A New Approach to Metallurgical Accounting
S Brochot¹ and M-V Durance²

ABSTRACT
In many cases, current metallurgical accounting practice does not consider the errors associated with the measurements used in obtaining the metal balance. Considering all measurement errors, including errors associated at each step of the process – from sampling and analytical errors to measurement errors in circuit instrumentation, can improve the accuracy of the final metal balance – assisting in the improvement of process performance, optimisation and control.

The consequences of the inclusion of measurement errors on metal balance for different circuit configurations and typical metallurgical accounting practice (two product and three product formulae) will be discussed in this paper.

Examples of the tools, methodology of implementation, and periodical metal balance tasks are presented to illustrate the advantage of this approach in meeting the different requirements of each department.

INTRODUCTION

If: Metal accounting is the estimation of (saleable) metal produced by the mine and carried in subsequent process streams over a defined period of time ... (Morrison, 2008a) it has become widely used to quantify the performances of production plants (metal recovery, losses, environmental impact) and to establish an accurate estimation for the metal inventory (stock taking and work in progress estimation). A large discrepancy between the estimated and actual inventory can have significant financial consequences. Similarly, poor estimation of metal recovery and losses can hide process issues and give inappropriate production planning. This is why ‘metal accounting provides interface between technical and financial performance measurement’ (Morrison, 2008a). These two cultures have two very different points of view and have difficulties to conciliate them. The main topic of disagreement is the uncertainty of measurement which implies uncertainty in the estimation of production and inventories.

The measurement uncertainty and the methods of reducing it have been widely discussed in many papers (Morrison, 2008b; Wortly, 2008; Holmes, 2004; 2008; Brochot, 2011). The objective of the current paper is to highlight the ways to improve the accuracy of the metallurgical accounting system itself through an implementation process, its granularity (the extent of detail to be taken into consideration), and its data reconciliation method and tools.

PROCESS OF METALLURGICAL ACCOUNTING
Metal accounting is a component of the general enterprise accounting. It constitutes a powerful tool to manage metal producing companies at their various stages: mine and mill, concentrator, smelter or hydrometallurgical plant, refinery, or a combination of these stages. It is the bridge between the technical and the financial point of views of the process. The process data generated to manage the production performances are used to valuate the products and stocks into financial data.

The main objective of a metallurgical accounting system is to help the company in managing process data to generate a material balance in order to obtain a metal accounting report. The secondary objective is to use the material balance to accurately calculate the process performances and help the process manager in optimising it. The metal accounting is generally established for a period of production. This period can be defined by a regular time period or by the period of production of a material batch. In accordance with the financial and accounting rules, the regular time period is generally a month.

In the lifetime of a company we can consider three life cycle levels for metal accounting:
1. Metal accounting system life cycle: this begins with the decision to implement the metal accounting system in a company and finishes with the decision to end it.
2. Production evolution life cycle: this regards the adjustments of the metal accounting system due to production evolutions such as a process change, a new production unit, or new products.
3. Metal accounting life cycle: this groups the periodical tasks to obtain a regular metal accounting report.

Metal accounting system life cycle
From the moment a company decides to implement a metal accounting system to the time the system reaches completion, three periods can be identified:

¹. Scientific Manager, Caspeo, 3 Avenue Claude Guillemin, BP36009, 45060 Orléans CEDEX 2, France. Email: s.brochot@caspeo.net
². MAusIMM, Executive Manager, Caspeo, 3 Avenue Claude Guillemin, BP36009, 45060 Orléans CEDEX 2, France. Email: mv.durance@caspeo.net
4. the ‘implementation’ groups all tasks to obtain an operational and efficient metal accounting system
5. the ‘production’ groups all tasks to regularly generate metal accounting reports and update the system according to notable evolutions
6. the ‘closing’ groups all tasks to finalise the last metal accounting taking into account the plant dismantlement.

