

Practical integrated metallurgical accounting solutions for supporting production decisions

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Abstract

Metallurgical accounting in the mineral processing industry transforms accumulated process data, including flow rates and assays, into a coherent information format. This is used to rapidly provide production reporting and key performance indications. Comprehensive and coherent data must be a component of any system expected to accomplish reconciliation in the mass-balancing process. Quality issues are thus improved with such desired methods via a mass-balancing engine utilizing the results of measurements acquired by various on-line sensors, analyzers and sophisticated laboratory equipment. Metallurgical accounting, when accomplished through such an engine, provides high-value information in a simple, straightforward and simplified manner. Exceptional utility is then transparently available to authorized personnel for access to metallurgical accounting reports, production reports, mass balance results, performance indicators, and so on. This paper discusses how such information can be used to "drill down" into each result set by consulting the data hierarchy to evaluate and validate calculations and input data used to produce the specific results being queried. The power of such a system resides in the full and true integration of all production and laboratory data. What is integrated are the data thus acquired via a single user interface, a single database, a single configuration tool, etc. From this comes the derivation of contextual information and its maintenance. It is possible to reduce metallurgical accounting and production reporting from possibly hours or even days to a matter of minutes. The result is maximization of information reliability and availability from masses of otherwise discrete and difficult to access key data.

Key words: Metallurgical accounting, Knowledge management, Plant processing data

Introduction

Integration in knowledge management systems. The operation and management of an industry-specific mineral processing plant data system requires the evaluation of data from various sources to get the most complete picture on the performance of the plant. The raw data available from the different sources are typically not consistent because of limited accuracy of the installed instrumentation. Some of the variables might be even not be available because the costs of instruments cannot easily be justified or because they cannot provide direct measurements.

By using an integrated data-management system, the inconsistency of the different measurements can be automatically resolved by mathematical methods or can, at least, be highlighted for further corrective or adjustment actions. These actions may be in the form of recalculations, formulae adjustments, or simple validation.

Additionally, the integrated data management system automates the flow of data between different departments of the mine production units, various data sources and information consumers throughout the site. Such an integrated data management system would make all information available in real time to those authorized users connected to the intranet or the company's wide area network (WAN).

Knowledge management

Structure and modules. Knowledge Manager (KM) is a modular solution (Fig. 1) and is the environment for a number of industry applications. It can be tailored to meet a company's specific requirements and can be expanded to incorporate up to several hundred users and multiple production plants. The basic system comprises all functions and components for communication and data collection, data storage and presentation. There exists a basic set of templates and ready-to-use

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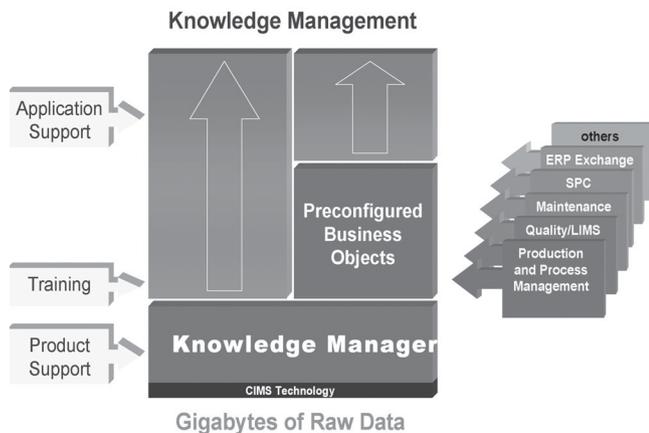


Figure 1 — Knowledge Manager modular structure.

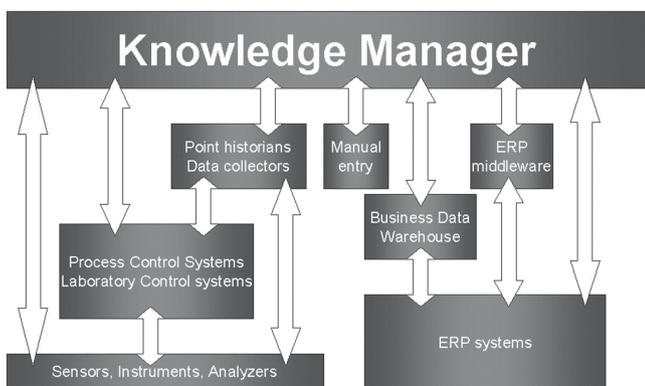


Figure 2 — Knowledge Manager and IT systems.

