SYNCHRONIZING A TRIPLE DRAGLINE STRIPPING SYSTEM IN THICK OVERBURDEN

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Abstract

This study addresses the use of combined stripping systems to investigate the technical feasibility of extracting thick coal seams underlying deep overburden strata. The possibility of using multiple draglines in tandem with bucket wheel excavator systems is explored. Pit geometry design alternatives incorporating a triple dragline excavation fleet with bucket wheel excavator-cross pit spreader sub-systems (BWE+XPS) are examined. A production simulation algorithm, which emphasizes synchronizing excavator units in the triple dragline system, is developed. The combined methodology is evaluated in Sector-D of the Afşin-Elbistan lignite basin, one of the most important resources for electricity production in Turkey. The results reveal that a combined stripping fleet may successfully perform overburden stripping at the predetermined rate and uncover coal seams.

Key words: Afşin-Elbistan lignite basin, bucket wheel excavator, cross-pit spreader, simulation

1   INTRODUCTION

Tandem stripping is described as an excavation system in which two or more machines are employed for overburden removal and one machine works behind another [1]. As the system is a multi-lift operation and can be applied to single and multiple seam situations, the first and therefore uppermost unit removes the top overburden lift, and so forth. A major advantage of tandem machines is stated to be that each machine is assigned a specific task. In the case of multiple seams or thick overburden, the stripping capacity required for the upper and thus leading unit is high. The lower and thus following unit should be equipped with a longer range and dumping height capability. Such tandem machines allow efficient fulfilment of these requirements. Another advantage of such tandem stripping systems is that ramping between benches or between overburden and interburden is eliminated, which results in cost reduction compared to a single machine case. Fig. 1a and Fig. 1b illustrate two conceptual cases where two draglines are used in tandem for overburden removal operation.
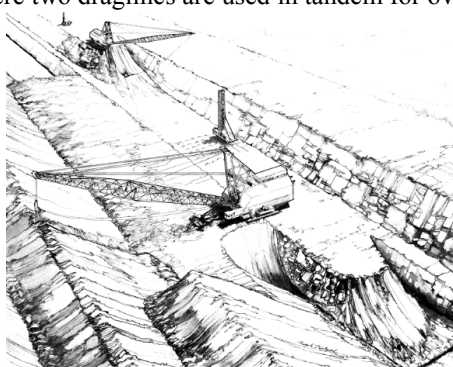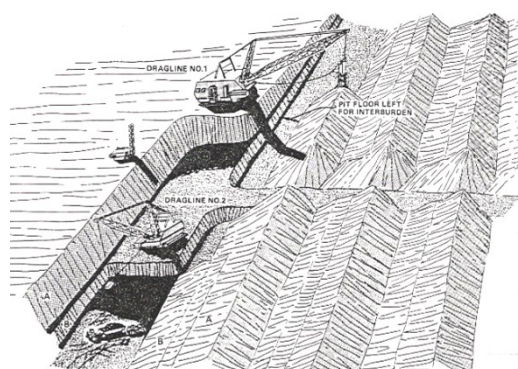

Fig. 1a Conceptual illustration of extraction of a coal seam with two draglines operating in tandem [2].
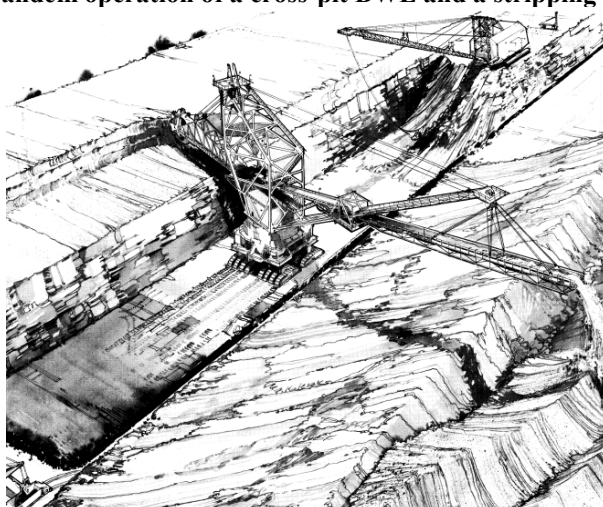
Fig. 1b Conceptual illustration of extraction of two coal seams with two draglines operating in tandem [1].