The implementation of a metal accounting system is a company project mobilising all staff: general management, financial, accounting, production, laboratory, metrology, information technology, purchasing, sales staff... It necessitates the initiation of a specific project team. Depending on the initial level of development of the company the following tasks have to be taken into consideration: a detailed definition of the objectives of the metal accounting and delimitation of the system; a review of the accounting rules and legislation; a review of the process documentation; a review of the existing measurement system; defining and design implementation of necessary additional measurements; the establishment of the measurement uncertainty budget (Brochot, 2011) involving the identification and implementation of some improvements; a review of the existing process information system (hardware and software) with the definition and design of the missing elements; the standardisation of the measurement system; the design of the metal accounting system through the material balance; the configuration of the initial reconciliation model; the tests and tuning of the initial reconciliation model using historical data then in production conditions; and finally the validation of the metal accounting system and normal production initiation.

The period of production starts with the validation of the metal accounting system through the initial reconciliation model and finishes with the last metal accounting period before dismantlement. Regardless of the type and frequency of the material balance, the following tasks must be carried out: the metal accounting calculation and reporting; the identification and implementation of any improvements in the measurement system and the data management; changing the system delimitation (system enlargement by taking into account new production units or system contraction when the units appear out of the scope); all resulting in the updating of the reconciliation model.

When a decision has been taken to stop the production and close the site, the following steps are required: the configuration of the final reconciliation model taking into account the stock exportation, the tailings disposal or the management of the wastes generated by the dismantlement; a metal accounting calculation of the last production period; the global or periodical metal accounting calculation during the dismantlement based on the final reconciliation model; the final reporting; the definitive backup of the databases (for possible subsequent control) and the dismantlement of the information system.

The ‘reconciliation model’ groups all the information defining the material balance, and the rules and algorithms allowing the generation of the metal accounting reports from the raw data generated by the company. This includes the definition of the accounting period, the material flow diagram (flow sheet) with the material movements (streams) and units of operation (nodes), the types of data managed in each stream (phase model), the calculation rules to obtain basis data resulting from the aggregation of raw data for the considered period, the calculation rules for the associated measurement errors, the data diagnostic and checking rules, the material conservation constraints, the engine for data reconciliation by material balance, the reporting formats with KPI calculation rules. All these elements can be managed by an integrated software solution such as Inventeo (Brochot, 2011; Caspeo, 2012).

**Production evolution life cycle**

Many instances may lead to the updating of the metal accounting system: process modification, new raw materials, new products, new units of operation, improvements in the measurement system, improvements or changes in the information system, improvements in the material balance techniques ... these updates necessitate modifying the reconciliation model.

Considering the period from the validation of a reconciliation model to the validation of an updated version of the reconciliation model, the following tasks should be executed: the validation of the reconciliation model; the metal accounting calculation and reporting for numerous periods; the identification of a modification of the metal accounting system necessitating an update of the reconciliation model; the updating of the reconciliation model; the tests and the tuning of the updated reconciliation model in production conditions; the validation of the updated reconciliation model and normal production with the updated system.

This period must be prolonged to correspond to more than one metal accounting period. If the reconciliation model has to be updated for each metal accounting calculation, this is an indication that it has not been well configured. A sound compromise between rare updating and the inevitable process evolution is to establish an average of six months between two updates (no less than three months). A modification in the metal accounting system must be anticipated. This means essentially that the metal accounting system has to be taken into account at the very basis of any modification decision.

**Metal accounting life cycle**

The metal accounting life cycle time commences with the starting time of the considered period. It finishes with the metal accounting validation. The validation occurs after the ending time of the considered period, and generally, after the starting time of the next period. For example, if the metal accounting calculation corresponds to one month, the period starts the first of the month at a given time and finishes the first of the next month at the same time. But the metal accounting calculation of that period necessitates additional days waiting missing measurements, intermediate approvals and validations before editing for the final report and final validation.

During this time, the following tasks are executed:

- Frequently during the metal accounting period: review the availability of raw data; check raw data using diagnostic tools; identify all exceptional events which could affect the material balance.
- At the end of the considered period: review the availability of raw data and identify missing data; review all exceptional events occurring during the considered period which can influence the material balance; check raw and basis data using diagnostic tools; verify raw data and fix mistakes; identify the imperative changes to introduce into the reconciliation model and update if necessary.
- Waiting missing data: check the availability of missing data; check raw and basis data using diagnostic tools; verify raw data and fix mistakes; if remaining missing or unverified data and mistakes become apparent repeat the previous tasks outlined at a later stage.
• When all raw data is available, verified and fixed: complete basis data generation; perform data reconciliation by material balance; check reconciled data using diagnostic tools and identify the remaining raw data mistakes or necessary means of adjustment; verify raw data, fix mistakes and return to complete basis data generation; if necessary, perform argued adjustment of error and basis data and return to data reconciliation; generate provisional reports; validate the material balance.

