# TOWARDS A TECHNOLOGY FRAMEWORK FOR EVALUATING AND OPTIMIZING THE METAL FLOW PROCESS FOR COPPER PRODUCTION

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**By**

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A research report submitted to the Faculty of Engineering and Built Environment, University of the Witwatersrand, Johannesburg, in partial fulfilment of the requirements for the degree of Masters of Science in Engineering

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**DECLARATION**

I declare that this thesis is my own, unaided work. Where use has been made of the work of others, it has been duly acknowledged. It is being submitted for the degree of Masters of Science in Engineering in the University of the Witwatersrand, Johannesburg. It has not been submitted before in any form for any degree or examination in any other university.

Signed:

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**ABSTRACT**

The copper usage around the world is increasing as it is an important commodity for the electrical and electronics industries. Although, production of copper in the world is increasing, it is declining in South Africa. Between the mining face and the final product in plant, a large quantity of copper is lost in various forms. The copper ore usually contains around 2% copper along with other elements like gold, zinc, sulphur etc., depending upon the ore mineralogy. To produce pure copper, a large quantity of waste is mined with it, which is around 98% of the quantity mined. The mining and processing of copper ore is spread over a large range of activities from production to processing.

The accurate measurement of mass and material transfer is significant as each process is dependent on the previous one. In the mining industry, metal accounting is carried out as a general practice to cater for production and reporting requirements. The issue with this practice is that it is not done to the required (high) level of confidence. However, there are digital tools available in the market that supports either mine or plant metal accounting. There is a need for an overall integrated system that will help both the mine and plant in the metal accounting process.

In this research, a hypothetical case study of a copper mine is used to study the ore flow process from mine to the final product in the plant. The AMIRA code for metal accounting is also discussed and the protocols for mass measurement, sampling, sample analysis, data collection, data analysis and reporting are outlined. A digital framework called WMI-OFA for ore flow analysis is proposed in accordance with the AMIRA code of guidelines that will be able to monitor and analyse the overall ore flow process. The WMI-OFA framework will be able to bridge the gap of information flow from mine to the final product in plant. It will also assist in reduction of ore losses during production with the real-time identification of bias in measurements.

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## DEDICATION

To my caring parents for their love and sacrifice, siblings for their unlimited support and teachers for their guidance and motivation.

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**LIST OF ABBREVIATIONS**

| | |
|---|---|
| AAS | Atomic absorption spectroscopy |
| AM | Autogenous mills |
| BM | Ball mills |
| DE | Increment delimitation error |
| DMT | Dry metric tonnes |
| EE | Increment extraction error |
| FE | Fundamental Error |
| GE | Grouping and segregation error |
| ICP | Inductively coupled plasma mass spectroscopy |
| LIMS | Laboratory information management system |

| | |
|---|---|
| OFA | Ore flow analyser |
| PE | Preparation error |
| QE2 | Long range quality fluctuation error |
| QE3 | Periodic quality fluctuation error |
| RFID | Radio frequency identification tags |
| ROM | Run of Mine |
| SAG | Semi-autogenous mills |
| $T_E$ | Total error |
| $V_A$ | Variance due to analysis |
| $V_M$ | Variance in mass measurement and moisture content analysis |
| $V_S$ | Variance due to Sampling stages |
| $V_{SP}$ | Variance due to sample preparation |
| $V_{TMA}$ | Total variance in Metal accounting |
| WE | Weighing error |
| WMI | Wits Mining Institute |
| XRF | X- ray fluorescence |

# 1 INTRODUCTION

The copper usage around the world is increasing as it is an important commodity for electrical and electronics industry. From mining to final product, large quantity of copper is lost in various forms during production and processing. This chapter discusses the world copper production statistics, the history of South African copper production, a typical overview of copper production process and an introduction of metal accounting and reconciliation process which if done accurately, will help in reduction of losses during production of copper.

## 1.1 Overview

Copper was an important commodity from the early times in the history of human civilization. The use of copper started about 10 000 years ago in coins, jewellery and house hold items (International copper study group, 2016). The demand for copper is still increasing and to meet this demand, production must also increase. In 2017 the world copper mine production decreased by 300 tonnes with respect to the production in 2016, from 20 100 tonnes in 2016 to 19 700 tonnes in 2017 (United States Geological Survey, 2017). The world trend of world copper production from 1991 to 2017 is shown in Figure 1.1. There is still a gap between demand and supply of copper. In 2015, the world copper production (Primary + Secondary) was 22870 tonnes while the demand was 23041 tonnes (United States Geological Survey, 2017). There was a shortage of 171 tonnes.

The production of copper in the world is increasing, whilst it is declining in South Africa. From 2007 to 2016 there was a considerable decline in the production. According to statistics from the Chamber of Mines, South Africa produced 108 700 tonnes of copper in 2008 which reduced by 65 257 tonnes in 2016 (Chamber of Mines South Africa, 2017). A trend of South African copper production from 1991 to 2016 is shown in Figure 1.2. The reason of reduction in the production resides in the problems faced by mining industry. It includes the fluctuating copper prices, variation of rand exchange rates, increase in mining and processing costs, mines getting deeper, increase in labour costs and environmental issues.

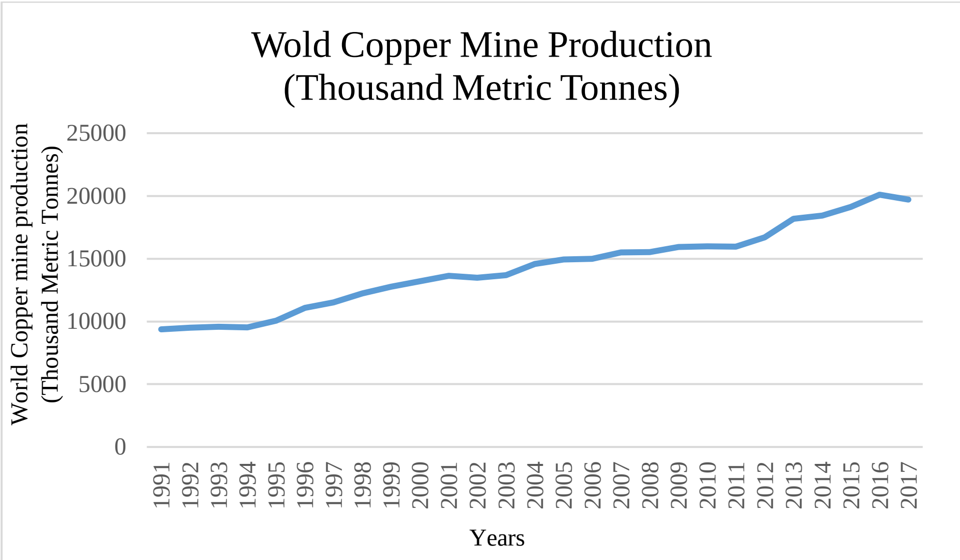


Figure 1.1 World copper production trend (United States Geological Survey, 2017)

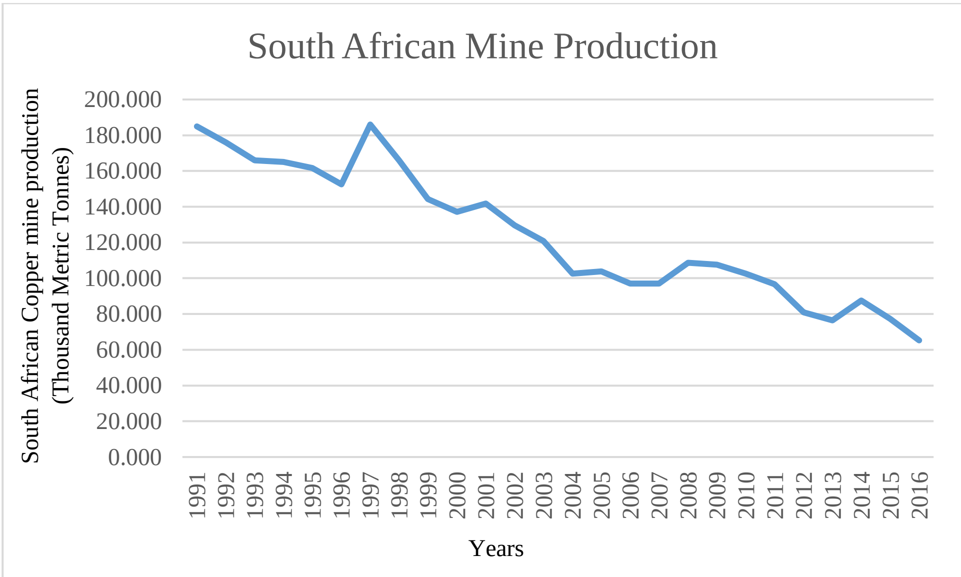


Figure 1.2 South African copper mine production (United States Geological Survey, 2017)

In the case of copper, the processing of ore produces harmful gasses along with solid and liquid wastes. The copper ore usually contains around 2% of copper along with other elements like gold, zinc, sulphur etc. depending upon the ore mineralogy. To produce pure copper, a large quantity of waste is mined with it which is around 98% of the quantity mined. During processing of copper ore around two tonnes of slag is produced and the slag typically contains 1.7 to 2.3 percent of copper per tonne of copper smelting slag (AydınRüşen et al., 2012). In 2015 the South Africa smelter production of copper was 71 800 tonnes. Therefore, the slag produced by local smelters was around 143 600 tonnes (71 800 x 2 tonnes per tonne of slag). The copper lost in 2015 in the form of slag was around 1 651.4 tonnes (71 800 x 2.3% per tonne of slag). In 2017, the world refined copper production was 19 441 thousand metric tonnes (International Copper Study Group, 2018), using the above approximation (AydınRüşen et al., 2012) the copper lost in slag is around 894,286 thousand metric tonnes, which is even more then the annual South African copper production.

From a mine prospective, the variables responsible for ore loss are inaccurate grade control results, movements during blasting, poor mining supervision, complicated crushing cycles and inaccurate measurements of mass (Tetteh, 2014). In the plant, the losses depends upon process efficiency, plant operating parameters, accurate measurements of input and outputs, accuracy of laboratory results and staff training. The last factor varies in different organizations but the remaining factors are controllable by applying protocols properly.

The accurate measurement of mass and material transfer has become more significant as ore processing is now spread to multiple plants operating independently and the ore from a mine is transported to several plants for processing. As a result, the evaluation of the final product after each stage becomes more significant.

## 1.2 Problem statement

The data collected during ore processing, outlines valuable information for the process industry. The reconciliation of the data collected at each step is necessary for the improvement in the process. It will also help in eradicating the practices which increase production cost. In the case of a single organization operating the mine and the processing plant, small errors in the metal value from mine to plant may not have much impact. However, in the case of toll treatment plants, which take raw materials form another mine or a pre-processing plant, the knowledge of the exact value of the metal present in the ore becomes very important (Gaylard et al., 2014).

To address this issue, a project under the name “AMIRA P754” was initiated. The major aim of the project was to develop a set of rules for metal accounting and reconciliation. These rules will be considered as the standard for any metal accounting process. The metal accounting system in a plant and mine can lack accountability and traceability (AMIRA, 2007). The data collected through different sources usually have large variability and is difficult to trace back. This often leads to false data capturing which results in poor planning and eventually leads to large losses.

In this study the current standards for metal accounting in the mine and plant will be studied. For this purpose, a copper mine will be considered as a case study.

## 1.3 Aims of investigation

The aims of this study are:

- To assess copper losses during the production and processing stages of a typical copper production process;
- To assess compliance of metal accounting standards of typical copper production process with current practices for copper processing;
- To investigate the effect of metal losses to premature closure of mines; and
- To report on ways to reduce waste during ore treatment.

## 1.4 Research objectives

To achieve the aims of investigation, the following activities will be pursued:

- Analysis of ore flow in a copper mine;
- Recommendations for a metal accounting framework for copper production;
- Recommendations for appropriate digital tools;
- Recommendations for optimising metal flow process for copper from the mine through plant; and
- The use of technology to optimise the copper recovery flow process.

## 1.5 Hypothesis

The current code of practice for metal accounting and the best practices do not cover the whole process, starting from mine to the plant. The AMIRA P754 code for metal accounting is mainly focused on plant. There is a gap in the information flow along the process flow from mine until final product in plant. There is a need of a framework that will be able to fill this gap. There are tools available in the market that supports either mine or plant only. There is a need for an overall system (for both mine and plant) that will help both the mine and plant in the metal accounting process. The tool should be in conformance with the current metal accounting guidelines (AMIRA P754) and the current best practices in the industry.

## 1.6 Overview of copper mining and processing

The process of mining and processing of ore is spread over long range of activities. These are outlined in mining value chain discussed in chapter 2. After the establishment and start of operations in a mine, the mining activities differ depending upon the mining process applied for mining. For example, open cast or underground mining etc. In underground mines, the ore after blasting, is collected and depending on size, the primary crushing is done inside or near the mine before transportation. The ore from crushing is then transported to the stockpile. From stockpile the ore is transported to the plant. The mode of transportation depends on the distance of stockpile from plant. If the plant is near stockpile the ore is loaded on the conveyer belts by front end loaders and if the plant is far, trucks are used for the transportation purposes.

In the plant, the processing is different depending on the ore being processed. In case of copper, there are two main processing streams. The ore is typically concentrated using froth flotation process. After the process there are two different routes for processing namely the pyrometallurgical and hydrometallurgical route. The pyrometallurgical process use smelting process for the removal of oxides and then anodes are casted. The cast anodes are then electrolytically refined to form 99.99 % pure copper which is then cast in bars or wires as required. The copper 80% of copper production is through pyro-metallurgical route. The ore flow and the important parameters of this route is discussed in detail in chapter 2.

## 1.7 Metal accounting

In the AMIRA P754 code of practice for metal accounting, metal accounting is defined as “The system whereby selected process data (pertaining to metal of interest) is collected from various sources including mass measurement and analysis and transformed into a coherent report format that is delivered in a timely fashion in order to meet specified reporting requirements" (AMIRA, 2007). In the metal accounting process production data is collected through sampling, sample analysis, mass measurements etc. It is vital that the data collection and analysis should be accurate and reliable because these results are to be used in different important areas including reports, decision making and for internal management. So, it is also important that the reports of the metal accounting are produced timely and is made available to the required persons. It is also of prime importance that the data collection should be traceable for the auditing purposes.

### 1.8 Ore flow balance sheet

The ore flow balance sheet is used in mine and plants for data collection. The data from different sources is gathered in the table and analysed. An example of a typical ore flow balance sheet for mine is shown in the Table 1.1 (Cawood, 2012). It contains on source of information (categories), mass, grade, percentage and content with respect to each category. The ore flow sheet can vary depending upon the mining and plant processes.

Table 1.1 Ore flow balance sheet (Cawood ,2012)

| Category | Percentage | Mass | Grade | Content(g) |
|---|---|---|---|---|
| Pay ore reserve | | | | |
| + Not in reserves | | | | |
| + Unpay Ore reserve | | | | |
| + Other sources stoping | | | | |
| +Stope Reclamation | | | | |
| +Stope Development | | | | |
| +Total broken ore in stopes | | | | |
| -Stored and Packed in stopes | | | | |
| Trammed from stopes | | | | |
| +Reef development | | | | |
| -Reef in ballast | | | | |

| Category | Percentage | Mass | Grade | Content(g) |
|---|---|---|---|---|
| -Development ore stored | | | | |
| -Total reef trammed | | | | |
| +/-Discrepancy | | | | |
| Hoisted as reef | | | | |
| +Shaft bins (Start of month) | | | | |
| Total in shaft bins for month | | | | |
| -Shaft bins (End of month) | | | | |
| Total from shaft bins | | | | |
| +Ore from reef dump/stockpile | | | | |
| To surface sorting plant | | | | |
| -Sorting | | | | |
| +Ore from reef picking plant | | | | |
| To mill bins | | | | |
| +Mill bins beginning of month | | | | |
| Total in mill bins for the month | | | | |
| -Mill bins (end of month) | | | | |
| -Tons milled | | | | |
| +Tons milled | | | | |
| +Slimes treated | | | | |
| Total tons treated | | | | |
| Mine call factor | | | | |
| Recovery/ residue | | | | |
| Recovery plus residue | | | | |

## 1.9 Methodology

Methodology was outlined during a workshop with Digi-Mine group, experts from industry and the School of Chemical and Metallurgical Engineering and is as follows:

**Identification of leading practices in mine metal accounting**
Metal accounting practices in copper mines will be studied, along with the ore flow for identification of variables and key points of data acquisition. For this purpose, a desktop study will be conducted.

↓

**Analysis of case study against leading metal accounting practices in mine & plant**
A case study of a copper mine will be considered for analysis against the standards and best practices, to analyse the efficiencies and conformance of the system with metal accounting standards.

↓

**Application of Technology & Recommendations**
Recommendations will be provided to improve the metal flow analysis process according to the standards and appropriate digital tool.

Figure 1.3 Research Methodology (Author)

## 1.10 Facilities required

The project will be done in Wits Mining Institute in collaboration with the School of Chemical and Metallurgical Engineering. The laboratories in the School of Chemical and Metallurgical Engineering will be used for lab scale extraction of copper ore if required.

## 1.11 Research report outline

**Chapter 1**

This chapter provides a brief introduction of the copper production statistics in the world and the share of South Africa in world copper production. It highlights the importance of reliable ore flow analysis and the metal accounting protocol. The problem, objective and methodology of research is also highlighted in the chapter.

**Chapter 2**

In this chapter, the mining value chain is described, and the copper production steps is discussed in detail. The ore flow in copper plant and mine is also discussed. In the end the case study of Platinum industry is discussed to outline the implication of metal accounting protocol and practices in a base metal refinery.

**Chapter 3**

In this chapter the AMIRA P754 code for metal accounting is discussed. The requirements and implications of the code is outlined in detail. The process of mass measurement, sampling, sample analysis, data collection, data analysis, reporting and reconciliation is also discussed.

**Chapter 4**

This chapter describes the case study in detail. The current practices and a digital framework for ore flow analysis from mining face up-to the final product in plant is conceptualised. The architecture and features of the digital system are also discussed.

**Chapter 5**

This chapter contains the recommendations for improvements of metal accounting process in the plant and mine. It also suggests the need for the use of a digital system for real-time identification of bias and to bridge the gap of information flow between mine and plant processes. It also outlines the future research opportunities on this topic.

## 1.12 Conclusion

The first chapter provided the framework of the research, the background of problem, research objectives and the expected outcome. An overview of the chapters is also provided. The next chapter will be Literature review. In this chapter the ore flow process in mine and plant is discussed along with a case study of Platinum industry in which the metal accounting protocol is applied, and the current practices are analysed against the standard protocol of metal accounting to understand the implication of protocol.

# 2 LITERATURE REVIEW

## 2.1 Overview

The mining process consists of series of steps. The ore passes through a series of value-adding steps before reaching the end user in the mining value chain. The knowledge of the exact quantity of ore being processed is very important. The exact location of mineral, the movement of ore, storage of ore; are all important from a mining perspective. Similarly, in a plant, it is important to know the exact quantity of plant feed and the products produced in each step during processing. The input, outputs and efficiency of each process have an impact on the next process. To prevent losses during production and to improve the efficiency of each process, it is important to know the quantity of material-flow between processes.

In this chapter, the ore flow in mine and plant is discussed. The potential areas of ore loss in mine and plant are outlined. In the end, a case study of platinum industry is also discussed to study the implications of AMIRA P754 code for metal accounting.

## 2.2 Mining value chain

The mining value chain outlines the series of steps involved in the value-added life cycle of mineral commodities. The details of these steps is discussed as under (Guj et al., 2017):

### 2.2.1 Acquisition and exploration

This is the first stage in the life of a mine. The main aim of this stage is to find the new ore deposits. It is a high-risk stage because of the significant investment involved in it.

### 2.2.2 Mine construction and development stage

In this stage, the ore deposit area is prepared for the ore extraction. It also involves the development of crushing, screening and concentration facilities.

### 2.2.3 Mining and concentration

In this process, the ore is mined and separated from waste by a process called concentration. The quantity of waste depend upon the ore grade and the mining methods used. The concentration process is usually carried out near the mine because of large quantity of waste mined during mining processes. If it has to transport to large distances, it will increase the transportation cost considerably.

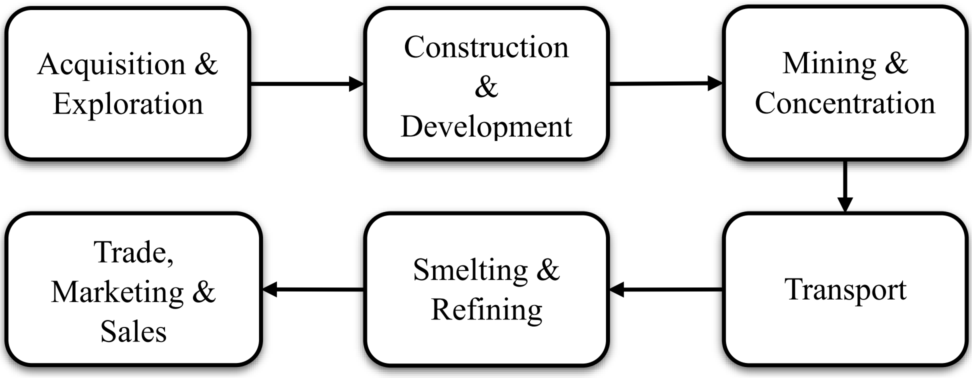


Figure 2.1 Mining Value Chain (Guj et al., 2017)

### 2.2.4 Transportation

This phase involves the transportation of ore from mine. Different modes of ore transportation such as trucks, conveyer belts and rail road are used by mining companies.

### 2.2.5 Smelting and refining

In this stage, minerals are extracted from the ore using physical and chemical processes. After smelting and refining the product is ready to be transferred to the market.

### 2.2.6 Trading, marketing and sales

This is the last stage of mining value chain in which the final product is sold to the market.

## 2.3 Ore flow in a mine

Mining of ore starts after the exploration and mine development stages of the mining value chain as discussed in section 2.2 of this chapter. The efficiency of the mining is highly dependent upon the exploration and mine development stages. It is important to extract ore with as less waste as possible. The process of ore flow in a mine is complex. A typical ore flow in an underground mine is shown in the Figure 2.3 (Hills, 2000).

