thus enabling predictive response to changes to meet sustainable mining and mineral processing requirement. This will create consistency in data used for decision-making and accurate reporting of salable quantities. As mentioned in Section 2, a cloud-based software system with a user-friendly graphic user interface (GUI) that has security features such as login per user ID could be used as a software platform for the proposed system. An additional benefit is the synchronization of operation data, eminence information live feedback and business value optimization. It should be borne in mind that the idea of predicting future performance is extremely dangerous as there is no guarantee that past and present practices will/can be followed. Ore type change and mining methods change. Predicting and forecasting any metal or metallurgical accounting is therefore a dynamic process and potentially subject to change (including improvement) and manipulation (both ethical and otherwise). For this reason, we propose that predictive modeling and forecasting using legacy data be done only to guide the operations and used in collaboration with current data and plant design. Changes that may occur on ore characteristic and plant modifications should always be factored when making any form of predictions.

The intelligent MAIMMS concept also plays a role in identifying metal accounting risk areas, reduction of reconciliation variability, accurate forecasting and data-driven decision-making in an integrated way, i.e. algorithmic estimation of salable metals based on metallurgical accounting/performance data. Regardless of site-specific accounting processes, a system such as MMAIMS will be able to provide the required standardization across the company's operations. This will also minimize errors introduced during capturing and transferring of data from one system to the other. Lack of reliability on reports generated by copying-and-pasting data into different worksheets or channeled through dynamic linking to other Excel workbooks can be solved through relying on automated daily, weekly and month reporting of metal and metallurgical results in MAIMMS. Previous studies (e.g. CASPEO 2018) that attempted to use a custom-designed metal accounting software (e.g. INVENTEO, Algosys Metallurgical Accounting (ION), Symphonite (Honeywell), Star LIMS, Metallurgical intelligence (MI), MMS (WIRE)) linked with the AMIRA code has shown significant improvement in the quality of information, report generation and auditability. Most of these software and systems have in fact all leading-edge database systems specifically designed for metal accounting applications. Most of them address the fundamental metal accounting issues as well as important features such as measurement precision handling, bias detection, and statistical data reconciliation. From our desktop and field research conducted as part of this study, we discovered that more companies are joining the bandwagon of designing new metal accounting systems. This includes software companies such as CAE Datamine, which is currently conducting trial PGM mines (South Africa), and ferrous metal mines (Australia). International mining companies such as Glencore are also currently testing an in-house metal accounting software. Although configuration and the interface are company specific, the formulation used in these software packages and systems are the same. The fact that we have too many software packages and systems aiming to achieve the same goals highlights the deficiencies in their practical applications and adequacy to fulfill both operational and governance requirements. One of the changes is that metal accounting systems are either designed by professionals with insufficient industry experience or very well-experienced engineers with no software design background or experienced individuals who have worked on one of two commodities and therefore assume that the software packages can be applied on every untested deposit. It is this reason that we suggest that the proposed MMAIMS can provide immense benefits if designed and implemented in collaboration with all relevant stakeholders and in accordance with the existing acts and codes of practice including recommendations discussed in this paper. Aside from data reconciliation improvement, MMAIMS can be used for stock management and metal inventory, analyze periodicity and simulate scenarios and data workflow and validation in the line of sustainable framework.

4. Conclusions

Metal accounting processes are applied variably by mining companies for the purpose of quantifying metal inventories and financial reporting statements. Comparison of the various existing metal accounting procedures, combined with a case study of a gold mine, reveals that the current practices provide a number of important metal accounting procedures. However, a fundamental change in the approach toward data integrated and auditable metal accounting system is long overdue. This change is reflected in our proposal for a more accurate and reliable systematic framework of the metal accounting of salable metals. Our proposed metal accounting framework includes various mass balance-risk drivers, aspects of operational measurements and data reliability, effects of plant configuration, data integration and security, corporate governance dynamics, and reporting of salable metals. The proposed approach considers the use of the currently available and future-oriented development in technological development (both hardware and software) in mineral processing and extractive metallurgy. Implementation will lead to better plant process control, transparent financial reporting, and an adequate understanding of interrelationships between different process activities. In addition, quantification of metal inventories can be more accurately constrained, and risks such as material misstatement can be identified with the aid of metallurgical and metal accounting information management system. We have recognized the need for a proactive design where metal accounting sampling has to be factored during the plant equipment design stages. This, in turn, will help ensure that metal accounting sampling is done as per the first principles that are based on the nature and composition of the ore. The use of MMAIMS will eliminate data security risks associated with multiple-user environment spreadsheets, create consistency in data used for decision-making and operation data synchronization. End to end metal accounting process visibility across the entire process will improve the audibility and transparency of metal accounting from mine to product, and facilitate good corporate governance and financial reporting of salable metal production and sales. Naturally, with any system, there are uncertainties in the data acquired which could affect the precision of the analyses. Additional delimiting factors may include conditional biases, adequate measures, such as data cross-referencing/replication and routine metal accounting system audits can help to ensure the quality of the data and ultimately assist in better reporting of salable metals.

For future research, the following areas are recommended:

- Developing the approach to integrate the metal accounting system in general and sampling specifically into process flowsheet and the plant equipment design stages.
- How metal accounting system could be integrated into a flexible and multi-stage geometallurgical framework, adaptable for variate of the ore type.
- The effect of feed ore variability on in-situ mineral reserves classification.

Note

1. The term audit is derived from a Latin word "audire" which means to hear authenticity of accounts is assured with the help of the independent review. In this paper, the term audit refers to the examination of ore and metals inventory, work in progress (WIP) books and to check the effectiveness of internal control systems in order to detect the effectiveness of mass balancing and metal recovery, prevent error in recording of material quantities and qualities, prevent fraud and ascertain the validity and reliability of information.

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No potential conflict of interest was reported by the author(s).

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