Guidelines for Ore Tracking System in the Complex Underground Transportation Got from the DISIRE Project

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Abstract. Tracking of a mined ore is now considered as one of the key issues for the needs of improvement of the whole value chain of metal production. Ore beneficiation processes (grinding, milling, floatating) aimed to increase the metal recovery and decrease the energy use as well as reconciliation of mining production depend on the identification of a mined ore. However, even if the ore is recognised at mining faces (with the help of analysis of channel samples and orebody modelling), after being mined it is blended on its way from various mining fields to the processing plants. In a complex transportation system consisting of belt conveyors with switching points, ore bunkers and shafts, batches of mined ore become anonymous. Following the growing needs of getting the knowledge from the transported or processed raw material, the DISIRE research project (within the Horizon 2020 framework program) was carried out in 2015-2018. It was focused on investigation of the Process Analyser Technology (PAT) tags for annotating the transported or processed bulk material for the needs of its further processes control and optimisation (economic, decrease of energy use). The DISIRE work package “Non-ferrous mineral processing” was devoted to implementation PAT tags for the identification of conveyed copper ore in the underground mines to get the data necessary to improve the ore processes settings control. The complex investigations consisted of the analysis of available data from existing information systems, tests of the use of labelled tags in the harsh operational conditions of the underground mine, digital experiments of simulating the ore flow throughout the transportation system, the specific modelling of the ore particles movement inside the shaft ore bunkers with the use of Discrete Element Method. These main research activities were supported by supplementary investigations like application of picture recognition techniques for differentiation of various ore batches and statistical analysis of ore loading process (by trucks from mining fields). The processing of the real data as well as the numerous in-situ experiments have proved the possibility of the application of PAT tags for the needs of ore tracking and allowed to set the guidelines of the ore tracking system. The ore tracking system should be based on the dedicated simulation model of the mine transportation system, supported on-line by the data from existing information systems that monitor mining production and machinery control. As the mining transportation system is subjected to frequent changes, PAT tag experiments should be repeated to validate the simulation model. Ore bunkers play a key role in ore mixing which should be identified with the help of DEM modelling. All investigations were done on the basis of the chosen KGHM S.A. underground mine set of real operational data. The copper ore mined in these mines is considered as one of the most complex in the world (and the most difficult to be processed), so the implementation of the ore tracking system would be of great value for the more effective ore processing.
1. Introduction

The needs of effective mined ore tracking throughout the whole metal production process consisted of ore mining, transporting and beneficiation are growing, following the rising understanding of the impact of the exact identification of ore parameters on the effectiveness of the ore processing. Surveys prove that even the neighbouring mines that exploit the same lode, differ from one another when compare their operational parameters (like exploitation gate), ore compound and effectiveness of ore beneficiation [9]. The specialised economic measures applied to evaluation the metal production results like Net Smelting Revenue [8] help to link mining operational parameters with profits. The resulting grade engineering® strategies are based on the identification of metallurgical ore parameters in-situ and control them throughout the ore processing processes [11]. Consequently, tracking the ore batches on its way from mining blocks to the processing plants is becoming the crucial element of the effective metal production chain control. The solution, based on logistic operations, includes assigning a mined ore batch (MOB) with a label that allows to keep the information already generated for the deposit (with the use of channel samples and orebody, digital modelling) with the MOB. The effective labelling the mined ore with dedicated RFID tags that are dropped into MOBs and thereafter read by antennas installed on the transportation route to get the embedded information has already been developed for the open pit operations [10]. The investigations of the application of such tags technology for the iron ore tracking [7] have led to launch the DISIRE project. It was focused on investigation of the Process Analyser Technology (PAT) tags for annotating the transported or processed bulk raw material for the needs of its further processes optimisation (increase the economic results and decrease the specific energy use) in various industry branches [12].