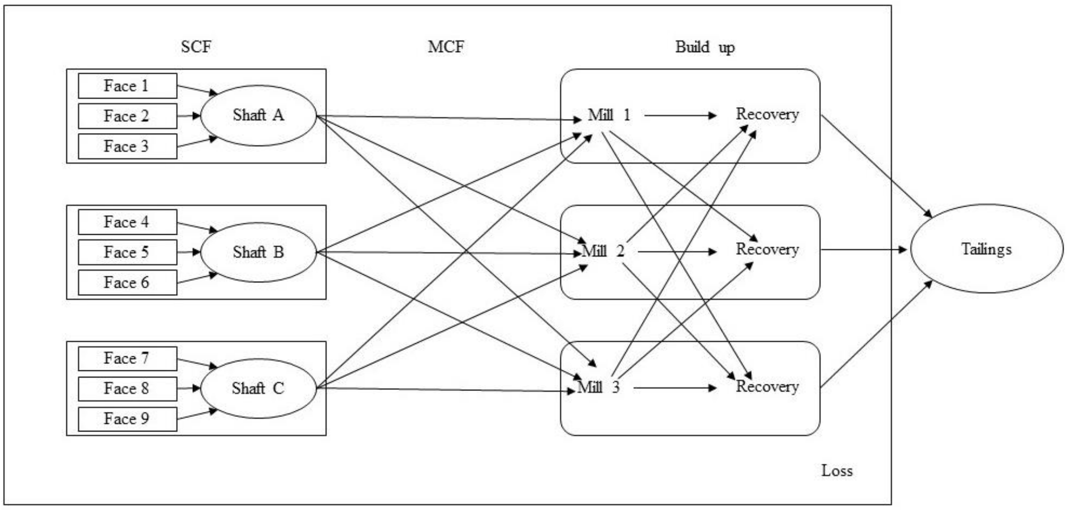


Figure 2.2 Typical ore flow process in a mine (Hills, 2000)

One of the reasons of this complexity is the number of steps involved in this process. The causes of these complexities are stated below (Hills, 2000):

- Multiple mine faces;
- Large number of shafts and pits;
- Different processing plants;
- One plant receiving ore from different mines;
- Production losses due to ore dilution;
- Inefficient plant process; and
- Different ore storage points.

To counter this complexity, a systematic approach is required for the metal content determination (Tetteh, 2014). Cawood (as cited in Tetteh, 2014) classified the losses as real and apparent loss. According to him apparent losses arise due to the issues such as over estimation of metal content, inappropriate sampling standards and incorrect relative densities applied. The real losses are actual physical metal loss such as losses during trammings, hoisting, extraction etc.

Tetteh (2014) studied the mine call factor at Anglo Gold Ashanti`s Iduaprium mine. The study outline the potential point of losses from a surface mine prospective. These points are listed in Table 2.1.

Table 2.1: Potential areas of loss in a surface mine (Tetteh, 2014)

| **Category** | **Loss Type** |
|---|---|
| Resource/ Reserve | • Incorrect geometry analysis of ore<br>• In-appropriate grade estimation algorithm<br>• Incorrect truck tonnage factor<br>• Incorrect use of in-situ and soil densities<br>• Downhole survey mistakes<br>• Failure of the ore body to show robustness |
| Survey | • Wrong coordinates of drill holes<br>• Incorrect mark out control |
| Sampling | • Insufficient sampling<br>• Loss due to poor sampling before assay<br>• Loss of sample<br>• Incorrect interpretation of ore geometry<br>• Application of wrong cut off criterion<br>• Poor quality control process |
| Blasting | • Excess heave<br>• Excess back break<br>• Excess flying rocks<br>• Under cuts of the toe<br>• Large boulders blasting |
| Material movement | • Beyond contact digging<br>• Wrong destination trucking<br>• Spillage during transportation |
| Clean up | • Grading over the ore zones<br>• Dozing ramps on ore faces<br>• Truck running on ore zones |
| ROM pad | • Ore left on the ROM pad<br>• Spillage from trucks<br>• Stockpile pads supercharging |

### 2.3.1 Mine call factor

The mine call factor (MCF) is defined as "The ratio, expressed as percentage, which the specific product accounted for in the product recovered from plant, plus that in tailings/residues bears to the corresponding product called for by the measurement and evaluation methods used at the mine" (AMIRA, 2007). If the processes involved in sampling and measurements are accurate and there is no loss of metal during handling, the mine call factor should ideally be 100% (Storrar, 1981). It is suggested by Storrar (1981) that the mine call factor is consistently below 80% should be taken as an indication of inaccuracy in the metal accounting system and management should investigate. The possible causes include the sampling process, over estimating the ore content treated by plant & mine and plant inefficiencies (Storrar, 1981).

## 2.4 Ore transportation

Ore transportation is the next step after mining in the value chain. The choice of correct transportation method is important for the smooth running of mine production. The selection of transportation facility for an underground mine depends on the following factors (Gonen et al., 2012)

- Ore reserve;
- Production capacity;
- Underground mining methods;
- Ground conditions;
- Thickness, depth and dip of ore body;
- Life of mine plan;
- Amortization;
- Discount rates;
- Development schedule; and
- Price of equipment.

During transportation loss of ore can also occur. Such as spillage from trucks, ore delivery to waste instead of stockpile and theft. To reduce these losses, the tracking of ore is required. It is also important for reconciliation process. The process of reconciliation is discussed in Chapter 3.

## 2.5 Ore flow in plant

For processing of copper ore, there are two metallurgical routes. They are pyro metallurgical and hydro metallurgical routes. Both routes are outlined in the Figure 2.2 (Forsén et al., 2017). The pyro-metallurgical route is more abundantly used in copper processing. In 2014, 14.2 million metric tonnes of copper was produced through pyro-metallurgy while 4.1 million metric tonnes was produced through hydrometallurgical processes (Forsén et al., 2017). In this section the pyro metallurgical route is discussed in detail.

Apart from the errors in measurements, the metal loss in plant is also dependent on the efficiency of the process. The factors that affect the efficiency of the process is discussed in this section. Some of these factors are dependent on the correct measurements of the inputs and outputs, which is the domain of metal accounting. Hence, correct metal accounting practices can assist in improving each process.

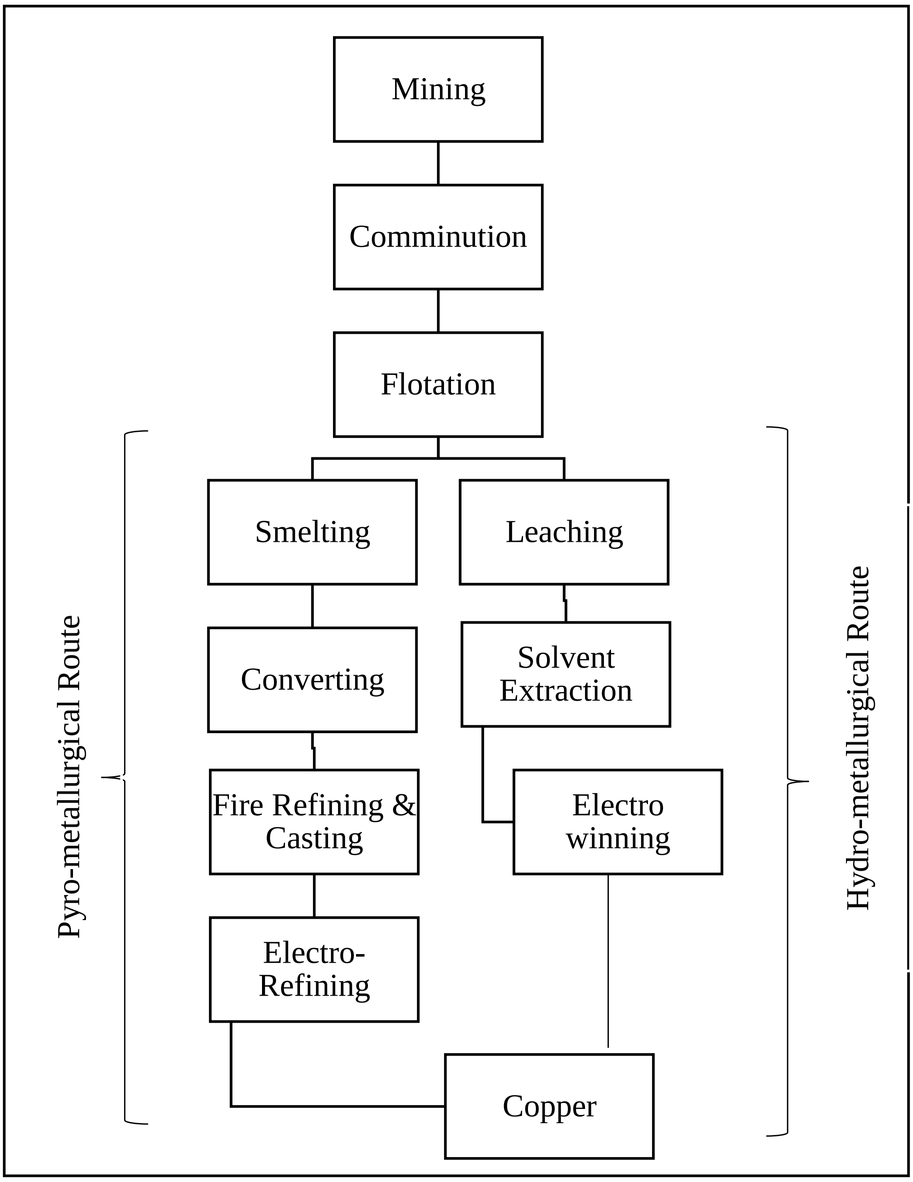


Figure 2.2 Hydro & Pyro metallurgical cycles of copper (Forsén et al., 2017)

### 2.5.1 Milling

The first step of ore processing in a plant is milling. The process reduces the particle size of the ore. The reduction of particle size depends upon the design of the milling process. Typically, the milling process consists of a series of mills called a milling circuit. The grinding circuit reduces the size of ore gradually to the required size.

It is generally assumed that to increase the efficiency of the milling processes, the blast energy should be increased to reduce the ore fragment size. However, the reduction in the fragment size can result in the loss of ore, and increased dilution

(Kanchibotla et al., 2015). The general inputs and outputs of the milling process is shown in Figure 2.3 (Schlesinger et al., 2011).

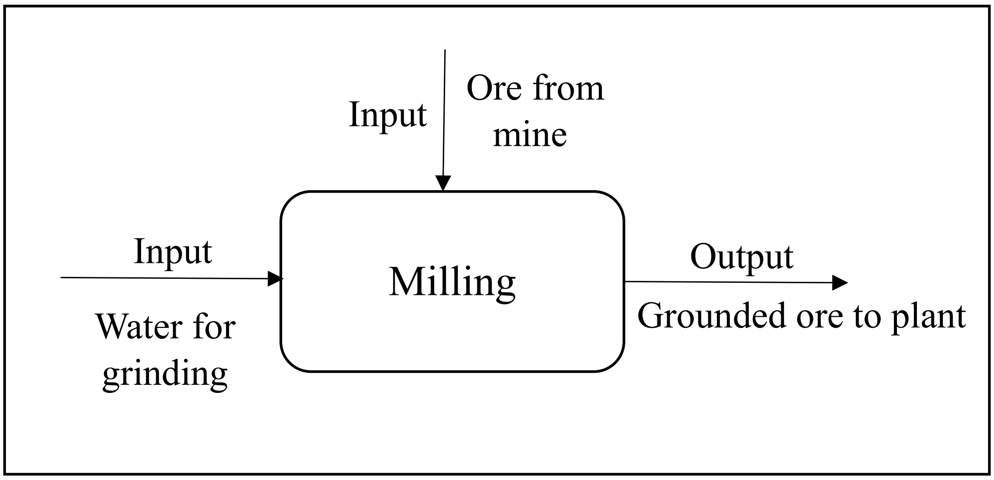


Figure 2.3 Inputs & outputs of milling (idea taken from Schlesinger et al., 2011)

A typical milling circuit use a combination of Autogenous mills (AM), Semi-autogenous mills (SAG) and Ball mills (BM). Laboratory scale tests are designed to find the optimum particle size distribution for Froth flotation. Over grinding of ore creates a negative impact on the efficiency of flotation processes. It also increase the energy consumption (Schlesinger et al., 2011).

Grinding circuit of a Copper mine is shown in the Figure 2.4 (Rose et al., 2015). The ore flow of grinding circuit is described below:

- The copper ore is fed to a cyclone crusher. The crushed ore from crusher is passed through a vibrating screen. The vibrating screen separates the fine and course particles;
- The fine particles are transferred to the stockade. The course particles are sent to another cyclone crusher (Raptor XL-2000);
- From stockade, the crushed ore is sent to the SAG mill for further crushing. The output of the SAG mill is classified using another vibrating screen;
- The coarse particles from the classifier are passed through cyclone crusher (Raptor XL-900) or back to SAG mill for further crushing;

- The fine particles from the SAG mill screening is then passed to the Ball mills. These mills further reduces the size. After passing through the mills the ground material is fed to the plant.

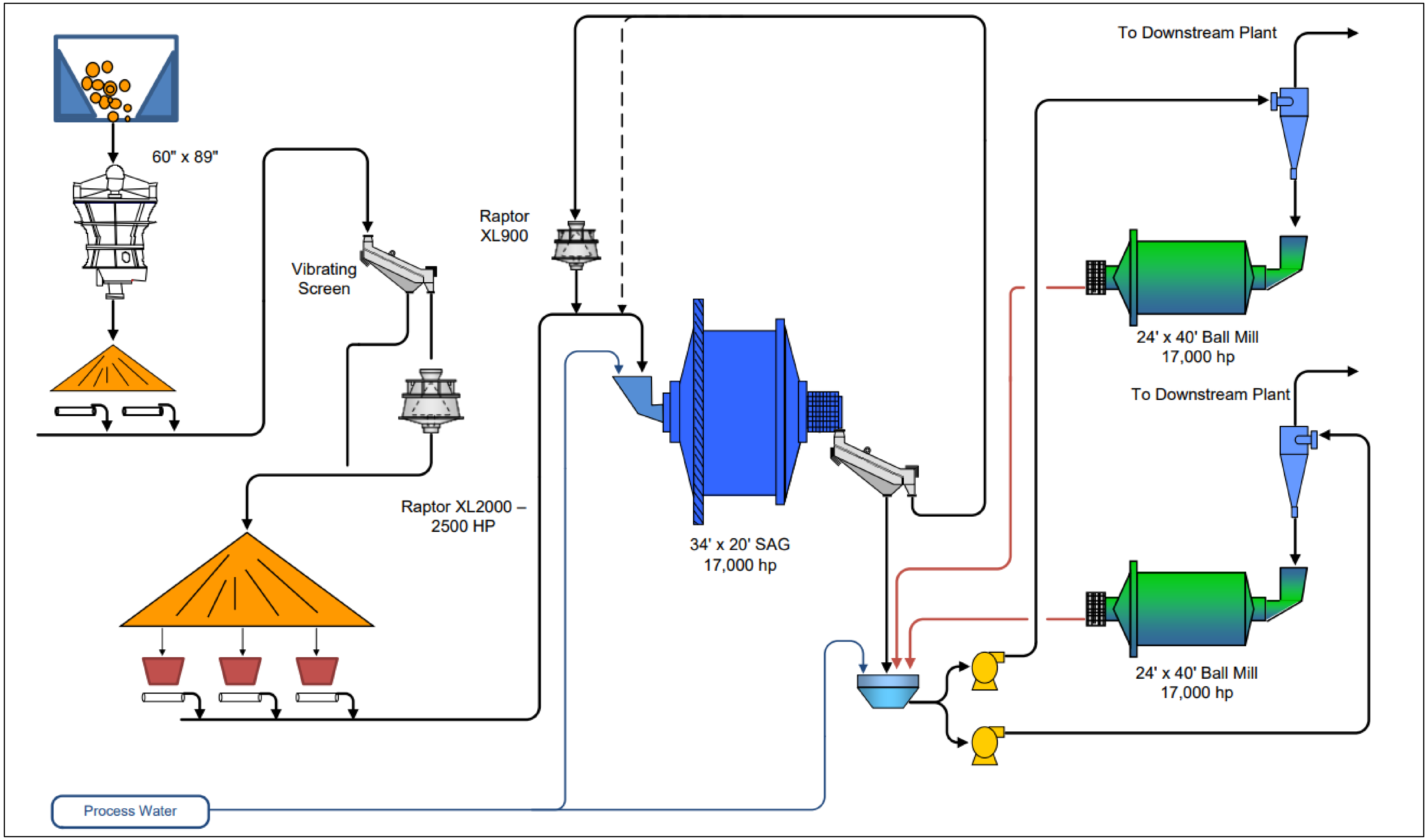


Figure 2.4 Milling circuit at Copper Mountain mine (Rose et al., 2015)

### 2.5.2 Froth flotation

The next process is Froth flotation in which ore from the mill is fed. In this process, copper-containing compounds are separated from gangue. After separation, the froth is passed for smelting and the gangue is discarded as tailings. Figure 2.5 (Schlesinger et al., 2011) shows the inputs and outputs of this process. The major inputs are grinded ore from mill, water, reagent and air. The outputs are froth and tailings. The Froth flotation process is described as under (Schlesinger et al., 2011):

- The process starts with the addition of chemicals to the slurry (a mixture of crushed ore and water). The copper containing compounds are converted to hydrophobic particles (water repellent). The remaining compounds are converted to hydrophilic particles;
- Air is pumped from the bottom of the cells. This air form bubbles which entrap the copper containing compounds (hydrophobic). These bubbles being lighter than the surrounding move upwards;
- The hydrophilic compounds remain in the water. These are left behind as gangue material and removed as tailings;
- A froth is created at the top of the cell. It entraps the air bubbles which were moving upwards in the cell. The froth is collected by plant workers periodically from the top;

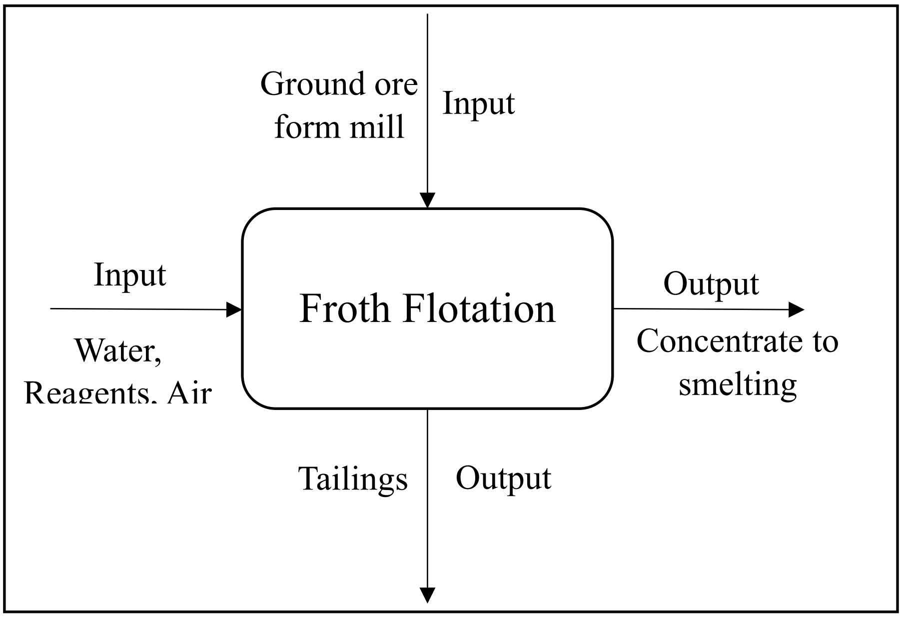


Figure 2.5 Ore flow in Froth Flotation idea taken from (Schlesinger et al., 2011)

The efficiency of Froth flotation process depend upon the following factors (Nashwa, 2007).

- Particle size;
- Pulp density;
- Water quality;
- pH; and
- Reagent dosage.

Particle size is an important factor for the optimisation of Froth flotation process (Trahar, 1981). The fine particles increase the froth stability by enhancing the rigidity of bubbles in the flotation column (Rahman et al., 2010). The effect of particle size on a flotation process in Barrick Oborn copper concentrator was studied by Crosbie et al. (2009). The concentrator process a mixture of open-pit and underground ore mined from Trekelano deposits. Before flotation, the ore was crushed by a grinding circuit consisting of Rod and Ball mills. The feed particle size from the mill is in range of ultrafine (CS5[1]) to a maximum of 425 µm. The flotation circuit is shown in Figure 2.6 (Crosbie et al., 2009). The circuit contains a series of roughers and scavengers. The final concentrate from all roughers and scavengers are collected in a collector.

The study shows that the loss of copper was maximum in the ultrafine (-CS5) and 106 µm size. The analysis of tailing shows that at the ultrafine particle size, the percentage of copper in the tailing is 75 percent while in the 106 µm size fraction, it is 12 percent. The recovery of copper, sulphur, iron and silicon dioxide is shown in the graph in Figure 2.7 (Crosbie et al., 2009). It shows that the maximum recovery of copper is achieved in the particle size ranging from ultrafine (CS5) to 53 µm. There is a significant drop in the recovery after 75 µm. It is evident from the above example that the particle size has a big impact on the efficiency of flotation process. Hence, the particle size should be carefully monitored for optimal recovery.

