Traceability in continuous grinding circuits

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ABSTRACT

Traceability is the means to identify and follow real or imaginary lots through a process chain. It gives the opportunity to back-track a chain of events, or to predict process outcomes given the origin of a lot.

Traceability can be used in different areas, e.g., in the middle of 1990’s traceability was a hot subject when different cases of food-carried diseases were exposed, but traceability is also used in other process industries to follow material and products during the processing. There is, however, a lack of traceability in continuous processes to compared with batch processes; The reason is that it is more complicated to identify a lot, and reach good traceability, in continuous process just because of they are contiguous.

In this work, an example is the continuous ore beneficiation process at LKAB (Luossavaara-Kiirunavaara AB, Sweden) Malmberget. The purpose is to trace the ore through the grinding sections by parameters and signatures like particle mineralogy, mineral associations and particle texture. To follow the material through the different process steps, analytical methods like optical microscopy and Particle Texture Analysis (PTA) are used.

In paper I, different traceability methods to achieve traceability in continuous processes are explained. The advantages and disadvantages are presented for each method.

Paper II is showing the relations between the materials that comes into the grinding circuits. It also explains the PTA result, such as modal mineralogy, mineral liberation and mineral association. The feed and discharge for each mill is thoroughly investigated in this paper, which confirms that there are slight variations in results between section 5 and section 6.

In paper III, data collected from the PTA analysis is subjected to multivariate data analysis. A multivariate model explaining the observations was developed. The results show that there are systematic variations in particle morphology along the process chain, but also between the grinding sections. The combination of automated process mineralogy and multivariate analysis is unique, and is first presented in this paper.
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LIST OF APPENDED PAPERS

This thesis is based on the work reported in following papers:


1 INTRODUCTION

1.1 General

In beginning of the 90’s mad cow disease or Bovine Spongiform Encephalopathy (BSE) was a important topic around the Europe. Only in Britain 137000 cases were reported (Lacey, 1994), it was a disaster for cattle market and many of farmers were ruined because of this reason. In May 1999 the chicken dioxin crisis were known and in beginning of 2001 the foot-and-mouth disease created crises in the food industry around the world (Dupauy et al., 2002). At the end of the 90’s the traceability and tracking of meat became very important and automated system from farms to slaughterhouses were developed and implemented (Mousavi et al., 2002).

As a consumer of meat it is important to know where the meat is coming from and for the food companies to be able trace back if something is detected with the meat. Traceability makes it possible to find the source of the causes and to be able makes changes fast. An ideal traceability system must be able to track the history of both product and activities that are involved in the process (Kim et al., 1995).

Traceability is today used in several industries, such as pharmacy, food, pulp and paper but also starting in the mining industry.

Mining or extraction of valuable minerals is one of the oldest and important industries in our time history. Minerals have been used for a long time, and still today the market is growing. Iron is the most commonly used metal around the world, and iron ore is the main raw material that is used in steel.

LKAB has since the beginning of the 1900’s produced iron ore products from mines in Kiruna and Malmberget and is today one of the world’s leading producers of highly refined iron ore products. The main product is pellets, for blast furnaces and direct reduction furnaces. Today there is a higher demand from the customers and to obtain a good quality it is important to have good control over the process and the raw material used.
1.2 Scope of the work

LKAB is a mining company that extracts and refines iron ore from deposits located at Malmberget and Kiruna. Because of the greater demand of pellets, the primary product at LKAB, the company invested in a new pelletising plant at Malmberget 2006. With a new pelletising plant the production increases, and raw material from both Kiruna and Malmberget is mixed into the feed. The iron ore from Malberget and Kiruna behave differently during the refinement process, because ore from Malmberget has a coarser grain size and different kind of grain boundaries and different level of contaminants compared to Kiruna ore (Martinsson and Wanhainen, 2000). This means that there might be a risk for quality variations in the final product, this is why traceability becomes an important aspect.

By looking at the mineralogical characters and the chemistry through the whole process useful data is collected to achieve traceability in the process.

There are also other factors which are interesting, the mineral shape has been stressed in many papers but in this case we are interested to find out any systematic changes during the process with the mineral grains.

This project is divided in three parts, the participant are three Ph.D. students from different divisions and their supervisors, also some people from LKAB are involved in the guidance of the project.

Figure 1. The structure of the project and connections among the researchers.
Cecilia Lund from the Division of Ore Geology and Applied Geophysics is collecting data from the ore bodies in the mine at Malmberget. Pejman Oghazi from the Division of Mineral Processing is collecting data from the concentrator at Malmberget and Björn Kvarnström from the Division of Quality and Environmental Management is collecting data from the pelletising plant at Malmberget. The main theme of this project is to achieve traceability from mine to final product.

1.3 Outline of the thesis
In this thesis a short introduction of traceability in batch and continuous processes is done in chapter 2 and the chapters after that are explaining mineral liberation and process mineralogy in general. In chapter 5 the experimental part is described and how the sample preparation was done. In chapter 6 the different analytical methods are described but also an introduction of using multivariate data analysis. Finally, in the last chapters there are results and conclusions and how future work might be brought forward.

2 THE TRACEABILITY IN A PROCESS

2.1 Process in industry
Processes can be divided in two types, batch processes or continues processes. There are several types of process industries, it is important to know the differences between different kind of processes regarding to how material is mixed and product is behaving in the process (Dennis and Meredith, 2000).

To produce a product the raw material will go through different operations such as mixing, separation, and chemical reaction. In continues processes the material will go through the operation that is mention above with nominal interruption.

Most of the research and use of traceability is done for batch processes or part production, i.e. food industry or pharmacy production. By using tags or markers it is easy to follow each batch through the process. In continues processes there are some factors that differs compared to discontinuous processes, it is not possible to tag the material during the process because the material usually changes state and form but there are also sub-flows and other reflux flows that is mixed with the main flow which makes the traceability problematical. It is necessary to have a good overlook over the process to be able to choose a suitable traceability method for continues processes, further information can be found in Kvarnström and Oghazi (2008).
2.2 Traceability

Traceability can be defined in many ways, the meaning is to be able trace or track and get information. Traceability can be defined as the ability to trace the history, application or location of an entity, by means of recorded identifications (ISO 8402, 1995).

There is not a lot in the literature about traceability, Töyrylä’s name is one author that is often mentioned when the word traceability is used. Töyrylä’s definition of traceability is “the ability to preserve and access the identity and attributes of a physical supply chain’s object” (Töyrylä, 1999). There are others that define traceability, Kvavmström has made an excellent table in his thesis where he lists them (see Kvavmström 2008, p. 6).

According to Golan et al. (2004) the definition of traceability can be broad, because most of the time the processes are very complex. Traceability is a tool to achieving different objective and can never be complete. To have control over all inputs in a certain process will be a hard work and very costly, he also mention that there are three words that is important with traceability, breadth, depth, and precision.

<table>
<thead>
<tr>
<th>Breadth: The quantity of the information that is collected. It is important to collect the key object that provides us with important information.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth: How far back or forward can the traceability be used, and how much is necessary?</td>
</tr>
<tr>
<td>Precision: How accurate should the traceability be in certain process?</td>
</tr>
</tbody>
</table>

Usually it is not difficult to determinate the breadth of the traceability if there is a good overview and knowledge of the process and the product. It is more difficult to know how far back the traceability can be used. The precision is a important part of the traceability by using different analytical methods and instruments it will help to achieve a good traceability. However, almost in every case it is the time and the economic issue that reconcile the limitation.
3 MINERAL LIBERATION

To be able to separate valuable minerals from the gangue or unwanted minerals it is important to have good liberation. Liberation is accomplished by crushing and grinding (comminution), and according to Wills (2006) the grinding step is the largest energy consumer in the concentrator but also one of the most important steps.

Analysis of mill products gives valuable information about the mineral liberation. It can easily be done by an optical microscopy; a polished section of the product is enough to judge if the mineral grains are liberated or not. A common method is point counting in grain size fractions (Minnis, 1984). Point counting is a slow process and because of the amount of data that is processed, it is a poor method to rely on.

Today with help of computers good information regarding mineralogy, particle texture, and liberation can be collected fast and easy. The degree of liberation for the main mineral in a mill product is then established by analysing a polished section. Mineral liberation can be measured by image analysis in two different ways, area method and linear intercept method. The area method is based on the areas of the mineral in question and of the host particle in the polished section, and by calculating the percentage of mineral in the particle then the liberation can be known.

The linear intercept method is done by measuring the length of the linear intercept across the exposed areas of the interesting mineral and the host particle in a polished section (Petruk, 2000).
4 PROCESS MINERALOGY

To understand the fundamentals of mineral processing it is important to understand and link every single stage in the process chain. It is the mineralogy and the properties of an ore which determines the conditions for the further processing. To meet these challenges an efficient process can be designed and the mineral treatment can be optimized. (Sutherland, Gottlieb et al. 2000). Moen (2006) defines process mineralogy as the mineralogy which is applied to the product in specific industrial process such as the mineralogy in the concentrator, pelletization or in other process stages.

It is necessary to identify what kind of minerals and textures the ore is consisting of due to the fact that the liberation characteristics are intimately related to the mineralogical texture (Lorenzen and van Deventer 1994). A large amount of information about the ore fines needs to be obtained, like particle mineralogy, porosity, mineral association, texture, hardness, size distribution, mineral liberation and mineral composition (Donskoi, Suthers et al. 2007).

Process mineralogy in this case can be used as a tool which gives detailed information of the mineralogy from different ore bodies which will be linked to mineralogy in the concentrator to improve the mineral processing performance. Traditionally optical microscopy has been used for the identification and quantification for both mineralogical and texturally properties, but this kind of instrument is consuming a long process time (Petruk 2000). The last decades there have been a great development in techniques related to image analyses system based on Scanning electron microscopy (SEM) for a more rapid quantitative estimation and description of mineralogy and particle textures (Gottlieb, Wilkie et al. 2000; Petruk 2000; Gu 2003). QEMSCAN® and MLA both developed in Australia, are the better known instruments. SEM-PTA used in this study is a similar instrument developed at NTNU, Trondheim, Norway (Moen 2006).
5 EXPERIMENTAL

Most iron ore contain significant amounts of gangue minerals that need to be eliminated to produce iron concentrates. At Malmberget, the dominant iron mineral is magnetite but also hematite occurs. Gangue minerals are mostly quartz, pyroxene, apatite, and feldspar.

5.1 Flowsheet

![Figure 2. Flowsheet for grinding section 5.](image)

Figure 2 shows a typical flowsheet for concentrating iron ore at Malmberget. The coarse materials at 10-15 mm in size are fed to a primary wet magnetic cobbing separator (M1). The magnetic concentrate is discharged into a primary ball mill (#1), and the ground product (pulp) is transferred to a secondary magnetic separator (M2). The resultant magnetic concentrate is then pumped into a secondary ball mill (#2). A tertiary magnetic separation unit (M3) finally upgrades the ground product and the concentrate is used as feed for the tertiary grinding stage (#3) (Tano, 2005). The new section 6, cf. Figure 3, lacks the wet cobbing stage.
Figure 3. Flowsheet for the new Malmberget grinding section 6.

Ball mill grinding is used in three consecutive steps, and wet low intensity magnetic separators in between which looks exactly as previous section. It is important to grind to, approximate 68% < 45μm to liberate gangue minerals, and to reach the desirable size distribution for the pellets feed.
Table 1. Data from the mills in section 5 and section 6 (data from LKAB, Malmberget R&D).

