

Development of a Software Tool for the Prediction of Coal-Blending Efficiency

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ABSTRACT; A coal-blending simulator for longitudinal stockpiles has been developed using the Visual Basic development platform for Windows®. The input to the simulator consists of the standard deviation and the autocorrelation of the coal property for which blending is attempted. The program initially creates a time series of property values for the coal delivered to the stockyard. Then, this input sequence is rearranged by simulating the operation of the stacking and reclaiming equipment. The output sequence of property values reflects the quality fluctuation of the coal fed to the power plant after blending. Results from the application of the simulator to the lignite mines of northern Greece show that coal-blending efficiency is a function of the capacity of the stockpile, the number of stockpile layers and the combination of the applied stacking and reclaiming methods.

1 INTRODUCTION

Coal quality control is a key factor in the improvement of overall coal combustion performance in terms of electricity generation costs and compliance with new stringent environmental standards. Various blending and mixing techniques have been proposed in order to reduce both the short- and long-term fluctuations of the coal quality characteristics. The capacity, shape and arrangement of the piles within the stockyard, the number of layers that are stacked in every pile and the applied coal-stacking and reclaiming methods are the major parameters that distinguish one technique from another. All of these parameters are closely related to the type of equipment that is installed in a stockyard.

2 COAL-BLENDING METHODS AND EQUIPMENT

The two main functions of a coal stockyard are buffering and blending. The successful design of a coal stockyard that can achieve high blending efficiencies requires the optimization of (i) the stockpile

length, (ii) the stockpile width, (iii) the number of stockpile layers, (iv) the quantity of coal per reclaimed cross-section, and (v) the position of the reclaimer in relationship to the stockpile. In order to properly select the above parameters, numerous factors relevant to the coal properties, the site-specific conditions and the specifications set by customers must be taken into account (Schofield, 1980).

The vast majority of coal stockpiles are longitudinal, arranged in series, in parallel or in series and in parallel. Circular piles are not common in the coal industry, although they have some important advantages (Zador, 1994).

The most commonly used stacking methods are the Chevron method and the Windrow method. According to the Chevron method, coal is stacked continuously along the central axis of the stockpile in such a way that a continuously growing triangular-shaped pile is formed (Figure 1). The Windrow method is applied in cases where high blending efficiencies must be achieved and the installed equipment does not allow the use of the Chevron method (i.e., where side-scraper reclaimers exist). Less popular are the conical and the strata methods. The conical method is used in cases where blending is

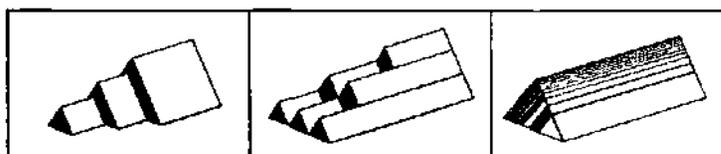


Figure 1. The Chevron, Windrow and strata methods of coal stacking.

not under consideration, while the strata method (Figure 1) is usually applied in stockyards where side-scraper reclaimers are installed (Zador, 1994).

The most widely used stockyard machinery is the boom-type bucket wheel stacker/reclaimer. Its traveling, slewing, luffing boom makes this machine flexible and easily adjustable even to special coal stockyard operations. Although it is a very versatile, high-capacity machine, it provides limited blending efficiency and at the same time it is difficult to automate its operations. Alternatively, reclaiming systems that dig material from the entire cross-section of the pile, such as bridge-type reclaimers with one or more bucket wheels, rotating drum reclaimers, disc-type reclaimers or chain-type scraper reclaimers, can be used. Other reclaiming systems may include the chain-type side scraper or the portal scraper reclaimers (Zador, 1994; Petersen, 1998).