Bucket wheel excavators (BWE) have been used in tandem with sidecast stripping machines such as stripping shovels and draglines. A good example is shown in Figure 2a where a cross-pit BWE called "the 5872–WX", which was mounted on the top of the main housing of a huge stripping shovel, digs the upper portion of overburden on the background while the blocky lower part is excavated by the largest-ever stripping shovel, "the Captain", in the foreground [3]. Another tandem combination may involve a BWE on the top overburden lift, followed by a dragline on the lower lift. Both machines may or may not operate on the same bench, which is cut by the BWE. Aiken and Gunnett [4] state that in order to improve spoil stability and comply with regulations regarding reclamation, the BWE, which operates on wider benches and produces more stable pit slopes, excavates the loose top bench material from the next cut and transports it across the pit, beyond the apex of dragline spoil piles. The dragline excavates the blasted bottom bench and casts the material an adequate distance to prevent any rehandling [2].

Fig. 2a Tandem operation of a cross-pit BWE and a stripping shovel [5].

Fig. 2b Conceptual illustration of tandem operation of a cross-pit BWE and a dragline [2].

Major disadvantages of such tandem systems consist in the difficulty in achieving a balanced production schedule and lower availability. Balancing the work loads of units in a tandem system is a crucial and

complicated process to ensure that a predetermined linear rate of advance can be maintained by all units. Lower availability results from the fact that failure of a specific unit may fail the whole stripping system. The severity of the failure should be expected to rise from the lowermost unit to the uppermost one.

The tandem operation of draglines for optimal overburden dump placement has been widely applied [2, 6]. Bahr [7] states that the potential use of tandem dragline pullback systems may be employed to reduce the use of truck/shovel pre-stripping, which is approximately three to five times the cash cost of large draglines. According to Rai [8], the tandem operation of draglines is understood to enhance the production and productivity-related aspects in a surface mine. Chironis [9] states that draglines are bound by their limited operating radius. In the case of thick overburden and thick coal seam(s), mine management should consider the feasibility of continuous material-handling systems. Kay and Bartsch [10] and Kesimal et al. [11] state that as the overburden depth becomes greater, the methods for removing the overburden become limited because of excessive cost or reduced productive capability due to the need for rehandling. To avoid the long distance transportation of the around-the-pit systems or costly truck haulage, cross-pit conveyor systems have been developed, which are intended primarily for applications where extensive rehandling makes dragline operations inefficient. Here, a combination of equipment such as the BWE-XPS and draglines can reduce capital expenditures and production costs. Johnson et al. [12] contribute to this statement with a similar question: as the upper operating ranges of draglines are approached, should new larger draglines be purchased for such expensive rehandling of material or should the management switch to auxiliary spoil handling systems? They state that there are doubts that larger draglines will provide relief in the total compliance of current reclamation; the rehandling of material has always been objectionable to a mining venture. Afşin-Elbistan Lignite Basin

2   AFŞIN-ELBISTAN LIGNITE BASIN

The Afşin-Elbistan lignite basin, which holds the greatest share in national lignite reserves, is located north of Afşin and Elbistan cities, Kahramanmaraş Province, in southeast Turkey. The basin, due mostly to the magnitude of reserves and geographic spread, is divided into sectors A through F [13]. In the basin, the topography rises mildly towards the north with average altitude being about 1150 m above sea level. The basal part of the lignite seam consists of thinly-bedded turquoise-coloured claystones with carbonate lumps and some organic matter. The lignite series, which underlie gyttja stratum, range from 10 m to 80 m in thickness and are of lower calorific value. Several clay and gyttja lenses of varying dimensions are dispersed throughout the seam. The waste immediately overlying the lignite zone is identified as gyttja, which is highly inhomogeneous and a sapropelic, dark-colored mud with organic matter and abundant gastropod shells. Gyttja series are overlaid by greenish, bluish claystones, marls and sandstones of coal measure rocks. At the top is laid marls, gravelstones and alluvium which is rich in organic matter. The lignite body thickens towards east and south in Sector-D of the Afşin-Elbistan lignite basin. The average thickness of lignite zone and overburden strata are 26 m and 64 m, respectively. The mining operator of Sector-A is the Electricity Generation Incorporated Company of Turkey (EÜAŞ) and their subsidiary, Afşin-Elbistan Lignite Establishment (AEL). The currently operating mine is the Kışlaköy opencast mine, which is equipped with six identical bucket wheel excavators, each employed on a 20-m high bench. Lignite and overburden are transported using a belt conveyor system. Five identical spreaders perform dumping of overburden [14].