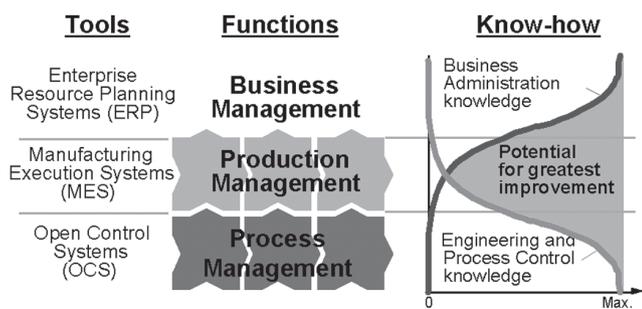


Figure 3 — Relationships between systems in a mine/plant.

Plant people and IT (information technology): Knowledge Manager is a solution for and by plant people. The concept has been designed, built and maintained by industry specialists together with IT development experts. Though using the latest and mainstream IT technology, the key to efficiency and utility relies on the principle that a Knowledge Manager is implemented for daily use by non-IT experts.

A solution using Knowledge Manager is primarily focused on production mine/plant management and personnel. The system is often “owned” and maintained by the users: plant management, production, maintenance or automation departments, especially in operations with limited or no IT departments. After fine-tuning, the system is often mainly used by administrative personnel as part of assisting plant management functions. Knowledge Manager system is built specifically for such a profile of ownership.

Information integration.

Production plant information management: Functionally, KM consolidates isolated data from a multitude of subsystems, turns it into meaningful information and produces the results for a variety of different purposes:

Via a Web-based user interface, results are directly presented to users in analyses, reports, lists, trends and graphs for both reporting and making plant decisions. Transformation to transactional data produces direct input for BDW (business data warehouse (BDW) and enterprise resource planning (ERP) systems. Key performance indicators (KPIs) are then processed for monitoring, reporting and storage in BDWs

To perform these functions, KM integrates and connects easily with other common plant IT systems. As a result of its central role in plant information management and its versatile connectivity, the system often acts as the integration platform between these systems. This provides the environment for production accounting purposes. KM handles information consisting of process and production values, calculations, energy consumption, plant emissions, running hours, events and alarms, raw material, fuel, product quality measurements, production stops and low rate production runs, etc. Most of this information requires reliability, consistency and is often time critical. Often the availability of the information is business critical and is required for operating permissions (Fig. 3).

By proactively using this information, the gap can be bridged between what is happening in the process and what is happening on the business side. KM not only makes relevant process and lab data available to production people, it also makes it available throughout the organization. By incorporating process, business, maintenance and even planning data, KM is a critical component in total plant optimization and management. Functionally, what is also provided is critical information for effective planning of limited resources (silos, shops, stocks, energy, etc).

Metallurgical accounting — general. Metallurgical Accounting, as perceived herein, ensures full coherency of available data while improving data quality through a reconciliation process of mass balancing.

The use of an engine to accomplish this allows for the various data sources within a mine/plant to be fully used, validated and improved. Consequently, the resulting information contributes added value to published information. Measurements that are often acquired at high costs with on-line sensors and analyzers, or sophisticated laboratory equipment, are used to their full extent.

applications for a wide range of reports and lists, which effectively supplements this system.

The basic version of such a system can be expanded by a variety of software modules to keep pace with specific requirements. There are specialized modules for production and process management, maintenance support, statistical process control, laboratory management, production accounting, etc. (Fig. 2).

Metallurgical Accountant™

Overview. In modern processing industry, maximum production is not enough anymore. Everyone must think in terms of maximum productivity. Key issues then become reliability, flexibility, and adaptability. Decisions are based on limited information, sorted and extracted from the huge amount of numbers available in process and management databases. To maintain their confidence in the numbers they use on a daily basis, managers and engineers must rely on systems that output performance indicators in a systematic approach, based on proven technologies and reflecting a clear image of the reality. Metallurgical Accountant offers to managers and engineers this reliability, flexibility and adaptability.