3 PREVIOUS WORK ON BLENDING MODELS

The development of coal-blending simulation models started in the 80s. The traditional models were based on probability theory formulas, combining the blending efficiency with the number of stockpile layers, the mass of the stockpile and other characteristics. Recently-developed models also incorporate the autocorrelation function of the series of coal segments that have to be homogenized (Gerstel & Werner, 1996).

Nowadays, apart from the simulation models, there exist several commercial coal-blending optimization packages. Some of them are focused on the mining operation and usually incorporate linear programming techniques for the determination of the combinations of mine blocks that satisfy certain objectives, such as the maximum utilization of the material blocks and the minimization of the production costs of the specified ore quality (Mortensen & Hill, 1996). Other blending optimization packages have been developed for coal port terminals. They can handle the complex calculations involved in determining the lowest-cost blend when parameters, such as heating value and sulphur, moisture and ash content have to meet certain specifications, and when there is a multitude of coal qualities to choose from (Sehgal et al., 1997 - Jasper Comm., 1998).

4 DESCRIPTION OF THE SIMULATION MODEL

The simulation model that is presented in this paper was developed using the Visual Basic development platform for Windows®. The model consists of two parts. In the first part, a series of coal property values is generated based on the standard deviation and

the autocorrelation of actual property measurements. This is termed "input series of property values" and may be generated for any time interval. These values are subsequently used as input to the second part of the model, which simulates the stockpile operation. The output from the model is termed the "output series of property values". Considerable effort has been made in the development of a simulation model for the coal-stacking and reclaiming procedures in longitudinal stockpiles that is applicable to different site-specific conditions. It should be noted that this simulator is currently designed to handle a single coal property in each simulation run.

4.1 Model assumptions

In order to simplify the simulation process, the following assumptions have been implemented:

- *The coal-stacking and reclaiming rates are constant.* As far as the stacking procedure is concerned, this operational regime does not represent the real case, where stacking rates are related to the mine production rate. However, this assumption does not affect model performance, since the key variable in coal blending is not time but quantity. It can easily be understood that if coal sampling (and characterization) is performed every x tons of coal of variable stacking rate, this is equivalent to regular sampling of coal fed at a constant rate, in the sense that the coal property value will be assigned to the same block (quantity) of coal.
- *The coal contained in the conical ends of each pile is not reclaimed.* This technique is usually applied in stockyards whenever high blending efficiencies must be achieved in order to overcome problems arising from the irregular shape of coal layers within the conical ends of the piles.
- *The boundaries of each coal segment (input and output) are determined by two triangular sections perpendicular to the longitudinal axis of the pile.* Each stockpile segment that is stacked during a single pass of the stacker (at a constant boom angle) is conical and its inclination is equal to the angle of repose of the handled coal. When a series of such segments is stacked in sequence, each segment can be represented by a triangular prism. In addition, the boundaries of each reclaimed stockpile segment is determined by the geometry of the complex movement of the bucket wheel and the boom of the reclaimer. Again, this is modeled as a triangular or trapezoidal section. However, on average, and if the input series of property values has strong autocorrelation, (which means, for instance, that the calorific value of the n^{th} input segment will not differ considerably from the calorific value of the $(n+1)^{\text{th}}$ input segment), this assumption does not affect the accuracy of the calculations considerably.

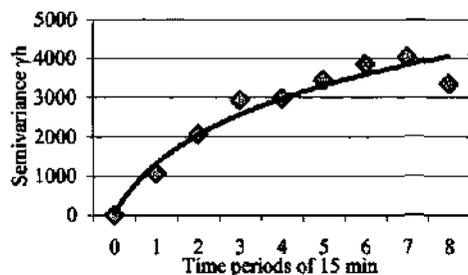


Figure 2. Comparison of the semivariance values of a generated NCV time series to the values obtained by actual sampling.

- *The size of coal particles is negligible compared to the dimensions of the stockpile segments.* The size segregation of coal particles (i.e., large particles roll to the stockpile base and fine particles remain at the top of it) during the stacking procedure is negligible.