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[1] CS5 is the size classification refers to the particle size of 8 micrometer (Runge & J.P. Franzidis, 2003)

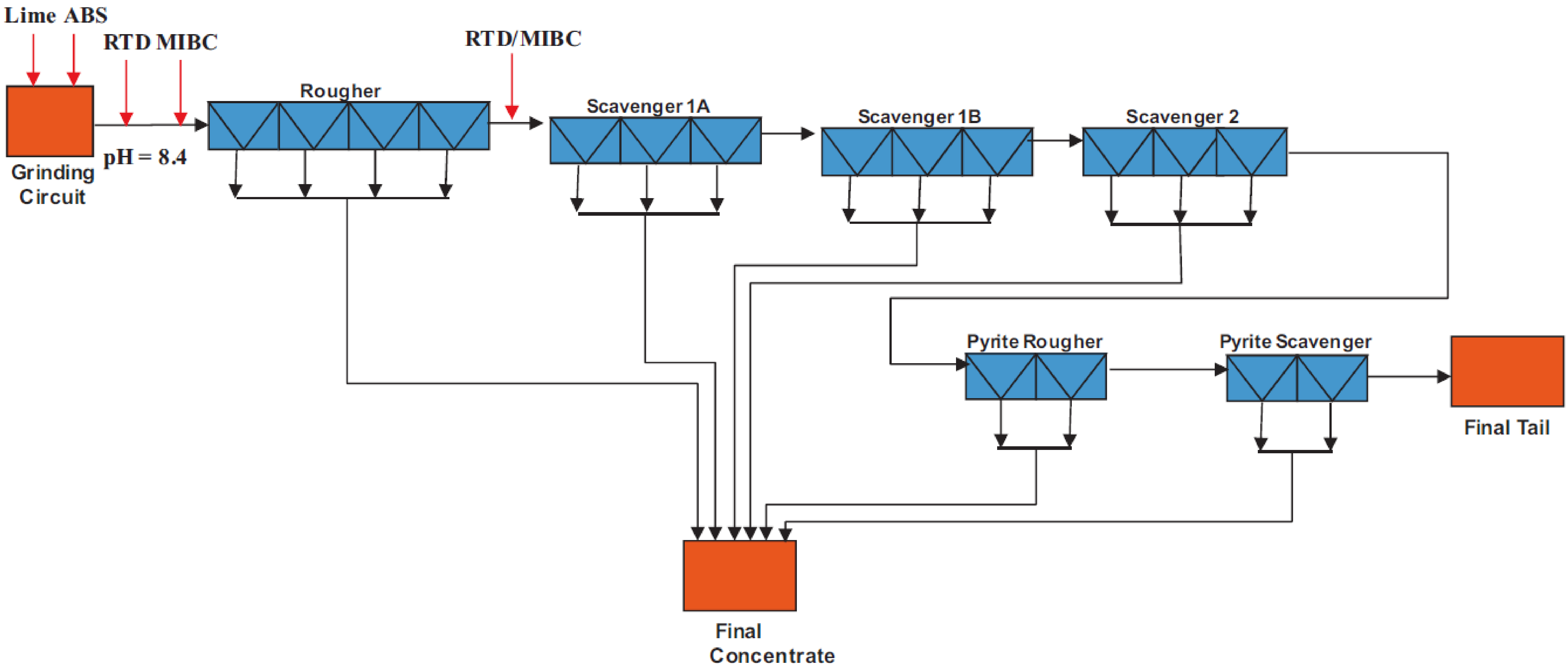



Figure 2.6 Flotation circuit at Berrick Osborn (Crosbie et al., 2009)

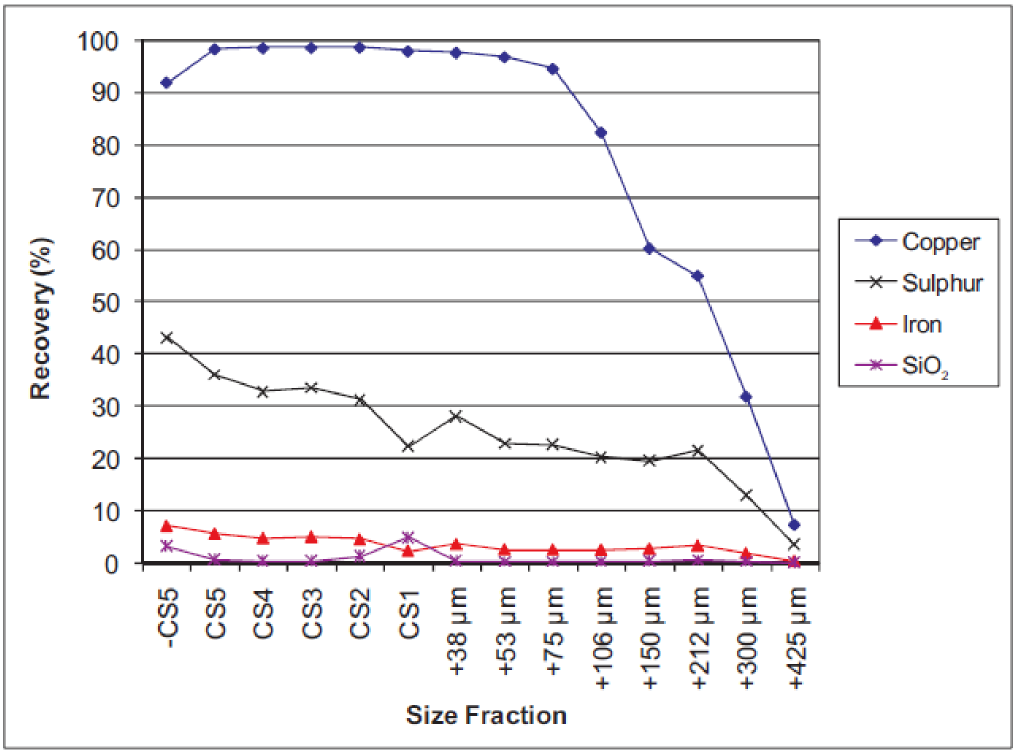



Figure 2.7 Percentage recovery with respect to particle size (Crosbie et al., 2009)

### 2.5.3 Smelting

The froth from flotation process is added to a smelting furnace to remove excess iron and sulphur. These elements form slag during smelting and converting process. During converting process, copper can react with oxygen to produce copper oxide and dissolve in slag. Therefore, slag is removed during smelting process to avoid copper loss. The output of smelting process are copper matte, slag and sulphur dioxide gas. The inputs and outputs of the process are graphically shown in Figure 2.8 (Schlesinger et al., 2011). A brief description of matte smelting process is as under (Schlesinger et al., 2011):

- Oxygen present in the system react with the particles of concentrate and flux in a furnace. It oxidizes the sulphide particles and produces large quantity of heat that melts the products. The proper mixing of feed and the particle size is important for proper oxygen contact;

- The matte passes through the slag and produces a layer under the slag. This process converts the copper oxide in the slag into copper sulphide (CuS) which decreases the copper amount in slag;
- The off-gas from furnace is removed continuously. The slag and matte are separated when the layers become thick enough.

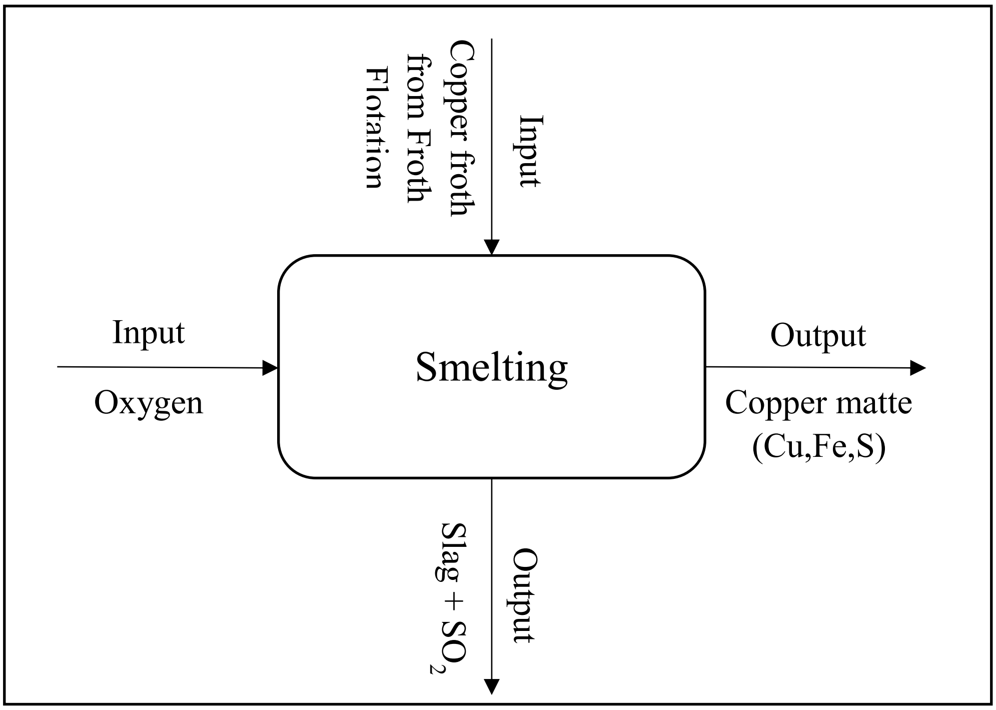



Figure 2.8 Ore flow in smelting (idea taken from Schlesinger et al., 2011)

The products of smelting consists on matte, slag and off gasses. The copper matte contains 40% to 70% copper (Coursol et al., 2012) depending upon the process. The slag formed during the process contains around 1% to 2% copper (Schlesinger et al., 2011). The loss of copper in the slag can be differentiated into mechanical losses and physio-chemical losses (Imris et al., 2000).

### 2.5.4 Converting

The matte form smelting process contains copper, iron and sulphur in the molten form. To remove iron and sulphur, the matte is oxidised in the presence of silicon-dioxide (flux). This results in the formation of copper, sulphur dioxide gas and molten slag. The reaction is given in the equation 2.1 (Schlesinger et al., 2011).

$$Cu\text{-}Fe\text{-}S + O_2 + SiO_2 \longrightarrow Cu + 2FeO.SiO_2 + SO_2$$

Equation 2.1 Copper conversion (Schlesinger et al., 2011)

The Converting process is described as below (Schlesinger et al., 2011):

- Silicon dioxide and oxygen is added in the matte. The addition of silicon dioxide converts the FeO and $Fe_2O_3$ to a molten form.
- The matte is added continuously while the slag is removed periodically. This eventually decreases the slag quantity and increases the amount of copper.
- This copper is then trapped from the furnace in the form of blister copper. The blister copper that is removed from the furnace is cooled to a solid to limit the probability of copper conversion to copper oxide.
- The sulphur dioxide gas produced in this process is captured and used to produce sulphuric acid.

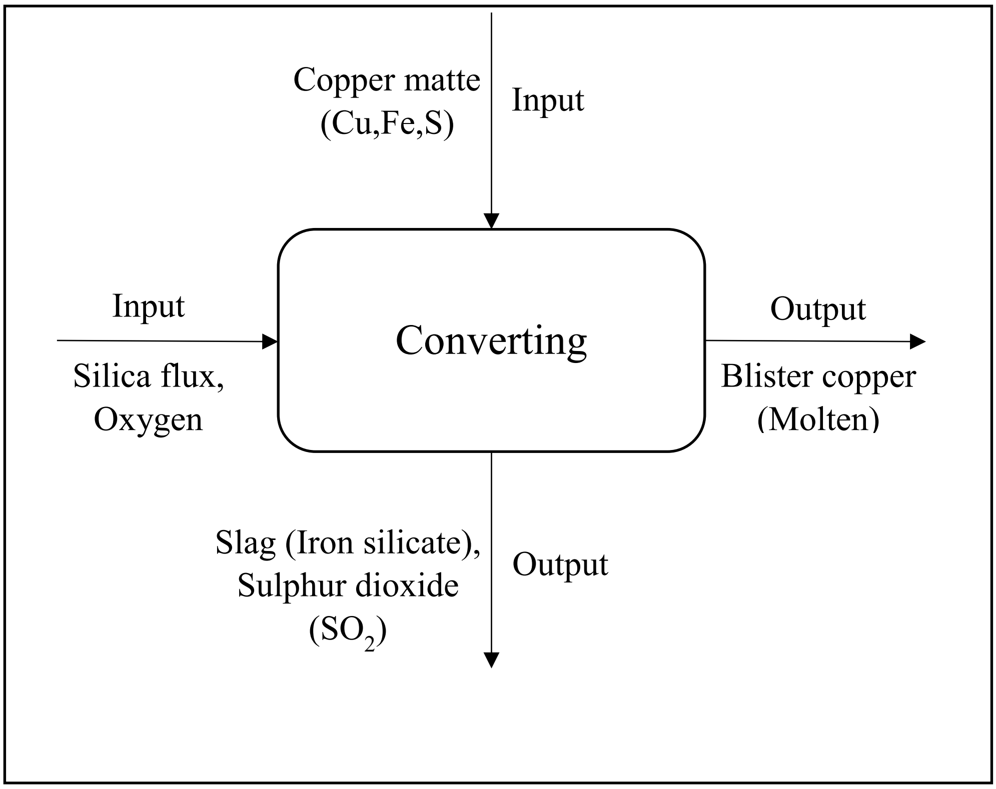



Figure 2.9 Ore flow in converting (idea taken from Schlesinger et al., 2011)

The flow of material is graphically shown in the Figure 2.9. The process of conversion is mostly carried out using Pierce-Smith furnace (Moskalyk & Alfantazi, 2003). The Pierce-Smith furnace is a long horizontal cylindrical box, lined with refractories. Following factors should be monitored for recovery optimisation of the process (Prietl et al., 2005):

- Temperature;
- Blister copper quantity;
- Quantity of sulphur, oxygen and impurity contents of blister copper;
- Slag composition; and
- Matte composition.

Prietl et al. (2005) further stated that to optimise the whole process, there is a need to get the information at specific time intervals during the process.

### 2.5.5 Fire refining

The copper produced during the conversion process contains impurities. The amount of impurities depends upon the source of copper (Jacob, 1972). The copper produced through the pyro-metallurgical process using Pierce-Smith furnace may contain impurities up to 0.02 percent of sulphur and 0.3 percent of oxygen (Schlesinger et al., 2011). The primary input of fire refining is the blister copper produced during conversion. The inputs and outputs of fire refining is shown in the Figure 2.10 (Schlesinger et al., 2011).

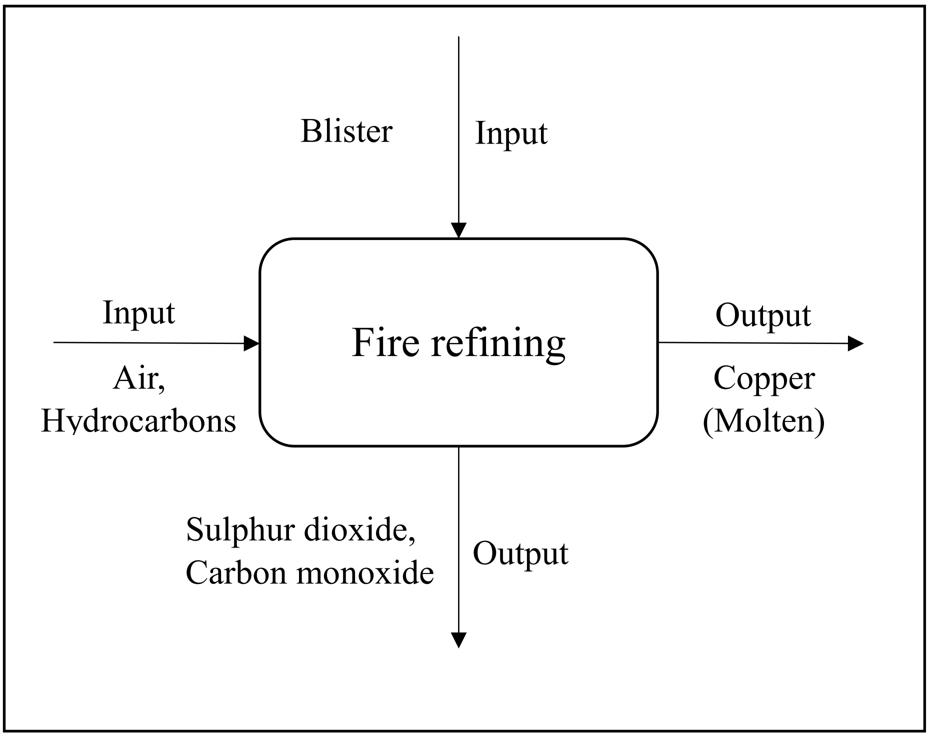



Figure 2.10 Inputs & outputs of fire refining (idea taken from Schlesinger et al., 2011)

The process of refining is carried out using a rotary furnace at 1200$^{o}$ Celsius. Air is blown in the furnace to convert sulphur into sulphur dioxide gas. For oxygen removal, a hydrocarbon such as methane, oil or propane is used (Schlesinger et al., 2011).

### 2.5.6 Anode casting

The liquid metal from fire refining furnace is poured directly to the moulds for casting. Anode casting is typically a continuous process. In this process, the empty moulds are placed on a rotating table. The liquid metal which is at around 1200° C is poured directly into the moulds (Schlesinger et al., 2011). After filling, the moulds are showered with water on both sides for cooling. The anodes are then stripped from the moulds. The physical and chemical properties of the cast anodes can affect the electro-refining process. The physical properties of the cast products depends upon the casting and the cooling conditions (Wenzl et al., 2007).

### 2.5.7 Electro-refining

The cast anodes contain impurities. To produce 99.99% pure copper, the anodes are further refined by electro-refining. The general schematic of electro-refining is shown in Figure 2.11. In this process, the copper from the cast anodes is dissolved in an aqueous solution of sulphuric acid and copper sulphate. An electric potential is applied to the system and as a result, copper ions move towards the cathode and get deposited while other elements are dissolved in the solution (Schlesinger et al., 2011). The electrolyte is then filtered and purified again. The cathodes are removed, washed and sold as final product.

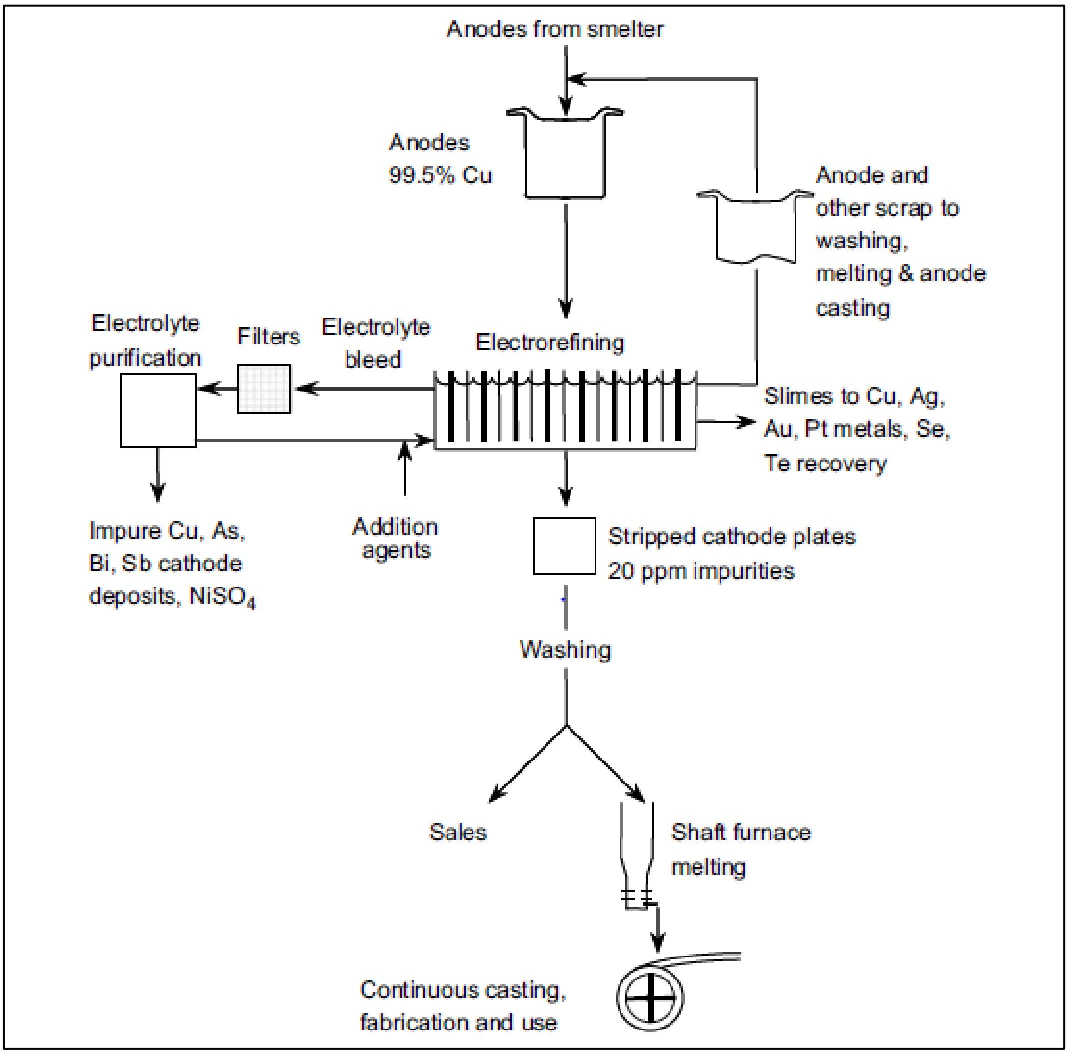



Figure 2.11 Material flow in casting (Schlesinger et al., 2011)

The process of electro-refining requires a large quantity of electrical energy as major driving force of the reaction. The amount of energy consumed during the process depends on the anode quality and the impurities in anodes (Forsén et al., 2017). During the process, impurities present in the anode either dissolve in the electrolyte or remain as anode slime. The impurities in anode can change its morphology and chemical properties during the process. These changes can affect the following during the process (Chen & Dutrizac, 1990):

- Anode passivation;
- Cathode quality;
- Electrolyte purification; and
- Recovery from anode slime.

The amount of impurities should be controlled for an efficient and pure cathode production. Such as, the presence of excess nickel and arsenic, affects the copper solubility and deposition rate (Forsén et al., 2017). It will also increase the density, viscosity, and decrease electrical conductivity of the electrolyte which in turn will increase the energy consumption of the process.

## 2.6 Importance of reliable metallurgical accounting

The process of metallurgical accounting provides the necessary information for the internal management and ~~to~~ corporate management. The metal accounting practice differs from plant to plant, depending upon the framework applied by the management of the organisation.

The process gathers information from different sources in plant and mine. This information is used as an indicator of mine and plant performance and assist in adjusting the plant parameters. Apart from the internal usage, this data is also reflected in the financial accounts of the company (Gaylard et al., 2014).

Another factor that emphasizes the need for reliable metal accounting is the introduction of treatment plants that do not operate under a single organisation. The ore from a mine is sold to multiple vendors that operate separately. Therefore, the knowledge of exact value of metal present in the ore becomes more significant. This also applies in the case of the processing plants. The ore processing is divided into different treatment plants. Such as, in case of a copper plant, the matte is produced in plant A, which is operating the mine and flotation facility. The matte is sold to plant B for further processing. The purchaser of matte needs to know the exact value of copper in the matte and the quantity of matte being transported.

It is important to have accurate data collection, reporting and analysis facilities in an organisation. This process can be improved by having a metallurgical accounting framework.

## 2.7 Metal accounting practice in Platinum industry – a case study

The metal accounting practice in platinum industry is discussed below to understand the implications of AMIRA P754 code for metal accounting. In South Africa, after 1990, the platinum production process was divided into different toll treatment plants (Gaylard et al., 2013). These plants take semi-processed ore from a parent plant and process it. A reliable analysis of the final product leaving a plant become more important. Gaylard et al (2013) analysed the current practices in the platinum industry and the potential areas of improvement are outlined with recommendations.

### 2.7.1 Sampling

The correct sampling procedure is a key for accurate and reliable results. Gaylard et al (2012) pointed out the important factors that should be considered while installing a sampler. Without considering these points, it is almost impossible to achieve unbiased samples with precision. These points are mentioned below (Gaylard et al., 2013):

- Minimum cutter gap;
- Minimum speed;
- Retention of the total sample;
- Correct installation; and
- Correct design.

Gaylard et al (2013) stated that according to his experience, the sampling practices in platinum industry are satisfactory and improving continuously.