Production accounting. One of the most time-consuming and tedious tasks dedicated to metallurgical engineers is the computation of production numbers used by the accounting department. This task requires the conciliation of hundreds of variables at the same time and often results in an oversimplification of the problem. Metallurgical Accountant is a software suite especially developed to fulfill the needs of automatic production reporting with reconciled information. One of its major features is its ability to run data reconciliation problems in background and only outputs results through reports and emails. Daily or shift material balances are automatically set up, run and reported to the configured addresses. A final step using engineer validation can be introduced in the chain.

Process monitoring. Everyone knows that online analyzers can be faulty, but no one knows when they become in a faulty state. Only process upsets can lead to the detection of badly operating analyzers. Indicative material balance (IMB) can effectively support process monitoring and help maintain the reliability of the numbers used in performance indicators calculations. This type of material-balance problem runs at relatively high frequency, in the order of minutes, and outputs the results directly in the real-time database supporting process operation. Reconciled information is then available for process operator and engineers.

What is meant by data reconciliation? Data reconciliation through mass balancing is the specific means by which information is made useful and functional. In the mine environment, sensors and instrumentation are rationalized in a manner so as to generate minimum levels of data redundancy. This enables mathematical improvement of data (supported by mass conservation equations). Data reconciliation via this means (mass balancing) improves accuracy of process and assay data. This resulting reconciliation benefits the entire plant operation by providing access to those variables/values that cannot be directly measured. Mass balance calculations use flow measurements and assay data to improve on input data relative to quantity and quality information in either real-time and/or reporting periods.

In most mineral processing industries with increasingly stringent economic constraints, analyses on fractions and sub-fractions have become part of the daily routine. Few data reconciliation solutions fully support these types of measurements and their complex inherent mass conservation constraints.

Reconciliation solutions pioneered by applications derived from other sources (such as the power and petrochemical industries) are, however, inadequate to reconcile Level III and Level IV data. These would include, for example, chemi-

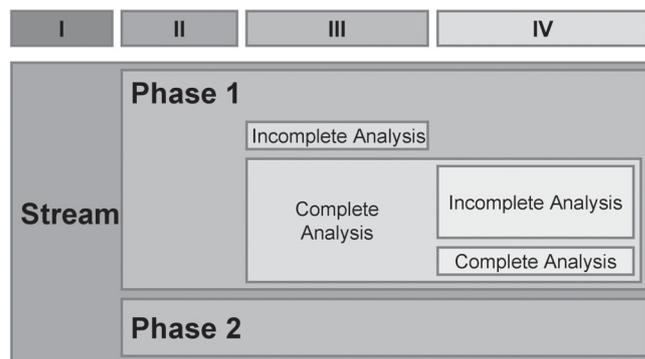


Figure 4 — Structure of the available measurements.

cal analysis of each size fraction of a solid sample and fineness analysis of the residue of the size fraction from a solid sample.

Data reconciliation with Bilmat™.

Description: Before discussing the algorithm of Bilmat and its functionalities, it is important to understand the structure of the measurements and the constraints associated to them. The data structure takes its root with the stream and represents Level I-type information (Fig. 4). The Stream can be split into phases. Bilmat handles two phases, 1 and 2, but does not allow for analyses in Phase 2. Complete and incomplete analyses can be handled for Phase 1. They correspond to Level 3 analyses. An Incomplete analysis provides information about a fraction of the bulk phase flow and leaves the rest unknown. A Complete analysis provides information about the entire bulk phase flow and allows for more detailed analyses at Level IV, replicating the structure of Level 3. It is obvious that the complete data structure imposes some constraints on the analyses and their relations. Bilmat is built to intrinsically handle all the structure constraints imposed by the most complex dataset.

The measurements at the various levels pertain to two large families: process and laboratory measurements. The lower the level, the higher are the chances the measurement comes from the process and the exact opposite with the highest level. Hence, Level I and II are basically flow rate measurements. The phase fraction is also part of these levels. Level III measurements are chemical analyses or distributions (size or density). In a case where there are many phases in a stream and they are not analyzed individually, they can be assimilated to a complete analysis. Level IV measurements are of the same type as Level III measurements but are made on each or one of the fractions of the complete analysis of Level III. Here, it is very important to handle the possible coherency constraints between Level III and IV analyses.

Levels II and I are linked and cannot be treated individually because the phase fraction bridges them. Where applicable, conservation equations are written for the stream, Phase 1 and 2 conservation as well as the equations for the phase fraction content of the stream.