2.1 Single/Tandem Dragline Stripping Systems

After studying the Afşin-Elbistan basin and thick lignite zone, it could directly be deduced that only high-capacity excavation systems could be employed. The depth of overlying strata and the thickness of coal seam necessitate the tandem operation of excavation units, preferably on both sides of the pit, and with a fleet of multiple units. As both strata appear to prohibit the use of single dragline systems, the remaining overburden will have to be removed by tandem dragline systems after the overlying strata is significantly thinned by utilizing loader-hauler combination systems. This study addresses the possibility of employing alternative overburden removal systems in strip mines with a deep overburden and thick coal seams, such as Sector-D of the Afşin-Elbistan lignite basin. Huge amounts of overburden to be removed in the basin obligate the deployment of the fleets of giant earthmovers like draglines, BWEs with belt conveyor systems and high-capacity loader-hauler combinations. A preliminary evaluation reveals that the overburden should be properly allocated among excavation systems to balance the work load of all stripping units. Likewise, in case the dragline systems are deployed at the lowermost bench to uncover the coal seam, the thickness of the bench, on which the draglines are deployed, becomes a vital design parameter. Thus this study initially aims to determine the dimensional feasibility of the single/tandem dragline systems in Sector-D of the Afşin-Elbistan lignite basin.

In order to evaluate the feasibility of dragline application under adverse conditions of such deep overburden and thick coal seam, several dragline range diagramming models, which were previously developed, are applied to the Afşin-Elbistan case. Variations in the thickness of overburden and coal throughout the property and the swell factor of overburden are taken into account during the geometrical modelling stage. Therefore, the coal thickness is assigned a range between 25 m to 70 m with 5 m increments. Material swell is allowed to

fluctuate between 30 per cent and 40 per cent. Likewise the overburden left for the dragline stripping is increased from a minimum of 10 m to a thickness at which no dragline/operating system is feasible. Hundreds of range diagram analyses with several dragline operating methods indicate that the single/tandem dragline stripping could only be applied to a thin slice of overburden left over the coal zone with one-bench methods. The tandem dragline methods appear to be difficult to use owing to the fact that the excessive thickness of the coal zone makes the allocation of overburden into slices an impossible task. Also, the bridges constructed on the high-wall side and the pullback pads on the spoil side would be far too high for digging depth capability of most very-large capacity draglines. For the reasons listed above, the studies are concentrated on triple draglines and BWE-XPS combinations for the overburden removal operations.

2.2 Triple Dragline Stripping Systems

A major problem associated with the multiple stripping systems is a proper distribution of work load among individual units. The optimum balance is reached when the rate of linear advance of all units is equalized. In a poorly matched or mismatched system, all dependent units would be slowed down to the pace of independent ones. In such a case, the retarded units should be expected to strip at an elevated cost. Another shortcoming is that the coal production rate, which may delay a preset target, is determined by the slowest unit in the fleet. From the safety point, Niemann-Delius and Thiels [15] indicate an unsafe condition where such stripping units operating in the same pit or bench may frequently approach each other, which create a critical and inadmissible operational situation.