4.2 Generation of the input series of property values

The first part of the model is designed to generate a time series of values regarding a single coal quality parameter, which will reflect the actual fluctuation of this parameter in the run-of-mine coal. Each value (element) in the data series corresponds to an average value for a given time interval, and assuming that the mine production rate remains constant, this value characterizes equal volumes of stacked coal (input elements or stockpile segments). The initial results that are presented in this paper are based on the use of the net calorific value (NCV) as the coal property to optimize through coal blending.

For effective application of a homogenization model, it is necessary for the input segments (stacking) to correspond to time intervals shorter than the time intervals that correspond to the output segments (reclaiming). The size of the input segments was chosen to be equal to the coal quantity consumed by the power plant in 15 min, based on the fact that the size of the output segments is equal to the coal quantity consumed in 1 hr. The size of the output segments was set so that it was equal to the so-called critical coal quantity of the boilers. The critical quantity (or period) is defined as the quantity of poor-quality coal (i.e., coal that does not meet the specifications) that can be burnt in a boiler without causing any drop in the power produced. The above-mentioned relationship between input and output element size ensures the contribution of at least 4 input segments for the formation of an output segment.

Therefore, to investigate the blending efficiency in a period of 1 month, the generation of property

values for 2880 input segments is required. Each element characterizes a stockpile segment with volume equal to the coal quantity received in the stockyard in a period of 15 min.

To generate the input series of the property value, the following data are required:

- 30 daily average net calorific values (d.a.NCV) of the run-of-mine coal, which is delivered to the stockyard within the investigated 1-month period.
- The standard deviation (sd) of the NCV of coal samples that represent fluctuations of the NCV with frequency equal to the size of the stockpile segments (i.e., 15 min).

These values are entered into a subroutine that generates pseudo-random numbers. The subroutine is available at the Internet site of NIST (NIST, 2000). For each d.a.NCV value, the subroutine returns 96 numbers, which follow a Gaussian distribution determined by the specified d.a.NCV and sd. Thus, each of these numbers corresponds to an NCV value that characterizes an input element, which contains the coal quantity consumed by the power plant in 15 min.

In order to ensure that the generated values are representative of the actual fluctuation of the NCV values of the run-of-mine coal, these 2880 values are rearranged, taking into account their autocorrelation. The autocorrelation function is an indication of the self-similarity between a series of spatially or temporally distributed measures of a property (Davis, 1986). The input series is rearranged several times and the resulting semivariograms are compared to a semivariogram which is considered to be representative of the actual fluctuations of the NCV (Figure 2). The latter semivariogram was determined by conducting a special sampling program at the South Field Mine of the Lignite Center of Ptolemais - Amynteon in northern Greece (Galetakis & Kavvouridis, 1999). This comparison is realized using a least squares comparing algorithm.

4.3 The blending simulation algorithms

The simulation of the blending procedure is based on the following parameters, which must be entered by the user of the simulator:

- the stockpile length,
- the stockpile width,
- the angle of repose of the handled coal,
- the coal quantity stacked within a 15-min period,
- the number of layers for coal stacking,
- the stacking method,
- the reclaiming method.

The simulation of the stockpile operation starts by assigning each of the 2880 input NCV values to a specified stockpile segment, which is accessed based on two coordinates: i, j . All the stockpile segments are included in an array with dimensions ixj , where i represents the stockpile layer and j represents the stockpile section (Figure 3).

6n	6n-1		5n+2	5n+1
4n+1	4n+2		5n-1	5n
4n	4n-1		3n+2	3n+1
2n+1	2n+2		3n-1	3n
2n	2n-1		n+2	n+1
1	2		n-1	n

Figure 3. Zig-zag placement of 3 x n input elements in a stockpile formed in 3 layers and n sections

Because of the zig-zag stacking of the stockpile layers, the following algorithm is used to calculate the position of the input elements within the stockpile (Gerstel & Werner, 1996):

$$\begin{aligned} \text{NCV}_{pile(i,j)} &= \text{NCV}_{input(i,j)} \text{ if } i \text{ is odd} \\ \text{or} \\ \text{NCV}_{pile(i, n+1-j)} &= \text{NCV}_{input(i,j)} \text{ if } i \text{ is even} \end{aligned} \quad (1)$$

where:

$\text{NCV}_{pile(i,j)}$, the NCV of the stockpile segment,
 $\text{NCV}_{input(i,j)}$, the NCV of the input element.