The DISIRE approach and its planned implementation to the non-ferrous mineral processing was devoted to implementation PAT tags for the annotation of conveyed copper ore in the underground mines to get the data necessary to improve the ore processes settings control was described in [2]. As stated there, because “the lithological structure of ore has a great impact on effectiveness of ore grinding and floatation, the identification of the ore preceding its delivery to the processing plants is considered to be a key information for the suitable settings of the processing equipment aiming to increase the metal recovery as well as decrease the specific energy consumption” [2]. The comprehensive study of the elements of the solution: availability of existing of the operational data for the ore tracking system [3,4], methods of modeling of the vast ore transportation network [3,5], the proposed workflow of the ore tracking system based on DISIRE tags [4], detailed modeling of the ore flow inside ore bunkers as well as the numerous experiments (both in the laboratories and in-situ) were reported in the final DISIRE project deliverable [1].

For the needs of setting the assumptions of the ore tracking system (OTS) and building the solutions the following terms are used:

- Mined ore batch (MOB) – a portion of ore mined from a mining face; it is assumed that MOB is positioned in-situ (e.g. single blast block at the mining face) and its compound can be identified (e.g. evaluated against the digital block model of the mined deposit); quality and technological parameters of the MOB are important for ore processing efficiency,
- Processed ore batch (POB) - portion of ore treated as a single input into the Ore Enrichment Plant,
- Ore Enrichment Plant (OEP)– complex production line, consisting of dedicated machinery equipment for grinding, milling, separating and floatating the POBs that produces a concentrate by extracting the metal from ore,
- Ore processing category (OPC) – class of ore quality which is defined by lower and upper limits of the analysed quality parameters with regard to technological requirements of the Ore Enrichment Plant,
- The effective OTS should provide in advance the OEP with the recognized OPC assigned to each POB that is supplied to the ore processing plant after being mixed from various MOBs
conveyed from the active mining blocks. The gathered knowledge and experience from the DISIRE project has led to the set of guidelines for the industrial OTS.

2. Investigations of the copper ore flow in the belt conveyor system

2.1. Complexity of BC transportation system of the KGHM Lubin mine

The underground transportation system in the KGHM “Lubin” copper ore mine with the proposed (for tests) locations of RFID tags dropping points (red arrows on the figure 1) was selected for the investigation. As presented on the figure 1, the division BCs are equipped with screens (loading points with ore crushing devices) where MOBs are delivered by LHDs and trucks from G1, G4 and G9 mining departments. The ore compound and grade in each department differ from one another [2, 9]. The ore is then conveyed by the main haulage BCs, stored temporarily inside the transitive and shaft ore bunkers (on the figure 1 pointed with the middle and left red arrows respectively). There are several scales (green boxes on the figure 1) where the actual output as well as cumulative tonnages of conveyed ore are recorded and these data can be interrogated and are used for reconciliation of mining production [6].

Figure 1. Map of investigated branch of the transportation system in the KGHM Lubin mine [1]

The map of the branch of the transportation system in the KGHM Lubin mine illustrates the key issues that were found to be investigated in order to analyze ore flow:
- The process of loading the BC with MOBs by LHD/trucks – the cyclical input to the BC transportation system,
- The ore flow through the bunkers – forced ore mixing, filling and unloading the bunkers,
- Working hours and stoppages of the selected objects of the BC system, travelling time of a MOB since its loading up to the delivery to the Ore Enrichment Plant (OEP).

The investigations of the ore flow through the BC system were carried out with the use of data from existing information systems and implementation of statistical, simulation and digital modelling methods and are described in the oncoming papers.
2.2. Existing information systems
The information environment of the ore transportation process as well as mining process has been extensively described in the DISIRE project deliverables [1]. The following elements of the existing KGHM information system of the mine are relevant and can be used either directly or indirectly for the ore tracking:

- MOPRONA – directly; selected reports from the relevant shifts; MOPRONA provides the on-line support of mining operations and ore production. [6] Data are fed to MOPRONA on a regular basis from mine plans, schedules, operational shift reports and other databases (BDG). In the MOPRONA schedules are compared with production reports. For a given shift each loading point on any belt conveyor (screen) is assigned with a known mining face from where the ore is hauled. Location of mining faces is documented on digital mine plans (DGN format). MOPRONA provides the reference of MBID (mining block identifier), mining department ID and truck (loader) identifier (TID).