<table>
<thead>
<tr>
<th>Section 5</th>
<th>Primary mill</th>
<th>Secondary mill</th>
<th>Tertiary mill</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model:</td>
<td>Mill, Mongdöshammar (CRK245)</td>
<td>Mill, Mongdöshammar (CRK245)</td>
<td>Mill, Mongdöshammar (CRK245)</td>
</tr>
<tr>
<td>Length / EGL:</td>
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<td>5700 mm</td>
<td>5700 mm</td>
</tr>
<tr>
<td>Diameter:</td>
<td>4150 mm</td>
<td>4900 mm</td>
<td>4900 mm</td>
</tr>
<tr>
<td>Inner dimension:</td>
<td>3920 x 5200 mm</td>
<td>4470 x 5400 mm</td>
<td>4470 x 5400 mm</td>
</tr>
<tr>
<td>Install effect:</td>
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<td>5600 kW</td>
<td>3600 kW</td>
</tr>
<tr>
<td>Used effect:</td>
<td>1450 kW</td>
<td>2550 kW</td>
<td>1450 kW</td>
</tr>
<tr>
<td>Speeds Per Minute:</td>
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<td>19.4 rpm</td>
<td>19.3 rpm</td>
</tr>
<tr>
<td>Total filling:</td>
<td>42%</td>
<td>42%</td>
<td>42%</td>
</tr>
<tr>
<td>Grinding media:</td>
<td>steel balls 60 mm</td>
<td>Cu-plate 25x32 mm</td>
<td>Steel balls, 25 mm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Section 6</th>
<th>Primary mill</th>
<th>Secondary mill</th>
<th>Tertiary mill</th>
</tr>
</thead>
<tbody>
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<td>Mill, Outokumpu</td>
<td>Mill, Outokumpu</td>
<td>Mill, Outokumpu</td>
</tr>
<tr>
<td>Length / EGL:</td>
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<td>8000 mm</td>
<td>8000 mm</td>
</tr>
<tr>
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<td>5500 mm</td>
<td>5500 mm</td>
</tr>
<tr>
<td>Inner dimension:</td>
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<td>5350 x 8000 mm</td>
<td>5350 x 8000 mm</td>
</tr>
<tr>
<td>Install effect:</td>
<td>2900 kW</td>
<td>5000 kW</td>
<td>5000 kW</td>
</tr>
<tr>
<td>Used effect:</td>
<td>3900 kW</td>
<td>3900 kW</td>
<td>3900 kW</td>
</tr>
<tr>
<td>Speeds Per Minute:</td>
<td>15.1 rpm</td>
<td>14.0 rpm</td>
<td>14.0 rpm</td>
</tr>
<tr>
<td>Critical Revolutions:</td>
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<td>18.7 rpm</td>
<td>18.7 rpm</td>
</tr>
<tr>
<td>Total filling:</td>
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<td>36% (max40%)</td>
<td>36% (max40%)</td>
</tr>
<tr>
<td>Grinding media:</td>
<td>steel balls 80 mm</td>
<td>Cu-plate, 24 x 32 mm</td>
<td>Steel balls, 25 mm</td>
</tr>
</tbody>
</table>

In this work all the focus was on the grinding circuits and the samples were collected from section 5 and section 6, in Table 1 all the data from the mills from the two grinding sections are shown. In both sections three mills are used in series. Mills from section 6 are larger compare by section 5 and have higher capacity.

5.2 Sampling and preparation

Samples were taken from both sections 5 and 6 in the same sampling campaign. They were taken before and after each mill, with one partial sample every 20 minute for a duration of three hours.

The feed samples were weighted and then filtrated at Malmberget. All the samples were then dried and cut by a Jones splitter into suitable proportions in the laboratory at Luleå University of Technology (LTU). The dry material was sieved with a Ro-Tap shaker down to 75 μm and wet sieved further to 38 μm.
Polished thin sections were made of the sieved fractions at NTNU.

6 CHARACTERIZATION AND ANALYTICAL METHODS

6.1 Binocular/ Optical microscopy

Mineral identification can be made in two different modes. The first stage is the macro-scale, by simply using microscope, acids and knife (Petruk, 2000).

The second stage contains the micro-scale methods that can be used for mineral identification, optical microscopy, X-ray diffractometer (XRD), scanning electron microscopy (SEM), and electron microprobe (MP) are some of the equipments that can be mentioned.

Optical microscopy is very important as a first approach, usually a binocular microscope is used in the first step for larger pieces. Binocular microscope gives us the first information of minerals and the textures. The magnification should not be over 50 X.

For a careful examination, the polarization microscope is used. The samples are usually prepared before they are examined, they are polished or polished thin and with reflected polarized light it will be easier to identify minerals, mineral texture, particle shape, and measuring the grain size. The magnification may be up to 1000X.
Figure 5. Example of the microscope, which can be used in optical microscopy (Nikon Eclipse E600).

There are two polarizing filters (the polarizer and analyzer) in the microscope. The polarizer is placed below the specimen stage and the analyzer is sited above the objectives and can be moved in and out of the light path as required. When both the analyzer and polarizer are in the optical path, their permitted light vibration directions are positioned at right angles to each other. In this configuration, the polarizer and analyzer are said to be crossed, with no light passing through the system and a dark field of view is present in the eyepieces, unless the mineral specimen changes the polarization of the light passing through it. Polarizing microscopy can be used both with reflected and transmitted light. Reflected light is useful for the study of opaque materials such as minerals. In this case polished thin sections were optically examined in transmitted and reflected light on a standard petrographical microscopy (Nikon Eclipse E600).

To characterise all the different mineral associations, textures and parageneses, a mineral identification were made of both the silicates and oxides.
6.2 Microprobe

An electron microprobe is a microscope that uses electrons to examine a sample. Electrons are charged and they are focused on the specific sample surface to produce morphological (roughness and shape) or chemical images of a sample surface. The microprobe is also used to qualitatively or quantitatively determine the chemical composition of a very small particle (1 micron) on a sample surface. It will also give a good overview over the chemical characterization of the sample.

(http://geoinfo.nmt.edu/labs/microprobedescription/home.html)

Mineral analyses were performed on a JOEL JXA-8500F electron microprobe at NTNU, Trondheim, Norway. For the microprobe analyses an accelerating voltage at 15.0 kV, a probe current at 95 μA and a < 1μm beam diameter were used.

Totally over 200 point analyses were made, representing both silicates and oxides on the major minerals to cover all different textural and mineral assemblage variations, observed in the samples. Beside this mineral identification, it also verified that the used sized fraction samples were representative.

6.3 Scanning electron microscopy

Scanning electron microscopy (SEM) is close to microprobe, the SEM produces images of high resolution, which means samples can be examined at a high magnification. The sample have to be conductive, the electrons from the SEM interact with the atoms in the samples that the sample producing signals that contain information about the surface and the composition (Watt, 1997). Back scatter electrons (BSE) are the electrons that backscattered from the sample when the primary electron beam hit the target and it is dependent of the atomic number of the phases.

The particle analyses were done on a Hitachi S-4300SE scanning electron microscopy equipped with Oxford Inca Feature software, NTNU, Trondheim, Norway.

For the particle analyses an accelerating voltage of 20.0 kV and a probe current at ~0.5nA was used.
6.4 Particle texture analysis

The Particle Texture Analysis (PTA) software is developed at the Norwegian University of Science and Technology (NTNU). By using Back Scattered Electron (BSE) from the scanning electron microscopy, images are analysed by means of grey levels and every grain of interest is also analysed by X-rays. All analysed grain size fractions are imported to the PTA software, where images analyses are done offline to process and evaluate if grains occur as liberated or in composite particles.

Standard queries can be done on the output results in a new database that contains information on the mineral liberation of any mineral, mineral association of any mineral and miniature images of particles of a certain texture category (Moen 2006).

To reduce the unclassified group of minerals an extensive identification of minerals and phases for classification should be done.

6.5 Multivariate data analysis

Multivariate data analysis (MVDA) is used when numerous data is collected from different system or measurements from a process. Hair et al. (1998) argues that MVDA refers to statistical methods that consecutively analyse multiple measurements on an entity. For having better overview of a process it is necessary to collect many data from different variables. By using MVDA many of these variables will be explained and expressed, it will be easier to understand which variable is the information-rich variable. Numerous industries collect countless data from their process and to get the best and most efficient result MVDA is an excellent tool.

Multivariate data analysis is based on projection methods, it builds a model by using a data matrix $X$ containing $N$ observations (samples). The Principal component analysis (PCA) is a multivariate projection method that reduces dimensionality of the data (Kourti et al., 1996) by showing us how the observations are related to each other in a simpler way.

As mentioned earlier PCA is a projection method of the original variables onto new ones, orthogonal and arranged according to their eigenvalue. This is done by splitting the matrix $X$ as:

$$X = AB^T + E$$
Where A represents the score matrix, and B represents the loading matrix, and E is the residual error (Prats-Montalbán, 2004). The result from PCA can be interpreted by using score plots and loading plots, score plots are created by intrigue observations scores on the new principal components Eriksson et al. (2006).  PCA have many advantages, one of them is to show us if there are outliers among the collected data and to be able to investigate them closer if it is needed.

Projections to latent structures by means of partial least squares (PLS), is another way to analyse how different variables are vital in the model. By selecting different variables as Y, it will give information how the selected variable(s) is related to other variables in the model.
7 RESULTS
In this chapter the result is summarised by presenting the three papers. Initially, the relation between the papers are described and followed by a list of papers.

7.1 Relation between the papers
Paper I discuss traceability from a broad-spectrum, but also how it is possible to achieve traceability in a continuous process. Different methods are described in the paper. Paper II continues to go deeper and look at the concentrator plant and the grinding section. Paper III develops the result from paper II and work on the result of paper II by using multivariate analysis tool.

Figure 6. Relation between the papers to each other.

7.2 Summary of paper I

7.2.1 Purpose of the paper
The main purpose of this paper is to explain different traceability methods that may be used to achieve traceability in continuous processes.

7.2.2 Outcome and conclusions
The traceability methods can be divided in two groups, off-line and on-line. Off-line methods aims to measure the time a particle stay in the process section and again when it will enter the next process stage. Different particles/atoms behave differently in the process stage, therefore the resident time distribution (RTD) must be estimated. It can be measured by adding a tracer substance in the process section. There are some important factors that must be under consideration; one of them is that not all of the particles have the same RTD. Hence, materials with different physical properties behave differently in a process step.

On-line methods require longer preparation and longer implementation times, because in each case a specially suited method is used.

In this paper there are three methods discussed:
Material signature, to find material signature or a “fingerprint” in a process it is important to sample and analyse the process carefully. The signature do not have to be unique to an individual particle, it may be unique for a group of particles. This method is appropriate to use when the material in the process is shifting shape or material with different properties are mixed. There are different methods to find a mineral signature; usually optical image analysis is used in the mineral industry.

Process data is another on-line method that can be used, by comparing different variables from the process, and do advanced analysis on the data, it will help to achieve traceability in the process. It is easy to collect the process data because usually the measurement tools are already installed in the process.

Traceable unit is also an on-line method that is usually used to achieve traceability in batch processes. In continuous processes markers can be used in the material flow to achieve the same result, but there are some issues that must be under consideration. To have a superior model it is important that the markers behave as the material in the process, and also they are durable while they go through different process stages. Radio frequency identification (RFID) is one technique that has been discussed. RFID tags have unique identification number that can be detected during the process and create a traceable marker. In the mining industry it is undemanding to measure them, simply by using a receiver that can measured the tags automatically. On the other hand one problem is the fragility of the tags, they can not be used in grinding or in high temperatures.

It is possible to use a mixture of these methods as well, all is depending on the existing process.

7.3 Summary of paper II


7.3.1 Purpose of the paper

The purpose of paper II is to see if it is possible to find a relation between the materials that comes in to the grinding circuits at LKAB, Malmberget. It is also a short introduction to the existing grinding sections at Malmberget, but also an investigation of the material that comes into the concentrator.

7.3.2 Outcome and conclusions

The samples were analysed with the PTA which gives plots and thumbnail images regarding mineral liberation, mineral association analysis and intergrowth analysis.
In comparing the two sections, it seems that the new section 6 is slightly more efficient in producing fine particles. It is clear that the new section 6 have a better grindability. The modal mineralogy for the concentrates (figures 7 and 8) is showing the percentages of minerals found in the analysed fraction based on examination of a sample from PTA. The modal mineralogy for the two sections shows slightly different results when comparing the fraction at 38μm. Section 5 shows that the magnetite content is higher in the primary mill than section 6. The reason of higher content in section 5 is that a wet cobbing stage is used before the grinding circuit. There are three major gangue mineral groups that are found in the material that comes in to the primary mill, these are feldspar, pyroxene/amphibole and apatite. The output of the secondary mill contains some more gangue minerals compared to the input of the secondary mill. This is caused by the breakage of large particles into the +38 μm fraction as a result of the grinding action within the mill.