Level III expresses the conservation of the individual analyses made on Phase 1. Level IV consists in specific analyses performed on the various fractions of a complete, "mother" analysis.

As stated in the mass balance document, the technique supporting both Matbal and Bilmat requires the error model i.e. the error attached to each measurement. This is often the major challenge in obtaining a reliable mass balance result

and explains why effort has been made to provide users with valuable tools to develop a good error model. The Visualization sheet and the validation module are two valuable tools to support the users in the development of the appropriate error model.

The Bilmat Engine. The BILMAT algorithm, originally developed at Laval University following the work of Hodouin (Hodouin Everell, 1980; Hodouin et al., 1981; Hodouin Flament, 1989) is based on fundamental principles that take into consideration the statistical properties of the data errors and all the mass conservation equations implied in a flow sheet. The algorithm solves the system of mass conservation equations in the case where the measurements are redundant - that is in a number greater than needed to calculate the missing data. Because the measured values do not verify the mass conservation equations due to errors in measurement, the algorithm adjusts them. The adjustments are made as small as possible and in agreement with the reliability of the measurements. Though, the adjustment realized on a measurement qualified as poor (i.e., obtained by poor sampling or poor analysis) can be larger than that on a measurement qualified as precise.

Generalized least-squares method: Many methods of material-balance computation assume that the experimental values of the assays are their best estimate. Below, a method is discussed in which the experimental values are also adjusted by an amount such that the sum of squares of all adjustments is minimum, whence the name “least squares” method.

If best estimates \hat{x} and \hat{W} are associated to each assay x and flow rate W , the maximum-likelihood estimators for a normal population of x and W are such that

$$\sum (x - \hat{x})^2 + (W - \hat{W})^2 = \text{minimum} \quad (1)$$

This estimator is also called an “estimator of minimum variance.”

In a process where x and W have been measured, one may want to calculate the best estimates \hat{x} and \hat{W} . These can be obtained by solving all valid mass balance equations in the flowsheet.

The notion of data redundancy is sometimes very subtle and hard to grasp at first. In particular the Bilmat presentation is based on the concept that the only true variables to be estimated are the flow rates and that the number of equations is therefore usually much larger than the number of unknowns. The solution to this problem also happens to produce better estimates of the assays. The MATBAL presentation, from the onset, classifies assays and flow rates as problem variables for which better estimates are sought. In that case the number of equations is smaller than the number of variables. Nevertheless, both programs solve essentially the same problem.

The Sensitivity Analysis in Bilmat (Hodouin et al., 1988): No material balance problem is complete without a value being calculated for the precision of the flow rate estimates and, ideally, for the resultant adjusted assays. In other words, the confidence interval of the material balance results must be estimated.

Therefore, the benefits of a sensitivity analysis are:

- assessment of the error on the estimates and
- reflection on the experimental results and on the error model used to perform the computation.

A following basic principles of statistics must be reviewed to better understand the sensitivity analysis:

- For a normally distributed variable, the mean value and the standard deviation of a series of measurements (sample) are the maximum-likelihood estimates of the distribution parameters. They are estimates of minimum variance.
- It is assumed that the residuals and the errors are normally distributed. The estimates being of minimum variance, the variance of the calculated variables is smaller than, of equal to, that of the experimental variables. Similarly, the variance of the residuals is smaller than that of the errors.

The sensitivity analysis consists in studying the relationship between the error model of the experimental data and that of the calculated estimates. The question is: How sensitive are the results of a mass balance computation to errors in measured variables?

A detailed and informative description of quality of performance indices calculations based on reconciled information can be found in Hodouin and Flament (1991)

Besides providing the evaluation of the reliability of the results, the sensitivity analysis allows a classification of the data with respect to the amount of information they contain. This aspect of the analysis is very important because it helps to define a more appropriate sampling strategy. The measurement corresponding to very informative data should be very carefully performed, at the same time variables that contain very little information can be eventually ignored in the data collection step.

Finally, sensitivity analysis aims at detecting outliers by comparison of the adjustment calculated by BILMAT to the assumed error model. However, it must be pointed out that the concept of outliers is relative to the assumed error model, as a particular value can behave as an outlier only because the error model is inadequate due to a bias or an under-evaluated variance.