### 2.7.2 Sample management:

The samples are collected and sent to the laboratories in "ready to analyse state" which means the samples were filtered, dried, divided and crushed to the required particle size before sending to the laboratory. The slurries were collected in open containers to avoid sample loss, but in open containers there is a chance of moisture loss as they are stored for about 8 hours (Gaylard et al., 2013). The samples are labelled using bar codes. However, some samples are transported using paper bags which have a high probability of contamination.

### 2.7.3 Sample analysis

The industrial sample analysis laboratories are properly managed and are accredited according to ISO standards. However, there are several considerations made for improvements including:

- The requirement of an internal laboratory protocol;
- Training of staff; and
- Need of a software-based information management system for the laboratory that allows easy and timely access to analysis reports.

### 2.7.4 Mass measurement

The measurement of mass in motion is susceptible to errors. Areas that requires accurate mass measurement are listed below (Gaylard et al., 2013):

- The ores transported from different mines and shafts in different areas, ore with different metrology and different transportation modes (rail, road and conveyer belts). The quantity of ore is thousands of tonnes per month;
- Concentrates in the form of slurries, filter cakes and dry powders to on-site smelters or to the toll smelting plants;
- Transportation of matte in the form of granules or lumps to in-house or third-party smelters;
- Transportation of the concentrate produced in base metal refineries to precious metal refineries in the form of cake or dry powders; and
- Final products (base and precious metals).

All the above-mentioned processes need accurate mass measurements, even if the whole process belongs to a single organisation. Accurate measurement is required for each input and output stream of the process. The accuracy of metal content calculations is dependent on these measurements. To achieve accurate mass measurements, the criteria as described by Gaylard et al (2013) must be applied. The most ignored points in relatively new plants during plant design, provisions during installation or to save cost are mentioned below (Gaylard et al., 2013):

- The location and selection of measurement streams; and
- The design, location and installation of the measuring instruments allowing easy measurements and calibration using standard techniques.

### 2.7.5 Mass measurement of ores

The correct measurement of ore quantity transferring from mine to plant is one of the most disagreed points between mine and plant workers (Gaylard et al., 2013). The reason for this is the level of uncertainty involved in the process. The transfer of the ore from the mine to the plant can use multiple sources. The ore is sometimes transferred directly from the mine using belt conveyers. If the ore is transferred to multiple plants, then trucks are used and, in this case, a 'truck factor' is used.

Sometimes, the ore is transferred to the plant from stock piles using a front-end loader. The loader put the ore on a conveyer or directly feed it to the primary crusher. The rocks moving on the conveyors have different masses and shapes. The accuracy of mass measurement increases when the rocks are crushed into small equal sized particles. Another main factor that causes problem in mass measurement is the moisture content. It has been noticed that the moisture content is often not measured with required frequency (Gaylard et al., 2013). Instead of measuring it, the old values are used that cause uncertainty in results.

### 2.7.6 Mass of tailings

The accurate measurement of tailings and slurries is very difficult due to their large volume. In very few plants the mass of tailings are measured. Typically, two product formulae is used to calculate the mass and content in slurries.

### 2.7.7 Mass of concentrate

There are two types of platinum mining operations in South Africa. The first being the ones having their own smelters and refining facilities, whereas others are the toll treatment plants. In integrated plants, the concentrate is dried and transported, or stored in the form of cakes. These cakes are measured using weighing balances or sometimes the weight balances of furnaces are used. In this case, problems can occur with the accuracy of the measuring balance and the amount of moisture in the cake, as sometimes the cake is too moist or sometimes too dry. The concentrate is also transported and stored in the form of slurry and it is measured by magnetic flowmeters. The lack of calibration of flowmeters and the effect of different ores can produce error in measurements.

#### 2.7.8 Mass measurement of matte

The matte is usually dried and converted into granules. These granules are stored in bags and weighed on platform scales. These bags are transported using trucks that are weighed twice by dispatcher as well as by receiver. The only problem that can occur is the change of moisture content because the bags are not water proof and the moisture can easily contaminate the product.

#### 2.7.9 Mass measurement of metal products

The base metals are also produced as saleable product, along with platinum during processing. The base metals include nickel, copper, cobalt and salts of these metals. The mass of base metals and the primary product (platinum) are measured with great care and under supervision. For transportation, the base metal concentrates are weighed and drummed while the salts are packed in bags. The platinum concentrate is sampled, dried, weighed and stored in the bags of 20-30 kg (Gaylard et al., 2013). It is possible that a small amount of moisture remains in the product even after drying.

#### 2.7.10 Measurement of density and moisture content

The measurement of moisture and density is one of the major causes of errors in the metal accounting systems. The effect of moisture content and density measurement become more prominent in the case of Run of Mine (ROM) ore and during stock takes. During the ore feeding to the plant, the mass of the ore is taken using a belt-weigher and the moisture content may vary from feed to feed. Sampling for moisture analysis is usually not done with required frequency. It was observed that the moisture content can change by some percentage values in small time intervals (Gaylard et al., 2013). The same problem exists in the measurement of density as in density measurement of slurries, the accurate mass should be known. If the measurement of mass is not accurate, it will affect the density calculations as well.

In conclusion, the metal accounting practices in platinum industry are in conformance with the AMIRA code. There is still a need of improvement in some areas such as sampling and sample analysis. It is evident from the case study that the protocols are effective. The mining industry should work towards its application for accurate metal accounting.

## 2.8 Conclusion

In this chapter, the typical copper ore flow in a plant and a mine is discussed in detail. The probable points of ore losses in mine are outlined. In plant, the factors affecting the efficiencies of the process are also discussed. In the end, a case study from the platinum industry is discussed to explain the metal accounting process and the causes of errors in metal accounting process. The case study points out the importance of the application of metal accounting framework in plant and mine. There is a need of in-depth study of the ore flow in copper mine and plant to analyse and reduce the potential losses arising due to inaccurate measurements, sampling, data collection and analysis.

In the next chapter, metal accounting protocols outlined in AMIRA P754 code for metal accounting will be discussed in detail along with other standards that can assist in ore flow analysis of a copper mine and plant.

# 3. STANDARDS FOR METAL ACCOUNTING

## 3.1 Overview

Chapter 2 described the general ore flow in a mine and plant. In this chapter, the AMIRA code for metal accounting and its implications will be discussed. The code structure, guidelines for data collection, analysis and reporting standards will also be elaborated.

## 3.2 AMIRA P754 code for Metal Accounting

In the mining industry, metal accounting is carried out as a general practice to cater for production and other requirements such as custody transfer. The issue with this practice is that it has not often being done to the required (high) level of confidence. The reasons for this problem are (AMIRA, 2007):

- Lack of knowledge and understanding of the principles of mass balancing and metal accounting;
- Lack of suitable measuring and sampling equipment;
- Last minute and ill-considered installation of equipment which is required for accounting purpose;
- Inadequate design of equipment;
- Poor operation and maintenance of equipment;
- Technical capacity and staff of laboratory facilities;
- Accuracy and timely reporting of results; and
- Lack of a protocols for metal accounting.

To cater for these problems, a project named "AMIRA P-754 code for metal accounting" was initiated. The idea was to develop a code of practice that can provide guidelines for reliable and accurate metal accounting. The idea was floated in the conference held in Cape Town, South Africa in 2001 (AMIRA, 2007). For the development of a code, a team was appointed under the leadership of Professor

Peter Gaylard in 2004 (AMIRA, 2007). The team was focused on the development of guidelines that will aid in conducting the activities like mass measurement, sampling, sample preparation, and sample analysis accurately.

### 3.3 Structure of code

The code provides metal accounting guidelines which includes ten guiding principles, procedures for mass balancing, sample collection, data collection, and data management systems. The code also has a provision for an exception report for the areas of non-conformance of code. A competent person is responsible for the overall metal accounting system and signing of reports. The code also provides examples to briefly describe its implications on different processes such as, base metal concentrators, pyrometallurgical operations, hydrometallurgical operations, platinum group metals, and coal mining operations. The structure of the code is shown in Figure 3.1.

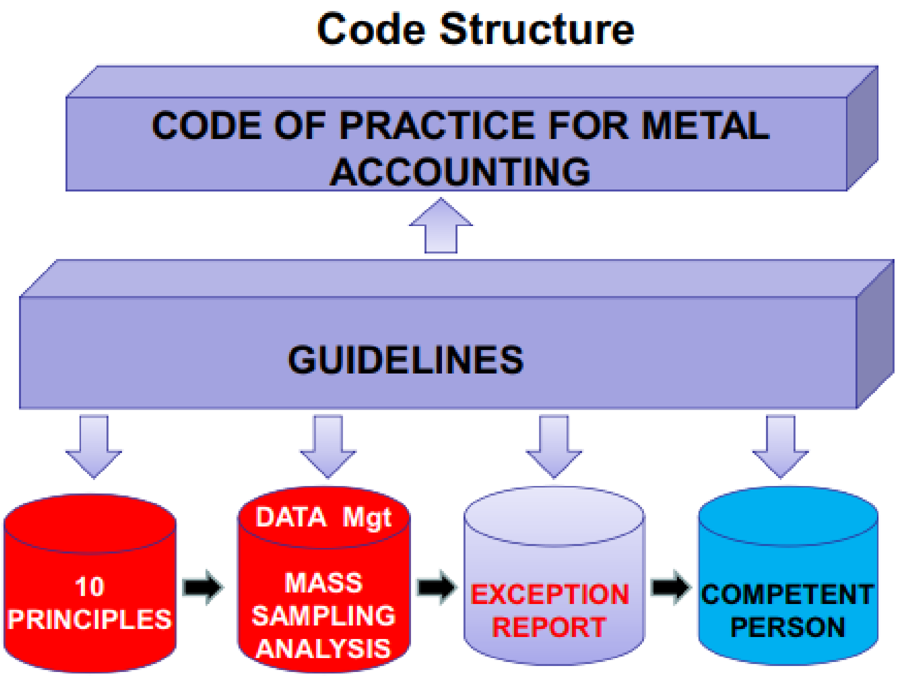



Figure 3.1 Structure of AMIRA P754 code of practice for metal accounting (Gaylard et al., 2009)

### 3.4 Structure of a metal accounting system

The metal accounting system is based on accurate and reliable data collected from the mine and plant. As stated earlier the data is collected through mass measurement, sampling and sample analysis and stock takes in plant and mine. After collection, the calculations for metal balancing and reconciliation are carried out. The analysed data is then projected in the form of reports to the plant management, stakeholders, financial and corporate management and audit committees. The competent person needs to look after the process, and if any process is unable to comply with the standards, then an exception report is prepared and signed off by the competent person. The structure of the metal accounting system is graphically shown in Figure 3.2 (Gaylard et al., 2009):

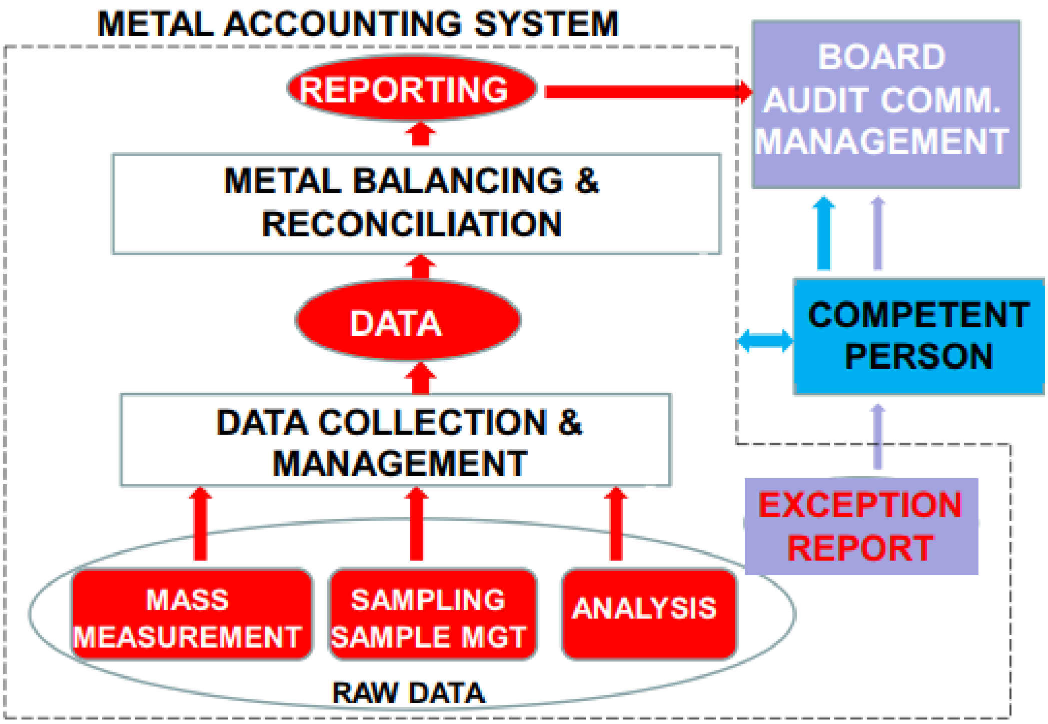



Figure 3.2 Structure of Metal Accounting System (Gaylard et al., 2009)

## 3.5 AMIRA P754 guidelines

As stated in section 3.3, AMIRA P754 outlines ten general rules that must be applied to every metal accounting system incorporated with other standards. These rules act as a guideline for a reliable metal accounting process. These guidelines are described below (AMIRA, 2007):

1. The system for metal accounting should be based on precise measurements of mass and metal content. The measurements must be based on "check-in check-out" system along with the best practices described. The system should be incorporated with an information management system with only one way of information flow.

2. The system should be clear and consistent, the source of data and information provided to the system should be transparent and understandable by the users. A risk assessment report should be produced for the metal accounting system considering risks from all aspects. The outcomes of the report should be considered in design and specification of the system.

3. The procedures for metal accounting should be properly documented. It should be easy to apply by the plant staff. The system should not be dependent on a single person and must be incorporated with clear control and audit trails. The calculations should follow the guidelines provided by the code and must be consistent with the rules of data handling.

4. The whole system should be audited internally and externally to ensure conformance with the code. The audit should be conducted according to the guidelines specified in the code. A review reports must be prepared which should indicate the risk assessments. If the risk is more than the permitted level, the report should propose the steps required to eliminate it.

5. The accounting results must be provided well in time to facilitate operational needs. The report must be able to accommodate information from other management systems such as financial management. The report of each

assessment should be prepared with management`s response to solve the related issues. The final report must be signed off by a competent person.

6. If provisional data is used in reports to meet the reporting requirements, the procedures and level of authorization for the replacement of provisional data with actual data must be outlined. If inaccurate data is identified in the report such as incorrect transfer of data, the procedure to be followed along with the level of authorization should be mentioned.

7. The system must be able to produce enough data for all necessary processes. These processes include data validation, handling of metal/commodity transfer and measurements of accuracies and error detection. The procedures for measurements and computation must be free from bias, up to a defined critical level.

8. For accounting purposes, the target accuracies of mass measurement, sampling and sample analysis must be identified for each input and output streams. The actual accuracies for metal recoveries should be mentioned in the audit report. These accuracies are calculated using statistical methods over a specific period of time. Any considerable bias which is considered substantial by company, should be reported to shareholders.

9. For in-process stock inventory, data should be verified through physical stocktakes on regular intervals or at-least annually. The level of authority and the procedures for stock adjustment and the treatment of unaccounted gain or loss should be mentioned.

10. The metal accounting system ensure the identification of any bias that can occur in the system. After identification, all efforts should be made to remove or reduce the bias to an acceptable level from every part of the system to an acceptable level.

### 3.6 Errors in measurements

Errors in measurement are classified into three types and are described below (AMIRA, 2007):

- **Human errors (mistakes)**

  These are the errors caused by human mistakes, for example, a wrong reading recorded by the operator, incorrect sample labelling etc.

- **Systematic errors**

  The measurement error due to defective measuring instruments is called systematic error. This error is difficult to identify and cannot be reduced by taking repeated measurements. It can be reduced by applying the best practices, proper calibration of equipment and by complying with the manufacturer specifications on the condition of use.

- **Random errors**

  The random errors are caused due to the change in the systematic and environmental conditions. Such as, the variance of measurement due to mechanical or electrical tolerances of the equipment or vibrations and noise in the instruments. These are the errors that remained after systematic and human errors and can be evaluated and quantified using statistical methods (AMIRA, 2007).

These errors can be minimized by using correct procedures, adequate training and the proper functioning, design, and maintenance of the equipment used for measurements (AMIRA, 2007).

### 3.7 Accuracy and Precision

#### 3.7.1 Accuracy

The accuracy means the actual “true values” obtained after a measurement. In metallurgical measurements, the true values are often unknown, which makes it difficult to differentiate between the accurate and precise value. Therefore, in the case of metallurgical operations, a measurement is correct if it is error free and within the limits of standard deviation as described in the system design (AMIRA, 2007).

### 3.7.2 Precision

For the measurements to be precise, the dispersion of the measured values around their mean value should be low. In other words, a precise measurement is repeatable. A precise measurement does not mean it is accurate. The total variance in the metal accounting process is the sum of variances taking place during different steps involved in the process. It is outlined in the equation 3.1 below (AMIRA, 2007):

$$V_{TMA} = V_M + V_S + V_{SP} + V_A \quad (3.1)$$

$V_{TMA}$ = Total variance in metal accounting

$V_M$ = Variance in mass measurement and moisture content analysis

$V_S$ = Variance due to Sampling stages

$V_{SP}$ = Variance due to sample preparation

$V_A$ = Variance due to analysis

To decrease the total variance in the whole process, variance in each step of the metal accounting process should be reduced. For this purpose, each process should be carefully designed and should be in conformance with the code.

## 3.8 Sampling

Accurate sampling is the basis of a reliable metal accounting process. It is important that the sample collected should represent the whole sampled lot or stream. In mining and processing industry, the material flow is in different forms such as slurries, slag or broken ore. It is vital that sampling should be carried out within acceptable accuracy limits. The aim of accurate sampling is to take sample in such a way that every particle in the sampling lot or stream have equal probability of being sampled (Morrison, 2008). The accuracy of the sampling process is dependent on the following factors (AMIRA, 2007):

- Accuracy of the sampling device;

- Design of the sampling device;
- Installation of sampler on the process flow;
- Analysis process applied to the sampling;
- Sampling protocol; and
- Heterogeneity of sampling material.

Common sampling practices that leads to incorrect sample collection are (Morrison, 2008):

- Sample collection from top or side of the conveyer belt;
- Sampling from top of the railway trucks or railway wagons;
- Taking samples from the side of the stockpiles; and
- Taking samples from the side of the slurry pipe.

The above mentioned practices are the cause of variance in the sampling process such as, sampling a slurry from side of the pipe. This sample will not be the actual representation of slurry because the particles in slurry segregate during motion. Taking a sample from side will not provide the actual composition. A good sampling strategy is to take full cross section from the slurry pipe.

### 3.8.1 Sampling strategies

Two types of sampling strategies are used in the mining industry. These are time-based and mass-based sampling strategies (Morrison, 2008). Morrison (2008) further explains that in a time-based sampling, the sampling stream is divided after equal intervals of time by an automated sampler. In this approach, the sample cutter is programmed to take sample after a specific time interval. In mass-based sampling, a weighing system is installed along with a variable speed sample cutter. The speed of the cutter is determined by the weight meter. The mass of the samples will remain the same for every sample taken. This system is difficult to install due to its complexity and high cost.

In a typical toll smelting copper plant, the sampling strategy is outlined in Table 3.1 (Morrison, 2008). The inputs for the plant are:

- The concentrate from the own mine;
- Purchased concentrate;

- Purchase copper; and
- Purchased mattes.

The different points for sampling are outlined in Figure 3.3. The sampling points for metallurgical accounting and plant control are separately identified. The sampling frequency and data required for metal accounting is stated in the Table 3.1 with reference to the figure (Morrison, 2008):

Table 3.1 Sampling strategy for metal accounting in Copper smelter (Morrison, 2008)

| Sample points | Sample Name | Sample Frequency | Metal Accounting |
|---|---|---|---|
| 1 | Own Mine concentrate | Each lot | Month composites for each concentrate |
| 2 | Purchased Concentrate | Each lot | Month composites for each concentrate |
| 3 | Purchased Mattes | The specified number of samples from each shipment | Composites for each shipment |
| 4 | Purchased Copper | Specified number of samples from each shipment | Composites for each shipment |
| 5 | Furnace Charge | Sample for each blend | |
| 6 | Control Matte | Each shift | |
| 7 | Blister Copper | Specified number of samples from each cast | Composite for each caste |
| 8 | Granulated Converter Slag | Each shift | Month composite |
| 9 | Slag Mill Feed Head Grade | Each shift | Month composite of shift samples |
| 10 | Slag Concentrate | Each shift and each batch shipped to the smelter | Month composite of shift samples and batch samples |
| 11 | Slag Mill Tails | Each shift | Month composite of shift samples |

| | | | |
|---|---|---|---|
| 12 | Granulated Reverberatory Slag | Each shift | Month composite of shift samples |
| 13 | Cooling Tower Dust | Daily | |
| 14 | Balloon Flue Return Dust | Monthly | |
| 15 | U-Tube Cooler Return Dust | Daily | |
| 16 | Reverberatory Baghouse Dust | Daily | Monthly composite of daily samples |
| 17 | Converter Baghouse Dust to Stockpile | Daily | Monthly composite of daily samples |

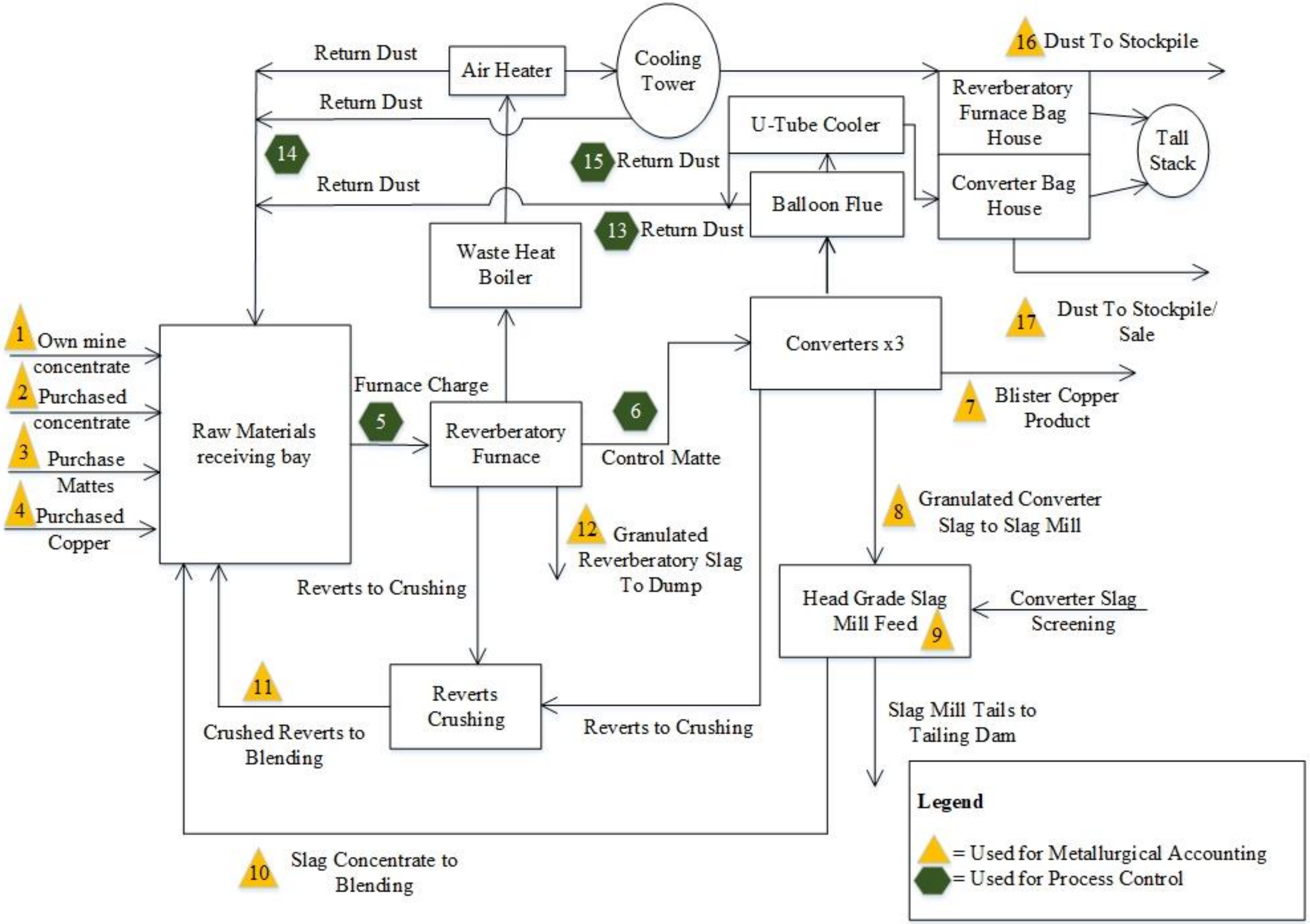



Figure 3.3 Sampling points in a toll treatment Copper Smelter (Morrison, 2008)

### 3.8.2 Errors in sampling

The error in the sampling is a sum of errors originating from different sources. The total error (TE) is stated in the equation 3.2 below (AMIRA, 2007):

$$TE = FE + GE + QE2 + QE3 + WE + DE + EE + PE \quad (3.2)$$

**Fundamental error (FE)**

The fundamental error arises due to the variation in the properties of sampling material such as the particle size, physical and chemical properties of the material (Minnitt et al., 2007). The fundamental error can be reduced by reducing particle size or by increasing the sampling mass. The fundamental sampling error cannot be removed. It can only be reduced by optimising other sampling errors.