4.3.1 The Coal-Reclaiming Method of Sections

In the case of coal reclaiming using the Method of Sections, the output elements are triangular shape and their dimensions are determined from the height of each pile and the coal quantity that is fed to the power plant silos every hour.

The simulation procedure is modified according to the relative length of the output elements and the stockpile sections formed during the stacking procedure. As the number of layers increases, the length of the sections also increases and may become longer than the length of the output segments.

The length of the output elements and the length of the stockpile sections are calculated based on the stockpile geometry.

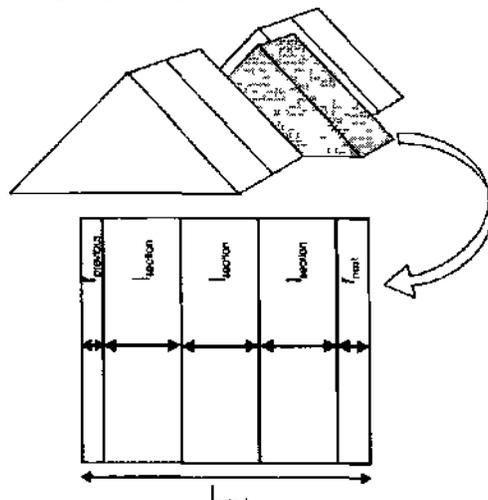


Figure 4 Schematic representation of a stockpile reclaimed using the Method of Sections

The calculations of the stockpile sections' length are modified according to the applied stacking method. The NCV value of each stockpile section is given by the following equation:

$$\text{NCV}_{section} = \left\{ \begin{aligned} &\sum_{i=1}^n \frac{\text{NCV}_{pile(i,j)}}{B} \\ &+ \sum_{i=1}^{n'} \frac{\text{NCV}_{pile(i,j)}}{2(n-0.5n')} + \sum_{i=n'+1}^n \frac{\text{NCV}_{pile(i,j)}}{n-0.5n'} \end{aligned} \right. \quad (2)$$

where the first sum corresponds to piles formed using the Chevron method and the second sum corresponds to piles formed using the Windrow method.

After the calculation of the NCV of the stockpile sections, it is possible to calculate the NCV of the output elements by calculating the average NCV value of all the stockpile sections that are included in the output element (Figure 4). The following general equation can be applied:

$$\begin{aligned} \text{NCV}_{output} &= \sum_{j=1}^j \left(\frac{l_{section}}{l_{output}} \text{NCV}_{section(j)} \right) + \\ &+ \frac{r_{previous}}{l_{output}} \text{NCV}_{section(j_0-1)} + \frac{r_{next}}{l_{output}} \text{NCV}_{section(j_1+1)} \end{aligned} \quad (3)$$

where:

NCV_{input} , the NCV of the output segment (reclaimed section),

j_0 , the first section of the pile which belongs completely to the specific output segment,

j_1 , the last section of the pile which belongs completely to the specific output segment,

l_{output} , the length of the output segment,

W_{uon} , the length of each section if $l_{uon} < l_{output}$, or the length of the output segments if $l_{uon} > l_{output}$.

$r_{previous}$, the length of the part of the pile section that remains out of the previous output segment, and

r_{next} , the length of the part of the pile section that is partly contained in the specific output segment.

Furthermore, this equation is modified according to the following parameters:

- the relative length of the stockpile sections and the output segments of the stockpile, which are determined by the lignite quantities contained in the input and output segments, respectively, and
- the exact location of the boundaries of each output segment in relationship to the boundaries of the stockpile sections.

