

IMPROVING EFFICIENCY OF THERMAL POWER PLANTS THROUGH MINE COAL QUALITY PLANNING AND CONTROL

by

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The main goal of coal quality control in lignite mines is to supply coal to power plants within certain quality constraints. Coal properties can affect the efficiency, reliability, and availability of both the boiler and the emission control units. This paper presents a new based integrated mine process simulation approach to investigate the variability of the calorific value in exploitation a complex lignite deposits. Results provide valuable insight into the performance of a continuous mining system in terms of controlling coal quality variability.

Key words: mine planning, variability of coal quality, simulation, coal blending

Introduction

The physical and chemical characteristics of coal are highly variable and affect nearly every operational aspect of a power plant, including forced outage rate, maintenance costs, auxiliary power requirements, net plant heat rate, emissions, and the ability to meet full load [1]. Globally, at least 20% of power plants, probably significantly more, can not achieve design output due to difficulties in sourcing coals which consistently meet boiler requirements [2]. This could be resulting in a reduction of 10% or more in potential output from the plants and may be causing a loss of 2% in total output from the power sector as a whole.

By optimizing design of coal quality planning and control procedures along the mining supply chain to provide compliant and consistent coal stock, power stations fired by coal can increase their power output while reducing negative effects on the plant and reduce emissions of pollutants of concern. This situation created a need for a better understanding of coal quality planning and control process in order to assist mines and thermal power plants (TPP) in developing coal blend firing strategies.

Coal quality impact on power plant operation

Coal fuels accounts for 42% of global electricity production [3], and is likely to remain a key component of the fuel mix for power generation to meet electricity demand, especially the growing demand in developing countries. To maximize the utility of coal use in power generation, plant efficiency is an important performance parameter. Efficiency improvements have several benefits:

- prolonging the life of coal reserves and resources by reducing consumption,

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- reducing emissions of CO₂ and conventional pollutants,
- increasing the power output from a given size of unit, and
- potentially reducing operating costs.

Recognizing the importance of fuel quality, coal specifications have become more restrictive, monitoring more intensive, and penalties more expensive. This can lead to increasing fuel cost as the demand for the most desirable sources escalates. Coal properties that most affect boiler operation, according to Cole and Frank [4], are ash content, ash composition, sulphur content, and moisture content. Higher ash content results in increased system throughput, increased erosion, and shortened boiler and ash handling systems. Schimmoller [5] discussed coal and ash handling in search of cost savings in coal-fired handling plant. Ash composition affects and influences the slagging of furnace walls and fouling of convection passes. Fouling decreases heat transfer and promotes wastage by external corrosion/erosion in the convection passes, air preheaters and the induced-draft fans. Excessive slagging blocks off the convection passes and plugs air preheaters. Sulphur content influences the operation and maintenance of feeders, pulverizers, furnace walls, platens, pendants, economizers, soot blowers, air preheaters, dust collectors, and induced-draft fans. Pyrite causes excessive wear of the pulverizer internals. Ash, sulphur and moisture directly affect the heating value of the coal and limit the capacity of the combustion system. The SO₂ emission reduction is usually achieved either with the installation of flue gas desulphurization systems or switching to lower sulphur coals. The NO_x emissions are reduced by combustion modifications or the installation of NO_x abatement and control systems. The interactions between these technologies and their impact on balance of plant are discussed by Nalbandian [6] in details.

Mine planning, coal control and homogenization

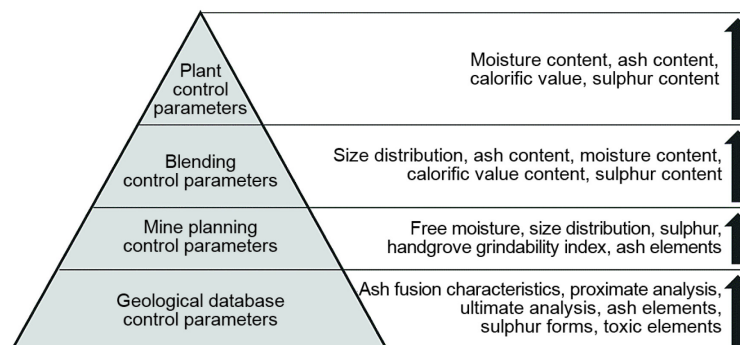
To meet customer's requirements, the planning and design of a mining operation have to focus on technical and operational measures to reduce the in-situ variability of critical coal quality parameters during mining digging and coal handling process. The aim of different design options is to transform the in-situ variability in the coal deposit to a level which meets TPP requirements. Thus, the key control parameters in the coal chain supply must be monitored to provide a reliable indication of quality *flow* in terms of both specification and consistency requirements, fig. 1.