Figure 7. Modal mineralogy for section 5.
The samples were also analysed with an optical microscopy to get a general picture of the material.

In Figure 9, the picture is also very clear and all minerals are easily identified by their colours and the mineral proportions can be determined by, e.g. point counting.
With this polished-thin section the minerals can be identifies and it is possible to observe the particle shape or the mineral associations, it is also possible to identify some mixed particles.

7.4 Summary of paper III


7.4.1 Purpose of the paper

In this paper the grinding sections have been in focus and the data are collected from the old and the new grinding sections. The main task is to find a way to make the traceability easy and practical. One way to reach traceability would be to find a process mineralogical signature or identification. For having a good traceability we need information from the system. It is important to analyze and look into the variables that have a crucial importance to the process.

7.4.2 Outcome and conclusions

The experimental effort in this paper can be described in three parts: pre-experimental preparation; performing the experiment; and analysis. The first two parts is the same as paper II, in this paper the analysis is added and exposed.

To improve the model it was important to reduce the number of variables, the variables in interest were those which describe the morphology.

By using multivariate tools it will help to find trends, dominating variables and groups among the collected data. Using this kind of analysis it is possible to create an understanding of the general differences for the two grinding sections.
Data collected from the PTA analysis were imported to the SIMCA program and analysed. From a statistical overview a multivariate model explaining the observations was developed. In the result from the analysis in this paper, principal component and score plots were examined to investigate which and how different parameters affect the model during the grinding process.

![Score Scatter Plot](image)

Figure 10. Score plot with mineral identification for incoming and outgoing material, section 5, primary mill.

The plots from SIMCA show that there are some sub-populations for the magnetite. However, it is interesting to follow a single mineral comprehensively for the length of a grinding circuit.
In Figure 11, there are several sub-populations to the lower left. These may be interpreted as a generation of mixed particles.
8 CONCLUSIONS

In this chapter conclusions are presented and recommendations for future work are also presented.

There are different methods that can be used to achieve traceability in a process, it is important to have a good knowledge from the existing process so that the right traceability method can be applied. During the comminution there are physical changes in particles through out the grinding circuit, the particle size of the ore is reduced and in the last mill the numbers of particles are very high in the slurry which makes the traceability more complex. In this case material signature is used to apply traceability in the grinding circuit at LKAB, Malmberget.

Samples from the concentrator is analysed by PTA, it is a very flexible system and gives a lots of information from each sample. Firstly, it is for the first time the slurry form a grinding circuit have been examined in such detail. By using state-of-the-art system to investigate the main and trace minerals in the slurry useful information is collected. By looking into the particle texture and gathering information about the mineral liberation, mineral association and modal mineralogy useful data is collect. Multivariate data analysis is used to treat the data from PTA to find out trends, dominating variables and groups among the collected data. Multivariate analysis compares the data from several thousand of particles at the same time, this is a state-of-the-art technique which is used in this thesis. By comparing MVA-data from grinding sections systematic similarities and differences are found.

Secondly, this kind of investigation gives detailed information from the concentrator that can be useful for other aspects as well, such as optimising the process. However, to have complete information from the grinding circuit it is necessary to have data from all the flows that is connected to the main slurry.

In this thesis the focus has been on the mills and how material is behaving in the grinding circuit, in future it is important to identify “sub-flows” that is connected to the concentrator and classify all the materials that is coming in and leaves the concentrator.
Today it is very common with bulk analysis, but they do not show how individual minerals behave at different stage. In future it is important to develop a system, which handels both bulk analysis and image analysis. With this kind of analysis, any irregularity would be detected in the process line and reduce the quality deviation in product. Presently, it takes time to get data from PTA, because of the queue time of analysis. By installing a similar system on site it would be more efficient to accomplish this type of analysis. Of course, it will take time and efforts to have it implemented as a standard process monitoring tool, but the benefit would be a better coupling between mine, cobbing plant and concentrator.
9 REFERENCES:


Paper A

METHODS FOR
TRACEABILITY IN CONTINUOUS
PROCESSES
- Experience from an iron ore
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Methods for traceability in continuous processes–Experience from an iron ore refinement process

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Abstract

Every production process is exposed to disturbances leading to production of defective products. The disturbances are seldom immediately discovered, and need to be traced afterwards. Traceability, or the ability to follow a product through the process, is therefore vital since it aids the localisation of the source of the disturbance. Traceability has for a long time been a possibility in part production, but in the continuous process industry it is still problematic. Examples of problems are complex flows, closed systems and large buffers. Hence, the purpose of this paper is to describe methods that can be used to achieve traceability in continuous processes, and give an example of when they may be applied. To identify suitable traceability methods, the literature search was conducted as well as discussions with researchers from the process industry. How the methods work is presented together with their advantages and disadvantages. Furthermore, an example of which traceability methods could be used for achieving traceability in a continuous iron ore refinement process is given. Seeing the diversity of available methods, achieving traceability in continuous processes should be possible.

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Keywords: Residence time distribution; Iron ores; Ore mineralogy; RFID

1. Introduction

An announcement of a product recall of about 90,000 locomotive toys was issued in September 2007 by Fisher-Price (US Consumer Product Safety Commission). Product recall announcements like the mentioned one are issued daily by companies around the world and most consumer product stores handle product reclamations daily. This exemplifies that defective products and product deviations are not always identified directly, even if this is desirable. Instead the causes often need to be traced back through the process from customer complaints. The ability to trace a specific product during the process, usually called traceability, is consequently important for identification and elimination of causes of product deviations. Other benefits of traceability are that it minimises the extent of product recalls and ensures lot uniformity in products (Juran and Gryna, 1980). Furthermore, traceability can be used to identify causes of positive changes in product characteristics.

Traceability is common in part production and often easy to achieve, since various kinds of identification markers can be attached to a unit. Moreover, the literature about traceability is dominated by applications in part production. However, creating traceability in continuous processes implies vast challenges: process flows can be parallel, serial and reflux; sub processes can be continuous as well as batch-wise. These challenges imply that other types of traceability methods are needed for creating traceability. To understand more easily how these traceability methods can be applied, the authors consider that an example is appropriate. A suitable continuous process for exemplifying how various methods could be used was found in the iron ore mining industry, and the refinement of iron ore...
to iron ore pellets (the process is described in Section 5). The reason for choosing the iron ore refinement process is that all the special challenges connected to continuous process industries are present in this process. Therefore, the purpose of the article is to compose and describe different traceability methods that can be used for achieving traceability in continuous processes, and to illustrate how a method for traceability may be selected from the characteristics of a process section. The refinement process of iron ore starts in the mines. However, in this paper only the methods for achieving traceability from the concentrator plants to the final customer are discussed.

2. Research methodology

This article is a result of extensive collaboration between the authors and the Swedish mining company LKAB. This collaboration focused on traceability and traceability methods in continuous processes. As a part of this collaboration, an iterative literature search was conducted aiming at identifying traceability methods. An initial literature search was performed in the databases Compendex, Emerald and ScienceDirect.

Most of the articles found were primarily related to other subject fields than traceability methods in continuous processes. However, from the related articles and discussions among the authors, colleagues and researchers at LKAB, new search strings, such as residence time distributions (RTD), trace elements, mineralogical signature and radio frequency identification (RFID), were identified. The second literature search together with the initial one led to the identification of the traceability methods described in this paper. The identified methods are described in Section 4, and each description includes a brief explanation of advantages, disadvantages, and examples of application. A conclusion from the literature search is that literature on traceability methods in continuous processes is rare and scattered in a diversity of research fields.

3. Theoretical framework

3.1. Traceability

In this paper three terms for traceability with distinguishing aims will be consistently used: traceability, traceability system, and traceability methods. Traceability is here defined as “the ability to preserve and access the identity and attributes of a physical supply chain’s objects” (Töyrylä, 1999, p. 38). Traceability is not binary but continuous and always present at some level. This means that it is possible to differentiate between what year, week, or day a product was manufactured.

Traceability system is defined as the system that enables traceability in a process by combining process information with models of material flow in the production process. According to Steele (1995), Töyrylä (1999) and Jansen-Vlugt et al. (2003), there are four elements connected to the design of a lot-tracing system:

1. Physical lot-integrity – How large a batch of raw material is and how well the integrity of the lot is maintained will determine the resolution or precision of the traceability system. The resolution of a system is the minimum number of units that cannot be individually separated during the process, and for example emanate from the same delivery batch.
2. Data collection – Two types of data are needed: process data that records process information, and lot-tracing data that keeps a record of movement and merging of batches.
3. Product identification – The linking of product and process data.
4. Reporting – Retrieval of data from the system, the actual use of the system.

The most important element is physical lot-integrity, since it determines the maximal resolution of a traceability system. The physical lot-integrity for a process is affected by three elements: lot mismatching, lot-end-mixing and lot-sequence mixing (Steele, 1995). Lot mismatching occurs when a new batch is created and the size of the batch does not match the original one, for example when numbers of units simultaneously treated in two parallel process steps differ. Lot-end-mixing arises if lots are processed in repetitive or continuous batches and the organisation fails to retain a clear separation between batches, for example when products from parallel process steps with different cycle times are merged. Lot-sequence mixing takes place if the traceability system depends on the first-in–first-out principle and the process fails to pursue this principle, for example when all the rework is conducted at the end of a shift. The physical lot-integrity element is also the element that is primarily affected by the differences in continuous production and part production, since batches are usually not present in a continuous process. The traceability systems used for achieving traceability in part production should also be useful for achieving traceability in continuous production, since it is only the methods for creating the models of material flow that differ.

A traceability method, the third term, is defined as a method that can be used for creating models for material flow in process sections. The same traceability method is rarely suitable to use during the process, because of changes in material properties and various operations in process stages. Therefore, suitable traceability methods need to be identified for different process sections, and the material flow, consequently, needs to be modelled step-wise. The traceability methods that are applied in part production processes can seldom be used in continuous processes, due to the mentioned differences.

The relations between the three terms may be described according to the following criteria: models for material flow in process sections are constructed with traceability...
methods. The different material flow models for the process sections are then combined by the traceability system to achieve traceability through the process.

The precision of traceability in a process is therefore dependent on the traceability system, which in turn relies on the models created by the traceability method. A mind-map of how the terms are related and affected by one another is shown in Fig. 1.

3.2. Continuous process

In a continuous process, the products are gradually and with minimal interruptions refined through a series of operations (Fransoo and Rutten, 1994; Dennis and Meredith, 2000). Therefore, there are no natural product lots in a continuous process. The raw material in a continuous process typically comes directly from the natural environment, for instance mines and forests (Fransoo and Rutten, 1994; Hild et al., 2000). In contrast to the raw material in part production, it is usually not processed. Therefore, the raw material in a continuous process is usually afflicted with a larger variation than the raw material in part production (Fransoo and Rutten, 1994; Hild et al., 2000). To minimise the influence of the natural variation in the raw material on the product and avoid interruptions in the production process, large mixing buffers are usually used during the process. Furthermore, reflux flows are common in continuous processes and often necessary for attaining an even and desired output from a process section. The physical characteristics of the material are often changed during the refinement process, which also makes it difficult to define a unit of measure (Fransoo and Rutten, 1994). Finally, the added value in continuous processes is usually quite low (ibid).

4. Description of traceability methods

Traceability systems are usually based on daily observations or mathematical models. The mathematical models are created from measurements of how the material flow is affected by different process parameters. The traceability methods may be classified according to what type of model they create. Traceability methods creating mathematical models are here categorised as off-line methods. In contrast, traceability methods creating models based on daily observations are classified as on-line methods. Off-line methods are used during a shorter period of time, in contrast to on-line methods, which are used repetitively. All on-line methods can be used as off-line methods, but the other way around is seldom possible. Fig. 2 shows a summary of the traceability methods presented in this paper.