Information flow. Mass balance sessions, if of prime importance, are not the ultimate goal of Metallurgical Accountant; its main role is to be in such a position that many management systems can use and benefit from the very reliable data generated within the product. This is why information, after every mass balance completes, is made available for any type of reporting (Fig. 5).

The metallurgical accounting task can be divided into the following six distinct steps: data acquisition, filtering, preprocessing, data reconciliation, validation and reporting. Every step has its own purpose, task and intelligence. The central part is obviously the data reconciliation step with three different steps to properly setup the problem with reliable values. Validation consists of a recommended step following reconciliation and within which an engineer electronically signs the results before they become available for publishing. During validation, all Bilmat modules are available to support the work such as the validation module aiming at the detection of bad measurements and/or badly adjusted values (Flament et al., 2001).

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Reconciled information.

Indicative mass balance – Description of IMB: The “indicative material (mass) balance” functionality is an additional feature of Metallurgical Accountant. The purpose of this indicative material balance is to provide on-line process monitoring with reconciled values. Therefore, there is no validation or manual interaction within the IMB process. It is a fully automated mass balance application.

- At a configurable period, 15 minutes for instance, the Metallurgical Accountant conductor starts the accounting cycle.
- The data acquisition module performs a data gathering into the real-time database. As for the accounting feature, filtering and pre-processing are performed. They are, however, configured for the specific task of indicative mass balance.
- Data reconciliation is executed in the same fashion as for the accounting purposes.
- No e-mails are sent for validation. The results are immediately posted for process monitoring usage. Performance indicators and some unmeasured streams analysis of flow rates become available with a high degree of reliability without being measured.
- Upon completion, the results can be written into the Metallurgical Accountant database, reported or written into the real-time database of the process.
- The cycle is completed and ready to the next indicative mass balance.

Metallurgical Accounting – Description of PMB:

- Upon triggering from the Metallurgical Accountant conductor, the data gathering and filtering engine scans

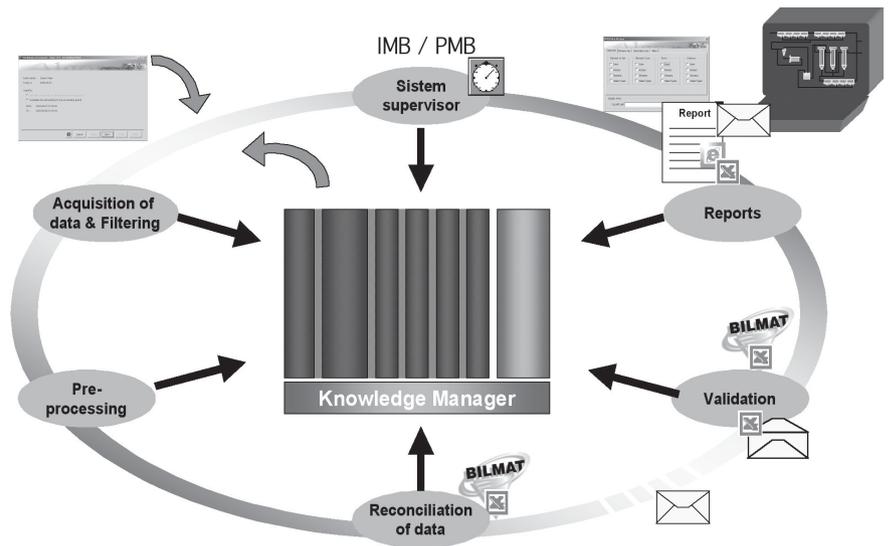


Figure 5 — Information flow within the accounting module.

the target databases for daily production data. When available, the raw assays and the production data from the real-time database are transferred into the Metallurgical Accountant database. If manual entries are required for a given scheduled mass balance, it is validated at this stage.

- The required data filtering is performed. Filtering can be implemented to remove bad readings from the balance. A bad reading can be totally excluded, its value altered according to preconfigured values or a replacement value can be calculated.
- Preprocessing may then be required in case of dynamic data reconciliation. It is also required to transform certain types of readings and force the fit into a mass balance problem.
- Bilmat™, the operative on-line PMB engine, reconciles the process data. The supporting Excel workbook is built according to the plant configuration during the concerned accounting period.
- The conductor sends an email to the process engineer for validation. The current Excel reconciliation document is sent as an attachment. The data processing cycle is now broken. Only the validation from the dedicated engineer can make the processing cycle continue.
- The process engineer receives the email with its Excel workbook attachment advising him that the raw and reconciled data are ready for validation. From any workstation, a stand-alone network version of Bilmat is used to validate both the raw and reconciled values. Any number of material balances can be executed locally without interfering with the database. The raw assays can be manually modified, and reconciled values recalculated at will.
- When the process engineer is satisfied with the results, a global comment about the validation can be added. Comments can also be entered on a per-value basis. The validated raw assays and the new reconciled values are then committed to Metallurgical Accountant database.
- The final production report is generated, viewed and printed if desired. Emails are sent to selected addressees.