Coal quality control begins with the controlling of geologically defined domains in coal deposit characterized by uniform properties such as: calorific value, sulphur, ash, moisture, etc. The purpose is to define block model and schedule of mineable blocks and control the production process of extraction to ensure compliance with the TPP requirements. The on-line monitoring of coal is to measure certain parameters directly applicable to coal quality control. Data acquisition and interpretation should be on real time bases in order to influence mining operations. The ability to fully exploit on-line information and rapidly feed it back into geological model will open up new possibility for improved decision making in operational mine planning and control. The certainty in predicting local coal quality for mining blocks is expected to increase precisions in mine operational planning decisions.

Successful production scheduling of coal extraction process is based on a reliable estimate of the spatial distribution of coal quality in the deposit and aims to define an extraction sequence that meets daily production targets in terms of coal tonnage produced and coal quality parameters (calorific value, sulphur content, or ash content) [7, 8]. The unit of daily production targets is usually a train load in the sequence of approximately 1500 tones that is shipped to the thermal power plant. However, such production mine units are not supported

by data gathered during geological exploration. The consequences are deviations from planned production targets, which have significant economic impacts for both mine and TPP. Accordingly, the understanding of small unit variability of coal quality parameters is critical to controlling the mine operation and meeting production targets.

Figure 1. Controlling key quality parameters in the coal supply chain



Model formulation

Operational mine planning and production scheduling aim to define the optimal mine plan which is subject of constraints imposed by applied mining equipment, geological conditions and the operational mining approach. The proposed methodology consists of two steps. First, we use genetic algorithm (GA) to match the equipment technology to mining blocks (sub-benches) while meeting production requirements. Second, we solve the linear programming (LP) problem to find the optimal digging capacity for each excavator in the production system, so that the estimated in-situ coal quality from the mining blocks (or sub-benches) and technological constraints achieve to produce optimal coal quality and tonnage.

Model will provide valuable insight into the performance of different elements along the continuous mining process in terms of planning and production control of coal quality. The acquired understanding of the quality of mined lignite will allow controlling the mining process to achieve operational production targets in terms of meeting specified quality within narrow thermal plant limits.

Technological block optimization

Technological block optimization process is shown in fig. 2. This application is enabled to perform the following mine operational planning activities on the bases of geological model according to the technological parameters of the bucket wheel excavator (BWE): design of the operating bench level for each BWE, design of the technological mining, and design of the BWE sub-bench cuts for each technological mining block according to in-situ coal quality.

The approach that is used for designing optimal technological blocks by using a GA which is integrated into a deterministic algorithm as follows: (1) create new block in accordance with auxiliary division P as the union of divisions of geological blocks seams; (2) identify waste subintervals, based on the calorific value (CV) threshold for coal-waste; (3) create new partition P' by merging adjacent waste intervals and saving those that are greater than the selectivity criteria; (4) merge neighbouring intervals that are thinner than the selective mining threshold, when possible waste intervals merge together, and coal also, otherwise merge re-

ardless on value; (5) the waste intervals that are higher than the selective mining threshold are marked as fixed and the optimization of division is performed for others.