• Generation of the metal accounting reports.

Once again, the workflow of these tasks, including validations and approbations, can be managed by the Inventeo software solution.

Measurements, measurement error and basis data

The metallurgical accounting is based on the calculation of the material balance of the considered system. This calculation necessitates raw data, such as masses, moisture contents or assays, which are obtained by measurements. As the measurement is a random process, it is subject to uncertainty which can be valued by its associated ‘measurement error’ (Morrison, 2008b). It concerns also the measurements of mass (Wortley, 2008), moisture or metal content, percentage of solids or density … these last measurements generally necessitate sampling, which is the main source of uncertainty (Holmes, 2004; 2008). All efforts have to be done to obtain correct sampling and measurement to avoid any bias. This bias would produce discrepancies between metal accounting and real production with the risk of unacceptable financial consequences. Nevertheless, the variance of the overall measurement error cannot be avoided and its calculation necessitates the establishment of its uncertainty budget (Brochot, 2011).

The quantity of material managed during the considered period of metal accounting is generally given by the sum of many mass measurements such as truck loads or production weights per shift. Similarly, the mean moisture or metal contents are calculated by the weighted average of the contents of many samples. The aggregation of this raw data gives the ‘basis data’ which is the sum of the total masses or the mean contents of the material during the accounting period. A measurement error can then be attached to the basis data using the error propagation calculation rules (Xiao and Vien, 2003).

Data reconciliation by material balance

Due to the measurement uncertainty, the basis data is incoherent regarding the material conservation laws (Hodouin and Everell, 1980; Herbst, Mehta and Pate, 1988; Fourniguet et al., 1997). To illustrate this incoherence, one can consider the example of a concentrator with the feed as the plant’s input stream and the final concentrate and tailings as the output streams. Assuming there is no accumulation of material in the plant (the work in progress is constant) the mass of dry ore feeding the plant during the period has to be equal to the sum of the masses of dry concentrate and dry tailings produced during the same period. If dry mass measurements have been performed for these three streams, their values have little chance in verifying this conservation law. Similarly, the masses of the metals are incoherent due to the uncertainty of the dry mass and metal content measurements. The incoherence can be observed when there is data redundancy: when there is more data than the required minimum to calculate the material balance. Only in the case that the feed mass flow has been measured (the masses of concentrate and tailings are unknown) and samples have been taken and analysed for the three streams, can the ‘two product’ formula be applied to back-calculate the masses of concentrate and tailings. In this case there is no redundancy except in the situation that many contents have been measured for each stream (Guerney, Dunglison and Cameron, 2005).

The objective of the data reconciliation by material balance is to find a set of estimates for the measured values which are as close as possible to the measurements and verify the material conservation laws. Material balancing allows one to describe the material flowing in the process. Knowledge of the process performances is then improved (Durance, Brochot and Mugabi, 2004). Sometimes, balancing behaviour reveals non-stationary processes or bad accuracy estimation. The information redundancy allows delivering coherent estimators more accurate than the initial measurements (Ragot et al, 1990; Ragot and Maquin, 2006). This approach allows for the detection of aberrant values and to reduce error due to sampling and measurement.

The objective of a material balance computation is to find a set of estimates, which is complete (all streams are perfectly described), as close as possible of the measured values and in agreement with the material conservation laws.

For each stream, the decomposition of the circulating material is as follows:

\[ Q_i = \text{quantity of material in stream } i; \] material can be dry or wet solids, solution, slurry

\[ X_{ik} = \text{fraction by weight of material class } k \text{ in stream } i; \] for metal accounting, the material classes are solids and solution, the fractions being the solid and liquid (or moisture) contents

\[ T_{ik} = \text{fraction of component } l \text{ in the material class } k \text{ in stream } i \]

\[ P_{ik} = \text{fraction of component } l \text{ in stream } i; \] in the case of the slurry, it is the global slurry content

The measured values \( Q_i, X_{ik}, T_{ik} \) and \( P_{ik} \) never satisfy constraints of material conservation because of deviation from the balance position and because of uncertainties associated with the measurements. Material balance calculates the estimates \( \hat{Q}_i, \hat{X}_{ik}, \hat{T}_{ik} \) and \( \hat{P}_{ik} \) which firstly satisfy the constraints and secondly have the maximum of probability to be the real values. This last point amounts to seeking the estimates \( \hat{Q}_i, \hat{X}_{ik}, \hat{T}_{ik} \) and \( \hat{P}_{ik} \) which are as close as possible to the measured values \( Q_i, X_{ik}, T_{ik} \) and \( P_{ik} \), in accordance with the accuracy attached to each measurement.