Owing to the large thickness of both overburden and coal seam, the application of terrace mining is adopted. The operation usually incorporates three or more machines. Essentially, the first dragline, which is equipped with a shorter boom and larger bucket, operates on the upper bench and excavates a greater portion of the overburden. The second machine excavates the lower bench material and dumps it behind the spoil pile created by the first one. The third dragline, located on a pad, which is prepared by levelling the piles already placed in the pit, works in pullback fashion to excavate the rehandled material and any barrier left on the edge of the lower bench and dumps it on the pad behind itself following a larger swing angle [16]. The phases of operation are given in Fig.3.
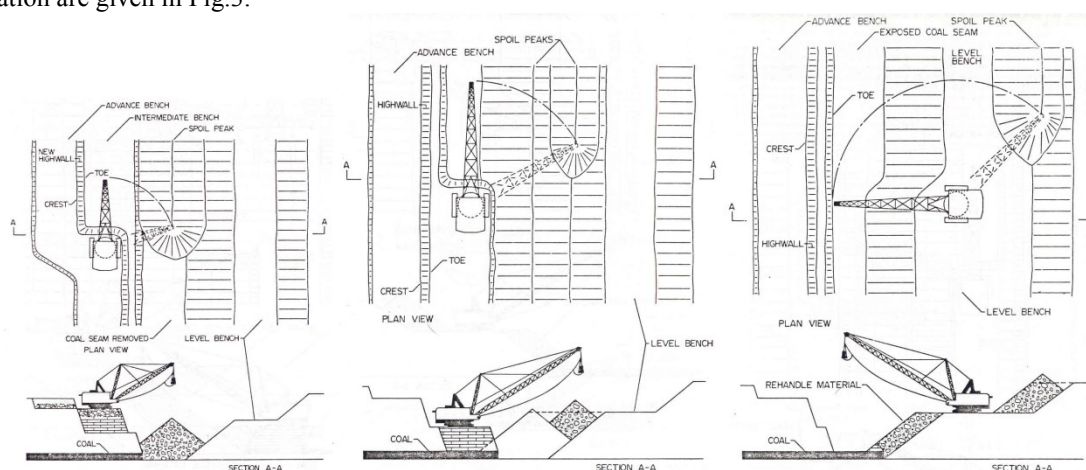

Fig. 3 Phases of terrace mining with triple draglines [16].

Synchronicity among stripping units in a tandem system is defined as the equality in the rate of linear advance. Erdem and Celebi [17] discussed likely consequences of the synchronous and asynchronous operations of a tandem dragline fleet. In the case of a triple dragline system with each unit being deployed on different benches, the unit operating at the highest bench is called the independent dragline (ID), which experiences no obstruction against advancement. The unit operating on the lower bench and thus following the independent dragline is called the semi-dependent machine (SDD) and the unit operating on the spoil side and totally uncovering the coal seam is called the full-dependent machine (FDD).

2.3 Optimization model

The goal of the optimization model is to select a triple dragline system that would uncover a predetermined amount of coal with a minimum waiting time. This objective is subject to a major constraint, which dictates that each unit in the fleet has to completely excavate a block of waste allocated to it within a specific period of time. The objective function and constraints are explained below.

Objective function: In a triple dragline system, there are two types of waiting, both of which should be minimized: the one that occurs during the continuing operations and the one that occurs after the operations are finished. ID may experience the second type while SDD and FDD are likely to encounter both of them.

1. Final waiting time of ID: The objective of this goal function is to designate the waiting time of ID. The optimization model considers a dragline operation to be composed of digging and walking. In addition, unexpected interruptions may delay the operations. Thus, the total time spent to excavate a block of waste is given in Eq. 1 for ID.

$$t_{sched} = t_{ID-dig} + t_{ID-walk} + t_{ID-delay} + t_{ID-fwait} \tag{1}$$

where:

t_{sched} - is the total scheduled simulation time allocated to the triple dragline system to uncover a predetermined tonnage of coal [s],

t_{ID-dig} - is part of the total scheduled simulation time spent by ID for digging [s].

$t_{ID-walk}$ - is part of the total scheduled simulation time spent by ID for walking between sitting locations within a cut and between adjacent cuts [s]. The walking algorithm takes into consideration the shortest distance to be moved, the walking speed and the length of the step of ID. For each walk period, compensation is applied for the preparation in the form of a fixed time period.