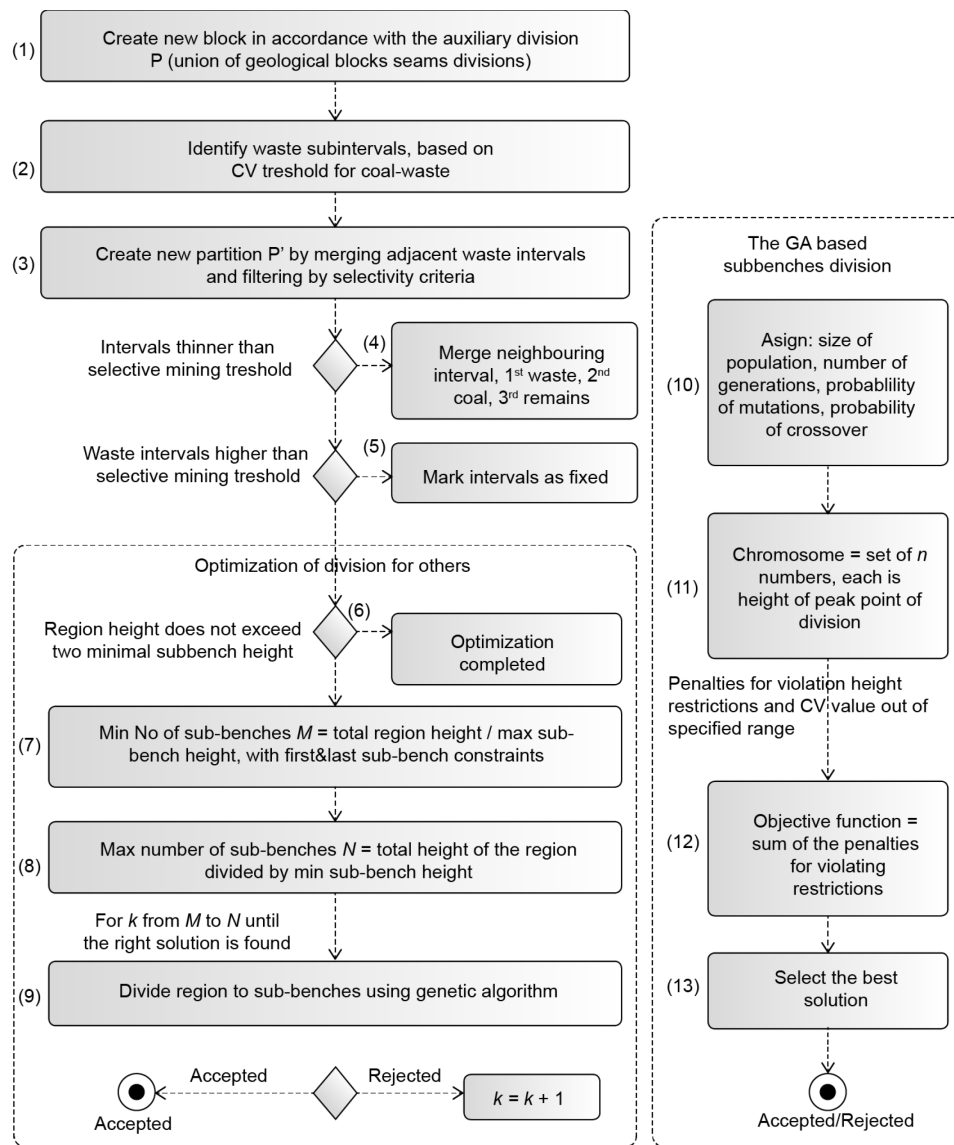


Figure 2. The technological block optimization based on GA

Optimization of division within a region is carried out as follows: (6) finish if the height of the region does not exceed two minimal sub-bench height; (7) the minimal number of sub-benches, M , is ratio of the total height of the region and sub-benches maximum height, considering the first and the last sub-bench constraints; (8) the maximum number of sub-benches, N , is total height of the region divided by sub-benches minimal height; (9) for k from

M to N initiate a genetic algorithm attempting to divide the region to sub-benches until the right solution is found.

The GE is defined as follows: (10) read and update the population size, the number of generations, the probability of mutations, the probability of the crossover; (11) chromosome is a set of n numbers representing the height of the peak point of region division; (12) the objective function is defined as the sum of the penalties for violating the restrictions (sub-bench height and CV value); and (13) at the end of the execution of GA, the best solution is accepted if its value is below threshold, and rejected otherwise.

Production plan and scheduling optimization

The objectives of this model are two-fold. First, the coal quality requirements for a planning period must be met, subject to some physical and geological constraints, mining methods and policies [9]. Secondly, the quantity requirements must ensure sufficient coal production for TPP. These two objectives have the highest priority in operational planning because of the lack of coal quality and quantity control inevitably has an adverse economic effect on the mine and power plant:

- (1) model should be flexible enough to represent properly mining working conditions during the period at which technological issues arise and
- (2) for each planning period, for example a shift, all available excavating machines and working crews should be engaged to keep the operational costs as low as possible.

Model implies that continuous mining system consists of n excavators with capacity of Q_i , $i = 1, \dots, n$. The objective eq. (1) is defined to optimize the mining block extraction sequences and effective excavator digging rates in such a way that minimizes deviation of low calorific value (LCV) from prescribed values:

$$F_{\min} = |LCV_1 - LCV_{\text{opt}}| Q_1 + \dots + |LCV_n - LCV_{\text{opt}}| Q_n \quad (1)$$

subject to:

- *Excavator capacity constraint.* It ensures that the excavator is working in technologically feasible range, not too slow but not more than it is possible for sub-bench height and position:

$$Q_{i\min} \leq Q_i \leq Q_{i\max}, \quad i = 1, \dots, n \quad (2)$$

- *Production demand constraint.* Equation (3) ensures that the total amount of extracted coal is equal or greater than the quantity required by the mine plan.

$$Q_{\min} \leq Q_1 + \dots + Q_n \leq Q_{\max} \quad (3)$$

- *Coal quality constraint.* Equation (4) ensures that the coal quality does not exceed the prescribed upper and lower bound:

$$CV_{\min} \leq \frac{CV_1 Q_1 + \dots + CV_n Q_n}{Q_1 + \dots + Q_n} \leq CV_{\max} \quad (4)$$

- Optionally, ash, eq. (5), and sulphur, eq. (6), constraints can be included as well:

$$\frac{A_1 Q_1 + \dots + A_n Q_n}{Q_1 + \dots + Q_n} \leq A_{\text{allowed}} \quad (5)$$

$$\frac{S_1 Q_1 + \dots + S_n Q_n}{Q_1 + \dots + Q_n} \leq S_{\text{allowed}} \quad (6)$$

Stockpile homogenization modelling

To meet the narrow quality specification required by a TPP, real-time logistic allows us to take corrective action directing coal to stockyard for pile homogenization designing pile with appropriate number of layers to reduce grade variance. The theory of variance reduction in pile-homogenization is well known process [10-12].