Mathematically, this is equivalent to minimise the objective function:

\[ J(Y) = \sum_i f(Y) \]

by means of the material conservation constraint equations (see below), where \( Y \) is the vector of estimates \( \hat{Q}_i, \hat{X}_{ik}, \hat{T}_{ik} \) and \( \hat{P}_{ik} \) and where \( f(Y) \) is the objective function of the stream \( i \) (Le Guirriec, Brochot and Bergounioux, 1995; Le Guirriec, 1996). \( f(Y) \) can be expressed as:

\[ f(Y) = \left( \frac{Q_i - \hat{Q}_i}{\sigma_i^{Q_i}} \right)^2 + \sum_i \frac{X_{ik} - \hat{X}_{ik}}{\sigma_{X_{ik}} X_{ik}}^2 + \sum_i \frac{P_{ik} - \hat{P}_{ik}}{\sigma_{P_{ik}} P_{ik}}^2 + \sum_{\text{all}} \left( \frac{T_{ik} - \hat{T}_{ik}}{\sigma_{T_{ik}} T_{ik}} \right)^2 \]
Minimising the objective function is equivalent to maximising the function:

$$e^{J(Y)} = \prod_i e^{J_i(Y)}$$

This function is the product of the normal distributions of probability of the measurements. The maximum probability is then reached and the estimates are the more probable values for the material balance. They are not the true values which will remain unknown, by definition of the random nature of the measurements. It is then assumed that the random variables associated with the measurements are following a normal distribution. If this assumption can be drawn for raw data, it is less likely the case when basis data is calculated from many raw data (Xiao and Vien, 2003).

This objective function uses the probability distribution of the measurements of the metal content, $T_{ik}$, for example, not the partial quantity of that metal, $Q_i X_k T_{ik}$, as it is commonly the case (Morrison, Gu and McCallum, 2002). This is particularly advantageous when the content measurements are more accurate than the mass measurements.

The constraints can be divided into material conservation constraints, user-defined constraints and data integrity constraints. The material conservation constraints are attached to each unit of equipment. The elements of the incidence matrix $M_{ik}$ have the value +1 when the stream $i$ is an input stream of the node $j$, -1 when the stream $i$ is an output stream of the node $j$, and 0 when the stream $i$ is not linked to the node $j$. The basic conservation laws are:

The global quantity conservation around node $j$:

$$\sum_i M_{ij} Q_i = 0$$

The partial quantity conservation for material class $k$ around node $j$:

$$\sum_i M_{ij} Q_i X_k = 0$$

The partial quantity conservation for component $l$ around node $j$:

$$\sum_i M_{ij} Q_i P_l = 0$$

The partial quantity conservation for component $l$ into material class $k$ around node $j$:

$$\sum_i M_{ij} Q_i X_k T_{ik} = 0$$

It is possible to sum some conservation constraints around node $j$ to obtain a new conservation constraint which can be used to take into account, for example, the phase transfer in a leaching or precipitation model.

The data integrity constraints are the closure constraints, such as the 100 per cent fitting and the mean ratio constraint:

$$1 - \sum_i X_{ik} = 0 \quad 1 - \sum_i P_l = 0 \quad 1 - \sum_i T_{ik} = 0$$

$$P_l = \sum_i X_{ik} T_{ik} = 0$$

The resolution of the system is based upon the Lagrange formalism and the iterative algorithms Newton-Raphson and Ito-Kunish (Le Guirriec, 1996). After resolution, the variance-covariance matrix of the estimates can be deducted and the error associated with the estimates can be calculated. It shows the accuracy improvement due to data redundancy.