All the methods presented are also useful in other types of industries than continuous process industries. However, it is not always necessary to use complicated methods for achieving traceability in continuous processes. An example of such a case is production in a single line with no reflux flows and no buffers.

4.1. Off-line methods (tracer methods)

Off-line methods aim at measuring the time a product/molecule/atom stays in a process section, the residence time, with experiments, and from the collected data creating models of the material flow. But, since some prod-
and radioactive tracer are the most commonly used
tools. Chemical tracer, radioactive tracer, visual observations,
methods for studying and investigating the RTD of particles are
for studying the material flow. Examples of different meth-
ods in the literature studied. These two methods are there-
fore described below in more detail.

4.1. Chemical tracer

One way to identify the RTD in a system is to add a
chemical compound to the input and measure the concen-
tration in the effluent flow as a function of time. Numerous
chemical compounds are available for estimation of RTD.
Furthermore, only an element of the compound may be of
interest if the compound dissolves in the material flow. The
applied tracer should be a compound that is accurately and
easily detectable, has similar physical properties as the
studied solid/fluid stream, acts like the studied solid/fluid
stream in contact with other surfaces in the process, and,
if a fluid is studied, is completely soluble (Wen and
Fan, 1975; Ambaud and Candelier, 2005). In addition, it is important that
the tracer does not affect the process or product and it
should preferably not be naturally occurring in the process.
Before the addition of the tracer, it is necessary to have
information about the background variation of the tracer
compound or element in the process, the analytical detec-
tion limit and the amount of material in the studied process
section. This information makes it possible to calculate the
minimum amount of compound that should be added.

There are several advantages to the chemical tracer
method. It is flexible, since various trace compounds are
available. This flexibility implies that the method may be
used for processes with gas, fluids, solids and slurry, and
in almost any environment. Moreover, special permits are
often not required, in contrast to the radioactive tracer
method. Hence, the chemical trace method is usually easier
to apply than the radioactive tracer method.

Disadvantages include for example that the method
can quickly becomes costly for larger systems, if combined with
expensive tracers and expensive analysis methods, since
more samples need to be analysed and an increased amount
of tracer needs to be added. The amount of tracer added
needs to be increased since the tracer often mixes with
the material flow. Hence, when using chemical tracers,
the RTD is often estimated stepwise for the material flow
in the process. Furthermore, it might be problematic to
take representative samples in continuous flows. Such an
element is sampling of crude ore in mines (Wills and
Napier-Munn, 2006). Using non-representative samples
severely affects the reliability of the final model. Finally,
analysis of output is seldom possible to perform in real time. The result therefore depends on how well the sampling strategy suits the material flow. However, a few on-line gauges have become available, such as optic, electric conductive and fluorescence analyses (Hu and Kadri, 1999).

4.1.2. Radioactive tracer

Another way to estimate the RTD is to use a radioactive tracer. The radioactive tracer method implies that a part of the actual flow is radioactively charged or that radioactive particles are added to the input. RTD is then estimated by measuring the output, which typically is done continuously with a Geiger counter. The choice of radioactive element depends on the material being traced, the duration of the experiment and the detection method (Lehinski et al., 2002).

There are many advantages to the radioactive tracer method. Measurements may, for example, be performed in real time at various points (Yianatos and Bergh, 1992). Since no sampling needs to be carried out, it is also possible to measure at several locations in a process simultaneously and also interior flow patterns in, for example, reactors. The method is also adaptable to different types of material streams, and can thus be used for analysing flows in most environments.

The major concern with the tracer method is the health hazards linked to the usage and the disposal of radioactive material (Ramaswamy et al., 1995). Consequently, the method usually requires special permits and it is also necessary to ensure that safety regulations are followed. Therefore, the method often demands large resources in the form of time and money.

The radioactive tracer method is often used when other tracer methods are inadequate or when interior flow is of special interest, for example localisation of zones in mixers with poor mixing.

4.2. On-line methods

On-line methods often demand longer preparation and implementation times, compared to off-line methods, since they normally need to be individually suited for the specific process. Therefore, on-line methods are usually more expensive. However, the continuous measurement often results in more accurate estimations of RTD, since the estimation is usually based on more data. Consequently, on-line methods are preferable to use. The final model is also less sensitive to process modifications, since it is possible to continually verify and update the model. The on-line methods described here are the methods that were identified during the literature studies.

4.2.1. Material signature

In many production processes, it is almost impossible to obtain identical raw materials. Such an example is that in a pork chop, the exact amount and combination of chemical elements will depend on the origin, nourishment, soil, birth date and other variables. Hence, almost all pork chops are unique, since they will differ from one another in some of the mentioned factors. Therefore, a way to achieve traceability would be to identify unique signatures or structures in a product. The signature does not need to be unique to individual products; it may instead be unique to a group of products. How small the group must be depends on the demanded precision of the traceability system. Examples of signatures that could be used are fibre length in wood, natural variability in raw material, and variation in chemical composition deriving from differences in background. To find material signature or “fingerprint” it is necessary to carefully sample and analyse the process flow. The analysis methods used depend on the type of production and the signature sought for. This method is suitable to use when the material is constantly changing shape or when materials with different properties are mixed, which often is the case in the mineral industry.

For mineral materials, textural properties such as grain boundaries and shape depend on the ore body from which the mineral is extracted, and how they are located in the ore body. In the past, mineralogical studies were made manually by using techniques depending on the skill of the human (Henly, 1992). Today automated mineralogical techniques have been developed and become common in mineral industries (ibid). Mineralogy of iron ore can be determined by using information from analyses such as X-ray diffraction methods (XRD), optical image analysis and scanning electron measurement techniques (Donskoi et al., 2006). To examine complex mineralogy, which is difficult to identify by optical analysis, it is advantageous to use a system that can give information about the mineralogy comprehensively and quickly. Particle Texture Analysis (PTA) is a system that can be used to analyse this kind of sample. The PTA software gives plots and thumbnail images regarding mineral liberation, mineral association analysis and intergrowth analysis; for a comprehensive description of PTA, see Moen (2006).

One benefit of PTA is that it shows how the gangue minerals are distributed over the fractions and how the gangue minerals behave. Another advantage of the mineralogical signature method is that the signature is always the same in the processes, although the shape of the material is changing. One concern is the cost and the time required for each sample to be investigated. However, the method is still new and may be further improved in the future.

4.2.2. Process data

In many production processes, the differences in the raw material result in process data variation. Hence, instead of material signature, variability in process data could be monitored.

Lundqvist and Kubulnieks (1995) created traceability in a paper and pulp production plant using process data. Traceability was possible to create by comparing the appearance time and forms of deviations in kappa number
(a measure indicating the bleach ability of wood pulp) and brightness (a measure of how much light is reflected) at different points in the process. From these comparisons, the RTD for process sections could be estimated, verified, and modelled.

The kappa number and brightness are two product parameters that are continuously measured during the process. Furthermore, the value of kappa number and brightness is often changed by the same absolute value in a process section or not changed at all. If a parameter with similar characteristics as the kappa number and brightness is present in a process, it can be used for achieving traceability.

One advantage of using process data is that the measurement tool usually already exists, and hence no further investments are needed. Furthermore, much data is directly available, since data from the measured points already has been gathered.

However, it may be difficult or even impossible to identify suitable variables to use for the estimation. In addition, the variable must display significant alterations over time, otherwise the RTD cannot be estimated by comparing the data for the variables.

4.2.3 Traceable unit

In part production, different batch structures are often used to achieve traceability. Batches do not usually exist in continuous processes, so using batch structures for achieving traceability is difficult. Creating virtual batches by dropping some type of marker in the material flow with regular intervals would, however, make it possible to use the batch technique for achieving traceability. The markers then act like imaginary start and end points of the different batches. Recording passage times of the markers along the process would then make it possible to trace a specific batch during the process. To achieve a genuine model, the marker must behave as the material in the material flow. Each marker should preferably be unique, so that the potential mixture in the flow can be modelled. The precision with which a product can be traced is determined by the interval between the markers.

Radio frequency identification (RFID) is one technique that could be applied. The technique offers the possibility to create a traceable marker, by using tags with unique identification numbers. RFID is commonly used for tracking goods in the manufacturing industry. This method is applied today for achieving traceability by some retailers, manufacturers, and health care and pharmaceutical industries (Li et al., 2006). The method has also been used for coal tracking (Lauf), see Wyld (2006) for more on RFID.

One of the strengths of the RFID technique is that every tag is unique and can be measured automatically. Consequently, the residence time in the process can be precisely estimated for each tag. Furthermore, the observed object does not mix with the material flow, and consequently the number of units added to the process flow is not affected by the size of the studied process. Finally, it is feasible to estimate the residence time distribution simultaneously for several process sections, since no sampling is required.

Nevertheless, there are many shortcomings with the RFID technique. One shortcoming is that the RFID technique does not offer the same flexibility for use as other mentioned methods. Examples of attributes that hinder the flexibility are the physical size and fragility of the tags. The fragility results in the tags not being possible to use in process sections with for example grinding or extreme temperatures. Moreover, the RFID technique uses electromagnetic waves for communication between the reader and the tags. Therefore, the technique is improper to use at distances larger than a few metres or when the tags are in direct contact with metals or fluids (Porter et al., 2004). Finally, the technique is sensitive to electromagnetic fields in the surrounding environment.

5. An example from a continuous process

LKAB (Luossavaara-Kirunavaara AB, Sweden) has since the beginning of the 1900s produced highly refined iron ore products from iron ore mines at Kiruna and Malmberget. The main product is iron ore pellets for blast furnaces and direct reduction furnaces.

In November 2006, LKAB inaugurated a new pelletising plant in Malmberget (hereafter PP2). After the start of the new pellet plant, the production volume increased and therefore the raw material taken from local ores in Malmberget was insufficient to uphold full production at the plant, due to, among other things, concession rights. Therefore, ore from Kiruna mines is also used in the production process. The different ores thus have to be mixed.

The iron oxides in Malmberget have a coarser grain size, different kinds of grain boundaries, different Fe-contents and levels of contaminants compared to those in Kiruna (Geijer, 1930). Hence, the iron oxides from Malmberget and Kiruna behave differently during the refinement process. This implies an increased risk of quality deviations in the final product and therefore more emphasis needs to be focused on traceability aspects, since it is important for the customer that the mineralogical characteristics and chemistry of the final product do not differ considerably over time.

The product affected by the mixing of raw materials is the iron ore pellets (hereafter pellets) produced at Malmberget. As a result, a traceability system is most important for this product. The pellets are produced in a continuous process that is illustrated in Fig. 3 and further described in the following part.

5.1 Production process

The Malmberget mine has more than ten different ore bodies that are currently in production. For each ore body, there are different characteristics such as mineralogical, chemical and textural properties.
From the mine, the material goes to the concentrator plant, which separates the minerals into two parts, tail and product. Before one of the concentrator plants, there is a cobbing step to separate the gangue mineral from the magnetite. In the two concentrator plants (CP1 and CP2), ball mill grinding is used in three consecutive steps with wet low intensity magnetic separators in between; see Fig. 4 for a flow sheet. It is important to grind to approximately 68% < 45 μm to liberate gangue minerals, and to reach the desirable size distribution for the pellets feed. The grinding circuits are the last stage in the comminution; in this stage the particles are reduced by a combination of impact and abrasion (Wills and Napier-Munn, 2006).

Keeping traceability in the grinding sections is problematic, since the particle size decreases resulting in an increase of the number of individual particles. An example of how the particle size distribution is altered during grinding is illustrated in Fig. 5. Moreover, the small size of the material complicates the possibility to achieve traceability in the grinding sections. Another major concern is that each section receives additional secondary material flows from other sections producing special products and general spillage within each section.