4.3.2 The Coal-Reclaiming Method of Benches

According to the Method of Benches, the reclaimer digs up above a fixed elevation in the stockpile on the entire length of the stockpile, thus creating a bench. The most economical way to accomplish this is to use 3 levels.

The simulation of coal reclaiming using the Method of Benches is based on the calculation of the

volumetric ratio for each layer in each bench. This ratio is calculated from the percentage of the bench cross-sectional area which is covered by each one of the layers (Figure 5). In the case of Chevron stacking, this area is calculated using the following equation, whose first part is valid for trapezoidal cross-sections and whose second part is valid for triangular cross-sections of layers:

$$E(i, k) = \begin{cases} \frac{(2\delta - \varepsilon)h'}{2} - E(i-1, k), & \text{if } y > h' \\ \frac{\delta y}{2} - E(i-1, k), & \text{if } y \leq h' \end{cases} \quad (4)$$

where:

i, k , the i.d. number of the stockpile layer and the bench, respectively,

h' the height of each bench, which is equal to 1/3 of the stockpile height,

y , the height of the part of the layer that is contained within the bench, which is calculated using the following equation (ϕ is the angle of repose):

$$y = \sqrt{iE \tan \phi} - (k-1)h' \quad (5)$$

δ , the width of each layer at the base of each bench, which is given by the equation:

$$\delta = 2y / \tan \phi \quad (6)$$

ε , the difference in the widths of each layer at the base and at the top of each bench (the difference of the two bases of a trapezoid), which is given by the equation:

$$\varepsilon = 2h' / \tan \phi \quad (7)$$

$E(i-1, k)$, the area of the portion of the previous layer which is contained within the current bench that can be calculated by the following equation:

$$E = \frac{d^2 \tan \phi}{4n} \quad (8)$$

where n is the number of layers and d is the width at the base of the whole stack.

It must also be noted that the length of output elements coming from different benches is not constant since the volume of the output elements must be kept constant and the cross-sectional areas of the three benches are different (Figure 5).

For the formulation of the output segments, equations similar to equation (3) are used. The difference between the two reclaiming methods is that while in the case of the Method of Sections there is one NCV value corresponding to each stockpile section, in the Method of Benches there are three NCV values that correspond to the three parts of the section that belong to each one of the stockpile benches.

Another difference between the two coal reclaiming methods is that in the Method of Sections no transition between segments on different benches is required, while in the Method of Benches special

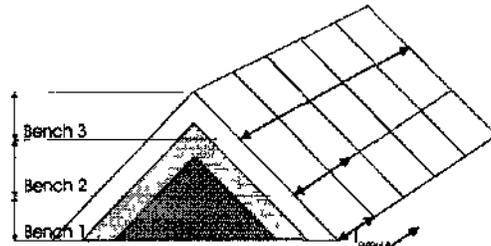


Figure 5. Cross-sectional view of a stockpile stacked using the Chevron Method and reclaimed using the Method of Benches.

algorithms have been developed to handle this transition. In the latter case, since every bench does not always consist of an integer number of output segments, at the end of each bench there usually exists a piece of coal that contains less coal quantity compared to the size of the output segments. In this case, in order to complete the last output segment of the bench, a piece of the next bench is added (Figure 6).

The length of the part of the next bench that must be reclaimed in order to complete the output segment that remained uncompleted at the end of the current bench is calculated by the following equation:

$$l_{next} = \frac{(Q-q)}{\frac{h'^2}{\tan \phi} (7-2(k+1))} \quad (9)$$

where Q is the coal quantity in an output segment, and q is the coal quantity which is contributed by the previous bench to this specific output segment. The latter is given by the following equation:

$$q = (l_{next} - c_{output}) \frac{h'^2}{\tan \phi} (7-2k) \quad (10)$$

where:

l , the length of the stockpile,

l_{next} , the length of the first stockpile segment of the lower bench, which was used to complete an output element during the transition of the reclaiming procedure from the current bench to the lower one. It is obvious that during the reclaiming transition from the 1st bench to the 2nd, l_{next} is equal to 0.