The objective of the simulation model is to calculate the homogenization efficiency of stacking and reclaiming coal from strata piles. Developed model has the following assumptions to arrive at the homogenization efficiency:

- each layer is stacked in the same traveling direction of the stacker,
- each layer contains the same amount of coal per meter pile length,
- the mass-flow of the input coal of the pile is constant, and
- the material is reclaimed simultaneously from all the layers at constant the mass-flow.

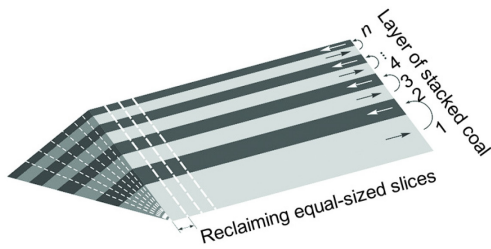


Figure 3. Schematic illustration of a strata homogenization pile

Figure 3 presents the strata blending pile rearrangement of the input coal relative to the output coal after reclaiming. Because of these assumptions each coal slice contains an equal amount of all intersected layers, *i. e.* the property of the slice equals the average property of the layers.

As can be seen from fig. 3, the output property of slice is a function of the input property and the volumetric contribution of layers in a slice. The mathematical modelling of the

property of two slices, s and s' , at mutual distance k , is [13]:

$$y_s = \frac{\sum_{i=a}^b x'_i v_i}{\sum_{i=a}^b v_i}, \quad y_{s'} = \frac{\sum_{j=c}^d x'_j v_j}{\sum_{j=c}^d v_j} \quad (7)$$

where y_s is the output property in slice s , $s \in \{1, 2, \dots, m\}$, $y_{s'}$ – the output property in slice s' , $s' \in \{k+1, \dots, m\}$, v_i, v_j – the volumetric contribution of layer number i, j in slice s, s' , $i, j \in \{1, 2, \dots, n\}$, x'_i, x'_j – the input property in layer number i, j intersected by slice s, s' , a, b – the first and last layer intersected by slice s , $a, b \in \{1, 2, \dots, n\}$, c, d – the first and last layer intersected by slice s' , $c, d \in \{1, 2, \dots, n\}$, $b - a + 1$ – the number of layers in slice s and $d - c + 1$ – number of layers in slice s' , and k, m, n – the numbers of output/input parts $k, m, n \in \mathbb{N}$.

The property of a slice is a weighted average of the volume and the input properties of the different layers. Calculation of the intersection of the layers and slices provides the volume contribution of the layers in the slices v_i and v_j in eq. (7). The homogenization efficiency is then obtained by calculating the statistical properties of the output (standard deviation and auto correlation function) and comparing them with the statistical properties of the input.

Case study – Description of the continuous mining system under study

To achieve an efficient continuous mining operation, the continuous mining system has to be designed to ensure meeting production goals in terms of coal tonnage and coal qualities day by day and over the whole life of the mine. Continuous mining systems at Tamnava West surface mine – Electric Power Industry of Serbia, fig. 4, contains parallel production lines that begin with excavators, followed by coal transport by conveyor belts and distribution at the coal distribution center where the coal is sent to stacker on stockyard with four distinct piles or directly to train loading station. The reclaimer and conveyor belts are used to transport lignite from stockyard to train loading. Finally, the lignite is dispatched to power plants based on their daily demands.