The next step is the pelletising plant. There are two pelletising plants in Malmberget, PP2 and the old PP1 from 1973. A flow chart over the pelletising plants in Malmberget is seen in Fig. 6. Several factors make it difficult to achieve traceability during the pelletising process:

- Some of the process steps entail reflux flows (lot-end-mixing).
- The surroundings of the material constantly change, from slurry to being dry and finally heated.
- There are several buffers, the result of which is that the flow cannot be characterised by a linear flow (lot-sequence mixing).
- Material from different concentration plants are mixed (lot-sequence mixing).
- The material flow is split into smaller flows and then merged at several places in the production (lot-sequence mixing).
- The material flow differs between the two pelletising plants (lot-end-mixing).

After the pelletising plants, the pellets are distributed to the final customers. A flow chart of the distribution chain is seen in Fig. 7. All three elements that may impair the physical lot-integrity are represented in the distribution chain: the transport and storage rooms differ in size (lot-mismatching); there are two possible ways of transportation to customer (lot-sequence mixing); there is no clear separation between batches (lot-end-mixing).

5.2 Application

Traceability can be created in the concentrator plants (Fig. 4) by using the mineralogical signature method. The mineralogical signature method is suitable to use since it can achieve traceability even when the form of the material is changing, as it does during the comminution. Materials from different parts of the process should be sampled regularly and analysed, with regard to the content of mineral at different fractions, mineral liberation and mineral associations. By doing so it should be possible to trace a product in the concentrator plant, since part of the mineralogical signature stays constant during the process.

Samples has been taken from each grinding section and analysed with PTA (Oghazi et al., 2007). The abundance of analysis data makes it necessary to use multivariate tools to identify patterns. By using multivariate analysis it is possible to see correlation between different grinding sections, but no conclusion may yet be drawn (Oghazi et al., 2008). For more details of the multivariate analysis on the PTA data, see Oghazi et al. (2008).

To achieve traceability in PP1 and PP2, several methods have to be used, since no single method is preferable for all the different process stages in the pelletising plants. The process data method is preferable to use for most of the process sections in the pelletising plant, since the material flow can be estimated with existing measurements in the process. However, this method is not feasible for the slurry and mixing tank system (steps one and two in the pelletising plants presented in Fig. 6) and the bin chamber (the
Fig. 4. The grinding section in the concentrator plants (CP1 and CP2) with magnetic separators.

Fig. 5. The typical particle size distribution diagram for the input and output in a grinding section. In the grinding circuit, the $d_{80}$ for the particles is reduced from 4000 $\mu$m to 70 $\mu$m and the variation in particle size is reduced.

Fig. 6. Flow chart for the two pelletising plants at Malmberget.
fourth step in PP2 viewed in Fig. 6). One reason is the large buffer in these process sections, which makes it difficult to estimate the material flow with the existing measurements. The mixing of two materials in the slurry and mixing tank system is another factor that makes the process data method insufficient to use for modelling the material flow.

The material flow in the slurry and mixing tank system can be estimated by using a chemical or radioactive tracer. The chemical tracer method is preferable here, since the material flow can easily be sampled and the size of the system is suitable for using a chemical tracer. Selection of a suitable chemical tracer is the next task. At this stage the material flow is a mixture of solid and fluids, and as previously discussed, the RTD can differ between solids and fluid. However, a previous investigation has shown no significant difference for RTD between solid and fluids in rod and ball mills at LKAB (Andreasson et al. 1985). And since the particles are smaller (same particle size distribution as the material of Mill#3(out) in Fig. 5) in this process section, it is assumable that the particles behave as the fluid. Lithium chloride is suitable as a tracer, because it is soluble in water, does not affect the process or the end product, does not occur in high concentrations, and can easily be analysed.

Estimation of the RTD in the bin chamber can also be made with chemical or radioactive tracer methods. Here too the chemical method is preferable. However, lithium chloride is not suitable as a tracer element since the material is dry. Fluorescent colour can instead be used as a chemical tracer.

The residence time has been measured for the slurry and mixing tank system by chemical tracer substance experiments. In the experiments, lithium chloride was added momentarily to the flow, and the concentration of lithium in the effluent flow was sampled and analysed. Based on the data from the experiments a mathematical model with two tanks was fitted to the data. For more details, see Kvarnström and Bergquist (2008).

In the distribution chain (Fig. 7), the RFID technique, the traceable unit method, may be appropriate to use for achieving traceability. This method is preferable as the residence time in the distribution chain is long and impossible to model by process data, as the material flow is a mixture of batch and continuous flows. Furthermore, the material (the pellets) is only exposed to insignificant external forces and the material is approximately the same size as a tag. The technique could be used to create virtual batches, since it is not realistic to equip each pellet with a tag. The tags would be used as the start and the end points of each batch. Process data can then be linked to a virtual production batch. Tags could be either attached directly to pellets or dropped into the material flow.

The RFID technique has been extensively tested in the distribution chain. The results show that the technique may be used to create traceability in the distribution chain. However, to achieve a sufficient read rate, more than 50%, it is necessary to use RFID tags that are larger than the pellets. In the test, no significant difference in the behaviour between the larger RFID tags and pellets was observed. The tests and the results are further described in Kvarnström and Nordqvist (2008).

6. Conclusion and discussion

Through the literature review and discussions with different researchers, suitable traceability methods for continuous processes were identified; the methods are summarised in Table 1. As illustrated above, there are several methods for creating traceability in continuous processes, and as the example demonstrates, they are applicable at different types of process sections. None of these methods can be seen as a panacea for developing a traceability system, since every method has its own strengths and weaknesses. The methods described in this paper should be seen as examples of methods, and not as a complete list.

Furthermore, the example shows that by applying suitable traceability methods, it should be possible to improve traceability. However, no complete implementation of the methods has been made, and it is therefore still uncertain if traceability can be achieved in the iron ore refinement process. Though the results are promising, there is still work to do before some final conclusions could be made about the possibility to achieve traceability in the iron ore refinement process. For example, the analysis data from the concentrator needs to be further analysed. In
the grinding sections many aspects need to be considered because the material is profoundly changed, for example the shape and the composition of the material is changed. The RTD of the bin chamber also needs to be investigated before traceability can be achieved.

The traceability mind-map presented in Fig. 1 gives a structured model view of how a company can proceed to reach a sufficient level of traceability in a production process. Moreover, the traceability mind-map tries to distinguish the different terms for traceability used in the literature. No corresponding attempt to distinguish the different terms for traceability used in the literature. No corresponding attempt to distinguish the traceability used in the literature. Instead, traceability has mostly been defined and used in conformity with different authors’ needs.

With the presented traceability methods, it should be possible to create traceability systems in continuous processes as well. The resolution of the traceability system in a continuous process will, however, often be inferior compared to traceability systems in part production processes. One major reason is that reflux flows are more common in continuous processes than in part production processes. Nevertheless, resources are always an important aspect that has to be kept in mind when choosing among different traceability methods and designing a traceability system.

The importance of traceability has been continuously increasing as a response to wishes to optimise the production process and new regulations. The importance of traceability in production processes can therefore not be stressed enough.

Acknowledgements

The authors are grateful for the financial support and assistance during sampling given by LKAB. Furthermore, we also sincerely thank our supervisors Bjarne Bergquist and Bertil Pålsson for their support and advice.

References


Table 1

A list of identified and described traceability methods with advantages and disadvantages

<table>
<thead>
<tr>
<th>Traceability method</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Off-line</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chemical tracer</td>
<td>– Flexible</td>
<td>– Dilutes</td>
</tr>
<tr>
<td></td>
<td>– Easy to use</td>
<td>– Needs sampling</td>
</tr>
<tr>
<td></td>
<td>– Low-cost</td>
<td>– Based on historical data</td>
</tr>
<tr>
<td>Radioactive tracer</td>
<td>– Flexible</td>
<td>– Health hazards</td>
</tr>
<tr>
<td></td>
<td>– No sampling needed</td>
<td>– Permits required</td>
</tr>
<tr>
<td></td>
<td>– Interior flows can be measured</td>
<td>– Based on historical data</td>
</tr>
<tr>
<td>On-line</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Process data</td>
<td>– Easy to use</td>
<td>– Hard to find</td>
</tr>
<tr>
<td></td>
<td>– Low-cost</td>
<td>– Low precision</td>
</tr>
<tr>
<td></td>
<td>– Based on real time data</td>
<td>– Initial sampling needed</td>
</tr>
<tr>
<td>Traceable unit</td>
<td>– High precision</td>
<td>– Lower flexibility</td>
</tr>
<tr>
<td></td>
<td>– No sampling needed</td>
<td>– Cannot be used for fluids</td>
</tr>
<tr>
<td></td>
<td>– Could be used in process sections with both batch and continuous flows</td>
<td>– Can only be used at shorter distance</td>
</tr>
<tr>
<td></td>
<td>– Material signature</td>
<td>– Material signature</td>
</tr>
<tr>
<td></td>
<td>– Flexible</td>
<td>– Large amount of data handling</td>
</tr>
<tr>
<td></td>
<td>– Informatif</td>
<td>– Time demanding</td>
</tr>
<tr>
<td></td>
<td>– High analyses precision</td>
<td>– Costly</td>
</tr>
</tbody>
</table>


An attempt to apply traceability to grinding circuits


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AN ATTEMPT TO APPLY TRACEABILITY TO GRINDING CIRCUITS

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ABSTRACT
LKAB has recently started start the new pelletization plant at Malmberget (MK3). The raw material is a mix from Kiruna and Malmberget. This means there will be different ores having different Fe-content and levels of contaminants. That is why the traceability of the process should be one of the crucial factors for future development of different product(s). Traceability generally means the ability of a system to indicate the current or historical state of activities.

The new pelletising plant necessitated an investment in a new grinding section in the concentrator. The difference, compared to the old section, is that the mills in section 6 are larger and have a higher capacity and in section 5 the coarse material is fed to a wet magnetic cobbing separator before the primary mill.

The particle size analysis from the section 5 gives similar results compared with the results of section 6. There are slight variations in the results; the older mills in this section produce a steeper final particle size distribution. It is, however, too early to say if this is linked to mill size, or if it is the result of a better, worn in, graded charge.

The Particle Texture Analysis gives a good overview how magnetite is liberated at every fraction and which minerals are associated to the magnetite.

1 Introduction
LKAB has since the beginning of the 1900’s produced iron ore from mines in Kiruna and Malmberget and is today one of the world’s leading producers of highly refined iron ore products. The main product is pellets, for blast furnaces and direct reduction furnaces. Today there is a greater demand from the customers and to obtain a good quality it is important to have good control over the process and the raw material used.

LKAB started the new pelletization plant at Malmberget (MK3) in November 2006. The raw material is a mix from Kiruna and Malmberget. This means there will be different ores having different Fe-content and levels of contaminants.
That is why the traceability of the process should be one of the crucial factors for future development of different product(s). Traceability gives us the advantage to have a better control over the material through the process and there can be adjustments if it is needed. It can show us “the current” values of different parameters and how much we have to adjust to achieve the goals. Traceability is much easier to use in batch processes than in continues processes. In food and pharmacy industries it is very common to use different traceability tools but in the mining industry, which is mostly a continuous process, traceability is an untouched area.

The main task is to find a way to make the traceability easy and practical. One way to reach good traceability would be to find a process mineralogical signature or identification. For having a good traceability we need information from the system. It is important to analyze and look into the variables that have a crucial importance to the process.

To elucidate how the raw material varies in different process stages we have to collect data and interpret these data. These aspects can come from automatic optical microscopy but also the tracing of different elements (XRD and PTA analyses). If it is possible to find specific distributions of chemical or trace elements, mineralogical or grain structure for a specific ore body, then we can use it as our “fingerprint” through the process line. As a test case, we looked at the new section 6 at the Malmberget concentrator and took samples before and after the grinding mills.

2 Material

Most iron ore contain significant amounts of gangue minerals that need to be eliminated to produce iron concentrates. At Malmberget, the dominant iron mineral is magnetite but also hematite occurs. Gangue minerals are mostly quartz, pyroxene, apatite, and feldspar.

The samples that were used in these studies were from the concentrator’s, old section 5 and the new section 6. The samples were sieved to have a good overview of the grinding and degree of liberation of the gangue at different particle sizes. Fractions that were examined in detail were 38, 75, 150, and 300µm. From the samples were thin and polished-thin sections prepared.
2.1 Flowsheet

Figure 1: Flowsheet for grinding section 5.