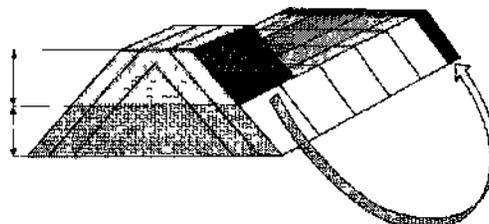


Figure 6. Output sequence for reclaiming a stockpile stacked using the Chevron Method and reclaimed using the Method of Benches.

c, the number of output elements which were reclaimed from the current bench.

In the case of the Windrow Method of coal stacking, the algorithm for the calculation of the NCV of the output segments is based on the geometry that governs the coverage of each layer in the cross-sections of the three stockpile benches. Assuming that all the rhomboidal layers can be divided into two sublayers with a triangular cross-section (Figure 7), the following equation is valid if the entire sublayer with triangular section belongs to the bench:

$$E_1 = \frac{y^2 / \tan \phi}{\left(2d - (4k - 2) \frac{h}{3 \tan \phi}\right) \frac{h}{6}} \quad (11)$$

where h is the height of the stockpile.

Four other equations have been derived, depending on the geometry of the cross-section.

5 RESULTS

The model, which was developed as discussed previously, was initially applied for the evaluation of a coal-blending procedure applicable to the lignite stockyards of the Lignite Center of Ptolemais - Amynteon, in northern Greece. Furthermore, the simulator was used to conduct several parametric analyses for different stockpiling/reclaiming options for the lignite produced at the South Field Mine in that area.

The input series of property values was generated based on the results of the daily average samples of the lignite that was burnt in Agios Dimitrios Power Plant within a period of one month. The autocorrelation function was determined by collecting a series of special samples using a sampling period of 15 min.

Thus, 2880 input elements were generated from the first part of the model. After the simulation procedure was completed, the model returned 720 output elements, each one corresponding to an NCV value of the lignite reclaimed from a stockpile

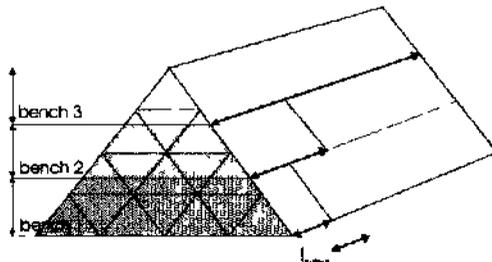


Figure 7. Cross-sectional view of a stockpile formed with the Windrow Method and reclaimed with the Method of Benches

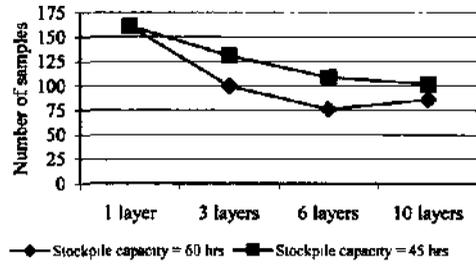


Figure 8. Reduction of the number of lignite samples with NCV below the power plant specifications, which results from the increase in the stockpile capacity

within a time period of 1 hr.

The results of the blending evaluation procedure are summarized in Figures 8, 9 and 10. The reduction in the number of lignite samples (occurrences) with an NCV lower than the power plant specifications, which results from the increase in the stockpile capacity, is presented in Figure 8. The reduction of the standard deviation of the NCV of the lignite, which results from the increase in the number of layers that form the stockpiles, is presented in Figure 9. It must be noted that the comparison was based on two different standard deviations. The first corresponds to the total number of lignite samples of the investigated period of 1 month (sd of 720 output elements). The other sd is calculated as follows: the simulator determines the number of stockpiles that were generated from these 720 elements; then, one sd is calculated for each group of elements comprising one stockpile; finally, the average of these sd values is compared to the first sd value which corresponds to the total number of output elements.