**Grouping and segregation error (GE)**

This error is due to the distributional heterogeneity of the material. Distributional heterogeneity is defined as the difference of composition in the small groups of the same size of sampling material (Pitard, 1993). Such as, sampling of ore from conveyer belt. The heavy ore particles will move at the bottom while the lighter particles will remain at the surface. The different causes of segregation are listed below (Pitard, 1993):

- Difference in the density of particles;
- Difference in particle size;
- Air turbulence (in case of fine particles);
- Vibrations in sampling material;
- Magnetic properties of the material; and
- Moisture content.

**Weighting error (WE)**

The weighing error occurs commonly in time-based sampling process (Morrison, 2008). It can happen when there is a lag in the flow of material, or the speed of the sampling cutter is not synchronised with the material flow speed. This error can be eliminated by using a mass-based sampling process, calibrating the sample cutter or by making the material flow smoother.

**Increment extraction error (EE)**

Increment extraction error is the result of incorrect extraction of sample increment[2] from the sampling stream. (ITRC, 2012). The main reason for this error is an incorrectly designed system. This error is eliminated if the sample material for an increment is taken without any loss (Holmes, 2009).

**Increment delimitation error (DE)**

Delimitation is defined as the boundary for an extended increment[3] (Pitard, 1993). The Increment delimitation error occurs due to incorrect sampler design. It results in the loss of material during sampling. As the sampler is unable to take the correct amount of sample due to the fault of design or maintenance (Holmes, 2009). The error is rectified by the proper design of the sampling cutter system.

**Preparation error (PE)**

The preparation error is related to those operations in which there is no change of mass such as crushing, grinding, mixing, etc. In these operations, the introduction of errors like contamination, moisture loss, dust loss, incorrect labeling, etc. comes under preparation error (Morrison, 2008). These errors can be removed by implementing correct sampling practices and training.

**Long range quality fluctuation error (QE2)**

This error is due to the change in the quality of sample material with respect to time. If the quality of the extracted increments varies, then the error can increase. To reduce the error, a higher number of increments should be obtained (Morrison, 2008).

---

[2] Increment is the material collected from a lot or stream by one pass of the sampler. It is combined with another increment to form the incremental sample (ITRC, 2012).

[3] Extended increment: "The volume of the increment that does not take into account the particulate nature of the material" (Pitard, 1993).

**Periodic quality fluctuation error (QE3)**

This error occurs when the sampler take increments from a location where the composition of the material is relatively different from rest (Morrison, 2008). Such as, while sampling stockpile, if the material is taken from the sides. The error will occur because the material at the sides of the stockpile may comparatively different from inside material. Therefore, the sample will have relatively different composition.

## 3.9 Sample management and preparation

The sample management and analysis provides essential data for metallurgical accounting. The sample management is as important as the collection of the sample. As mentioned earlier, during sample collection, it is ensured that the sample is a correct representation of the whole lot and is free from any contamination. The sample management process ensures safety of sample during storage and analysis. It is assured that the sample is kept in right environmental conditions, safe from any loss or contamination. It is also important that sample is properly labeled. Improper labelling can result in loss or swipe of the samples.

Sample preparation process involve pre-defined steps. These steps may differ from mine to mine, but some steps remain the same throughout. Some of the important steps for sample preparation are stated below (AMIRA, 2007):

### 3.9.1 Moisture determination

The moisture determination of a sample should be carried out as soon as possible after collection. The sample should be kept in airtight containers to prevent the moisture loss. During drying, the temperature should not be more than 105$^{o}$ C (AMIRA, 2007). If sample division is required, it must be assured that the moisture loss is prevented during the process.

### 3.9.2 Sample reduction

During sample reduction, the external contamination and sample loss must be prevented. A properly designed sample reduction equipment should be used to reduce the sample. For this purpose, experiments should be conducted to establish the correct sample reduction process.

### 3.9.3 Sample mixing

The sampling mixing should be done in a properly designed equipment to reduce losses and contaminations. For this purpose, blenders or mixing trays should be used. Such as, Y blenders are suitable for sample mixing because the sample loss in the form of dirt is minimal in this case. If a sample is reduced in a properly designed system, the sample mixing may not be required (AMIRA, 2007).

## 3.10 Sample Analysis

Sample analysis is carried out at the on-site laboratory. It is important that the analysis is reliable, and the analysis procedures are according to the leading practices and standards. The results of the analysis are used in important decisions like custody transfers. For instance, checking quality of the final product before selling. If the laboratory results are inaccurate or biased, it will result in penalties, loss of financial value and reputation of the organisation. For this reason, the sample analysis is carried out using modern technologies. The introduction of advanced technology allows for better accuracies, precision and time saving compared to the old methods. In the past, each sample was analysed using different chemicals in the lab which were prone to bias in the results. Some of the commonly used technologies in the modern laboratories are:

- XRF (X-ray fluorescence);
- Inductively Coupled Plasma spectroscopy;
- Atomic absorption spectroscopy;
- Scanning electron microscopy etc.

A comparison of these technologies are given in the table 3.2 (Morrison, 2008):

Table 3.2 Comparison of characterisation techniques for sample analysis (Morrison ,2008)

| Instruments | Advantages | Disadvantages |
|---|---|---|
| Atomic Absorption Spectroscopy (AAS) | • Accurate preparation of standards<br>• Good sensitivity to low ppm (Parts per million)<br>• Low cost<br>• Low inter-element effects | • Relatively slow due to the sequential analysis method<br>• Curved calibrations<br>• Slower analytical perpetration of solid samples |
| Inductively Coupled Plasma Mass Spectroscopy (ICP) | • Accurate standard perpetrations in solution form<br>• Good sensitivity to precipitates<br>• Low inter-element effects and can be reduced using internal standards<br>• Multi-element simultaneous analysis<br>• Linear calibrations | • Slower analytical preparation of solid samples<br>• Capital cost is high as compared to AAS. |
| X-ray Fluorescence Spectrometry (XRF) | • Analytical range at 100ppm - 100%<br>• Fast simultaneous and sequential analysis<br>• Very high precision<br>• Linear calibration | • Assignment of accurate values to standard<br>• Mineralogical effects<br>• Very high capital cost as compared to ICP and AAS |

Most of the laboratories are now equipped with a Laboratory Management System. These systems allowed data collection, analysis, quality control and reporting to be efficient and less time-consuming.

### 3.10.1 Quality assurance in laboratory

The results of a laboratory must be credible, unbiased and reliable. Therefore, the accuracy of results and laboratory processes is very important. For quality assurance of the laboratory, there are international standards which should be followed. Such as, ISO 17025 "General requirements for the competence of testing and calibration laboratories" which outlines the management and technical requirements for a laboratory (Morrison, 2008).

Apart from compliance with the international standards, there must be some analysis techniques devised internally (in the lab) for quality assurance. These techniques are used for validation of analytical methods and results. There are well developed analytical and statistical methods for the identification of bias in the system. These methods include twin stream analysis, use of certified reference materials, Shewhart graphs and CUSUM graphs, etc. (Morrison, 2008).

## 3.11 Mass measurements

The primary objective of mass measurement is to detect the exact quantity of a material or mass flow (AMIRA, 2007). It is the first step in the metal accounting process. Each commodity in the mining operation which is measured for mass, contains some moisture in it. Therefore, the moisture content determination has a direct impact on the mass measurement. The actual mass used in the metal accounting process is the dry mass. Therefore, the knowledge of the exact moisture content is very important. The mass measurement operation is carried out for the following purposes (Morrison, 2008):

- Mass measurement for Primary metal accounting and custody transfer;
- Mass measurement for Secondary metal accounting; and
- Mass measurement for plant control only.

The Final product measurement usually receives the most attention, and the process equipment is adequately monitored and calibrated. The plant is generally fed by ROM ore. It means that the size of ore is variable, and the quantity is large. This makes it difficult and expensive to accurately measure the mass of ore feed and therefore have a lower accuracy level compared to the final product. The ore feed is weighed in hoppers, bins, conveyor belts, in the trucks or front-end loaders. These measurements are not accurate. Following are the factors affecting the accuracy of the mass measurement process (Morrison, 2008):

- The physical properties of the material (size, homogeneity, size distribution, density, composition, etc.);
- The changes in the flow rate;
- The method of measurement (equipment) used;
- Type of equipment used;
- Design and installation of equipment;
- Operating conditions;
- Calibration and maintenance of equipment; and
- Environmental factors.

A typical material flow diagram of a copper smelter is shown in Figure 3.4. The inputs consisting on the concentrate from own mine plus the material bought from third-party mines which are first stored in the raw material bay. The inputs to the plant are measured using weighbridges. The mass measurement points are illustrated in Figure 3.4. The measurements required for plant control and metal accounting are separately shown. It is important to know that the mass measurement points for plant control are not the same as for the metallurgical accounting. The methods for daily and monthly reconciliation can also differ from one another. Such as, for daily reconciliation, the number of crane grabs is counted and for a monthly reconciliation the opening/closing stocks and receipts are used. The details of data source, daily and monthly reconciliation methods for each point is described in Table 3.3.

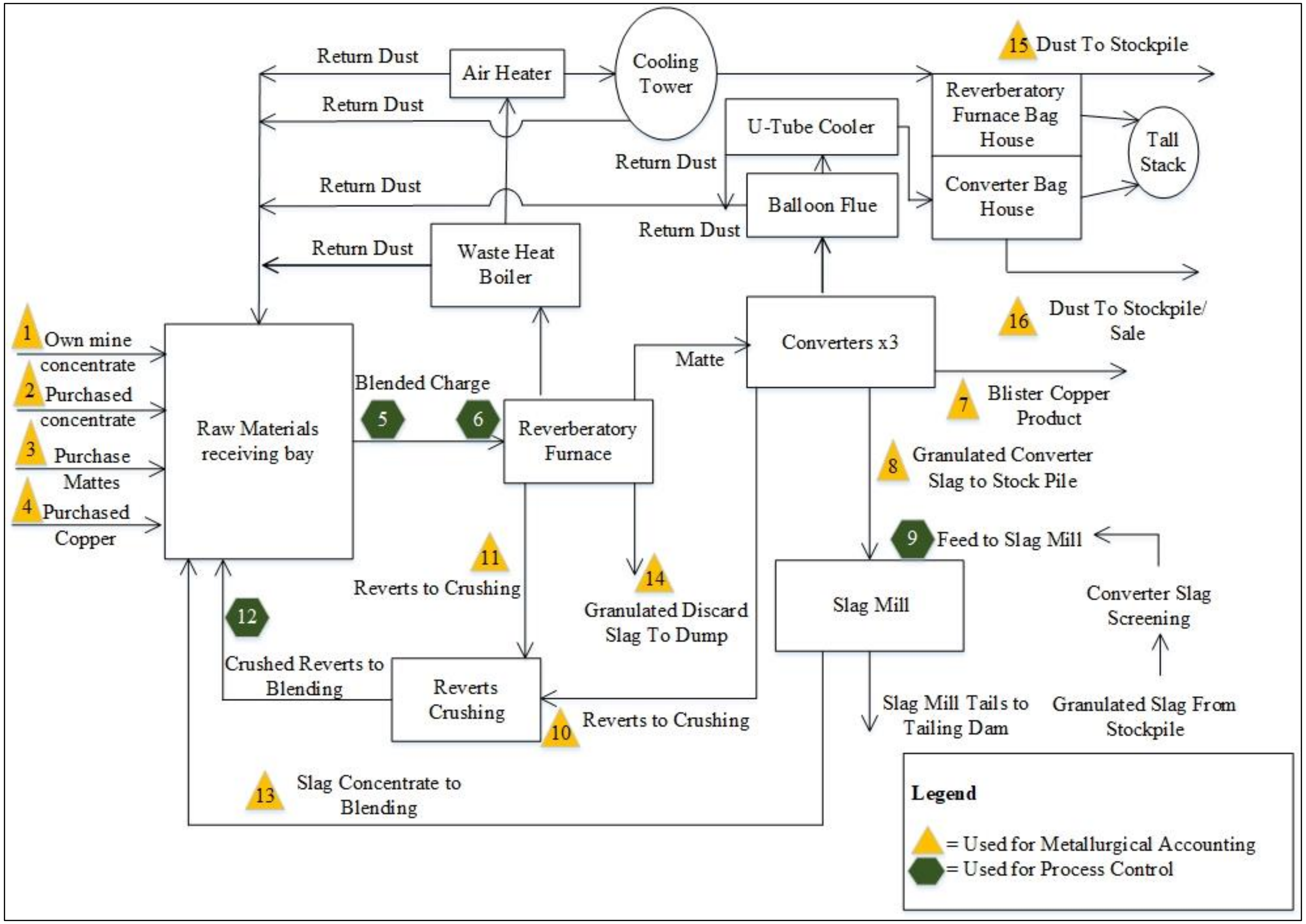



Figure 3.4 Mass measurement points in a typical Copper toll smelting plant (Morrison, 2008)

Table 3.3 Mass measurement strategy for a conventional copper smelter (Morrison, 2008)

| Figure Ref # | Weight Point name | Data Source | Daily Reconciliation | Monthly Reconciliation |
|---|---|---|---|---|
| 1 | Own Mine Concentrate | Weighbridge | Number of crane grabs at blending bay/visual stock estimation plus weight from 5 | Opening Stock, Closing Stock, and receipts |
| 2 | Purchased Concentrate | Weighbridge | Number of crane grabs at blending bay/visual stock estimation plus weight from point 5 | Opening Stock, Closing Stock, and receipts |
| 3 | Purchased Mattes | Weighbridge | Number of boat ladles/visual stocks | Opening Stock, Closing Stock, and receipts |
| 4 | Purchased Copper | Weighbridge | Number of boat ladles/visual stocks | Opening Stock, Closing Stock, and receipts |
| 5 | Blended Charge to Day Bins | Load Cells on Belt | Blend weights from crane grabs | Stock estimates from day bins |
| 6 | Furnace Charge After Day Bins | Load cells on the belt | Weights from 5/ Visual estimate of day bins | |
| 7 | Blister Copper product | Weighbridge | | Opening Stock, Closing Stock and tonnage produced |
| 8 | Granulated converter slag to stockpile | Weighbridge | Weighs from point 9 / | Opening Stock, Closing Stock and Receipts |

| | | | | |
|---|---|---|---|---|
| | | | Visual Stock estimation | |
| 9 | Feed to Slag Mill | Load Cells on Belt | Visual estimation of converter slag stock/converte r slag screening stocks | Opening & closing stocks of converter slag and screenings/receipt |
| 10 | Converters Revert to Crushing | Weighbridge | | Opening & closing stocks and Tonnage produced |
| 11 | Reverberatory Reverts to Crushing | Weighbridge | | Opening & closing stocks and Tonnage produced |
| 12 | Crushed Reverts to Blending | Load cells on belts | Stocks at blending/weig hs from point 10 & 11/ Number of crane grabs at blending bay | Opening & closing stocks and Tonnage produced |
| 13 | Slag Concentrate to Blending | Weighbridge | Daily slag mill mass balance | |
| 14 | Granulated Discard Slag | Weighbridge | | |
| 15 | Reverberatory Baghouse Dust to Stockpile | Weighbridge | | Opening & closing stocks and Tonnage produced |
| 16 | Converter Bag House Dust to Stockpile | Weighbridge | | Opening & closing stocks and Tonnage produced. |

### 3.12 Data management

In the mine and plant, the data set is big because the data is received from different sources. It is required to protect data integrity and ensure that the data is safe. The key attributes of a data management system is as under (Morrison, 2008):

- Completeness;
- Correctness;
- Control;
- Efficiency; and
- Security.

In the mining industry, several digital technologies are being developed for (big) data storage. The commonly used data management technologies are spreadsheets (e.g., Microsoft Excel) and database management systems (Oracle, SQL server, etc.). These systems are provided by different venders while some companies use custom made systems as per their requirements. The data sets (in mine and plant) gets bigger with the passage of time and becomes difficult to understand. This introduce the risk of errors. A new approach is required using big data and software for smart mining.

### 3.13 Data analysis

In metal accounting, as stated earlier, it is recommended to use "Check-in Check-out" approach for balances. It states that everything which goes into the system must be equal to what is output of the system (Morrison, 2008). This rule can ideally be applied to all the systems either for primary or secondary metal accounting system. Any deviation from it must be taken as an abnormality in the metal accounting system. For a typical mining process the standard equation for "Check-in Check-out" is as follows (Morrison, 2008):

$$\text{Outputs (Total)} = \text{Inputs (Total)} \pm \text{Inventory change} \pm \text{Stock change} \qquad (3.3)$$

The metal accounting system is not generally accurate, and there is some level of discrepancy present in it (AMIRA, 2007). It is important that the discrepancy should not be more than the allowed limit. A report should be prepared on the allowed limits of variances and its reasons. This report must be signed off by a competent person.

For metal balance, the recommended strategies are outlined in the guidelines provided by AMIRA. These strategies are described in the Table 3.4 (AMIRA, 2007):

Table 3.4 Recommended Strategies of Metal Balance for different operations (AMIRA, 2007)

| Type of Operation | Example |
|---|---|
| **Type 1:**<br>• High Grade / high-value feed<br>• Medium Flow rates<br>• High-value Product<br>• Significant plant Inventory<br>• Weigh and sample all inputs: Check-In<br>• Weigh and Sample all output: Check-out | Smelter, Metal Refinery<br>**Recommended Strategy:**<br>• Check-in /Check-out |
| **Type 2:**<br>• Low-value feed – Medium to high flow rates, often of coarse feed<br>• High-value product<br>• Low mass, High-value plant inventory<br>• Weigh and sample product | Gold Operation<br>**Recommended Strategy:**<br>• Reconstitute tailings at the measured feed rate and production |
| **Type 3:**<br>• Low-value feed<br>  ○ Medium to high flow rates<br>  ○ Sampled after the primary grind<br>• Low-value product<br>  ○ Sampled as concentrate shipments<br>• Low plant inventory<br>• Conveyer weighs scale or weigh feeder for feed mass into the plant.<br>• Accurate sampling of fine tailings, feed analysis and tailing analysis at the measured feed rate and production rates. | Base Metal Concentrator<br>**Recommended Strategy:**<br>• Mass balance<br>• Feed analysis of concentrate and tailings. |
| **Type 4:** | Coal Operation, Iron Ore |

| | |
|---|---|
| • The high tonnage of feed and products.<br>• Minor rejects. Low plant inventory.<br>• Detailed product specifications<br>• International standards for sampling and characterisation.<br>• Custody transfer mass will often be a draught survey or a train loadout weight. | **Recommended Strategy:**<br>• To Weight and sample feed & product streams |
| • Type 5:<br>• High value, Low tonnage feed<br>• High-value products.<br>• Minor reject streams. Significant plant inventory<br>• Weigh & sample all inputs: Check-in<br>• Weigh & sample all outputs: Check out | Precious metal refineries<br>**Recommended strategy:**<br>• Check-in Check-out |
| **Type 6:**<br>• Low value, High tonnage feed.<br>• Minor rejects based on particle size and density.<br>• Minimal plant inventory | Aggregates<br>**Recommended Strategy:**<br>• Weight feed and product streams |
| **Type 7:**<br>• Low-grade high tonnage feed.<br>• Residue remains in situ in some cases<br>• Very high, difficult to measure process inventory.<br>• Non-steady state, two-phase slow reaction kinetics | Heap Leaching<br>**Recommended strategy:**<br>• Weight sample and analyse feed stream and products.<br>• Accurate solution balance should be done.<br>• Periodic check of heap solution inventories and heap residual metal content. |
| **Type 8:**<br>• Medium to a low value and high tonnage feed.<br>• Low process inventory.<br>• Requires mineralogical analysis.<br>• Products are in bulk, bags or containers. | Industrial Minerals<br>• May be treated as a commodity<br>• May be produced as different grades<br>**Recommended Strategy:**<br>• Weigh feed and product streams |

### 3.13.1 Recovery

For metal balancing purposes, the recovery is divided into actual recovery and built-up recovery. The actual recovery is the ratio of the sum of all outputs over the sum of all inputs. It is usually expressed as a percentage. The actual recovery is based on "Check-in Check-out basis." The formulae for actual recovery is stated below (AMIRA, 2007):

$$\text{Actual recovery \%} = \frac{\text{Sum of all outputs}}{\text{Sum of all inputs}} \times (100) \tag{3.4}$$

The built-up recovery is the ratio of the sum of all useful outputs over the sum of all outputs expressed in percentage. The formulae for built-up recovery is stated below (AMIRA, 2007):

$$\text{Built- up recovery \%} = \frac{\text{Sum of all useful outputs}}{\text{Sum of all outputs}} \times (100) \tag{3.5}$$

The theoretical recovery is sometimes used in the metal processing industry and is defined as the difference between metal input and metal losses over total metal input, stated in percentage. The equation for Theoretical recovery is as under (AMIRA, 2007):

$$\text{Theoretical recovery \%} = \frac{\text{Metal Input - Metal loss}}{\text{Metal Inputs}} \times (100) \tag{3.6}$$

### 3.13.2 Accountability

For the measure of accountability two formulas are provided in the AMIRA code of practice. It is defined as "The comparison of the total output of a plant, or a part of the plant to its total input expressed in percentage" (AMIRA, 2007). For the calculation of accountability, following expressions are devised (AMIRA, 2007):

$$\text{Accountability \%} = \frac{\text{Sum of all outputs + Stock \& inventory change}}{\text{Sum of all Inputs}} \times (100) \tag{3.7}$$

The formulae mentioned above are recommended by the code of practice for metal accounting purposes for a specific time period as it does not include the dormant process stocks. There is another criterion that includes those factors and is as follows (AMIRA, 2007):

$$\text{Accountability \%} = \frac{\text{Sum of all outputs} + \text{closing stock}}{\text{Sum of all Inputs} + \text{opening stock}} \times (100) \qquad (3.8)$$

During the metal accounting process, it is important that the equation used for recovery and accountability should remain the same throughout. Hence, it is of prime importance that the system should be properly designed. It is recommended that the strategies outlined in the Table 3.4 should be used during the system design.