Figure 1 shows a typical flowsheet for concentrating iron ore. The coarse materials at 10-15 mm in size are fed to a primary wet magnetic cobbing separator (M1). The magnetic concentrate is discharged into a primary ball mill (#1), and the ground product (pulp) is transferred to a secondary magnetic separator (M2). The resultant magnetic concentrate is then pumped into a secondary ball mill (#2). A tertiary magnetic separation unit (M3) finally upgrades the ground product and the concentrate is used as feed for the tertiary grinding stage (#3) (Tano, 2005).

The flowsheet for the new grinding section 6 is shown below.

Figure 2: Flowsheet for the new Malmberget grinding section 6.

Here, ball mill grinding is used in three consecutive steps with wet low intensity magnetic separators in between. It is important to grind to, approximate 68% < 45µm to liberate gangue minerals, and to reach the desirable size distribution for the pellets feed.
3 Experimental

3.1 Sampling
In this case, the feed sample was taken manually when the material was in motion at a point of free fall, by making a cut at right angel through the falling stream. The other samples were taken throughout the circuit before and after the grinding stage(s). The samples were weighted and then filtrated at Malmberget. In the laboratory at LTU the samples were dried and then cut by a Jones splitter into suitable proportions. The dry material was sieved with a Ro-Tap shaker down to 75 µm and wet sieved further to 38 µm.

3.2 Analysis
Mineral identification can be made in two different modes. The first stage is the macro-scale, by simply using microscope, acids, knife, and agenser for coloring (Petruk, 2003). The second stage consist of the micro-scale methods that can be used for mineral identification: optical microscopy, X-ray diffractometry (XRD), scanning electron microscopy (SEM), and electron microprobe (MP).

Optical microscopy is important as a first approach, usually a binocular microscope is used in the first step for larger pieces. Binocular microscope gives us the first information on minerals and the textures. The magnification should not be larger then 50 X. For a careful examination, the polarization microscope is used. The samples are usually prepared before they are examined, they are polished or polished thin and with reflected polarized light it will be easier to identify minerals, mineral texture, particle shape, and measuring the grain size. The magnification may be up to 1000X.

Figure 3: Example of the microscope, which can be used in optical microscopy.
There are two polarizing filters (the polarizer and analyzer) in the microscope. The polarizer is placed below the specimen stage and the analyzer is sited above the objectives and can be moved in and out of the light path as required. When both the analyzer and polarizer are in the optical path, their permitted light vibration directions are positioned at right angles to each other. In this configuration, the polarizer and analyzer are said to be crossed, with no light passing through the system and a dark field of view is present in the eyepieces. Polarizing microscopy can be used both with reflected and transmitted light. Reflected light is useful for the study of opaque materials such as minerals.

Figure 4: Transmitted light 06KV001 (in) 150µm

The picture in Figure 4 shows how the different minerals are liberated and distributed over the sample plain. The picture is very clear, with a polished-thin section the minerals can be identifies and it is possible to observe the particle shape or the mineral associations.

Transmitted light microscopy is the general term used for any type of microscopy where the light is transmitted from a source on the opposite side of the specimen from the objective. The transmitted light is passed through a condenser to focus it on the specimen to get very high illumination. Transmitted light is used to locate the transparent minerals.

In Figure 5, the picture is also very clear and all minerals are easily identified by there colours and the mineral proportions can be determined by, e.g. point counting.
Figure 5: Partly crossed nicoles (interference colours) 06KV001 (in) 150µm

Figure 6: Reflected light 06KV001 (in) 150µm
Reflected light is used for opaque minerals; light is directed vertically through the microscope objective and reflected back through the objective to an eyepiece. The ring in the picture is a marker added to help in localising the SEM analysis spot.

3.3 Particle Texture Analysis:
To have a good view over the different samples, Particle Texture Analysis (PTA) was used. The PTA data collect is based on the Oxford Inca Feature software and the existing scanning electron microscope. Using Back Scattered Electrons (BSE) the images are analysed by means of grey level, and every grain of interest is analysed with X-rays. When every grain size is analysed, the data will be imported to the PTA software. With the Inca data information the images will be processed and calibrated (grey-scale and binary images); and the grains will be identified and evaluated if they are liberated or in composite particles and which minerals occur in the composite mineral (Moen, 2006). The PTA software gives plots and thumbnail images regarding mineral liberation, mineral association analysis and intergrowth analysis.

4 Result
4.1 Size analysis
The size distributions of particles in the material for both sections (Sections 5 and 6) are shown in Figures 7 and 8 respectively.

The particle size analyses of the feed and the products in the grinding process show the reduction of particle size \(d_{80}\) from 3300 µm in the feed to 68 µm in the final product. The overall grinding ratio in the circuit is calculated to about 48. The grinding ratio in the primary mill is dramatically higher than the secondary and tertiary mills, which is due to the well known fact that the larger particles grind easily. Size distribution analyses from the output of the primary mill and the input to the secondary mill indicate that the LIIMS mainly separates
smaller fractions. This may explain why the feed to the secondary mill is coarser than the discharge from the primary mill. On the other hand, the analysis from output of the secondary mill reveals that the magnetic separator does not change the particle size for the feed to the tertiary mill.

The particle size analysis from the section 5 gives similar results compared with the results of section 6. There are slight variations in the results, the finer feed to section 5 is due to the wet cobbing preceding the primary mill. The older mills in this section produce a steeper final particle size distribution. It is, however, too early to say if this is linked to mill size, or if it is the result of a better, worn in, graded charge.

4.2 Mill efficiency

There are two major ways to easily compare operating mills: grindability and apparent work index (Tano, 2005). Grindability index ($G_i$) showing the produced amount of material finer than 45 µm is calculated according to Eq. (1).

$$G_i = \frac{S_D^{45\mu m} - S_F^{45\mu m}}{100} \times \frac{1000 \times F}{P}$$

Where $S_D^{45\mu m}$ and $S_F^{45\mu m}$ is the percentage of material finer than 45 µm in discharge and feed, respectively. F is the amount of feed [tonne/h] and P is the mill power [kW].

The apparent-Work index ($W_{app}$) is shown in Eq. (2).

$$W_{app} = \frac{P}{10 \times F} \times \frac{1}{\sqrt{d_{80,\text{out}}} - \frac{1}{\sqrt{d_{80,\text{IN}}}}}$$
Where $P$ is mill power [kW], $F$ is the amount of feed [tonne/h] and $d_{80}$ is the 80% passing size [$\mu$m] for discharge and feed, respectively.

Table 1: Grindability and Apparent-work index.

<table>
<thead>
<tr>
<th>Section 6</th>
<th>Feed</th>
<th>Disch.</th>
<th>$d_{50}$ in</th>
<th>$d_{50}$ out</th>
<th>Power</th>
<th>feed</th>
<th>Grindability</th>
<th>Apparent-Work index</th>
<th>$W_{app}$</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>[% &lt;45 $\mu$m]</td>
<td>[% &lt;45 $\mu$m]</td>
<td>[µm]</td>
<td>[µm]</td>
<td>[kW]</td>
<td>[t/h]</td>
<td>[kg &lt;45 $\mu$m/kWh]</td>
<td>[kWh/ton]</td>
<td></td>
</tr>
<tr>
<td>06KV001</td>
<td>4.0</td>
<td>23.0</td>
<td>3250</td>
<td>315</td>
<td>1918</td>
<td>350</td>
<td>34.7</td>
<td>14.12</td>
<td></td>
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<tr>
<td>06KV002</td>
<td>13.0</td>
<td>41.0</td>
<td>320</td>
<td>125</td>
<td>3419</td>
<td>343</td>
<td>28.1</td>
<td>29.72</td>
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<tr>
<td>06KV003</td>
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<td>63.0</td>
<td>125</td>
<td>77</td>
<td>2728</td>
<td>335</td>
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</table>

<table>
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<th>$d_{50}$ out</th>
<th>Power</th>
<th>feed</th>
<th>Grindability</th>
<th>Apparent-Work index</th>
<th>$W_{app}$</th>
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<tbody>
<tr>
<td></td>
<td>[% &lt;45 $\mu$m]</td>
<td>[% &lt;45 $\mu$m]</td>
<td>[µm]</td>
<td>[µm]</td>
<td>[kW]</td>
<td>[t/h]</td>
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<tr>
<td>05KV001</td>
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<td>19.0</td>
<td>4780</td>
<td>315</td>
<td>1461</td>
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<td>32.0</td>
<td>11.95</td>
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<tr>
<td>05KV002</td>
<td>12.0</td>
<td>37.0</td>
<td>330</td>
<td>143</td>
<td>2573</td>
<td>274</td>
<td>26.6</td>
<td>32.86</td>
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<tr>
<td>05KV003</td>
<td>38.0</td>
<td>60.0</td>
<td>140</td>
<td>74</td>
<td>2463</td>
<td>268</td>
<td>23.9</td>
<td>28.96</td>
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</tbody>
</table>

The result gives that all mills in the new section 6 have a better grindability compared to the old section. However, for the coarse end of the particle size range it is not clear, since there is no consistent difference between the sections.

4.3 Point analysis
The different sieve fractions were examined in the polarization microscopy and interesting areas, which contain different minerals, were marked (ringed). The marked areas were used for closer examination in the SEM. The different particles were marked for the EDS (Energy Dispersive X-ray Spectroscopy) analysis.

EDS analysis gives an estimate of what elements occur in a sample (qualitative), or in a much more rigorous process compared with this case a precise and accurate (quantitative) chemical analysis. Three different images were examined; all were from the same sample 06KV001 (in, 150µm). This sample was chosen because it contains most gangue minerals, since the feed to section 6 does not undergo any wet cobbing.
Figure 9: Ring 1 06KV001 (in, 150µm). Pyroxene/Amphibolite (A); Apatite (B); Plagioclase (C); Biotite (D); Pyroxene/Amphibolite (E); K-feldspar (F).

The pyroxene and the amphibolite are both marked as A and E. The reason is that both minerals are similar to each other and it is difficult to tell apart the minerals through chemical analysis and structure analysis. With the used analysis, it is possible to identify them as separate phases.

Figure 10: Ring 2 06KV001 (in, 150µm). Legend, see Figure 8.
The different minerals are identified by focusing the electron beam on the desired particle and the EDS detector collect the X-ray signals. The signals are sent to the EDS analyser that sorts the signal for different signals.

4.4 Particle Texture Analysis (PTA)

![Graph showing mineral content in different fractions](image)

Figure 11: Content of minerals in different fractions from section 6 (06KV001 in).

It is important that the liberation data for minerals in a sample come from a sieve fraction. Test and comparisons have shown that measured liberation of specific size particles in unsieved samples are not the same as the sieved sample. For unsieved samples, the result is not correct (Petruk, 2003). The material from Malmberget was screened to produce fractions with sieve ratio 2, starting at 38 µm.

As it is shown in Figure 11 it is clear that the magnetite content decrease with fraction size. Feldspar and pyrox/amphibole are more evenly distributed over the size fractions, while apatite occurs largely below 100µm.
Figure 12: Liberation of Magnetite 06KV001 (in).

In Figure 12 the fractional liberation of the magnetite is shown. The magnetite is overall well liberated in the fractions examined. The yellow colour shows that the magnetite is liberated to 100 percent, and the orange more than 95 percent.

Figure 13: Magnetite associated with other minerals 06KV001 (in).

In Figure 13 it is once again shown that most of the magnetite is liberated, but there is also some other minerals that is associated with magnetite. In the largest fraction, associated minerals are plagioclase and ilmenite.
Figure 14: Gangue mineral content in section 6.

Figure 14 show that the primary mill also contains other minerals then the main mineral (magnetite). Then after the second mill, other unwanted minerals are almost eliminated from the process.

The modal mineralogy (Figure 15) is showing the percentages of minerals found in the analysed grain-size fraction based on examination of a sample. As mentioned earlier, there is no large difference between the sections, although it is shown that the magnetite content in section 5 is higher than section 6.
Modal mineralogy for section 6

Figure 15: Mineral content for different section at 38µm.