$t_{ID-delay}$ - is part of the total scheduled simulation time spent by ID for unexpected delays which are simulated in the model by random processes [s]. The scheduled time excludes all planned repair and maintenance activities. After finishing each continuous operating period, a random number is generated from the uniform distribution between 0 and 1. If the generated number is greater than the operating efficiency, the dragline is delayed for the following time [18] (Eq. 2):

$$t_{ID-delay} = t_{cop} \left(\frac{1}{f_{op}} - 1 \right) \tag{2}$$

where:

t_{cop} - is continuous operating period [s],

f_{op} - is operating efficiency [decimals].

The excavation is a process in which the size of individual overburden blocks can be figured out deterministically. Volumetric calculations can be performed with exact formulations. However, the bucket fill factor and cycle time are two non-deterministic parameters, which are dependent upon several factors. The nature of both parameters lends itself well to a random assignment. The model simulates the excavation of a specific waste block by assigning the fill factor and cycle time at every cycle. The excavation is completed when the volume of total material moved exceeds that of the block.

The final waiting time thus causes operating costs to rise as a function of time period during which ID is idled. So, the objective is set as to minimize the final waiting by selecting a dragline of optimum capacity (Eq. 3).

$$Min = \left\{ t_{ID-fwait} \right\} \tag{3}$$

where:

$t_{ID-fwait}$ - is part of the total scheduled simulation time spent by ID for waiting idle after completing excavation of its allotted block.

An ID with larger capacity should be expected to strip the block ahead of scheduled time.

2. Operational waiting time of SDD: The second goal function aims to select a SDD with the minimum waiting time during operations. The decomposition of the total time spent to excavate a block of waste is given in Eq. 4 for SDD.

$$t_{sched} = t_{SDD-dig} + t_{SDD-walk} + t_{SDD-delay} + t_{SDD-opwait} + t_{SDD-fwait} \tag{4}$$

where:

$t_{SDD-dig}$ - is part of the total scheduled simulation time spent by SDD for excavation [s],

$t_{SDD-walk}$ - is part of the total scheduled simulation time spent by SDD for walking [s],

$t_{SDD-delay}$ - is part of the total scheduled simulation time spent by SDD for unexpected delays [s],

$t_{SDD-opwait}$ - is part of the total scheduled simulation time spent by SDD for waiting for ID during operations [s].

When the linear rate of advance of SDD is higher than that of ID, it will frequently attempt to approach it, in which case it is kept idle for subsequent cuts until a preset safety distance is maintained by the advance of ID. The time elapsed to restore the safety distance is recorded as the waiting of SDD during stripping operations (Eq.5).

$$t_{SDD-opwait} = \sum_{i=1}^{n} t_{SDD-cutwait}$$

$$t_{SDD-cutwait} = t_{ID-cutext} - t_{SDD-cutext} \tag{5}$$

where:

$t_{ID-cutexc}$ is the time spent by ID for excavating a cut [s],

$t_{SDD-cutexc}$ is the time spent by SDD for excavating a cut [s],

n is the number of cuts SDD has waited for ID to restore the safety distance,

$t_{SDD-fwait}$ is part of the total scheduled simulation time spent by SDD for waiting idle after completing the excavation of its allocated block [s].

In a synchronous stripping system that is composed of multiple excavators, the linear rate of advance of units should be closely matched. By this way, the waiting time of all dependent units during operations can be minimized. In addition, the pace of the system should match a specific rate that is required to uncover the predetermined acreage of coal. In this way, the undesired final waiting times of all units can also be minimized. The associated objective function for the SDD is given in Eq. 6.

$$Min = \left\{ t_{SDD-opwait} \right\} \tag{6}$$

3. Operational waiting time of FDD: The third goal function aims to select a FDD with the minimum waiting time during operations. The decomposition of the total time spent to excavate a block of waste is given in Eq. 7 for FDD.

$$t_{sched} = t_{FDD-dig} + t_{FDD-walk} + t_{FDD-delay} + t_{FDD-opwait} + t_{FDD-fwait} \tag{7}$$

where:

tFDD - dig is part of the total scheduled simulation time spent by FDD for excavation [s],

tFDD - walk is part of the total scheduled simulation time spent by FDD for walking [s],

tFDD - delay is part of the total scheduled simulation time spent by FDD for unexpected delays [s],

tFDD - opwait is part of the total scheduled simulation time spent by FDD for waiting for SDD during operations,

tFDD - fwait is part of the total scheduled simulation time spent by FDD for waiting idle after completing the excavation of its allotted block [s].