### 3.13.3 Two product formulae

The Two product formulae is a very useful method to calculate different components of a process streams. It is a common practice to analyse the input and output streams of a process. The mass of tailings or rejects is usually not measured. Such as, in a typical flotation circuit the feed and product streams are measured and assayed. The tailings are usually not measured. In this case, the two product formulae can be used to calculate the mass and assay of tailings. For a single product Flotation process, the two product formulae is written as (Morrison, 2008):

$$\text{Feed} = \text{Product} + \text{Tailings} \qquad (3.9)$$

The two product formulae is applicable if the ''Check-in Check-out" method is justified by the process. If feed is denoted by 'F', product by 'P' and tailings by 'T' and the % grades (assays) of a particular metal in feed, product and tailings is represented by 'f', 'p' and 't'. The two product formulae will be (Morrison, 2008):

$$F \times f = P \times p + T \times t \qquad (3.10)$$

Equation 3.10 can be used to find out the mass or % grade of the unknown variable. If all the components of the equation are known by measuring the streams, the two product formulae can be used to find any bias in the measurement. This can be done by comparing the measured and theoretical (calculated) results.

## 3.14 Reporting

Reporting is an important part of the metal accounting system. It is important that the reports are timely produced and are accessible to the relevant people, such as people responsible for the plant control, auditing and higher management. It is important that the data in reports is reliable and free from errors. For this purpose, a data management system should be used in which the data is not editable without the permission of an authorized person.

As stated earlier, it is essential that the final report should be signed off by a competent person and subsequently by higher authorities if necessary. The reporting structure of a typical metal accounting report is shown in Figure 3.4 (Morrison, 2008). The reporting time is on the X-axis, while the Y-axis represents the management level. Each level must report to its higher level. The arrowheads represent the data flow from one report to another. For example, the daily production report is prepared by the mine/plant management, who reports to the operation management. The data from daily production reports is added to the monthly metal accounting report. A quarterly report is made for the finance department, senior management, audit committee and board of directors. Similarly, the annual metal accounting report takes input from monthly, quarterly and six-monthly report.

The reports of metal accounting can have the following target audience (Morrison, 2008):

- Plant operators, managers, and supervisors;
- Operational management;
- Audit committee;
- Senior management;
- Finance department;
- Marketing department;
- Financial auditors; and
- Board of directors.

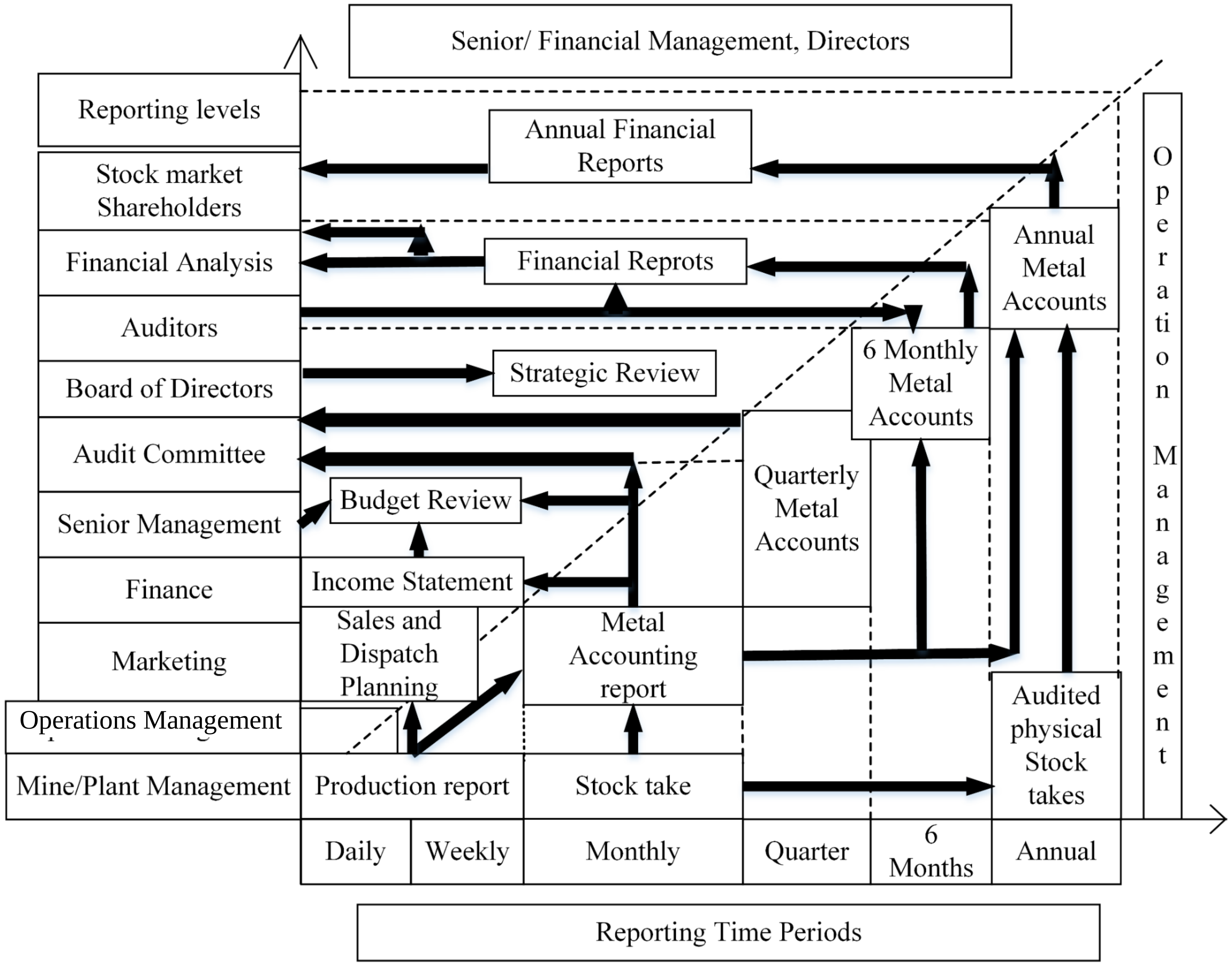



Figure 3.5 Structure of Metal Accounting Report (Morrison, 2008)

The above-mentioned departments will have different data requirements to be included in the report. Such as, for plant operators and managers, the daily and monthly production data is important. The marketing department needs the weekly or bi-monthly production details and the grade of final product. For a report to be reliable and free from errors the following points should be considered (AMIRA, 2007):

- The reports should be prepared by an adequately trained competent person. The person should understand all the technical inputs of the report and data to be included in the report;
- The data to be used in the report should have minimum manual data inputs. For this purpose, the use of a computerised system is recommended;
- The data should be within the error limits, and these limits should be acquired using recommended data analysis techniques;
- The data in the report should be traceable back to the source;
- The reports should be available to all, who requires the report data. An access control should be applied for editing to ensure data integrity;
- The data in the report should not be editable. If editing is required, it should only be done by the permission of the competent authority;
- The report format should be simple and adaptable in case of changes in the plant processes;
- The report should have a procedure for the reconciliation of mass balance so that the errors can be identified, and rectification could be carried out if necessary;
- The report should be signed off by the metal accounting committee or any other authority before the approval of the audit committee;
- The report should comply with the international standards of auditing;
- The key performance indicators should be mentioned in the report along with the targets; and
- The report should have previous production information as well, so that the trends can be analysed for future.

## 3.15 Role of competent person

A competent person is an experienced person who is responsible for the metal accounting system. This responsible person is the one assisting in solving any issues that may arise in the process. A competent person is responsible for the following (AMIRA, 2007):

- Final approval of metal accounting system design;
- After the installation of the system, the person is responsible for the audit of the system to make sure that the system follows the code and design specifications;
- The person is responsible for the periodic audits of the system during operations to ensure the compliance of the system with standards. The person should point out the problems and provide assistance in solving them; and
- The person is responsible for the submission of reports according to the standards and should also point out the issues in the system.

It is essential that the competent person is accredited with the local or international body responsible for the metal accounting systems (AMIRA, 2007). In case of any issues, the company should contact the accreditation body with which the person is accredited.

## 3.16 Reconciliation and fault finding

The process of reconciliation is the comparison of the production estimates. The data from different sources such as mine, milling, smelting etc. are compared with the inputs and outputs overtime. The process of reconciliation as described in AMIRA code for metal accounting is (AMIRA, 2007):

“A metallurgical balance which relates with the production of saleable and rejects or waste materials from a process back to its source as ore or other feed material. It should be provided with the defined and stated errors as for any other metallurgical balance."

The reconciliation process is a part of the overall metal accounting system, as the process of reconciliation needs a track for every input back to the source. Therefore, it is important that the inputs should be properly tracked. In an environment where mine is operating its concentrator, the mine to mill reconciliation become more significant. A typical reconciliation cycle for mine is shown in Figure 3.6 (AMIRA, 2007). The arrows in the figure indicate the reconciliation path for each process. Such as, the process plant measurements should be compared with the grade control production estimates. In the same way, the mined ore should be compared with the grade control production estimate.

If there is a difference between the production and the reconciled values. The reason for the difference is important to be find out and rectified. If more than one variable is responsible for the bias, the variable affecting the most should be rectified first.

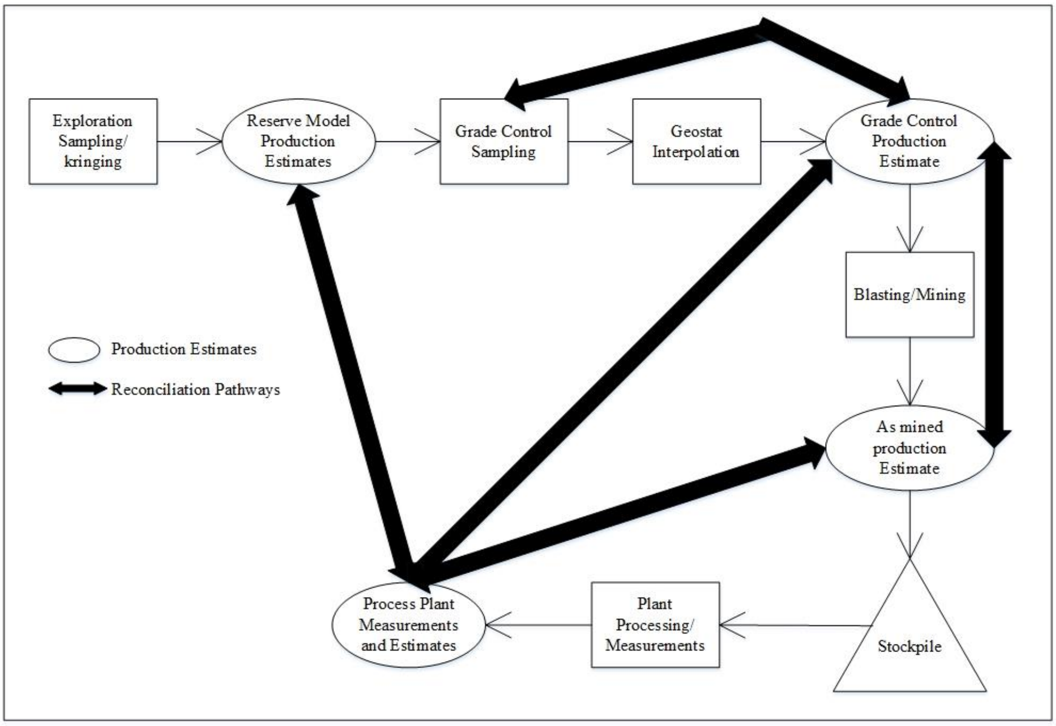



Figure 3.6 Typical Reconciliation Path (Morrison, 2008)

### 3.17 Conclusion

The chapter discussed the AMIRA code of practice for metal accounting in detail. Use cases were discussed to elaborate different metal accounting activities for the in-depth understanding of the process. The process of data collection, analysis, reporting and the typical issues affecting the metal accounting process are also discussed.

In Chapter 4 a case study of copper concentrator will be discussed in detail to understand the ore flow analysis methods.

# 4 TOWARDS A TECHNOLOGY FRAMEWORK FOR ORE FLOW OPTIMISATION

## 4.1 Overview

Chapter 3 provided an overview of the AMIRA P754 code of metal accounting and its implications in a plant. Chapter 4 provides an overview of the current digital metal accounting tools. It will also discuss a hypothetical case study of a copper mine and plant. This case study will then be used to propose an architecture of a technology framework that will help in evaluating and optimising copper metal flow process in a mine and plant.

## 4.2 Metal accounting tools

In the 21$^{st}$ century, a number of digital technologies has been developed. They are able to provide digital analytical solutions for mining and metallurgical problems. The mines and plants are using digital tools for production and plant control. Systems like SCADA and DCS provide control interfaces for plants. These systems allow the plant technical staff to monitor the working of plant equipment and processes from a control room. They are also capable of providing an estimate of production from each process by monitoring the pumps, weighbridges, and flow meters. For metal accounting purposes in a mine and plant, there are available tools which can provide assistance to plant and mine personnel. The problem with these systems are that they only provide solutions for either mine or plant. Some of the tools are discussed below:

### 4.2.1 MPPI Global

MPPI global provides software named “Optimum” (MPPI Global, 2018). The software can do multiple plant and mine based analyses. It also provides a metallurgical accounting tool for plants. The data from different measurement points is entered into the software manually or through plant historian[4]. The software is also capable of taking data from laboratory management systems (LIMS). The data is then analysed against the limits provided to the software. The

[4] A plant historian is a software that takes data from different plant equipment and save it into the data base

software provides the following built-in functionalities to assist metal accounting (MPPI Global, 2018):

- Integrated mass balance;
- Identification of source of variance in measurement;
- Reconciliation of production data; and
- Produce production details for monthly metal accounting reports.

Three modules named as Analytics, Reports and Data portal provide analysis, reporting and data entry features. The production statistics can be visualized on a dashboard in the form of charts, graphs and tables. A typical view of OPTIMUM dashboard is shown in the Figure 4.1 (MPPI Global, 2018)

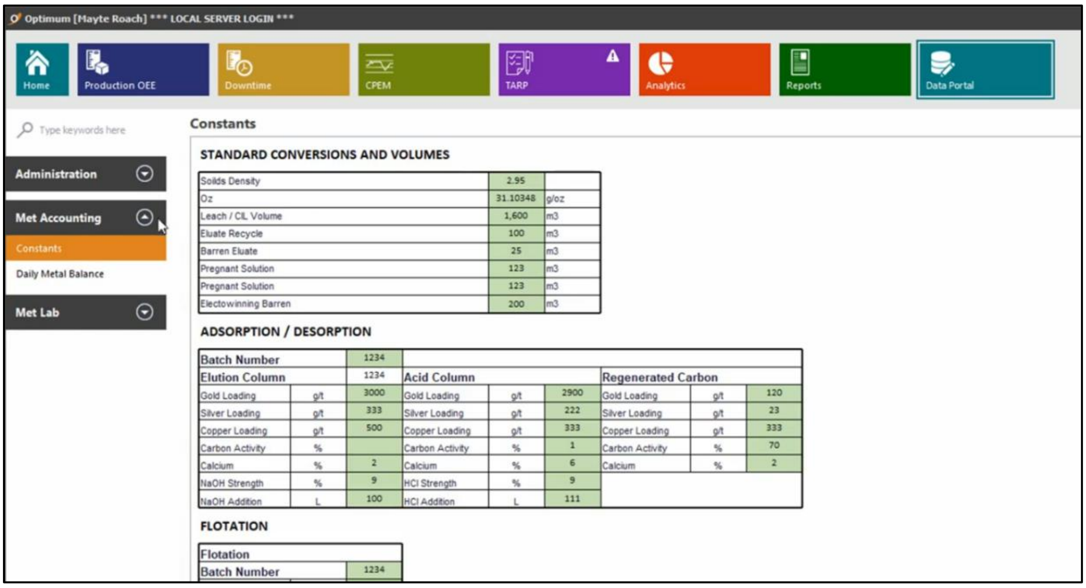



Figure 4.1 OPTIMUM DASHBOARD (MPPI Global, 2018)

### 4.2.2 Metallurgical Intelligence®

Metallurgical intelligence® is a software for plant metallurgical accounting and laboratory management provided by Metallurgical Systems. The software is incorporated with LIMS to manage the plant laboratory and take data input from it as well. The data from plant processes is stored in the software manually or taken by software from a plant historian. The tool allows the plant staff to add parameters for data analysis. These parameters are then used by the software to analyse the data. The results of the analysis is then presented in the form of charts, graphs and tables. For this purpose, a third-party tool is used. The tool also provide security features like passwords to limit the access to data. Only the responsible person can enter or edit data in the software. Reports can also be generated automatically in the format provided to the software. The software is designed to comply with the AMIRA P754 code of metal accounting (Metallurgical Systems , 2018).

### 4.3 Case study overview

A typical process flow of a copper mine and plant is shown in Figure 4.2. The plant is producing Copper anodes by refining ore through a pyro-metallurgical process. The series of pyro-metallurgical process steps are discussed in Chapter 2. For metal accounting purposes, the smelting and conversion process are considered as one single step. The ore flow, sampling points and analysis method is discussed below:

- **Mining**

The copper ore is extracted from an underground mine. The mining face is sampled for the ore grade and waste measurements before mining. The sampling provides an estimate of the ore grade and waste mined. The ore from 4 underground mine faces are fed to the 2 crushers. The ore from face 1 & 2 is fed to crusher 1 and ore from face 3 & 4 is fed to crusher 2. These crushers reduces the size of the ore to facilitate the ore handling and movement on conveyer belts. These crushers have dedicated conveyer belts which feed the main conveyer to the surface. The total ore mined is physically measured by a belt-weigher mounted on the conveyer belts which feed the primary conveyer belt and the ore is analysed by an on-belt x-ray analyser on each conveyer. A sampler is also installed to collect samples for laboratory analysis. This analysis provide a cross check for the on-belt x-ray analyser. In case of any discrepancy, the respective area should be investigated. The face sampling also provides a reference for the ore grade measurements. In the mine, generally the survey measurements are taken once or twice a month. These measurements provide a cross check for the tonnage delivered to the stockpile from the mine.

- **Stockpile**

The ore delivered to the stockpile is generally measured by stockpile sampling and surveying. The opening stock, closing stock and ore delivered to the plant provides the measurements for the stockpile inventory. The ore is delivered using trucks to the plant. The number of trucks and truck factors is also used to provide an estimate of the ore delivered to the plant.

- **Milling**

The ore transferred to the plant is measured using on-belt mass measurements, an online x-ray analyser for grade estimation and an automated sampler is used for the sample collection for ore analysis. The measurement points are shown in the Figure 4.2. The mill is fed from the mill stockpile using conveyer belt.

- **Froth flotation**

The milled ore is dried and stored in the raw material shed in the plant. The feed for froth flotation is measured by an on-belt mass measurement scale and sampled by automated sampler before entering into the flotation cell.

The rougher concentrate stream has a digital density meter, magnetic flow meter and a cross cut sampler to collect samples for metal accounting. The product of rougher is transferred to the oxide cleaner which then produce the final floatation concentrate. The final concentrate is then dried and transferred to the smelting process. The dried concentrate is sampled and weighed before transfer. The final tailings (from scavenger and cleaner) has a multistage sample collector and an on-stream analyser.

- **Smelting**

The concentrate received from the flotation process is in a dried form. The samples are taken from each lot and the mass is measured. The dried concentrate is transported using rail cars. In this case, the mass of each car is measured, and the total number of rail cars are calculated. For metal accounting, the composite sample for each metal accounting period is used. For the opening and closing stocks, the receipts of the concentrates should be used. For daily measurement of feed grade, the opening stock grade and the receipt for the day provides an average grade.

The reverberatory furnace slag is skimmed manually. For measurement of the slag produced, the mass of each ladle transferring the slag is taken. The slag is sampled manually using a spoon.

The converter slag is grounded, weighed and sampled before it is added back to the reverberatory furnace. The slag is weighed on a belt-weigher and sampled using an automated cross-belt sampler. The matte is sampled manually and weighed on a weighbridge. The matte is then transferred to the anode furnace using an overhead crane for fire refining and casting.

- **Anode casting**

The anode furnace is used to remove the final traces of iron and sulphur form the matte. The melted copper is then poured directly into the moulds. The anodes have relatively fine composition and physical structure. The mass of the anodes is measured using a mass balance and are sampled for laboratory analysis from each batch.