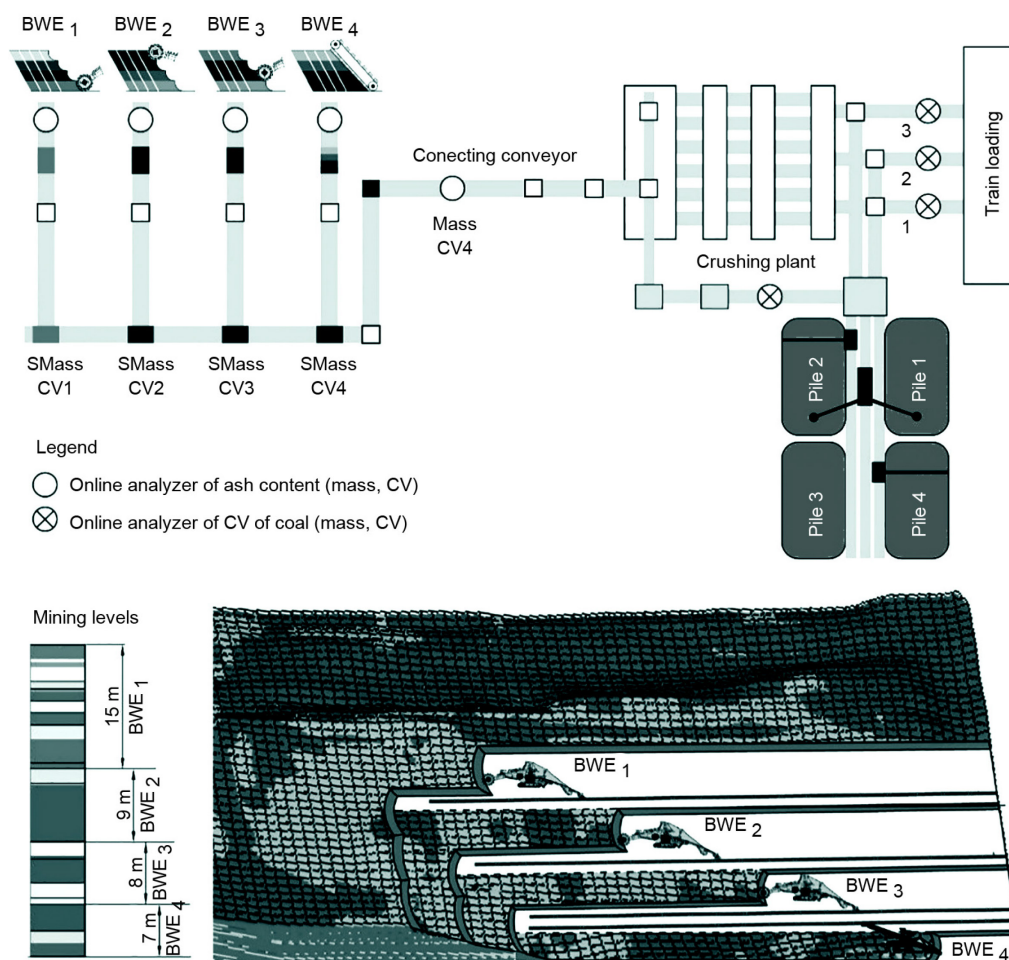


Figure 4. Continuous mining system on Tamnava West surface mine

The objective of this study is to illustrate the effect of the proposed mine operational planning methodology (GA and LP models) on the performance of a complex continuous

mining system. To analyze the performance of the proposed approach, the case study is presented in a completely known and a fully mined part of a Tamnava West lignite mine during three months' period in 2016.

The real value 2-D coal model of verified deposit data-set is used as the ground truth to assess the optimization method for building the simulation experiments. The original dataset contains 100 mining blocks which are divided into four mining strips. Each excavating block is 50×50 m, and the total mass of coal in blocks is about 4 million tones of coal.

Coal quality is estimated for each mining block using interpolation inverse distance with power of 2 and mass calculation is based on grid system using the Geovia Minex software. Estimated coal plies quality parameters within studied area are: LCV 5238-8332 kJ/kg, HCV 7094-10017 kJ/kg, ash 10-22%, and moisture 47-62%. Quality parameters for clay rock partings within studied area are: LCV 306-3294 kJ/kg, HCV 931-4886 kJ/kg, ash 28-55% and moisture 32-51%.

Figure 4 schematically shows block model of mined part Tamnava West pit. The block model is divided into four areas and each area is assigned to one excavator. The mining operation uses four BWE at three benches in different altitude and proceeds by conveying along the belts up to mass distribution center. Destinations are determined based on the type of materials and waste is conveyed to spreader on dump site and the coal is transported to train loading station or to the stockpile yard.

The specific issues of excavated coal quality during this period are related to the large variation of coal quality. Figure 5 shows the coal quality in three months period delivered to TPP from opencast mine Tamnava West. Each dot on the figure presents a train of approximately 1500 tons of coal, horizontal line in the middle is the optimal value (6700 kJ/kg), while thin solid lines depicts range of $\pm 5\%$ of optimal value and dashed lines denote range of $\pm 10\%$ of optimal value, that are threshold values acceptable for TPP. The delivered coal has much higher average coal heating values than required, not only in presented period but also in the others as well.

Checking the fluctuation of the grades plotted in fig. 5, directly loading the trains with all coal on a block-by-block basis make the mining processes inefficient, with high financial losses. Out of 2751 trains, 72 trains (3%) has heating value below the minimal required value 6030 kJ/kg, 607 trains (22%) is above maximal value of 7370 kJ/kg and 2072 in required range (75%). If smaller range with $\pm 5\%$ around optimal value is analysed, than 246 trains (9%) has heating value below the value 6365 kJ/kg, 1261 trains (46%) is above maximal value of 7035 kJ/kg and 1244 in required range (45%). Average value for this period is 6990 kJ/kg that means the average value for all trains is more than 4% above the requested calorific values of 6700 kJ.

Figure 5 also presents the histogram of CV per train, where it can be subsumed that lower values could have been mixed with higher values to reach the target range of values. Better utilisation, or recovery of the deposit would be reached if the coal with lower CV, that was selectively mined, was combined with higher coal quality. From the presented example, it is evident that this possibility exists.