- The production mass balance cycle is now completed and ready for the treatment of the next period.

Inventory management. The inventory management system keeps track of material flows and the inventory of raw materials, fuels, and intermediate and final products. This is accomplished by taking the data on production and consumption from the process control system, and data on shipments/received material from the dispatch system. This information is used to keep the technical (i.e., calculated) inventory data up to date. The inventory management system supports stock modeling with grade blending, in, for example, tanks and mixing stock beds. In other words, the inventory management system tracks quantity and the chemical composition of process materials as well as finished product in various storage locations.

The inherent inaccuracies of reports of material flows are accumulated over time in calculated technical inventory data. To correct these and other discrepancies, the actual stock levels are measured or estimated regularly (e.g., once a month) and entered into the system in order to adjust these stock levels. Adjustments of the stock levels are further used to fine-tune and balance production and consumption data (Fig. 6).

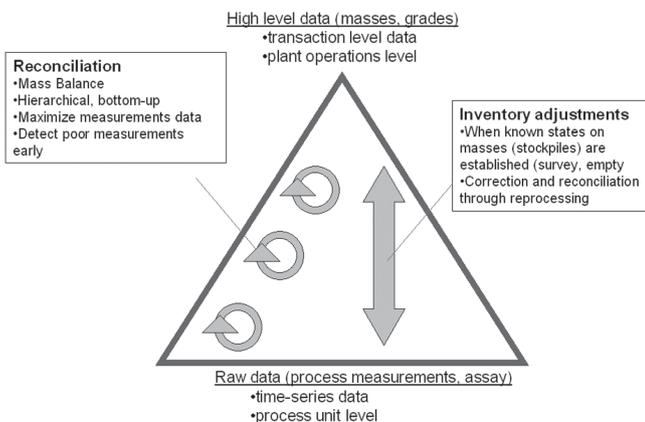


Figure 6 — Adjustments vs. reconciliation in the data hierarchy pyramid.

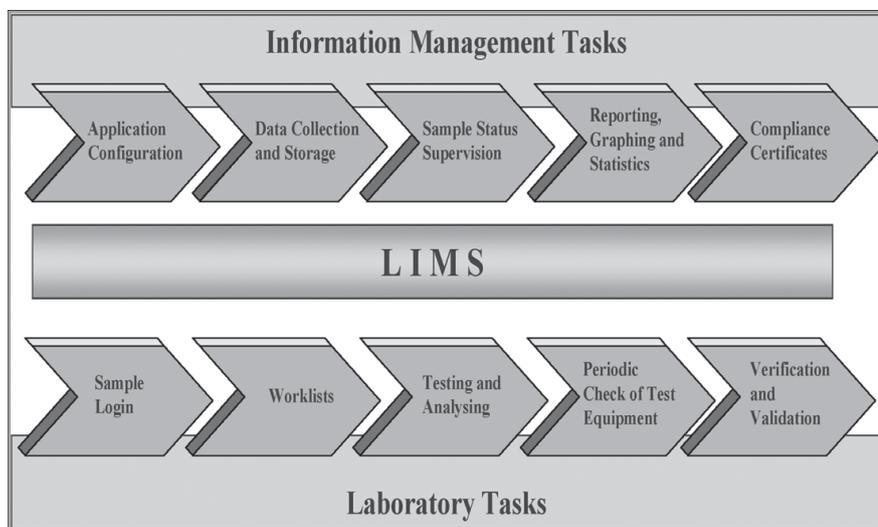


Figure 7 — Overview of KM LIMS tasks.

To support such adjustments, the ideally configured system provides interactive reports and graphs with drill-down capabilities on all material flows to and from stocks. These high value-added functions are part of our system and support the user in a manner designed to quickly detect and resolve inconsistencies in the inventory data with maximum flexibility tailored to specific plant needs.