The BILCO software was developed by BRGM to solve material balance problems in the field of mineral processing, which is characterised by its great complexity in the material description. It offers an interactive, quick and accurate way of solving material balance problems in a vast number of applications. It has been used for metal accounting in association with spreadsheets using its component object modelling (COM) interface (Durance, Brochot and Mugabi, 2004; Muza, 2005). Now, the Inventeo solution offers a complete range of tools for metal accounting directly addressing databases without spreadsheets as recommended by the AMIRA code (AMIRA, 2007; Morrison and Gaylard, 2008).

**Granularity of Material Balance**

The quantity of information used to calculate the material balance has a large impact on the accuracy of the metal accounting. Lyman (2005) highlighted the improvement in the material balance accuracy when using intermediate process streams. The extent of detail, the granularity, of the system concerns also the accounting frequency, the material flow diagram, the material characteristics by using multi-phase and multi-element balancing, the way to estimate the inventory of stocks and work in progress (WIP), or the raw data used to calculate the basis data.

**Accounting Frequency**

The metal accounting is generally established for a period of production. This period can be defined by a regular time period or by the period of production of a material batch. The regular time period is generally a month from a fixing time of the first day of the month to the same time of the first day of the next month. It can be also a quarter or a year for a quarterly or yearly accounting, a day or a shift for the process follow-up. The batch approach is mainly used for process follow-up but can be included and consolidated into a time period balance for metal accounting. In both cases, the metal accounting is an iterative task which is repeated regularly.

In most companies, the financial department imposes a monthly metal accounting. It is generally associated to a monthly stock taking allowing a more accurate estimate of the stocks and WIP (see below). Quarterly and yearly metal accountings are generally obtained by summing the individual monthly accountings. If this method is more or less imposed by accounting rules and legislation, it is not the more accurate. Indeed, calculation of the material balance over a longer period has the advantage to reduce the beginning (opening) and ending (closing) inventories compared to the total material movements. As it is usually admitted that the stock estimates are less accurate than the material movements (Wortley, 2008; Holmes, 2008; Connelly, 2009), the weight of the variance of the stock estimates into the global variance of the metal accounting is reduced. In addition, specific stock taking can be carried out annually with more accurate methods of measurement.

Conversely, shorter period accounting is generally less accurate. If it is interesting to calculate material balance per day or per shift for process follow up and production reporting, it cannot be used as it is for metal accounting. Indeed, there is no stock-taking at this frequency and all inventories are just rough estimates with a large associated error (Cargill, Freeman and Gilbertson, 2002; Muza, 2005). The intermediate frequency can be used, such as on a weekly basis in gold mines (Guerney, Dunglison and Cameron, 2005; Guernerly, 2008).
Material flow diagram

Most of the metallurgical accounting systems reduce the material flow diagram to one node representing the plant and to the input and output streams (Morrison, Gu and McCallum, 2002; Jansen, Morrison and Dunn, 2007). In the case of a mining company, reconciliation between the mine and the concentrator through the intermediate stockpiles and/or blending beds is considered (Morrison, Gu and McCallum, 2002; Morley and Moller; 2005). The one node approach is also used per plant area. In this case, the material balance is calculated sequentially with the risk to accumulate errors from one area to the next (Cargill, Freeman and Gilbertson, 2002).

The redundancy of data is a way to improve the accuracy of the material balance. Due to the propagation of variance through the material conservation laws, the error associated to the reconciled data (estimates resulting from the data reconciliation by statistically coherent material balance) is lower than the error associated to the corresponding basis data derived from measurements. A way to add redundancy to the system is to use a more detailed flow sheet with intermediate streams and nodes. It has to be limited to the streams for which there are measurements: weighing, sampling, assaying. The number of streams without measurement has to be reduced to its minimum. Some units of operation have to be grouped in one node if they have ‘unknown’ streams between them. For example, in a closed grinding circuit, if the circulating load is unknown (neither weightometer nor sampling), the mill and the hydrocyclones are grouped in one node with the circuit feed as the input stream and the over mill and the hydrocyclones are grouped in one node with the input stream and the overflow as the output stream.

When using only one node (the plant) for the material balance, the inventories (stocks and WIP) are globalised for that node and accounted all together. When using intermediate nodes, each inventory can be individually accounted through a specific node for the stocks or a unit operation node for the WIP. Stock variations are then directly linked to their node and accounted all together. When using intermediate balance, the inventories (stocks and WIP) are globalised for the process stage.