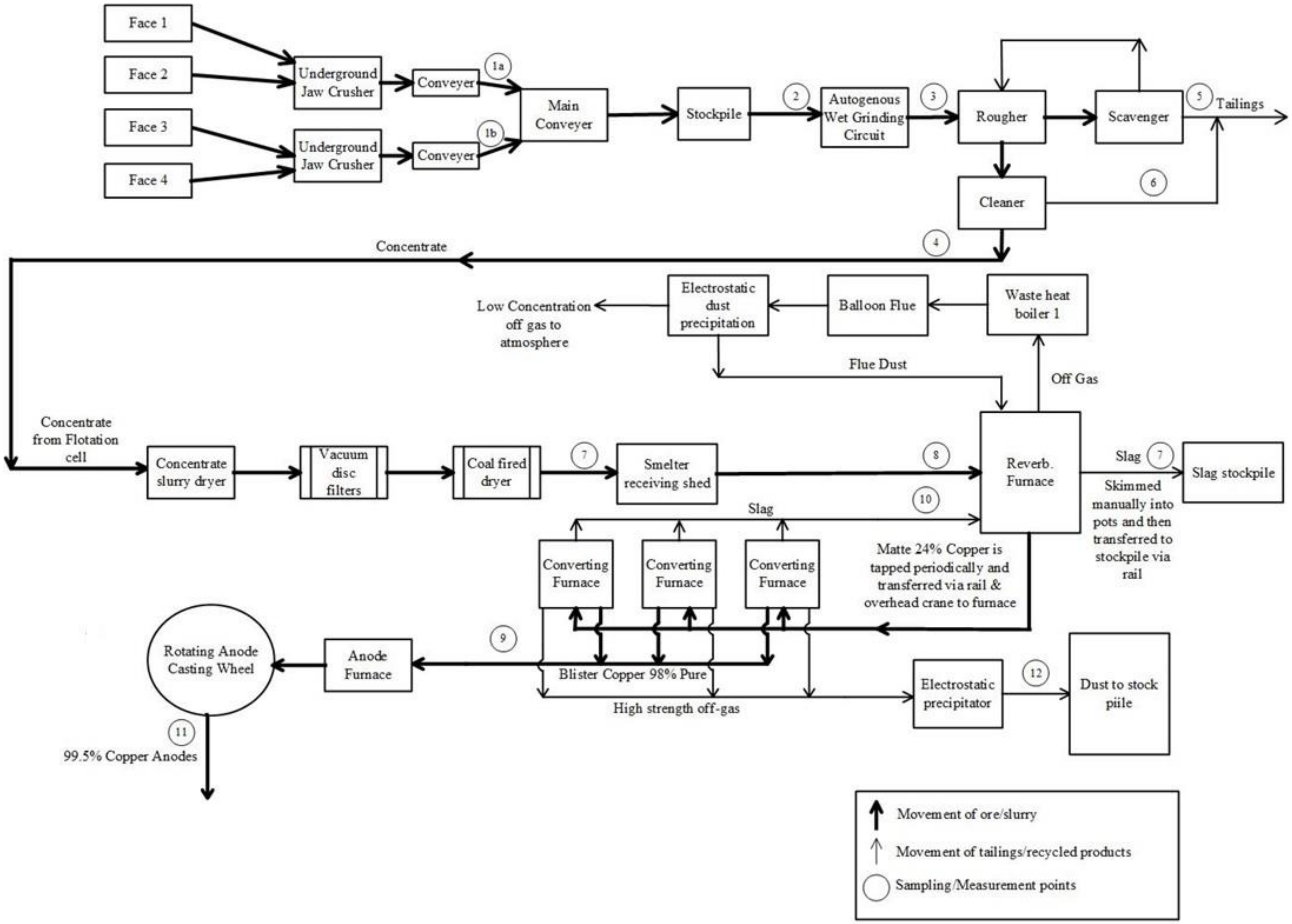



Figure 4.2 Ore flow of Copper mine and plant (Source: Author)

## 4.4 Conceptualisation of the framework

The digital tools available in the market are able to provide the metal balance solutions for the mine or plant separately. The ore flow from the mine to the final product in the plant is evaluated separately. The up-stream processes are provided by limited information about the previous processes. For example, the smelting process receives data in the form of a report from froth flotation. The mining data is unavailable to the smelter before a certain amount of time. If the data is available, the smelting plant can adjust the production variables before the concentrate arrives to the smelting plant. Moreover, it will also assist in the mine and plant reconciliation process. For this purpose, there is a need of a digital tool that can analyse the ore flow from the mine till the final product in the plant**.**

### 4.4.1 Architecture

In the current operational scenarios, the metal accounting processes of a mine and plant are done separately. There is a limited flow of information between the two processes. The data from the mine, concentrator and smelter is collected, stored and analysed individually. The reports are prepared based on the analysed data and selected information is shared only with the succeeding processing plant. The decision-making process is also done in silos as the detailed data is unavailable or not available timeously. This not only results in production losses but also limits the opportunity for the improvement in the overall process.

The current and proposed process of ore flow in the mine and plant is shown in the Figure 4.3. In the current process, the data analysis is done in the mine and plant separately in their own domains. In the proposed process, all the data form the mine and plant flow in a central server for storage and analysis. Some of the mines and plants have individual servers, therefore, these servers can then be connected to the main server and data flow should be redesigned accordingly. The main aim is to gather the information into a single database. The gathered data is then analysed, and reports are prepared which can be visualized on computer dashboards or physically. This data is then used for the decision-making process.

This approach will increase the transparency, help in auditing and reconciliation processes. As most of the data will be taken automatically, the trail of data collection will be stored in the system. The proposed system is named as WMI-OFA (Wits Mining Institute - Ore Flow Analyser). The proposed architecture of WMI - OFA is shown in the Figure 4.4 and Figure 4.5. The main data sources are mine, stockpile, concentrator and smelter. As mentioned earlier, the data gathered from the measurement points and sample analysis is stored in the server. The data is analysed against the provided limits for bias, variance calculations and data adjustments. The calculations for financial reports can also be done using the financial data. The analysed data can be seen on the dashboard in real-time and reports can be generated. The analysed data is also monitored by mine and plant technical staff for decisions making processes.

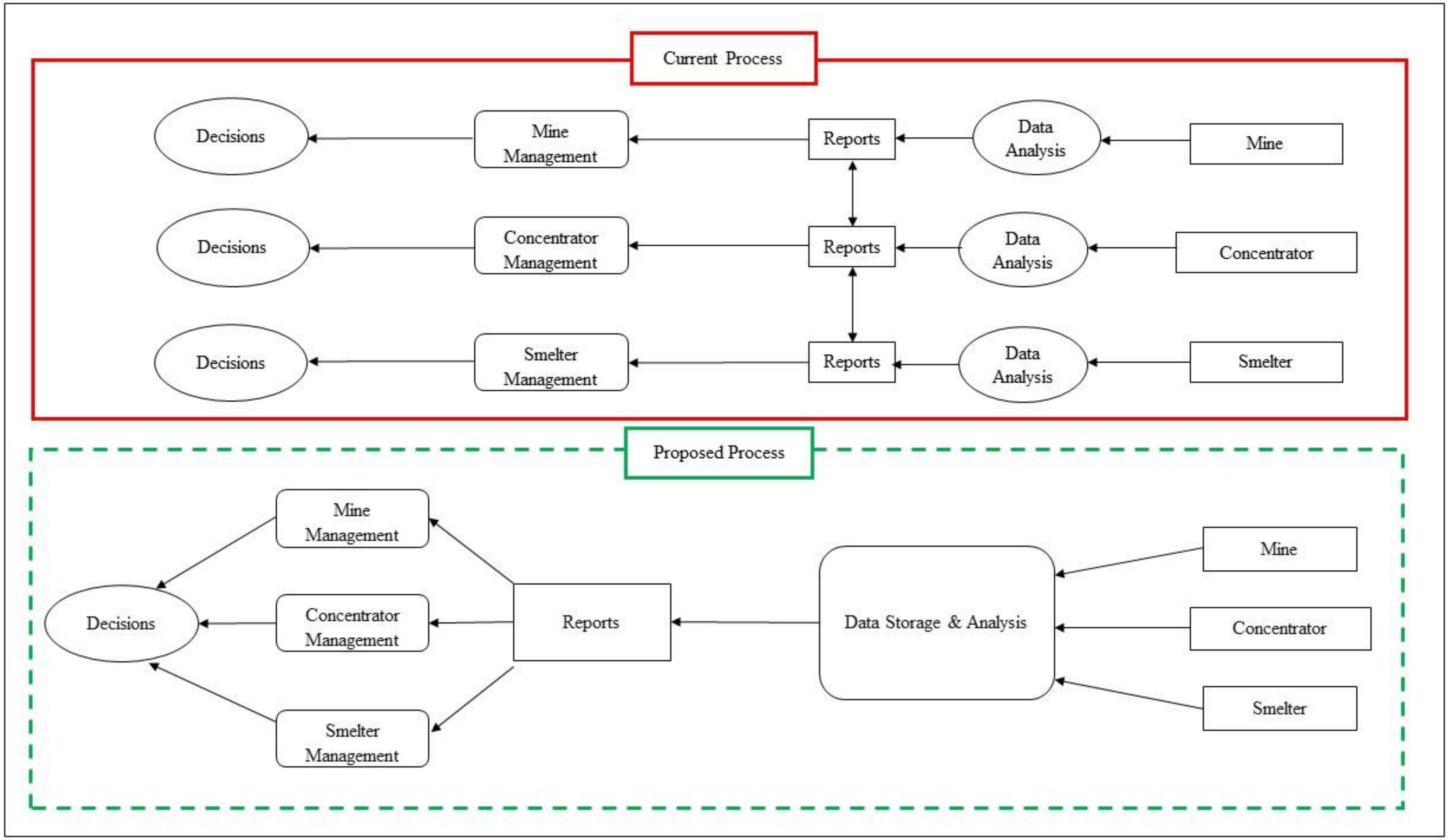



Figure 4.3 Current and proposed method of data collection and analysis in mine and plant (Source: Author)

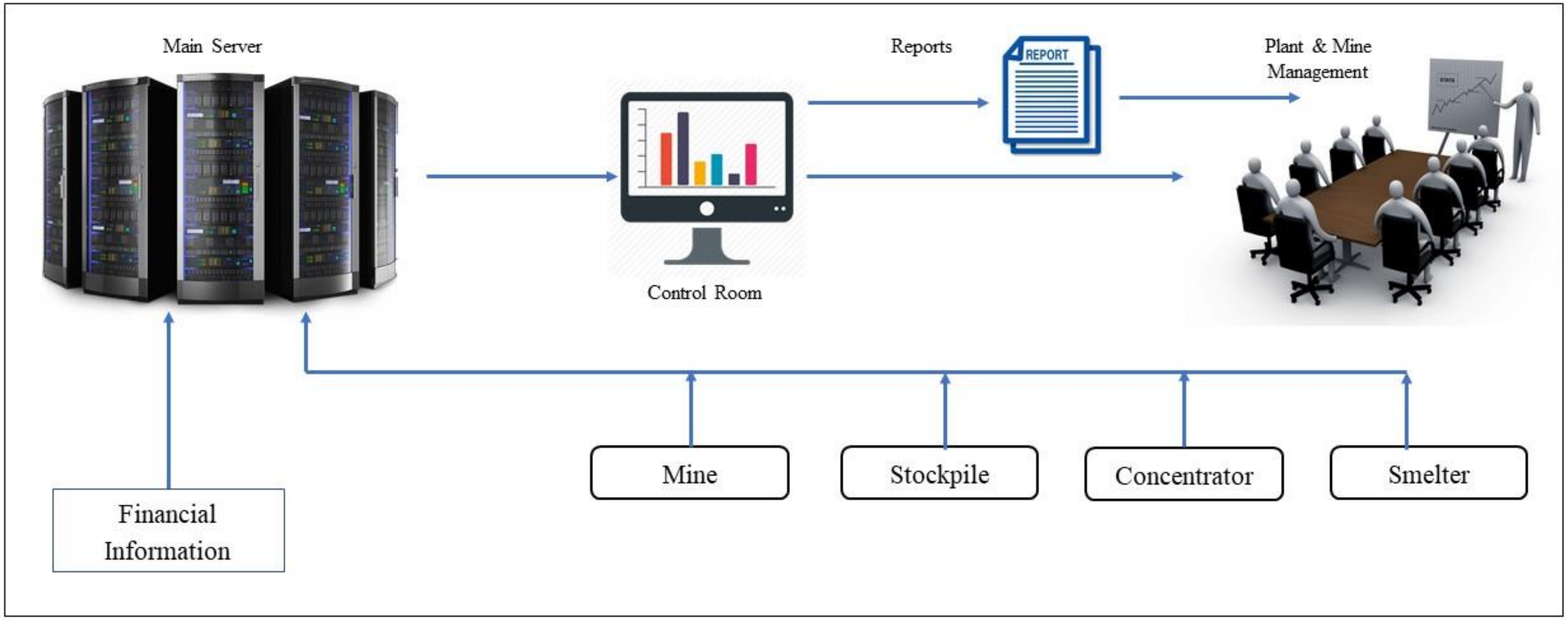



Figure 4.4 Proposed architecture of digital tool WMI-OFA (Source: Author)

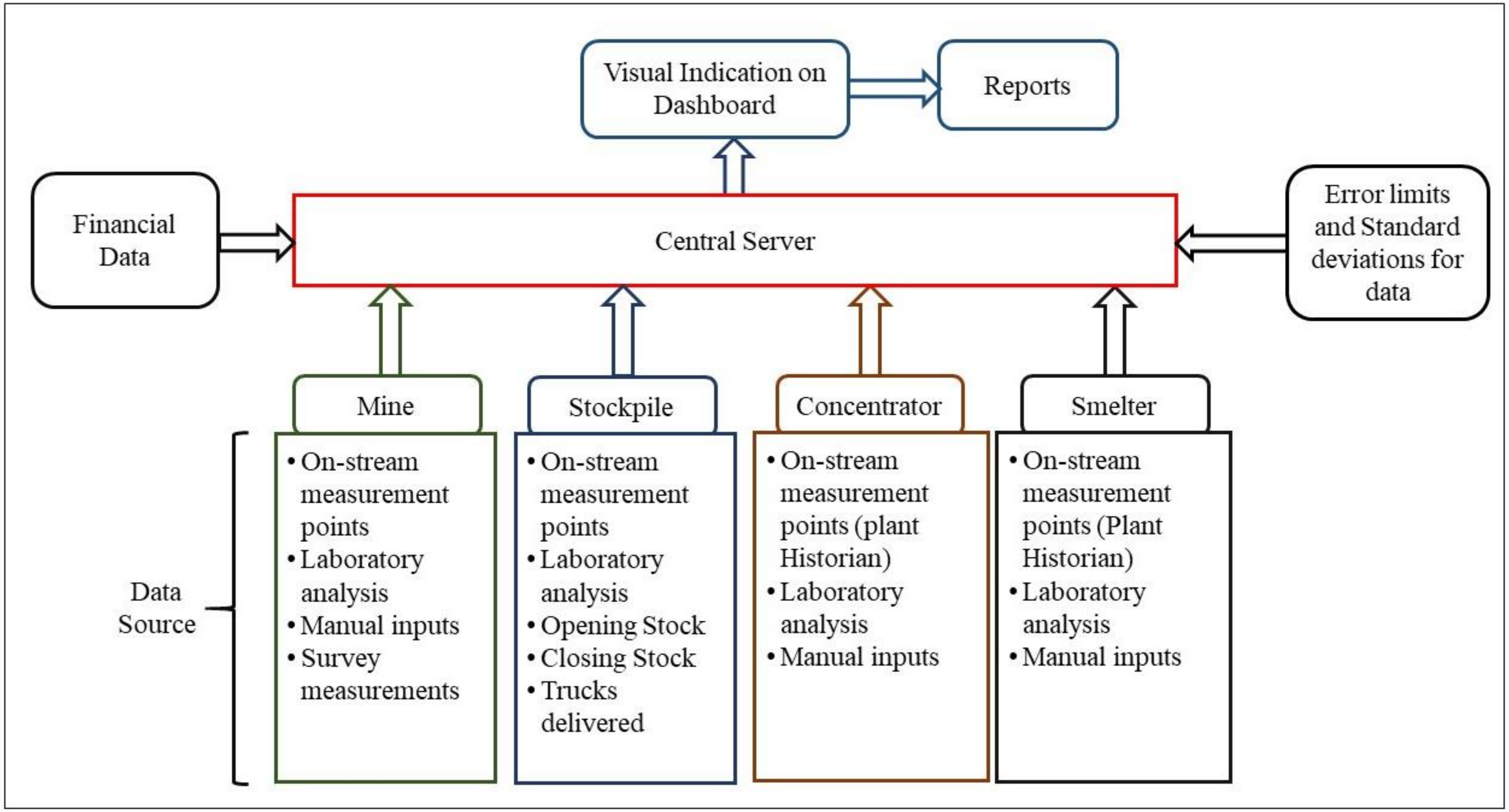



Figure 4.5 Architecture of WMI-OFA along with the sources of data in mine and plant (Source: Author)

### 4.4.2 Benefits of 'WMI – OFA'

The benefits of the digital tool are described below:

- Direct data input from mine and plant at data collection points;
- Tracking the ore flow from the mining face up to the final product in the plant;
- Keeping records of mass and material flows;
- Integrating mine and plant metal accounting systems;
- Integrating with the Laboratory management systems;
- Complying with existing standards of metal accounting systems and best practices;
- Access to all stake holders in their specific domains;
- Safe from data tempering;
- Analysis of data received from different sources;
- Produce reports; and
- Detecting any irregularity in the system for follow-up investigation.

### 4.4.3 Data acquisition

The data in the mine and plant is generated through different sources. The major sources of data are:

- **Mine plan**

  The planned production and grade estimates are stored in the data base. The mine plan provides the planned production estimates. The tool should be able to analyse the actual production with that planned as mentioned in the plan. The points of difference between the actual and planned values will be calculated by the tool and the reason for this variance should can be manually entered after investigation.

- **Mine survey**

  A mine survey is conducted before and after mining of the ore. It provides an estimate of the tonnage mined from a specific area of the mine. The mine survey data should be a part of the central server data base. The survey tonnage will then be compared with actual tonnage.

- **Mine and plant sampling**

The information of the samples collected in the mine and plant should be entered in the database. The following data about a sample should be stored:

  - Sample name and identification (id);
  - Location of sample;
  - Sample date and time;
  - Purpose of sampling;
  - Sampling criterion;
  - Quantity of sample (size);
  - Name of tests performed; and
  - Results.

The laboratory information management system (LIMS) database should also include the above-mentioned data. If a LIMS has its own database, then the data should be transferred to the central server. If a LIMS is working as an integrated part of the central database, then the digital tool should take data from the database whenever required.

- **Laboratory analysis results**

The points of sampling for metallurgical accounting is outlined in the Figure 4.2. These samples are analysed in mine and plant laboratories. The tool should be able to integrate with the laboratory management system. The data from the laboratory should be automatically transferable to the central data base. The variance limits of the analysis should be a part of data transferred to the database. These limits will then be used in the analysis and propagation of variance.

- **On-belt analysis and mass measurements in mine**

The measurement of mass in a mine and plant is important as it is one of the major inputs of production during mining and processing. The mass measurement data should be automatically transferred from the measuring instruments to the database. The measurement devices are usually connected to the plant and mine management systems. If the necessary information for metal accounting is gathered this way, then this system should be integrated with the metal accounting tool. If this is not the case, then necessary steps should be taken to gather the required information and it should be stored in the central database. The data from the on-belt analysers in a mine and plant should be stored in the database relative to the mass flow. For example, if the tonnage is being recorded on an hourly basis, then the ore grade should also be stored for each hour. An example of tonnage with respect to the on-belt analyser data is shown in Table 4.1.

Table 4.1 Example of data storage in database (Source: Author)

| Date | Time | Reference No. | Mass of ore (tonnes) | Ore grade % Cu |
|---|---|---|---|---|
| 01-01-2018 | 0700 | MP11180700 | 50 | 3.0 |
| 01-01-2018 | 0800 | MP11180800 | 45 | 3.1 |
| 01-01-2018 | 0900 | MP11180900 | 52 | 2.9 |
| 01-01-2018 | 1000 | MP11181000 | 49 | 3.0 |
| 01-01-2018 | 1100 | MP11181100 | 51 | 3.2 |
| 01-01-2018 | 1200 | MP11181200 | 50 | 3.0 |

- **Stockpile**

The material movement in the stockpile should be monitored and stored in the database. The ore received by the stockpile, ore delivered to plant, number of trucks, mass of each truck, stockpile name/ number, opening stocks, closing stocks, ore grade in stockpile are some of the variables that should be stored in the database. The source of the ore should also be mentioned if the mine has different stockpiles for different faces or different ore grades. For example, for the mine considered in this case study, it is assumed that face 1 and 2 (group 1) are mined in one shift while Face 3 and 4 (group2) are done in the subsequent shift. The ore is also collected in 2 different stockpiles. Therefore, the ore source is known, and it should also be mentioned.

### 4.4.4 Data storage

The data stored in the relational data base system should have the following attributes:

- **Unique data name**

  The data name is a reference number assigned to each data entry into the data base. This number is usually a combination of alphabets and numeric values. It is assigned by the data base automatically to each data set.

- **Data source**

  It should reflect the source of data, for example, if the mass measurement is stored in the database using an on-belt mass measurement device, the name and location of the device should be mentioned.

- **Time and date**

  The data should be stored against the date and time of the data acquisition. It will help in identifying the data trail during the audits and the comparison of data is also easy.

- **Actual data**

  It reflects the actual data that needs to be recorded, such as mass or volume flow at a specific time.

- **Manual data entry**

  The manual data entry should be avoided as it can introduce errors. If it is necessary, then the reason of entry and the name of the person should also be listed. The manual data entry should be password protected to preserve data integrity.

### 4.4.5 Data analysis

The data analysis is an important stage of metal accounting. The data analysis techniques are discussed in Chapter 3. The analysis is carried out to ensure that the data being used for the metal accounting purpose is error free and fit for use. Each data collection technique contains some errors, e.g. the mass measurement devices have a standard deviation value. Therefore, it is important to know that the data acquired is within the acceptable range.

The data analysis techniques and the allowable limits must be stored in the data base. The tool should have a built-in function to analyse the data being stored in the data base. If the data is suspected to have any variation compared to the previous data or the data inputs of the previous processes, the system should provide an indication to investigate the reason of the abnormality. The use case for the identification of bias in readings is discussed in section 4.7.