Simulation an approach to control coal quality

The objective of the investigated Tamnava West mining operations is analysis of the ability to control lignite quality at the stage of operational plans using GA and LP models without utilizing the stockyard and otherwise with utilizing homogenization piles to meet quality specification per train load for the TENT thermal plants. Considering the target unit of

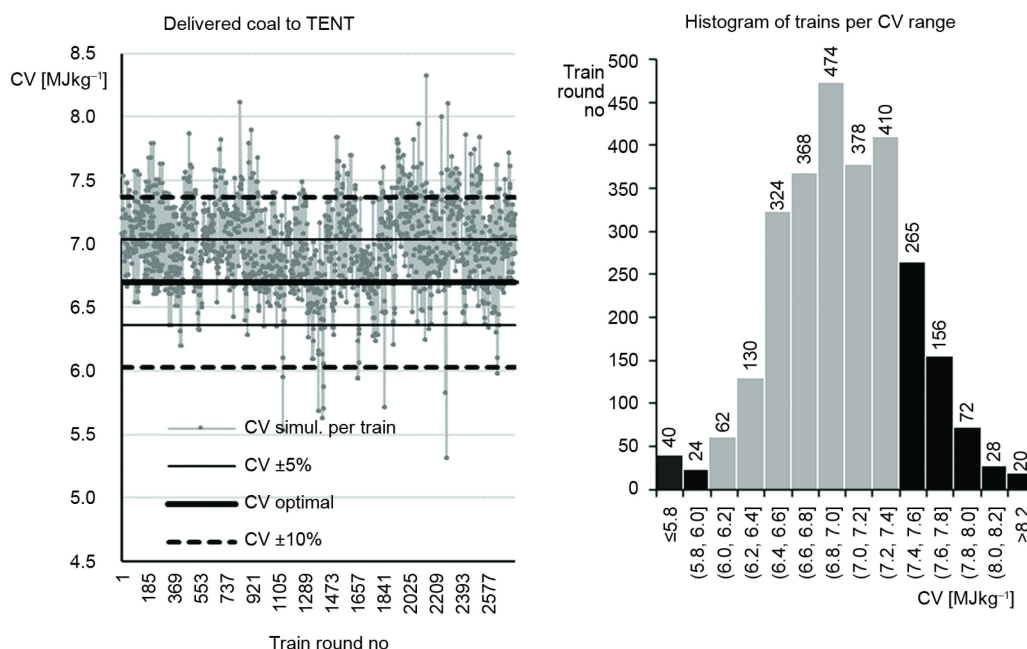


Figure 5. Actual delivered coal to TPP during 3 months' period from Tamnava West pit

1500 tones and the opportunity to homogenize coal within mining block sub-benches for each excavator locations, the continuous coal flow from each excavator is optimized. The optimized extraction sequence represents the operational mine plan for the considered mining period of three months. Therefore, the first-time concepts of different areas of research are combined to develop integrated approach for operational coal quality management. Figure 6 illustrates this approach, which is defined by the following steps.

- (1) Based on available exploration data, a coal model is generated for capturing geological uncertainty and reserves are assessed as the basis for short-term mine planning and production control. This block model is referred to as a mining technological blocks. In general, techniques can involve interpolation, geostatistical estimation as well as simulation.
- (2) Operational production scheduling and operational decisions are optimized to ensure that coal production targets are achieved most efficiently. These optimization tasks are performed using mathematical optimization techniques: genetic algorithm and linear programming.
- (3) When executing the mine operational plan, based on these optimized decisions and utilizing the scheduled digging blocks, coal tonnage and CV can be predicted at different excavating locations in the extraction and material handling process. Depending on these estimates coal can be directed to train loading or stockyard for additional pile homogenization. Namely, for direct train loading is specified range of $\pm 5\%$ of nominal coal quality (6700 kJ/kg), while the coal out of this range is homogenized on stockyard.
- (4) Differences between model-based prediction and TPP requirements in terms of lower and upper bounds of CV we investigate additional reduction of variability on stockyard using piles.