The benefits of the knowledge-based expert optimizing system as described here are:

- consistency of process operation,
- higher operator performance,
- improved productivity,
- better product quality,
- savings in energy and maintenance/environmental costs,
- ease of maintainability and
- long-term process enhancement.

LIMS: General functionality. KM LIMS is designed to manage the quality information according to good lab practices. This management covers tasks from the routine quality controls to final product quality controls and compliance certificates. The function of LIMS is to provide advanced means to document quality information, make it easily accessible, transparent and to increase the knowledge of plant personnel of what is happening in the process. The system provides the basis for direct process and quality control, for day-to-day management decisions in production and marketing and for long term improvements and developments.

LIMS includes functions such as automatic and manual data collection, data validation, data consolidation, long-term storage, calculations, sample logging procedures, sample status reports, work lists, standard and compliance reporting features, easy to use means for trending, graphing and options for EXCEL and SPC applications.

Tasks can be divided into two main categories (Fig. 7):

- information management tasks and
- laboratory tasks

Quality-related information thus becomes an integral part of a plant information system. The quality information collected from the raw materials, process and final products can be divided into the following three groups:

- quality analysis to provide timely feedback to production process control,
- raw material and fuel analysis for recording and adapting production quality planning and
- end-product quality analysis for compliance reporting

LIMS in a collaborative solution. Expensive instruments (e.g., chromatographs) are often installed only in one laboratory of an enterprise and perform analysis services for multiple production plants. These production plants are usually geographically spread. In such a situation, samples taken from multiple production plants are sent to the plant with the specialized analysis equipment. However, these plants could all have their own independent LIMS server because most

of the analyses are done locally in the production plants.

When a sample is registered in Plant A and sent to Plant B for certain analyses, collaboration between KM LIMS A and B is required (Fig. 8). The workflow is mainly executed in the lab from Plant B, while the information requirement is mainly in Plant A. KM LIMS supports such implementations. Obviously a communication infrastructure between the two locations must be available.

Integrated solution for production decision: The CVRD – Sossego Case

Sossego Project, CVRD, Brazil: Overview. Sossego will implement an integrated data-management system using automatic collection of data from multiple sources in the plant. The data are then used by various copper-specific software applications that operate as part of the integrated system (Fig. 9). They include:

- data reconciliation,
- metallurgical accounting,
- production and inventory management,
- maintenance support and integration to Maximo and
- LIMS.

This is the latest installation of CVRD. It will have an “integrated” plant information management system, i.e., a PIMS/MES than runs on a single server with one software infrastructure, database, etc. where the five copper specific minerals applications are installed as additional “software plug-ins.” Most previous plants have installed separate point solutions or applications running on separate servers, which can require complex interfacing and upgrading. This integrated solution will achieve a lower overall life cycle cost.

Data reconciliation. The functionality of this application is data reconciliation through mass balancing. Data reconciliation via mass balancing improves accuracy on process and assay data

Metallurgical accounting. Metallurgical Accountant in Sossego’s PIMS provides integration of all production and laboratory data to a single user interface, using a single database and engineered by a single configuration tool. Functionally, this procedure results in the reduction in time necessary for using these data for reporting and control from several hours, or days, to minutes. Information reliability and availability is maximized.

Production and Inventory Management. The inventory management system keeps track of metal from the entry of ore

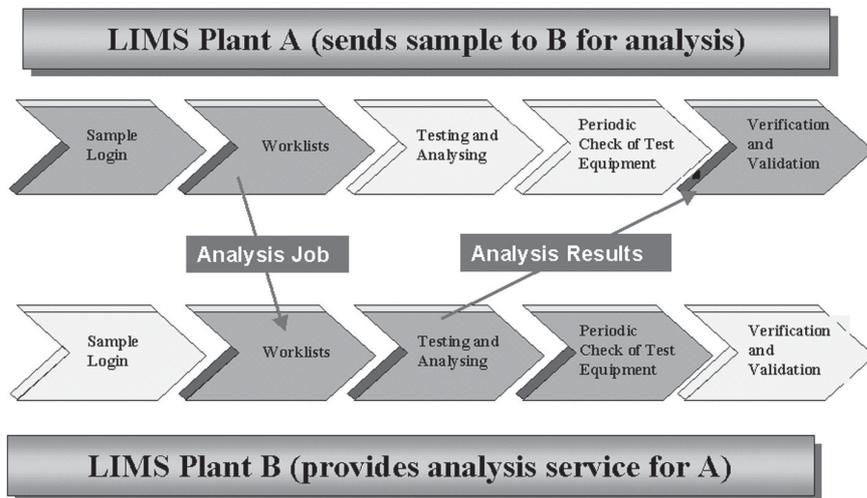


Figure 8 — Collaborative LIMS.