## 4.5 Reporting

It is important that the system should be able to produce metal accounting reports in-time. Generally, the metal accounting reports in the industry are either not properly prepared or not timeously produced. This affects the mine and plant decision making process. The reports generated should be in accordance with the AMIRA P754 code. The reporting requirements are mentioned in the Chapter 3. Each level of management have different report requirements. Therefore, the reports should provide the information required to the respective persons. The report formats for each level should be a part of the tool. To generate reports for a specific time period, the user should only specify the beginning and ending dates and an automated report should be generated for the user.

## 4.6 Mine to Plant ore flow sheet

An ore flow sheet from mine face to final product in the plant is shown in Table 4.2. The ore flow sheet is in accordance with the process flow shown in Figure 4.2. The left side shows the data need for the metal accounting. The ore flow sheet combines the measuring points of a mine, stockpile, froth flotation, smelting and refining processes.

The tonnage, ore grade and production is assumed to illustrate the combined ore flow. The mine produce copper from 4 different faces. The final copper grade produced is 3.1% copper. The concentrate received ore grade is 3.07% copper. The final concentrate produced by the smelter contains 28.7% copper. Theoretically, the flotation process produce copper concentrate containing around 30% copper (Schlesinger et al., 2011). The concentrate grade produced in the smelter is slightly lower than the theoretical value. The reason can be the fluctuation of head grade and feed grade compared to planned.

The flotation concentrate is fed to the smelting plant. As mentioned earlier, the smelter feed is in dried form. The smelter output is 98.6% blister copper. It is in accordance with the theoretical matte grade. The typical copper percentage in matte is around 99% copper (Schlesinger et al., 2011). The smelter slag contains 1.6% copper. The typical slag copper concentration is 1-2% copper (Schlesinger et al., 2011). Hence, the slag copper concentration is also within limits. The final product of the smelting process is 2947 dry tonnes of matte. The matte contains 2907 tonnes of copper. The final plant product is in the form of copper anodes. The mass of each copper anode is 400 kg. The total copper anodes produced is 7262 having 99.4% copper. The total copper produced is 2887 tonnes.

Table 4.2 Mine to plant ore flow sheet (Source: Author)

| **Mine** | **Actual (DMT)** | **% Cu (Actual)** | **Copper Produced (DMT)** | **Planned (DMT)** | **%Cu (Planned)** |
|---|---|---|---|---|---|
| Ore mined (Face 1 & 2) | 95000 | 3.0 | 2850 | 100,000 | 3.2 |
| Ore received by mills | 95000 | 3.0 | 2850 | 100,000 | 3.2 |
| Total Ore grinded | 95000 | 3.0 | 2850 | 100,000 | 3.2 |
| Ore Mined (Face 3 + 4) | 98000 | 3.2 | 3136 | 100,000 | 3.4 |
| Ore received by mills | 98000 | 3.2 | 3136 | 100,000 | 3.4 |
| Total Ore grinded | 98000 | 3.2 | 3136 | 100,000 | 3.4 |
| Total ore mined | 193000 | 3.1 | 5983 | 200,000 | 3.3 |
| Difference | 7000 | | | | |
| **Stockpile** | **Dry metric tonnes (DMT)** | **% Cu (Actual)** | **% Cu (Planned)** | | |
| Ore received from mine | 193000 | | | | |
| Ore sent to plant | 150000 | | | | |
| Opening Stock | 1000 | | | | |
| Closing Stock | 44000 | | | | |
| **Concentrator** | **Dry metric tonnes (DMT)** | **Cu%** | **Copper (tonnes)** | **Recovery (%)** | |
| Mill received | 150000 | 3.07 | 4605 | | |
| Total ore crushed | 148000 | 3.07 | 4543 | | |
| Rougher Feed | 148000 | 3.07 | 4543 | | |
| Rougher Concentrate | 12500 | 20.1 | 2512 | | |
| Final Concentrate | 10498 | 28.7 | 3012 | | |
| Cleaner/ Scavenger Tailings | 137500 | 1.11 | 1530 | | |
| **Smelter** | **Mass (DMT)** | **Cu%** | **Cu (tonnes)** | | |
| Feed concentrate | 10498 | 28.7 | 3012 | | |
| Reverberatory furnace slag | | | | | |
| Conv. Slag Concentrate to rev. furnace | | | | | |
| Total Smelter inputs (Actual) | 10498 | 28.7 | 3012 | | |

| | | | | | |
|---|---|---|---|---|---|
| Total Smelter inputs (Planned) | | | | | |
| Blister Copper Produced (Actual) | 2947 | 98.6 | 2907 | | |
| Blister Copper Produced (Planned) | | | | | |
| Converter slag produced | | | | | |
| Reverts to crushing | | | | | |
| Reverberatory furnace slag | 7551 | 1.4 | 106 | | |
| Converter dust to stockpile | | | | | |
| Feed concentrate opening stock | | | | | |
| Feed concentrate closing stock | | | | | |
| **Refinery** | | **Mass (DMT)** | **Cu%** | **Cu (tonnes)** | |
| Concentrate Received | | 2947 | 98.6 | 2907 | |
| Number of Anodes casted | 7312 | | | | |
| Mass of Anodes casted | | 2924 | 99.4 | 2906 | |
| Cast Anodes to recycle | 50 | | | | |
| Total anodes produced | 7262 | 2904.8 | 99.4 | 2887 | |

## 4.7 Indication of Bias in measurements

The identification of errors in measurements is important for the metal accounting process. The digital tool (WMI – OFA) should be able to identify the measurement variances if it is above the limits. A case of comparison of measurements is discussed here.

Figure 4.6 and 4.7 shows an example of the ore delivered to a flotation plant form the mine. The ore delivered to the plant is measured by measuring the mass of each truck using a weighbridge. The plant measurement is taken using a weighbridge fitted on the conveyor belt. The percentage variance allowed and respective indications on the dashboard are shown in the Table 4.3. It is assumed that a variance of up to 2% is allowed. If the variance value is more than 2%, the indication on the screen will show the level of discrepancy by yellow and red colours respectively.

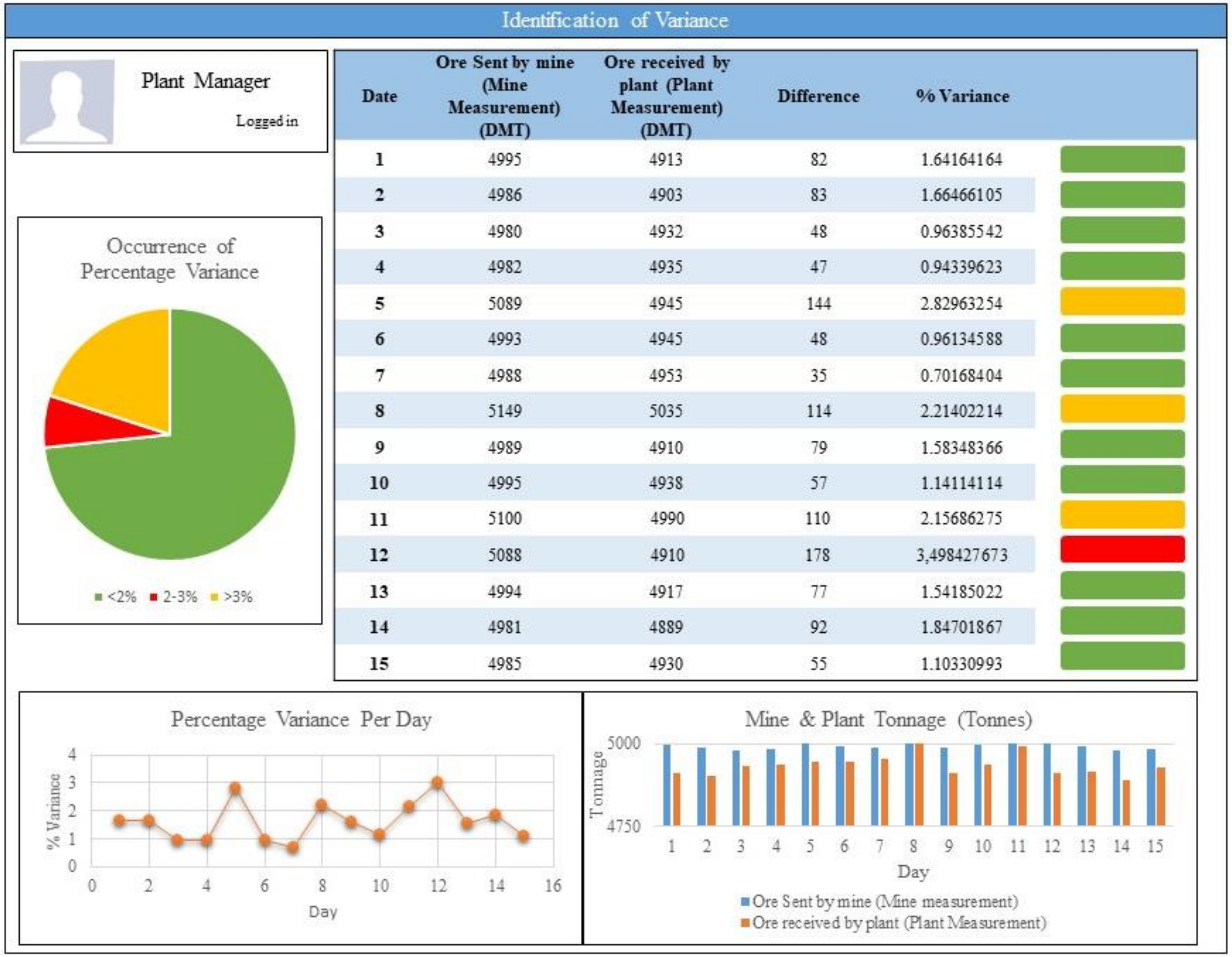
Table 4.3 Limits of variance and visual indication (Source: Author)

| Limit | Indication |
|---|---|
| Up to 2% | |
| Between 2% - 3% | |
| More than 3% | |

Figures 4.6 and 4.7 show mine and plant measurements for 15 days. In the case shown in Figure 4.6, the variance is increased 4 times. It is between 2 and 3% twice, while it was more than 3% only once. The reasons for this variance can be investigated.

In Figure 4.7, the dashboard shows an indication of increasing variance each day. The variance increased from 2.1 % and it reaches to above 4%. This is an indication of a problem in the measuring instruments either from the mine or plant side. This problem should be investigated in detail and rectified as soon as possible. The ore from the milling process is fed to the flotation plant. If the inputs of the flotation cell is properly measured, then the identification of the problem becomes easy. The tonnage of mine, mill received, and the inputs of the flotation circuit can be correlated to each other and the point of discrepancy can be identified and then it is checked physically. Before the checking, the tool should do the identification of the problem as well by back calculating the outputs and feed material and checking for the error.

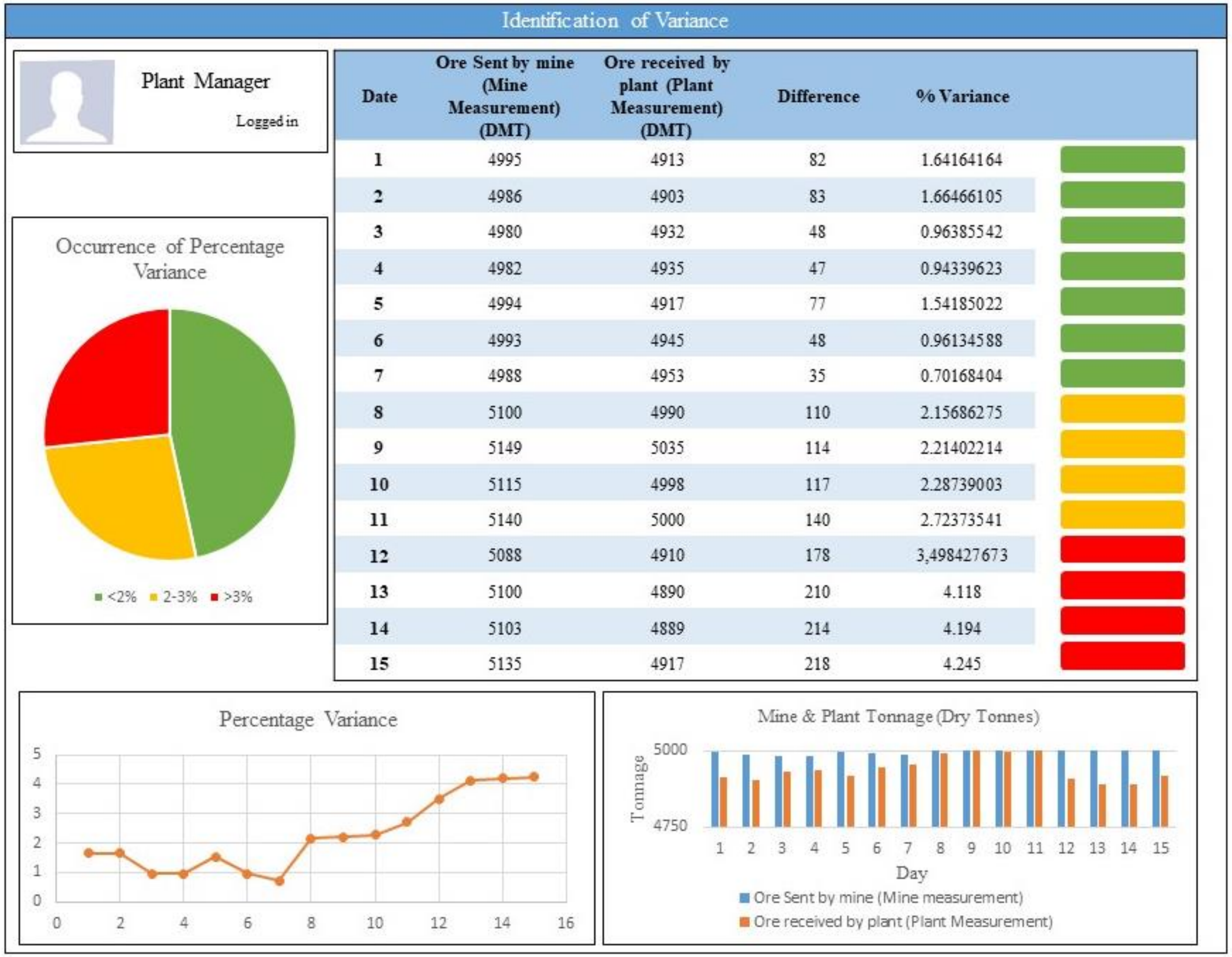
Apart from the indication of variance, the dashboard also provides graphical visualization of percentage variance in a given time, the difference of mine and plant tonnages and the pie chart showing the occurrence of variance in the data set. It is important that the person should login to the dashboard for the visualisation of data. The dashboard provides customize visual display of the data required for each person, e.g. the mine personnel can customize the view of dashboard to visualise the required data.



| Date | Ore Sent by mine (Mine Measurement) (DMT) | Ore received by plant (Plant Measurement) (DMT) | Difference | % Variance |
|---|---|---|---|---|
| 1 | 4995 | 4913 | 82 | 1.64164164 |
| 2 | 4986 | 4903 | 83 | 1.66466105 |
| 3 | 4980 | 4932 | 48 | 0.96385542 |
| 4 | 4982 | 4935 | 47 | 0.94339623 |
| 5 | 5089 | 4945 | 144 | 2.82963254 |
| 6 | 4993 | 4945 | 48 | 0.96134588 |
| 7 | 4988 | 4953 | 35 | 0.70168404 |
| 8 | 5149 | 5035 | 114 | 2.21402214 |
| 9 | 4989 | 4910 | 79 | 1.58348366 |
| 10 | 4995 | 4938 | 57 | 1.14114114 |
| 11 | 5100 | 4990 | 110 | 2.15686275 |
| 12 | 5088 | 4910 | 178 | 3,498427673 |
| 13 | 4994 | 4917 | 77 | 1.54185022 |
| 14 | 4981 | 4889 | 92 | 1.84701867 |
| 15 | 4985 | 4930 | 55 | 1.10330993 |



Figure 4.6 Example of visual indication of bias in mass measurements on a dashboard of WMI - OFA (Source: Author)



Identification of Variance

| Date | Ore Sent by mine (Mine Measurement) (DMT) | Ore received by plant (Plant Measurement) (DMT) | Difference | % Variance |
|---|---|---|---|---|
| 1 | 4995 | 4913 | 82 | 1.64164164 |
| 2 | 4986 | 4903 | 83 | 1.66466105 |
| 3 | 4980 | 4932 | 48 | 0.96385542 |
| 4 | 4982 | 4935 | 47 | 0.94339623 |
| 5 | 4994 | 4917 | 77 | 1.54185022 |
| 6 | 4993 | 4945 | 48 | 0.96134588 |
| 7 | 4988 | 4953 | 35 | 0.70168404 |
| 8 | 5100 | 4990 | 110 | 2.15686275 |
| 9 | 5149 | 5035 | 114 | 2.21402214 |
| 10 | 5115 | 4998 | 117 | 2.28739003 |
| 11 | 5140 | 5000 | 140 | 2.72373541 |
| 12 | 5088 | 4910 | 178 | 3,498427673 |
| 13 | 5100 | 4890 | 210 | 4.118 |
| 14 | 5103 | 4889 | 214 | 4.194 |
| 15 | 5135 | 4917 | 218 | 4.245 |



Figure 4.7 Dashboard indication of continuous increase of variance in measurement on WMI - OFA (Source: Author)

## 4.8 Conclusion

Chapter 4 described a case study of a hypothetical copper mine producing copper anodes as final product. A combined ore flow sheet is designed and used to provide a combined data visualisation from mine until the final product in the plant.

The chapter also proposed an architecture of digital framework (WMI – OFA) that can gather, analyse and provide a visual report of the ore flow in the mine and plant. It is proposed that all the data form the mine and plant should be stored in one database and should be used for reporting and important decision-making processes.

Chapter 5 will provide the conclusion, recommendations and future work needed to be done for the analysis of the framework and its usefulness in a mine and plant production scenario.

# 5 CONCLUSION AND RECOMMENDATIONS

## 5.1 Overview

Chapter 4 provided the proposed architecture of a digital tool (WMI -OFA) that will be able to monitor and evaluate the ore flow process in a mine and different processes in a plant. It will also help in decision-making by real-time indication of abnormalities in the system.

Chapter 5 outlines the key findings, conclusion and recommendations deduced from this study. It also provide recommendations for future research on this topic.

## 5.2 Key findings of research

The key findings of the study are stated below:

- The process of copper production consist of a series of steps, and each step is dependent on the previous one.
- The optimisation of the entire process requires the understanding of each step, keeping in mind the overall process. For example, if the flotation plant knows the exact mineralogy of the ore (which is to be delivered to the flotation plant) at the time of mining. It will help in planning to optimise the flotation parameters according to the ore mineralogy. It will also help in reducing waste produced during the process.
- Accurate and reliable sampling, mass measurement and sample analysis is important for the reduction of losses, improving production and profitability.
- In the plant, the ore flow measurements are carried out mostly using mechanical and electronic equipment, which are accurate and reliable if proper maintenance is done.
- Mine measurements and sampling involve humans, which introduce risk of errors. There is a need to reduce human involvement in the process.
- There is a considerable difference in the ore grade which is delivered to plant from mine. There is a need to investigate the reasons and take steps to eradicate it.
- This research conceptualised a digital system named WMI-OFA for evaluating and optimising the ore flow process in copper production. It should be used as

a case scenario for the development of a real-time system for ore flow analysis in mine and plant.

### 5.3 Conclusion and recommendation

The mining and processing of copper ore is spread over a large range of activities from production to processing. The accurate measurement of mass and material transfer is significant as each process is dependent on the previous one. Metal accounting in the mining industry is carried out as a general practice to cater for production and reporting requirements. The issue with this practice is that it is not done to the required (high) level of confidence. Considering the need to design an overall integrated system that may help both the mine and plant in the metal accounting process a copper case study was carried out.

The analysis of the case study highlighted the causal factors for the losses during the ore flow in mine and plant. The foremost causal factor is the difference between the mass and grade measurement of ore delivered specifically between the mine and the flotation plant. The primary reasons amongst others for this difference are that the plant measurements are typically more accurate because of a streamlined flow of ore, less human involvement and use of well-maintained mechanical and electronic devices. The reduced ore particle size also contributes towards better measurement efficiencies in the plant.

The use of spreadsheets for data storage and analysis is very common in mine and plants. These spreadsheets become more complex with the time as the amount of data being stored increases. The data is also entered manually which increases the chance of errors and overwriting of formulas. The use of spreadsheets should be replaced by database software linked to a system like WMI-OFA. It will reduce complexity, provide automated data analysis, reports generation and can also indicate any bias occurring during measurements. Hence, the application of digital technologies in a mine and plant for ore flow analysis can help in minimizing the potential losses and increased production. The recommendations are provided considering the research objective and are as follows:

- The AMIRA P754 code for metal accounting provides a detailed guideline for copper metal accounting. If the code is applied to the required level of confidence in the copper mining industry, it can help in reducing potential losses, increase the overall efficiency and add value.

- The AMIRA P754 code for metal accounting mainly focuses on plant processes. Therefore, there is a need for a similar code focusing on mining operations to facilitate the mine ore flow process.
- The use of an integrated digital software like WMI-OFA is essential to bridge the gap of information flow between the mine and processing plant.
- The lack of data and delayed information flow between mine and plant affects the overall process. It results in the loss of value and sub-optimal use of the resources. A real-time flow of information along the mining and processing steps can help in addressing the above-mentioned issues.
- The loss of ore during mining, transportation and processing is often identified when significant losses have already been occurred. The real-time monitoring of information can reduce this loss to a significant level by timely identification of problematic areas.
- There is a need to apply digital technology for real-time measurement and monitoring of mining processes. For example, typically the survey of tonnage mined are done twice a month by mine surveyors. This reduces the chance of identification of issues and bias in process. If technologies like laser scanning or video analytics are applied, it can reduce the time of data acquisition and provide better evidence during disputes.
- The technologies like Radio Frequency Identification (RFIDs) Tags can be used to track the ore flow from mine to stockpile and from stockpile to plant. The use of SMART TAG™ which use RFIDs for material flow tracking in mining and processing environment is studied by Isokangas et al., (2012). These authors recommended the use of SMART TAG™ for the material flow tracking in mine and plant.

## 5.4 Future research

The current work conceptualised the framework for ore flow analysis in a copper mine and plant. More research is required to analyse the implications of the framework and the requirements to apply the framework in a real mine and plant environment. The current work used a hypothetical case study of a copper mine. In future research, actual data must be used to analyse the framework against the current practices. It is also important to analyse the cost factor for implementation of such a system against the value gained through the system.

In summary, the chapter presented the conclusion of the study and recommendations. The chapter suggested the use of a digital system that can manage and monitor the ore flow from the beginning of mining till the final product in the plant. The chapter also motivates that there is a need for more research to take the concept framework to produce a real-time system that can be implemented in real mine and plant environment.

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