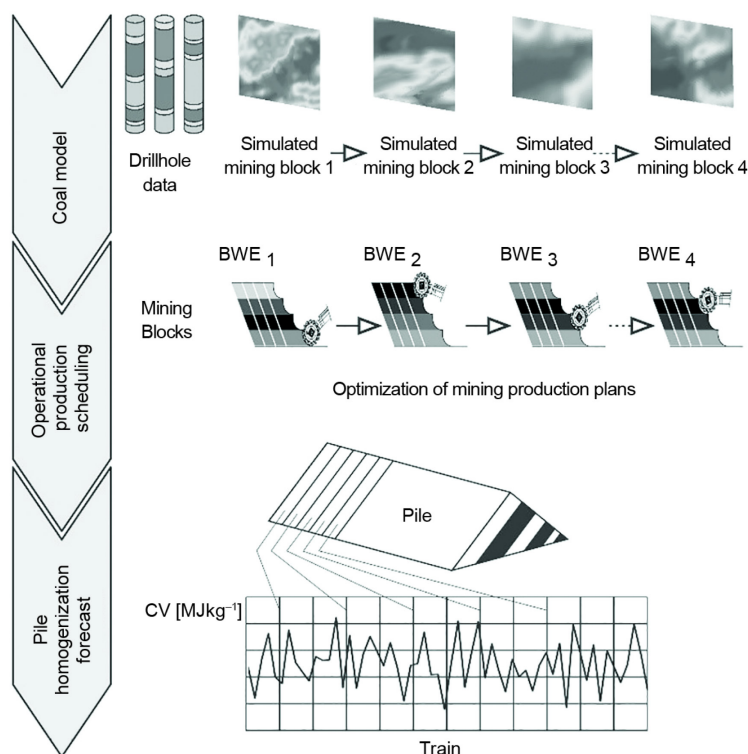


Figure 6. Integrated simulation approach to coal quality control

Figure 7 shows the model based prediction of CV (moving averages) of excavated coal blocks at four positions, while the fig. 8 shows the prediction of the CV when operating four excavators at the same time based on 45 simulation runs (bold thick line) and the average of the realizations (thin grey lines).

Figure 8 shows the quality of the coal in three months' time for simulated using GA and LP optimization. Similar to fig. 5, each dot on figure presents a train of approximately 1500 tons of coal, horizontal line in the middle is the optimal value (6700 kJ/kg), while thin solid lines depict range of $\pm 5\%$ around optimal value and dashed lines denote range of $\pm 10\%$ around optimal value, that are threshold values acceptable for TPP.

As specified in step (3) of this section, simulation procedure reduces standard deviation of coal quality per train. In presented experiment (tab. 1), this reduction is around 30%, that means reduction of standard deviation from 497 kJ/kg to 348 kJ/kg. The number of trains below 10% threshold decreased from 72 to 24 (from 3% down to 1%), the number of trains above 10% threshold decreased from 605 kJ/kg to 358 kJ/kg (from 22% down to 13%), while the number within 10% range increased from 2074 kJ/kg to 2369 kJ/kg (from 75 up to 86%). For smaller, 5% range number of trains below threshold value 6365 kJ/kg is 98 (4%), above 7035 kJ/kg is 1227 (45%) trains, while 1426 (52%) are within the range. After analysis of 5% range, it was decided to use narrow 5% range for direct train loading, while the rest of coal should be sent to blending piles on stockyard. That means, 52% of coal would be directly sent to TPP, while the 48% would be set to stockyard for blending. The results of simulation of stacking and reclaiming for coal out of 5% range are presented in fig. 9, where each dot