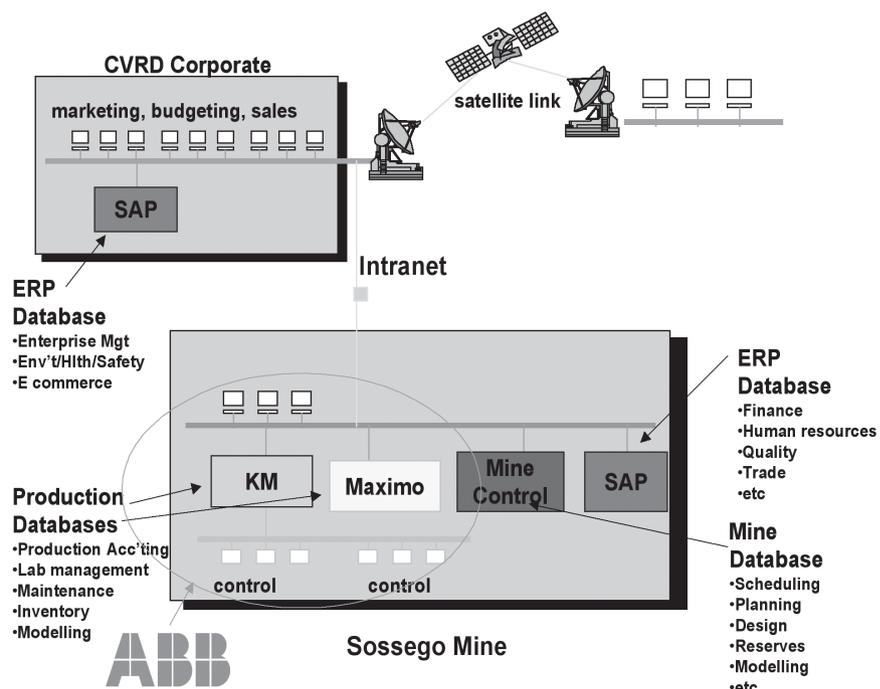


Figure 9 — Sossego case.

materials into the crushing area through to the Cu concentrate stockpile. The system takes the data from the process control system and shipments and received material from the dispatch circuit. This information is used to keep the technical (i.e. calculated) data up to date.

Maintenance support. The maintenance management system used at Sossego is Maximo™ that requires information, available in the PIMS. The first task of the maintenance support module is to administer the relevant run time and load factors on plant equipment. (This is required for condition-based monitoring and maintenance planning.)

The second task is to track all the production stops and breakdowns in the plant. These stops are classified using

predefined cause and effect diagrams. In addition to production stops, low production rates can be recorded as events. All unplanned stops that require repair or maintenance are uploaded to the maintenance management system.

LIMS at Sossego. The (laboratory information management system (LIMS) at Sossego supports the entire laboratory workflow from scheduling of samples, preparation, ID entries, recipes for analytical procedures, special requirements, tracking, results, approvals and validations through acceptance and process inputs.

Conclusion

Modern mineral processing employs various forms of metallurgical accounting for a variety of critical applications. Availability of information required to economically manage the multiple-process task units in an integrated operation depends on speed and accuracy as well as a reliable means of coherency. To maximize the benefits of acquisition of quality results derived from both in-process and centrally located sensors, an engine for gaining detailed metallurgical accounting information is required. Integration of production and quality data via such an engine using one common database avoids issues of difficulties in reconciliation and maintenance of the many types of data collectors throughout the operation. The benefits are gains in productivity and quality operations

provided by means of such an engine reduces the time required for access. Thus, reports and ultimate utilization of needed critical information are available in a matter of minutes instead of hours. This leads to real management capability, production economies and profitable operation. Accessibility and, therefore, immediacy of useful information also eliminates the time-consuming resolution otherwise required for dealing with massive data and their relative complexity of discrete data sources.

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