The accuracy improvement when increasing the granularity of the flow diagram has been theoretically proved and illustrated in particular cases (Lyman, 2005).

Multi-phase and multi-element balancing

It is always preferable to use raw data directly derived from a measurement than results of calculation from many measurements. It is the case with the wet mass and the moisture content. Most of the material accounting systems use the dry mass for solid material balance (Morrison, Gu and McCallum, 2002; Guernsey, Dunglison and Cameron, 2005; Jansen, Morrison and Dunn, 2007). The dry mass is well derived from the measured wet mass and moisture content but only the dry mass is used for data reconciliation. If the measurement system allows the calculation of the water balance, it is preferable to use the wet mass and the solid content (complement of the moisture content) for the solid balance. The variables are then:

\[ Q_i = \text{mass of material (solids and water) in stream } i \]
\[ X_i = \text{fraction by weight of solids in stream } i \]

and the material conservation laws are the conservation of material (solids and water: wet solids, slurry):

\[ \sum_i M_i Q_i X_i = 0 \]

and the conservation of dry solids:

\[ \sum_i M_{ij} Q_i X_{is} = 0 \]

The advantage of these formulas is to keep the individual accuracy of wet mass and solid content measurements. It also increases the redundancy when the water balance can be simultaneously calculated.

When considering hydrometallurgical plants, the multi-phase balance is absolutely necessary (Deglon and Gaylard, 2008). Considering an ore leaching plant or selective precipitation plant, the handled material is slurry with solids (ore or precipitates) and solution. Both are characterised by their metal contents (metals or other elements if they are relevant for metal accounting). The variables are then:

\[ Q_i = \text{mass of slurry in stream } i \]
\[ X_{il} = \text{fraction by weight of liquid (solution) in stream } i \]
\[ X_{is} = \text{fraction by weight of solids in stream } i \]
\[ T_{ism} = \text{fraction of metal } m \text{ in the solids in stream } i \]
\[ T_{ilm} = \text{fraction of metal } m \text{ in the liquid in stream } i \]

with the constraint:

\[ 1 - X_{il} - X_{is} = 0 \]

The material conservation laws are the conservation of slurry which is always used (except if some losses, such as evaporation, cannot be measured):

\[ \sum_i M_{ij} Q_i = 0 \]

the conservation of solids which is used for all process stages, for which the solids are neither dissolved nor precipitated such as decantation, filtering, classification, or cyanidation (for which the loss of ore mass is negligible compared to the measurement errors):

\[ \sum_i M_{ij} Q_i X_{is} = 0 \]

the conservation of liquid which is used for all process stages in which the solids are neither dissolved nor precipitated:

\[ \sum_i M_{ij} Q_i X_{il} = 0 \]

the conservation of metal \( m \) in the solids which is used for all process stages in which the metal is neither dissolved nor precipitated:

\[ \sum_i M_{ij} Q_i X_{is} T_{ism} = 0 \]

the conservation of metal \( m \) in the liquid which is used for all the process stages in which the metal is neither dissolved nor precipitated:

\[ \sum_i M_{ij} Q_i X_{il} T_{ilm} = 0 \]

In the case of a phase change (solid dissolution or precipitation), the global mass has to be considered for the metal \( m \):

\[ \sum_i M_{ij} Q_i X_{is} T_{ison} + \sum_i M_{ij} Q_i X_{il} T_{ilom} = 0 \]

All these equations are mass based while the measurements are generally volume based (tank volume, volumetric flowmeters). The slurry density has to be measured and the mass error calculation is based on its measurement error.
The simultaneous material balance calculation of many components adds redundancy to the system and improves the accuracy of the metal accounting (Morrison, Guin and McCallum, 2002; Guerney, Dunglison and Cameron, 2005). The choice of the components to balance is crucial for the quality and the accuracy of the material balance. The metals (or components) of economical interest have to be considered. But other components can be accounted for their ability to improve the material balance. That is the case of major components for which accurate content can be measured. These components can enhance the poor estimates of some masses. Some components which are clearly separated in some units of operation can improve the material balance whereas some masses cannot be measured. In pyrometallurgical plants, where the mass conservation cannot be verified due to gas losses, some components report only in the measured streams such as Si in a furnace reporting to matte and slag.