5 Conclusions
In comparing the two sections, it seems that the new section 6 is slightly more efficient in producing fine particles. By the result from table 1, it is clear that the new section 6 have better grindability. However, more sampling and more data is necessary.

The gangue minerals were identified through the point analysis (Figure 8 and 9). The dominants minerals were feldspar and pyroxene. If is shown in Figure 10

182
that they are more evenly distributed over the size fraction while quartz occurs below 100 µm. That is why it is hard to find quartz in the point analysis, since the fraction used for point analysis was 150 µm, and consequently quartz did not show up in the point analysis.

The PTA system is very flexible and is based on a commercially available particle analysis system. The point analysis is valuable for samples with different minerals, it make it very easy to identify the different mineral in the sample. In Figure 15 it is shown that the magnetite content in section 5 is higher than section 6. In this report however, the PTA information is from the feed to section 6 only. To be able to compare the two grinding section, we need to have PTA information for the other points in section 6, as well as the corresponding points in the old section.

Particle shape analysis is another decisive factor to be investigated in the future work. This can be done on the recorded images from the polarization microscope.

In the future work, it is also planed to use multivariate statistical analysis on the data. This, since all the measurement methods produce a lot of information about each sample, and it is hard to manually extract the most relevant data from the total data set.

6 Acknowledgement
Financial support from LKAB Research and Development is gratefully acknowledged. We would also like to thank Prof. Terje Malvik and Dr. Kari Moen for supervising and helping with the process mineralogy analyses.

7 References


http://www.microscopyu.com/articles/polarized/polarize intro.html
Paper C

Applying traceability to grinding circuits by using Particle Texture Analysis (PTA)
Oghazi, P., Pålsson, B., Tano, K., (Submitted)

Submitted for publication in Minerals Engineering:
Applying traceability to grinding circuits by using Particle Texture Analysis (PTA)
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LKAB, SE-983 32 Malmberget, Sweden 2

Abstract
LKAB has started a new pelletizing plant at Malmberget, where the raw material will be a mix of ores from Kiruna and Malmberget. The new plant necessitated an investment in a new grinding section in the concentrator. As usual, the new section has larger mills. It also lacks the wet cobbing stage present in the old sections.
Comparing the results from the new section with the old sections show that they give similar results. There are slight variations; the older mills produce a steeper final particle size distribution. Also, it appears that the new mills are more efficient, since they have higher calculated grindability indices.
To better understand the differences between the sections, and the process implications of the new grinding section, a combination of Particle Texture Analysis (PTA) and the statistical method Multivariate Analysis (MVA) is used. It shows that it is possible to identify and follow systematic changes in the particle morphology of the mill products. Also, that there are differences between the old and new grinding sections.

Keyword: Traceability; Grinding; Multivariate analysis

1. Introduction

LKAB has since the beginning of the 1900’s produced iron ore from mines in Kiruna and Malmberget and is today one of the world’s leading producers of highly refined iron ore products. The main product is pellets, for blast furnaces and direct reduction furnaces. Today there is a higher demand from the customers and to obtain a good quality it is important to have good control over the process and the raw material used.

LKAB started the new pelletization plant at Malmberget (MK3) in November 2006. The raw material will be a mix from Kiruna and Malmberget, i.e., different ores having different Fe-content and levels of contaminants (Martinsson and Wanhainen, 2000).

That is why the traceability of the continuous process is one of the crucial factors for future development of granular product(s). Traceability gives the advantage to have a better control over the material through the process and there can be adjustments taken, if needed. It can show “the current” values of different parameters and how much we have to adjust to achieve the goals. In food and pharmacy industries it is very common to use different traceability tools but in the mining industry, which is mostly a continuous process, traceability is an untouched area.

As mentioned earlier, traceability is common in part or batch production and often relatively easy to achieve, since different kinds of identification markers can be attached to a unit or different parameter can be measured at different process stages. In continuous processes on the other hand the main part of the collected data relate to process variables that are frequently measured, while product data are limited and infrequently measured (Hild et al., 2000).
Also, the literature dealing with traceability is dominated by applications from parts production. However, creating traceability in continuous processes implies vast challenges: process flows can be parallel, serial and circular; sub-processes can be continuous as well as batch-wise; have large buffers or no interruptions in product handling. The purpose of this paper is to compile and describe how process mineralogy could be used for achieving traceability in continuous processes. In this case the grinding sections are in focus, and multivariate data analysis is used to interpret the mineralogy and textures of the minerals in this section.

2. Material

Most iron ores contain significant amounts of gangue minerals that need to be eliminated to produce iron concentrates. At Malmberget, the dominant iron mineral is magnetite but also hematite occurs. Gangue minerals are mostly quartz, pyroxene, apatite, and feldspar (Geijer, 1930).

Material from the mine is sent to the concentrator plant which separates the minerals into two parts, tail and product (Kvarnström and Oghazi, 2008). The samples that are used in these studies are from the concentrator’s, old section 5 and the new section 6.

2.1 Flowsheet

Figure 1 shows a typical flowsheet for concentrating iron ore at LKAB. The coarse material at 10-15 mm in size is fed to a wet magnetic cobbing separator (M1). The magnetic concentrate is discharged into a primary ball mill (#1), and the ground product (pulp) is transferred to a primary magnetic separator (M2). The resultant magnetic concentrate is then pumped into a secondary ball mill (#2). A secondary magnetic separation unit (M3) finally upgrades the ground product and the concentrate is used as feed for the tertiary grinding stage (#3) (Tano et al., 2005).

![Fig.1. Flowsheet for grinding section 5.](image-url)
The flowsheet for the new grinding section 6 resemble the one for section 5, the only difference is that there is no wet cobbing stage before the primary mill. Here, ball mill grinding is used in three consecutive steps with wet low intensity magnetic separators in between. It is important to grind to, approximate 68% < 45µm to liberate gangue minerals, and to reach the desirable size distribution for the pellets feed. In the result part there is a complete data of how each mill performs (Table1).

3. Experimental

3.1 Sampling

Feed samples were taken manually when the material was in motion at a point of free fall, by making a cut at right angle through the falling stream. The other samples were taken as manual pulp samples with pear shaped scoop throughout the circuit before and after each grading stage. The samples were weighted and then filtrated at Malmberget. In the laboratory at LTU the samples were dried and then cut by a Jones splitter into suitable proportions. The dry material was sieved with a Rot-Tap shaker down to 75 µm and wet sieved further to 38 µm.

3.2 Particle Texture Analysis

It is important that the liberation data for minerals in a sample come from a sieve fraction. Test and comparisons have shown that measured liberation of specific size particles in unsieved samples are not the same as the sieved sample. For unsieved samples, the result is not correct (Petrük, 2003).

To have a good view over the different samples, Particle Texture Analysis (PTA) was done at NTNU, Trondheim, Norway. The PTA data system is based on the Oxford Inca Feature software and an existing scanning electron microscope (Moen, 2006). Using Back Scattered Electrons (BSE) the images are analysed by means of grey level and every grain of interest is analysed with X-rays. With the Inca data information the images will be processed and calibrated (grey-scale and binary images); and the grains will be identified and evaluated if they are liberated or in composite particles and which minerals occur in the composite mineral. When all particles is analysed, the data will be imported to the PTA software. The PTA software gives plots and thumbnail images regarding mineral liberation, mineral association analysis and intergrowth analysis.

3.3 Multivariate Data Analysis

For achieving good control and having better overview of the process data it is necessary to collect data with many variables and many properties from the process. By using multivariate data analysis (MVDA) these variables will be explained and expressed and condensed into a few latent variables or principal components so it will be easier to understand the importance and contribution of each variable.

Multivariate data analysis is based on projection methods. One, Principal Component Analysis (PCA) is a projection method of the original variables onto new ones, orthogonal and arranged according to their eigenvalue. This is done on all the data contained in a matrix $X$, where $T$ represents the score matrix and $P$ represents the loading matrix (Wold et al., 1984).

$$ X = TP^T + E $$
Other MVDA techniques are PLS (projection to latent structures), SIMCA (soft independent modelling of class analogies), and MSPC (multivariate statistical process control) are not used here, since this contribution is centred on pattern recognition. The MVDA is run with the software program SIMCA-P+, version 11.5 (Eriksson et al., 2006).

4. **Result**

4.1. **Size analysis**

The size distributions of particles in the material for both sections (Sections 5 and 6) are shown in Figures 2 and 3 respectively.

![Particle size distribution Section 5.](image)

The particle size analyses of the feed and the products in the grinding process show the reduction of particle size ($d_{80}$) from 4700 µm in the feed to 70 µm in the final product. By comparing section 5 and 6 there are slight variations in the results, the finer feed to section 5 is due to the wet cobbing preceding the primary mill. The older mills in this section produce a steeper final particle size distribution. It is, however, too early to say if this is linked to mill size, or if it is the result of a better, worn in, graded charge.
The particle size analysis from section 6 gives similar results compared with the results of section 5. The grinding ratio in the primary mill is dramatically higher than the secondary and tertiary mills, which is due to the well known fact that the larger particles grind easily. Size distribution analyses from the output of the primary mill and the input to the secondary mill indicate that the LIMS mainly eliminates smaller gangue minerals fractions. This may explain why the feed to the secondary mill is coarser than the discharge from the primary mill. On the other hand, the analysis from output of the secondary mill reveals that the magnetic separator does not change the particle size for the feed to the tertiary mill.

4.2. Mill efficiency

There are two major ways to easily compare operating mills: grind-ability and apparent work index (Tano, 2005). Grind-ability index ($G_i$) showing the produced amount of material finer than 45 µm is calculated according to equation (1).

$$G_i = \frac{(S_D^{45\mu m} - S_F^{45\mu m}) \times 1000 \times F}{P}$$  \hspace{1cm} (1)

Where $S_D^{45\mu m}$ and $S_F^{45\mu m}$ is the percentage of material finer than 45 µm in discharge and feed, respectively. F is the amount of feed [tonne/h] and P is the mill power [kW].

The apparent-Work index ($W_{app}$) is shown in equation (2).

$$W_{app} = \frac{P}{10 \times F} \times \frac{1}{\sqrt{d_{out}}} - \frac{1}{\sqrt{d_{in}}}$$  \hspace{1cm} (2)

Where P is mill power [kW], F is the amount of feed [tonne/h] and $d_{80}$ is the 80% passing size [µm] for discharge and feed, respectively.
Table 1. Grindability and Apparent-work index.

<table>
<thead>
<tr>
<th>Section 6</th>
<th>Feed [% &lt;45 µm]</th>
<th>Disch. [% &lt;45 µm]</th>
<th>d50 in [µm]</th>
<th>d50 out [µm]</th>
<th>Power [kW]</th>
<th>[t/h]</th>
<th>Grindability [% &lt;45 µm/kWh]</th>
<th>Apparent-Work index Wapp [kWh/ton]</th>
</tr>
</thead>
<tbody>
<tr>
<td>06KV001</td>
<td>4.0</td>
<td>23.0</td>
<td>320</td>
<td>125</td>
<td>315</td>
<td>350</td>
<td>34.7</td>
<td>14.12</td>
</tr>
<tr>
<td>06KV002</td>
<td>13.0</td>
<td>41.0</td>
<td>320</td>
<td>125</td>
<td>3419</td>
<td>343</td>
<td>28.1</td>
<td>29.72</td>
</tr>
<tr>
<td>06KV003</td>
<td>42.0</td>
<td>63.0</td>
<td>125</td>
<td>77</td>
<td>2728</td>
<td>335</td>
<td>25.8</td>
<td>33.21</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Section 5</th>
<th>Feed [% &lt;45 µm]</th>
<th>Disch. [% &lt;45 µm]</th>
<th>d50 in [µm]</th>
<th>d50 out [µm]</th>
<th>Power [kW]</th>
<th>[t/h]</th>
<th>Grindability [% &lt;45 µm/kWh]</th>
<th>Apparent-Work index Wapp [kWh/ton]</th>
</tr>
</thead>
<tbody>
<tr>
<td>05KV001</td>
<td>3.0</td>
<td>19.0</td>
<td>4780</td>
<td>315</td>
<td>1461</td>
<td>292</td>
<td>32.0</td>
<td>11.95</td>
</tr>
<tr>
<td>05KV002</td>
<td>12.0</td>
<td>37.0</td>
<td>330</td>
<td>143</td>
<td>2573</td>
<td>274</td>
<td>26.6</td>
<td>32.86</td>
</tr>
<tr>
<td>05KV003</td>
<td>38.0</td>
<td>60.0</td>
<td>140</td>
<td>74</td>
<td>2463</td>
<td>268</td>
<td>23.9</td>
<td>28.96</td>
</tr>
</tbody>
</table>

The result gives that all mills in the new section 6 has a better grindability compared to the old section. However, for the coarse end of the particle size range it is not that clear, since there is no consistent difference between the sections.