When the pace of FDD is higher than that of SDD, it will frequently attempt to approach SDD, in which case it is kept idle for subsequent cuts until a preset safety distance is maintained by the advance of SDD. The time elapsed to restore the safety distance is recorded as the waiting of FDD during stripping operations (Eq. 8).

$$t_{FDD-opwait} = \sum_{i=1}^{n} t_{FDD-cutwait}$$

$$t_{FDD-cutwait} = t_{SDD-cutext} - t_{FDD-cutext} \tag{8}$$

where

$t_{FDD-cutexc}$ is the time spent by FDD for excavating a cut [s],

n is the number of cuts FDD has waited for SDD to restore safety distance [s],

The third objective function, which aims to select a FDD with the minimum operational waiting time, is given in Eq. 9.

$$Min \left\{ t_{FDD-opwait} \right\} \tag{9}$$

Constraints: All three draglines in the fleet must complete the excavation of the allocated overburden blocks within the scheduled time period (Eq. 10).

$$V_{ID} \geq V_{ID-block}$$

$$V_{SDD} \geq V_{SDD-block}$$

$$V_{FDD} \geq V_{FDD-block} \tag{10}$$

where:

V_{ID}, V_{SDD}, V_{FDD} and $V_{ID-block}$, $V_{SDD-block}$, $V_{FDD-block}$ are the total volumes excavated by ID, SDD and FDD [m³] and the total volumes that must be excavated by ID, SDD and FDD within the scheduled simulation time [m³], respectively.

In the multiple-unit excavation systems, an appropriate distance is maintained between machines in order to eliminate likely interactions and allow time for the ground preparation for the following dragline(s). In the optimization model, a safety distance of two cut lengths of ID is to be maintained between ID and SDD on the high-wall side. Therefore, SDD can only start digging after ID has advanced two cuts and the time spent to excavate the first two cuts is added to the total time of both machines. Obviously, in the case of both draglines being perfectly synchronous, there will be some operational waiting time for SDD even if it does not wait for ID after the first two cuts (Eq. 11).

$$L_{SD-hi} \geq 2L_{ID-cut} \tag{11}$$

where:

L_{SD-hi} is the safety distance to be maintained on the high-wall side,

L_{ID-cut} is the length of cut of ID.

The appropriate safety distance, which is equal to two cut lengths of SDD should also be left between SDD and FDD, which operates on the pullback pad on the spoil side. Again FDD can start digging after SDD has advanced two cuts (Eq. 12).

$$L_{SD-sp} \geq 2L_{SDD-cut} \tag{12}$$

where:

L_{SD-sp} is the safety distance to be maintained on high-wall side [m],

$L_{SDD-cut}$ is the length of cut of ID [m].

2.4 Model solution

The developed model has a hierarchical structure. Before proceeding with the production simulation module, the dragline triplet must satisfy all the requirements set by the geometry module where the dimensions associated with the range diagrams are computed. An embedded drawing facility transfers the designed pit data to a DXF file by which the pit geometry can be visualized with most drafting packages.