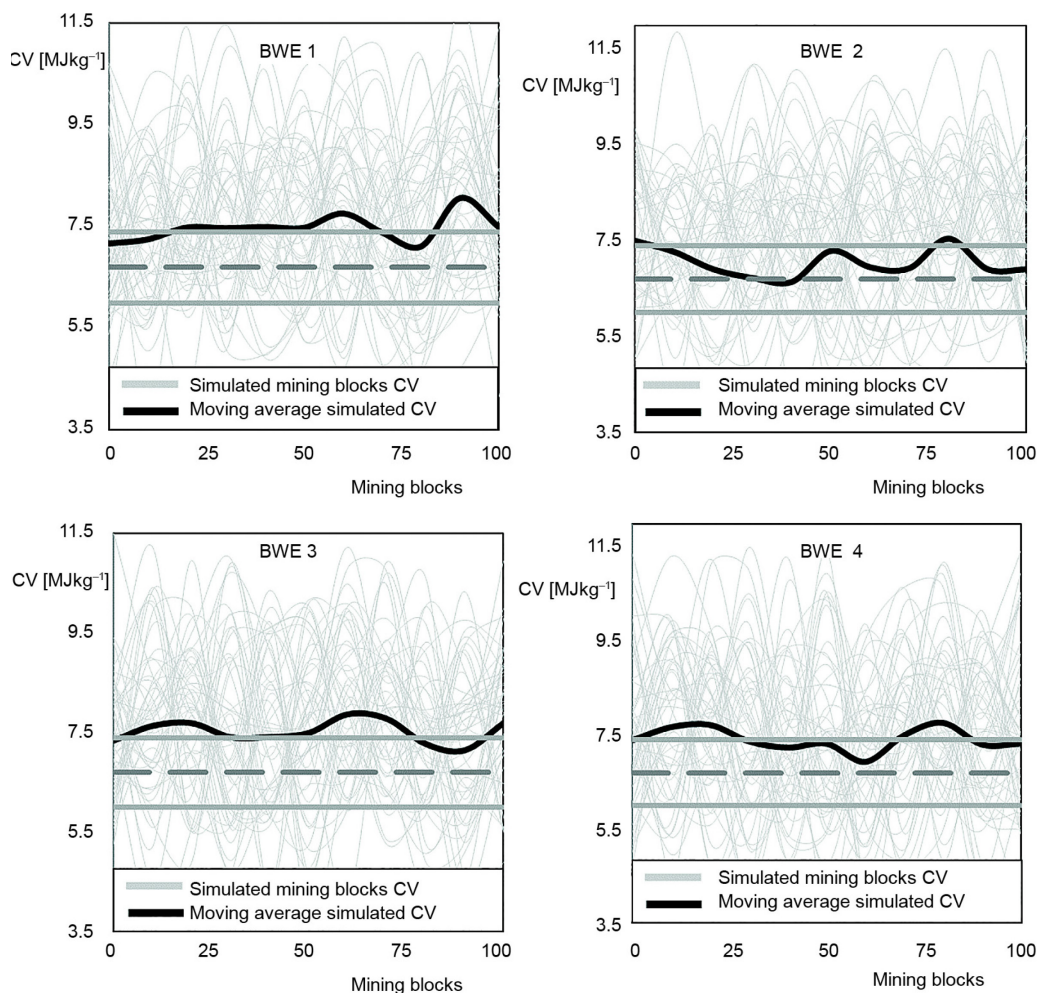


Figure 7. Predicted CV of excavated coal by each of four BWE

presents one pile with blended coal of 90.000 tons. It can be observed that out of 26 piles only one was above the specified range for only 14 kJ/kg (0.2%), that one can overcome using combination with direct loading that is within narrower 5% range. Standard deviation of CV, as a measure of homogenization effect, has drop from initial 497 kJ/kg and simulated 348 kJ/kg down to 209 kJ/kg, that means the ratio of final and initial standard deviation is 0.42. It means that the delivered coal to TPP is significantly homogenized and within required range using this approach.

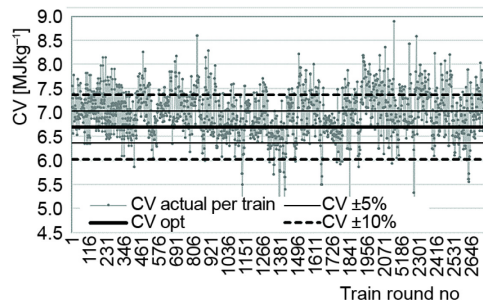


Figure 8. Predicted CV of delivered coal by trains (1500 tons per train) from four excavators at the same time after using GA and LP optimization

Table 1 shows a reduction in coal variability for two simulated scenarios (GA/LP without of stockyard and with stockyard). This forecast of a reduction in variability is obtained by combining simulated in situ block-sub-bench CV using GA and LP simulation approach, and the strata blending pile emulator. This match between the forecasted values from the model and real historical data demonstrates the efficiency of the methodology proposed.

Table 1. Reduction in CV variability for different scenarios

Standard deviation of CV [kJkg ⁻¹]	Actual data set	Simulated data GA-LP	Stockyard data	Reduction of variability [%]
Input – real data	497	–	–	–
After GA/LP approach	–	348	–	30
After the homogenization piles	–	–	209	58

The advantage of utilizing proposed operational planning approach demonstrated by a substantial improvement in certainty in predicting and homogenization CV. The results can be basis for optimizing the mining operation and adjusting the coal quality day to day depending upon the customer's requirements and the deposit geological setting. These properties of the software allow for investigating the in-situ variability of coal quality parameters and its behaviour along the extracting, conveying and blending process.

Furthermore, integrating potential economic consequences, *e. g.* penalties per deviation, will allow quantifying the financial risk of not meeting production targets due to in-situ variability and uncertainty in knowledge about the deposit.

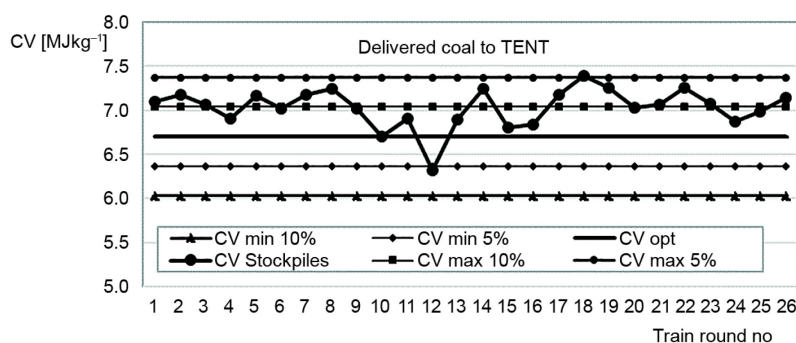


Figure 9. Predicted CV of delivered coal by trains (1500 tons per train) after pile homogenization

Conclusions

Case study results deliver a valuable insight into the effect of homogenization and improvement of predicting CV-values of shipped coal to TPP as a function of the operational planning approach. The integrated simulation approach is a valid and powerful tool to explore the effect of geological uncertainty on the expected performance of complex continuous mining systems. It provides a valuable tool to the mine planning engineer to foresee critical situations affecting the continuous and reliable supply of raw coal. Obtaining the best results from minimum homogenization is vital because homogenization raises operating costs and lowers system efficiency. However, on-site blending allows blends to be created and altered to suit

the power plant with far more precision than may be achieved without efficient operational mine planning.

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