- Belt Conveyor scales – directly; data from the relevant shifts; Scales provide the data on tonnages recorded on-line on observed conveyors.

- BDG – indirectly (via MOPRONA). Geological database of channel samples. This provides with sample data: sample identifier (BHID), plane coordinates (X,Y), lithological compound and grade.

- Datamine Studio – optionally: if available it will provide the 3-D orebody quality and structural block model of the copper ore seam which can be used for evaluation mining blocks (identified by their MBID) to provide the MOBs with the actual lithological compound assessment [13].

The chart on the figure 2 shows the aggregated information about the ore loaded onto an investigated BC. This information was obtained from the MOPRONA system. As the arrivals of trucks on loading points are also recorded in MOPRONA, each MOB can be identified at the screen of a BC loading point (on the input to the BC transportation system).

![Figure 2. Variations of ore supply during 20 consecutive shifts supplied onto 4 loading points of a division BC (data source: MOPRONA [3])]
The KGHM also successfully implements information systems for supporting the complex processes of copper ore enrichment - FloVis, MillVis, ConVis [4]. ConVis helps to optimize the ore grinding (probably the most energy consuming process) supplied from various mining fields. The information about the ore compound can be used for better stabilization of ore granulation to increase the efficiency of grinding and maintain the stable crushed material flow onto mills feeders [4].

2.3. Analysis of the input ore flow to the BC system
The analysis of the ore supply to the BC system was crucial for the whole ore flow process understanding. The investigation of a full working week data were focused on identification of the distribution of arrival of trucks that supply the ore from various mining fields (see figure 1). The results have provided the data for modelling the ore flow within the BC system and are to be published soon. Some general conclusions are as follow:
- The haul truck courses did not exhibit normality of distribution of mean inter-arrival times and cannot be described by some reliable probability distribution.
- The mean time between arrival of trucks of a bigger payload is longer as these trucks are usually used for longer distances.
- Also these mean inter-arrival times change from one day to another following the changes of location of active mining faces.
- The empirical distribution of the mean inter-arrival time can be used for modelling the ore supply to the BC system.

2.4. Addressing key issues of the ore flow – modelling the ore flow through bunkers
The investigated BC system in the Lubin mine contains several bunkers of different size and shape. These bunkers are places where ore from various mining fields is blended. Therefore the exact modelling of movement particles with the use of Discrete Element Method (DEM) was applied. The results of this investigation are to be published soon. On the figure 3 the modelled flow of RFID tags that are transported together with annotated by them MOBs are shown. The complexity of a bunker shape and alternative modes of its operation (the bunker can be discharged by left, right or both chutes) require dedicated DEM models of these modes. This is a very specific element of the BC transportation system and cannot be disregarded in the ore tracking investigations.

![Figure 3](image)

Figure 3. 3-D modelling of the shaft bunker developed for the detailed DEM modelling of the ore flow (left and middle left objects), simulated flow path of RFID tags with open right (middle right) and both (right) chutes that discharge the ore bunker [1]

The bunkers are operated manually and the moments of opening their chutes are recorded. This allows to use the suitable pattern of the ore flow model for the representation of the actual ore flow. Experiment results of the tags flow were used for the validation of the DEM model.
3. Simulation model of the BC transportation system

KGHM mines in Poland operate underground vast BC systems of a total length of some 150 km. Avoiding stoppages of the ore flow from mining fields to the processing plant has the highest priority. Reliable operation of the BC depends on both careful, advanced maintenance procedures and numerous ore bunkers and ore flow switching points (in the shaft loading area – see figure 1) embedded into the system. The cost of the increased system reliability is the loss of an easy ore tracking that would be available in a simple, single route, BC system. These transportation systems consist of continuously operating BCs and cyclically - trucks and LHDs supplying ore from mining departments and skips. The resulting transportation solution meets constraints of all involved objects but it is difficult to model and optimize. The preferred method of analysing and optimising of such systems are simulation models [5]. The flexible and versatile simulating environment provided by FlexSim - a discrete-event simulation software program was selected [13]. The complex simulation model of the transportation system (SMTS) of the investigated KGHM Lubin mine was built (Figure 4). The SMTS was tested with regard to real production data obtained from MOPRONA. [1,3,5]. The input of ore from mining departments was modelled on the basis of on the analysis results mentioned in the section 2.3 while the ore flow through the bunkers represents the DEM modelling results (section 2.4). The experiment of annotating the ore with tags (see next section) provided the data for validation of the SMTS. The obtained results of both in-situ and digital experiments are analysed.