**Inventory of stocks and work in progress**

There are two methods to manage the inventories:

1. The quantity and quality of the real stock are accounted for at the beginning (opening) and at the end (closing) of the considered period. The beginning inventory is then considered as an input stream and the ending inventory as an output stream, the ending inventory becoming the beginning inventory of the following period.

2. Only the variation of the stock is considered as an output stream with a positive mass value when the stock is growing and a negative value when it is decreasing.

Naturally, the first method is preferable as it is closer to the reality and the stock taking gives an estimate of its quantity and quality at a given time. The second method can be used in case of uncertain stocked quantity which cannot be measured directly.

As previously pointed out, the stock taking is difficult to perform and less accurate than the material movements (Wortley, 2008; Holmes, 2008; Connelly, 2009). The WIP measurement is difficult and generally much more inaccurate. It is sometimes preferable to ‘calculate’ the inventory (mass and contents) from data which have been measured in material flow conditions. In that case, a ‘stock model’ is used, considering the feeding streams and the reclaiming streams with their timetable (quantity and quality of material versus time). The stock can be considered as a perfect mixer (such as an agitated tank), a FIFO (first input, first output) or a LIFO (last input, first output). Using this method, it is preferable to identify each stock (stockpile, tank, etc) with a node in the material flow diagram. Indeed, the main risk is to consider the discrepancies between the expected and real production into the stocks and, after many months, obtain a figure far from the reality. The management of small stocks with frequent depletion can reduce this risk and yields a more accurate material balance.

More advanced stock modelling may be required when stock taking is too difficult or costly, such as heap leaching (Gebhardt and Cross, 2008) or cathodes in progress which can be accurately obtained by indirect measurement.

**Basis data calculation**

As defined above, the basis data is the result of the sum of the masses or weighted average of contents. It is preferable to use raw data than data processed by another system (such as historian). The main difficulty resides in the association between masses and contents in order to calculate a weighted average which is more accurate than a simple mean.

**INVENTEO SOLUTION**

The Inventeo solution (Caspeo, 2012) offers a set of tools capable of addressing most of the requirements described above through the reconciliation modeller. The material accounting frequency can be configured and various scenarios can be considered depending on the availability and quality of raw data. The material flow diagram can be drawn with the desired level of details. The phase model tool permits the description of the material in terms of many phases with up to two levels of description (such as solid/liquid contents and metal contents). Each basis data can be obtained by aggregation of raw data coming from third party databases. Similarly, variance models calculate the measurement error associated to each basis data. The material conservation laws can be easily generated and modified to take into account particular cases which can occur. The analysis tools, based on check in, check out methods, help in identifying abnormal basis data outside the acceptable incoherence due to their level of confidence.

The data reconciliation engine calculates the statistically coherent material balance in one pass. All the streams and components are simultaneously estimated taking into account the level of confidence (accuracy) of each basis data. At the end of the material balance calculation, the errors associated to the estimated values are then calculated. These errors, compared to the error of the corresponding basis data, quantify the improvement of the metal accounting. The analysis tools, based on statistical comparison between basis and reconciled data, are able to point out any issues such as bias or unaccounted losses.

**CONCLUSIONS**

A metallurgical accounting system has to conciliate two points of view: the technical point of view for which the material balance is the product of a statistical approach of the reality and the financial point of view for which the metal balance refers to an exact and coherent economical value in the accounting system. Nevertheless, the material balance is based on measurements which are random processes. The measurement error has to be considered when corrections take place during the data reconciliation process. If the data reconciliation is based on a statistical coherent material balance, as proposed in this paper and implemented in the Inventeo solution, the obtained estimated values are the more probable ones. These values can be accepted by the financial point of view if they have not to be adjusted in the future due to wrong estimation. Any possible future adjustment has to be as small as possible and taken into account as soon as possible. It can be then accounted as gains and losses reported with known and unknown losses. Only an accurate, coherent and transparent metal accounting system can offer this advantage.

Many ways for the improvement of the accuracy of the metallurgical accounting system have been reported in this article. The implementation of such a system appears as a company key project requiring continuous improvements linked to the process changes and measurement system enhancement. If a solution such as Inventeo can address most of these requirements, the implication of the personnel of the company constitutes the main key to its success.

**REFERENCES**