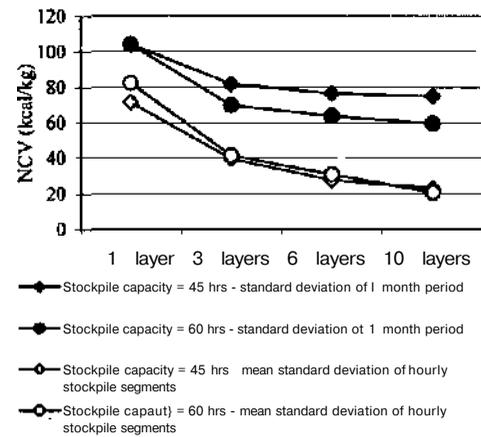


Figure 9. Reduction of the standard deviation of the NCV, which results from the increase of the number of layers that form the stockpiles

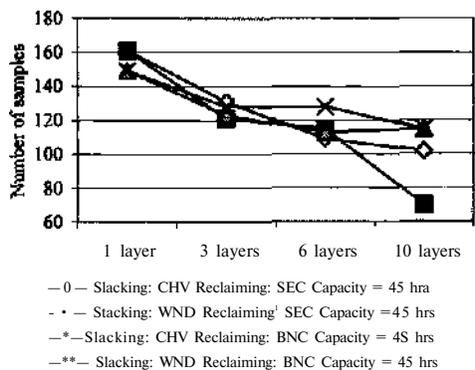


Figure 10. Differences in the number of samples that deviate from the specified lower limit of NCV, which result from four different combinations of stacking and reclaiming methods (CHV= Chevron, WND=Windrow, SEC=Method of Sections, BNC= Method of Benches)

The differences in the number of samples that deviate from the power plant specifications, which result from four different combinations of stacking and reclaiming methods, is presented in Figure 10.

The results can be summarized as follows:

- stockpiles consisting of 6 or 10 layers have approx. 50% smaller number of samples that do not meet the lower NCV specifications of the power plant. The standard deviation of the NCV of the lignite reclaimed from the same stockpiles is also considerably reduced;
- a stockpile capacity increase of 33% results in approx. 20% reduction in both the number of lignite samples that do not meet the lower specification of the fuel and the standard deviation of the NCV;
- the section method of reclaiming, when combined with the Windrow method of stacking in stockpiles consisting of 10 layers, gives significantly improved blending efficiency.

6 CONCLUSIONS

Nowadays, coal quality control is considered the primary tool for improving coal combustion performance in the power plants of the Ptolemais area. As a result, the overall cost of electricity generation can be significantly reduced.

The model which was presented in this paper is innovative since it can predict the coal quality fluctuation, taking into account both the statistical characteristics of the nm-of-mine coal quality data and the geometry of the stockpiles and of the stockyard machinery movements. Thus, this model can contribute considerably to the reliable evaluation of

different coal-handling scenarios applicable in coal stockyards.

This is particularly interesting for the stockyards of the mines and power plants of the Ptolemais area, which were initially designed to provide lignite-buffering storage, rather than a coal-blending facility.

Finally, the model was used for a parametric analysis regarding possible improvements on the lignite-handling procedure that is applied to the lignite produced from the South Field Mine of the Ptolemais area. The results show that there is room for improving current stacking/reclaiming practices at that mine.

ACKNOWLEDGEMENTS

This paper is based on research work conducted in the framework of a project entitled "Development of an automated system for lignite quality control and homogenization applicable in the mines and the thermal power plants of Ptolemais, Greece", funded by the "Program of Research Scholarships" of the General Secretariat for Research & Technology of the Greek Ministry of Development.

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