Figure 4. FlexSim simulation model of the transportation system (SMTS) – the analyzed branch of the KGHM Lubin mine transportation system: mining departments area (top), shaft area (bottom) [1]
Several alternative variants of ore supply from mining departments to the BC system were simulated and analyzed. The sample chart (Figure 5) presents simulated values of aggregated tonnages of metal in three copper ore lode lithology supplied to the OEP during 5 days of production of all active mining fields. The SMTS can easily respond to any constraints scenario given to input data (like stoppages of production in any mining department, selective blasting and run-of-mine ore supply and the others. More detailed simulation results are described in oncoming papers.

![Sample Chart](image)

**Figure 5.** Tonnages of lithological fractions obtained from the FlexSim simulation of 5-day mining of the analyzed branch of the KGHM Lubin mine [1]

4. DISIRE experiments
The industrial DISIRE experiments was performed within several consecutive working shifts on the right branch of the KGHM Lubin mine transportation system (see Figure 1). Two reading antennas were installed at the shaft head, on the entrance to the OEP (Figure 4). The pellets were dropped in 3 selected sites (marked by red arrows on the Figure 1):

- P1 – the main haulage conveyor supplying the ore directly to the crusher at the underground shaft bunker; this site was the closest to the reading gate (300m horizontal), pellets were conveyed through the crusher, then stored temporarily in the south shaft bunker (see figure 3), hoisted to the top and loaded onto the TG2 or TG3 main conveyors equipped with the reading gates,
- P5 - the main haulage conveyor supplying ore to the bunker (with a capacity of 4500 tonnes) and then through several conveyors to the P1 conveyor (3160m of the total transportation route length)
- P8 (M41a) – the loading point at the M41a division conveyor supplied with ore by loaders and trucks directly from the mining faces; ore is conveyed via several conveyors to the P5 and then to the shaft (9015m of the total transportation route length).

In total 598 pellets (299 pairs) were dropped: 100 pairs for P1 and P5 and 99 pairs for P41a. They were then read at the reading gates throughout the next 48 hours. 397 tags were eventually read. The survival rate exceeds 65% - much more than it had been expected under such hostile conditions (big ore lumps, material spillage out of the belt, crushing of the conveyed ore in the crushers prior to loading the skips in the shafts). The table below (Table 1) contains the summarised data about the pellets survival rate.
Table 1. Survival rate of tags read by reading gates [1]

| Dropping site | M41A     | P5     | P1     | Total |
|---------------|----------|--------|--------|-------|
| Number        | 147      | 158    | 92     | 397   |
| Reading rate  | 73.5%    | 79.8%  | 46.0%  | 66.4% |
| Small tags number | 58    | 67     | 37     | 162   |
| Reading rate  | 58.5%    | 67.0%  | 37.0%  | 54.2% |
| Big tags number | 89     | 91     | 55     | 235   |
| Reading rate  | 89.9%    | 91.0%  | 55.0%  | 78.6% |

Mixing of ore streams annotated by tags on 3 sites can be recognised on the chart presenting number of tags from each dropping point that were read in consecutive hours of recording. The pellets marked only a part of the ore that was hoisted by shafts to the OEP, the other ore streams were supplied from other mining areas.

![Figure 6. Recorded ore mixing for the tagged ore stream (for 3 dropping points) [1]](image)

The idea of the experiment depends on tagging the MOBs with pellets, therefore the sequencing of read pellets and the distribution of their travelling time are of the greatest interest.

5. Guidelines for the ore tracking system

The aim of the OTS is to make the reliable assessment of the OPC of the ore supplied to the OEP. The information is needed well in advance to let the OEP staff enough time for the adjustment of the processing machinery. Few hours or even a full working shift allowed on the ore processing equipment detuning would be appreciated rather than even more accurate ore recognition which is obtained too late to activate appropriate changes of the machinery settings.