4.3. Particle Texture Analysis (PTA)

The PTA gives us information of how different minerals are distributed at different fractions. As it is shown in Figure 4 it is clear that the magnetite content decrease with fraction size. This is due to the sugar grain structure of the Malmberget magnetite, which easily breaks along grain boundaries. Feldspar and pyrox/amphibole are more evenly distributed over the size fractions, while apatite occurs largely below 100µm.

Fig. 4. Content of minerals in different fractions from section 6 (06KV001 in).
The PTA also shows how minerals are liberated in different fractions. In this case magnetite is overall well liberated in the fractions examined, but there is also some other minerals that are associated with magnetite. In the largest fraction, associated minerals are plagioclase and ilmenite.

The modal mineralogy in figure 5 is showing the percentages of minerals found in the analysed grain size fraction based on examination of a sample. As mentioned earlier, there is no large difference between the sections, although it is shown that the magnetite content in section 5 is higher than section 6.

![Modal mineralogy for section 5](image)

![Modal mineralogy for section 6](image)

Fig. 5. Mineral content for different section at 38µm.
Figure 5 for section 6 show that the primary mill also contains other minerals than the main mineral (magnetite). Then after the second mill, the unwanted minerals are almost eliminated from the process. However in outgoing secondary mill (06KV002 out) the gangue minerals increase slightly which means that some selective grinding of coarse gangue minerals here occurred.

With PTA it is also possible to have a god overview over the mineral liberation. It is calculated by the area method, an area of mineral in interest is measured and also the host particle in the polished section, and calculating the percent of mineral in the particle. However, the liberation result is not shown here, since the liberation was 90% or better in all cases.

### 4.4. Multivariate analysis

All the data from the PTA were collected and arranged in different Excel files, and then imported into the software SIMCA. Each particle was an observation in a data file with variables according to Table 2. A typical PTA data for one sample contained of 7000-10000 observations/particles. PCA-models were created to check for pattern in the data. Here, the score and loading plots are used. They give important information about variables that are responsible for the pattern seen among the observation and how they are related to each other.

Table 2. List of mineral identifications and parameters which were extracted from PTA and used for analysis. (The morphology parameters are written *Italic*.)

<table>
<thead>
<tr>
<th>Minerals:</th>
<th>Parameters:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetite</td>
<td><em>Area;</em> (Area of whole feature in square microns)</td>
</tr>
<tr>
<td>Ilmenite</td>
<td><em>Length;</em> (Max feret)</td>
</tr>
<tr>
<td>Rutile</td>
<td><em>Breadth;</em> (Min feret)</td>
</tr>
<tr>
<td>Plagioclase</td>
<td><em>Perimeter;</em> (Perimeter of whole feature in microns)</td>
</tr>
<tr>
<td>Quartz</td>
<td><em>Aspectratio;</em></td>
</tr>
<tr>
<td>Pyroxene/Amphibole (Pyx/Amf)</td>
<td><em>Direction;</em> (Angle)</td>
</tr>
<tr>
<td>Biotite</td>
<td><em>Perimeter²</em>; <em>Shape;</em> 4π×<em>Area</em></td>
</tr>
<tr>
<td>K-feldspar</td>
<td><em>ECD;</em> 4×<em>Area/π</em></td>
</tr>
<tr>
<td>Enstatite</td>
<td>Mean grey level; (Mean image grey level for each particle)</td>
</tr>
<tr>
<td>Apatite</td>
<td>% Element (wt %)</td>
</tr>
<tr>
<td>Titanite</td>
<td></td>
</tr>
<tr>
<td>Calcite</td>
<td></td>
</tr>
<tr>
<td>Sulphides</td>
<td></td>
</tr>
<tr>
<td>Unclassified</td>
<td></td>
</tr>
</tbody>
</table>
4.4.1 Overview

The first analysis is run to get an overview based on all identifications and parameters in Table 2.

Table 3. Overview of R2 and Q2 for the model of feed to section 5.

<table>
<thead>
<tr>
<th>Components</th>
<th>R2X</th>
<th>R2X(cum)</th>
<th>Eigenvalues</th>
<th>Q2</th>
<th>Limit</th>
<th>Q2(cum)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 Cent.</td>
<td>0.174</td>
<td>0.174</td>
<td>11.3</td>
<td>0.112</td>
<td>0.0153</td>
<td>0.112</td>
</tr>
<tr>
<td>1</td>
<td>0.157</td>
<td>0.33</td>
<td>10.2</td>
<td>0.161</td>
<td>0.0155</td>
<td>0.256</td>
</tr>
</tbody>
</table>

R2X (cum) explains the cumulative of the sum of squares of all the X’s explained by the extracted components. Q2 (cum) explains the total variation of the X’s that can be predicted by a component.

The score plot shows the relationship among the observations (minerals). This plot can be seen as window in the X space, where the objects (particles) are projected on a 2 dimensional hyperplane in the 65 variable space. In figure 6 it is shown there is a separation between the magnetite and the gangue minerals in the second direction. There is also a separation between the gangue minerals which put them in different groups.

Fig. 6. Score plot coloured according to mineral identifications for feed material in to section 5 (38µm).
In the first PCA overview the material is clearly spread out in the first direction. In figure 7 which is a loading plot, show the importance of different variables in the X matrix. It explains how different variables contribute to the model which is shown in the score plot.

As it show in figure 7 gangue and magnetite are positioned in opposite direction, this explain why the gangue and magnetite are so well separated in the score plot (figure 6). On the top right side of the loading plot the morphology variables are gathered. It is these variables which need to be investigated more.

4.4.2 Comparison of feed and discharges to a mill

The first analysis aimed to compare the feed and discharge for each mill. By excluding all variables except the morphology ones (those in upper right red ring in figure 7), the model was improved.

Table 4. Overview of R2 and Q2 for the developed models for section 5.

<table>
<thead>
<tr>
<th>Components</th>
<th>R2X</th>
<th>R2X(cum)</th>
<th>Eigenvalues</th>
<th>Q2</th>
<th>Limit</th>
<th>Q2(cum)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 Cent.</td>
<td>0.627</td>
<td>0.627</td>
<td>5.02</td>
<td>0.581</td>
<td>0.111</td>
<td>0.581</td>
</tr>
<tr>
<td>1</td>
<td>0.183</td>
<td>0.81</td>
<td>1.46</td>
<td>0.109</td>
<td>0.125</td>
<td>0.626</td>
</tr>
<tr>
<td>2</td>
<td>0.117</td>
<td>0.927</td>
<td>0.936</td>
<td>0.168</td>
<td>0.143</td>
<td>0.589</td>
</tr>
<tr>
<td>3</td>
<td>0.055</td>
<td>0.982</td>
<td>0.439</td>
<td>0.693</td>
<td>0.167</td>
<td>0.874</td>
</tr>
</tbody>
</table>

Fig. 7. Loading plot for the PCA model, feed material to section 5.
The loading plot in Figure 11 shows that size parameters carry most of the information in the first direction while mean grey have a great influence in the third direction. The first direction is length information.
With the same model and the score plot coloured according to mineral classification it is possible to see how the minerals differentiate. The main parameter pulling magnetite away appears to be Mean grey. This is what to be expected.

![Score plot with mineral identification for feed and discharge to the primary mill material, section 5 (38µm).](image1)

Fig. 12. Score plot with mineral identification for feed and discharge to the primary mill material, section 5 (38µm).

However if the same plot is stripped to leave only magnetite information, sub-populations of magnetite emerges, cf. Figure 13.

![Score plot for magnetite for feed and discharge to the primary mill material, section 5 (38µm).](image2)

Fig. 13. Score plot for magnetite for feed and discharge to the primary mill material, section 5 (38µm).
To this moment it is not entirely clear what causes the split on sub-populations. The lower value of Mean grey and shorter length indicates that the two minor groups may constitute of mixed particles.

The loading plot for the primary mill section 6 is very similar to the loading plot from section 5, and therefore not shown. This proves that the pattern found is systematic. PC direction 1 carries length/size information, while PC3 is mostly Mean grey.

Table 5. Overview of R2 and Q2 for the developed models in Section 6.

<table>
<thead>
<tr>
<th>Components</th>
<th>R2X</th>
<th>R2X(cum)</th>
<th>Eigenvalues</th>
<th>Q2</th>
<th>Limit</th>
<th>Q2(cum)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 Cent.</td>
<td>0.623</td>
<td>0.623</td>
<td>4.98</td>
<td>0.575</td>
<td>0.111</td>
<td>0.575</td>
</tr>
<tr>
<td>1</td>
<td>0.185</td>
<td>0.808</td>
<td>1.48</td>
<td>0.127</td>
<td>0.125</td>
<td>0.629</td>
</tr>
<tr>
<td>2</td>
<td>0.113</td>
<td>0.92</td>
<td>0.902</td>
<td>-</td>
<td>0.223</td>
<td>0.143</td>
</tr>
<tr>
<td>3</td>
<td>0.0579</td>
<td>0.978</td>
<td>0.464</td>
<td>0.666</td>
<td>0.167</td>
<td>0.864</td>
</tr>
</tbody>
</table>

4.4.3 Gangue mineral changes in the sections

To understand the beneficiation process, it is necessary to investigate the gangue minerals more carefully. Usually iron ores occur in formation with siliceous rocks, and other minerals such as apatite and feldspar are also present. The section 5 results for apatite and feldspar are shown in Figures 15 and 16 respectively.
Most of the particles are distributed in the first direction; it is the morphology parameters that affect most in first direction cf. figure 11. In the score plot some particles are found outside the confidence interval and are marked with a red circle, by investigating this group with a contribution plot in SIMCA it shows that these particles are larger than average apatite particles.

Fig. 16. Score plot for incoming and outgoing feldspar in section 5.
The score plot for apatite in section 6 is very similar to section 5, but there are some differences. It is obvious that there is more apatite in section 6 after the last mill compared to section 5. A significant factor is that there is no cobbing stage before section 6, and it is also important to have control over all reflux flows and other flows that are connected to this section.

Fig. 17. Score plot for incoming and outgoing apatite in section 6.

Fig. 18. Score plot for incoming and outgoing feldspar in section 6.
5. Conclusion

The main benefit of multivariate analysis on particle texture data is that it simultaneously compares several thousand particles. This kind of investigation is state of the art in this area and it can provide unambiguous of information about how each process step influences the material.

The combination of PTA and MVDA seems to be a promising development. Further refinements would be to use MVDA models to discriminate between “good” and “bad” feed materials using SIMCA classification techniques.

By comparing different sections and different minerals it can be shown how the cobbing stage affect the circuit. By comparing the feldspar and apatite it is obvious that the apatite continue to exist during the whole circuit, while most of the feldspar is separated after the first separation stage. It seems that the free particles disappear while mixed particles continue to exist in the circuit.

By comparing section 5 and 6, a direct similarity is found between the two section but also some divergences, which can depend on the cobbing stage or other factors that the grinding mill differs from each section.

It would be interesting to further investigate the material from both sections by using optical microscopy. Optical analysis will better identify the intergrown minerals.

However, more samples are taken from all reflows and they need to be analysed, it will show us how different flows affect the product flow.

Acknowledgements

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