The comprehensive investigations of the ore tracking issues in the KGHM underground copper mine have led to formulating the guidelines for creating the effective ore tracking system. The OTS fully dependent on RFID tags (as implemented in several open pit mines [10]) annotating MOBs would need thousands of tags per day and the results obtained from tags read on the entrance to the OEP would be delayed. Moreover, extensive mixing of the transported ore inside ore bunkers (as found both in the digital studies and during the experiment in-situ) raises the uncertainty of the assessment of the ore compound that would be averaged from the read tags. Instead, the approximate assessment can be provided in advance by simulations. The simulation model has to strictly follow the current BC transportation system layout and has to be tuned on-line with the use of actual production data.
However, the tags experiment provides the valuable data for tuning the DEM models of the ore mixing and flow in bunkers that cannot be obtained otherwise. Therefore, the PAT tags technology is considered as a necessary element of the effective OTS. The tags experiments should be repeated when the BC system is rebuilt (new conveyor routes added, new ore bunkers installed, major changes of the location of ore loading points causing significant variations of the tonnages of ore supplied from the actual mining departments, etc.).

The general structure of the effective OTS for the underground ore mine with the vast mining area and complex cyclical and continuous (BC) system should be as follows:

1. The classification of the ore for its processing (OPC) has to be arranged with regard to actual needs of OEP requirements and the expected level of accuracy of the identification of the compound of POB. The limited number of ore classes should strictly reflect the alternative variants of ore processing machinery settings.

2. The core of the OTS is the live simulation model of the transportation system (SMTS). The STMS represents the current transportation system. The STMS is on-line fed with the current operating data from mining departments (loaded ore tonnages, BC scales records) and from the available geological databases. The processed information is used immediately for updating the OPC assessments for the oncoming POBs. The SMTS provides the OEP staff (and the information systems supporting the OEP) with the assessment of OPC (values, trends) of the oncoming POBs for several required levels of accuracy that depends on the future time periods (current and next shift, next day, following shifts/days).

3. The SMTS utilizes the supplementary, specific models of the ore input distribution and the generated patterns of the ore movements in bunkers for the ore flow simulation. These supplementary models are updated following observed changes of the mining process (opening or closure of mining fields, refurbishment of ore bunkers, etc.). They are used in the SMTS with the help of embedded “intelligent” model parameterization module. Implementation of the fuzzy logic algorithms is the obvious choice for the proposed solution.

4. Simulation cannot be based only on the other digital models, not being checked against the in-situ measurements. There is a special procedure of periodical validation the SMTS with the use of RFID tags experiments as developed for the DISIRE project. The results are used for the retuning of the SMTS. The regular maintenance of the SMTS is considered as the vital element of the effective OTS.

5. The feedback to the SMTS from OEP information systems would be of great value, assuming that the on-line classification of the POB made by the OEP staff is feasible. Such input should be investigated and – if available – introduced in the SMTS.

The presented guidelines are already supported by the investigation results that were carried out for the DISIRE project. The development process is necessary to complete the solution ready for implementation.

6. Conclusions

The summary of the selected issues of the completed DISIRE project investigations of the ore flow in the complex KGHM Lubin transportation system was presented. More DISIRE experiments results are under investigation yet and are being published gradually. Basing upon these experiences, the effective ore tracking system for the vast underground mine should be built as a simulating system which is supported by the existing information systems in the mine. The ore flow in any complex transportation system, consisting of belt conveyors, ore bunkers and switching points of ore stream has to be modelled individually with regard to specific models of the ore input and ore transport through bunkers (input, ore movements inside a bunker, discharge).

The developed BC transportation system simulating models, the DEM models, the statistical analysis of the available operating data have given the valuable material ready for further maturing up to the
level of industrial implementation. The details of the investigations results are currently at the stage of publishing. The PAT solution investigated by the DISIRE project has been acknowledged as an important element of the considered ore tracking for the complex transportation system of the underground copper ore mine.

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