Though geometrical computations are deterministic in nature, the times spent for each component of digging, walking and delays are stochastic procedures, which are suitable to be processed by simulation. The optimization model, which is of discrete event character, allows a dragline triplet to be simulated at a time. The model works as follows: Initially all draglines are located at the starting point of the pit and ID is allowed to excavate two cuts of material while SDD and FDD are idled. ID operates in routine fashion as advancing one cut at a time with the sole hindrance being unplanned stoppages modelled by random processes. When the safety distance is reached on the high-wall side, SDD is allowed to operate while FDD is still idled. FDD on the spoil side can thus start excavation only after SDD has advanced two cuts. Time periods during which SDD and FDD are idled are recorded. Both draglines are always controlled by the state of the dragline higher in the hierarchy before advancing to the next cut. Thus as SDD is controlled by ID, at the same time it controls FDD. Because the cut length of each dragline is different, SDD and FDD may have violated their assigned safety distance at a specific moment in time. Then, such dragline is immediately stopped until the required space is restored. Again the time passed during halting is added to the total time spent for waiting during operations. In the case ID finishes the excavation of its allocated block ahead of the scheduled time, it is stopped and the remaining time is recorded as its final waiting time. Now SDD becomes a new ID, which is allowed to operate unconditionally. If it completes the excavation before the simulation time ends, then FDD can spend the remaining time freely for operating alone in the pit.

3 TRIPLE DRAGLINE STRIPPING SYSTEM SELECTION

3.1 Data and model run rationale

The optimization model is tested in Sector-D of the Afşin-Elbistan lignite basin. The physical characteristics of the proposed mine and the basic operating parameters of three selected large-sized draglines for the first run are given in Tables 1 and 2.

Tab. 1 Characteristics of the surface mine used in optimization model

Overburden thickness left for dragline stripping [m]	65
Coal seam thickness [m]	26
Berm width between benches [m]	10
Overburden and coal seam highwall bench angle [degrees]	65
Angle of repose of the spoil piles [degrees]	35
Swell factor of overburden material [per cent]	30
Bucket fill factor [per cent]	90
Yearly scheduled operating time [h]	7000
Overall operating efficiency [%]	80
Yearly coal production to be realized [t]	25 000 000
Yearly stripping volume to be realized [bank m³]	50 000 000

Tab. 2 Basic dimensions of draglines used in simulation model

	ID	SDD	FDD
Operating radius [m]	97.5	97.5	111.3
Bucket capacity [m³]	119.8	119.8	88.2
Tub radius [m]	24.4	24.4	25.6
Length of a step [m]	2.6	2.6	2.1
Walking speed [m/min]	241.0	241.0	N/A

Prior to the simulation, all draglines in the triplet must satisfy a range of requirements, which include linear, areal and cubic dimensions along and across the block on both sides of the pit. Swing angles and rehandle percentage are then computed. The simulation is done on straight overburden blocks of equal length. Since the overburden on the high wall side is allocated among benches, the minimum taken thickness for the upper bench on which ID operates is 30 m with 1 m increments. Thus, the maximum thickness of the lower bench on which SDD operates counts down from 35 m with 1 m decrements. The height of the pad on which FDD operates is determined by the geometry module. For every pit configuration, the optimization model is run until the triplet fails to realize yearly volume of material to be stripped.

3.2 Model results and discussion

The results of the first optimization run, which include the time periods in percentages elapsed for tasks, are presented in Figures 4, 5 and 6 for ID, SDD and FDD, respectively. The following outcomes are inferred:

a) The triplet passed the production limit successfully 15 times for upper-bench thickness values between 30 m and 45 m.

b) For ID the final waiting time is an inverse measure of bench thickness, the optimum of which is 45 m. The total time spent for key-cutting, main-cutting, walking and delaying rises with the increasing bench thickness and thus the size of cut.

c) For SDD the minimum waiting time is 23 per cent for a bench thickness of 35 m while the maximum total waiting time exceeds 50 per cent at a 20 m bench. SDD is always idled either in the form of waiting during or after operations indicating that it is an over-capacity dragline. At this moment, no bench thickness is optimum for SDD.

d) For all successful cases, FDD waits after the operations are finished indicating to the fact that it also is a slightly over-capacity dragline under given conditions. The fluctuation of the total time spent for rehandling is due to changing the rehandle percentage, which is determined by the current pit geometry.

To be able to trace synchronicity among the draglines in the triplet, the linear advance rates are plotted against a reference bench thickness. It is obvious that for a fully synchronous triplet, the advance rate of all units should be as close to each other as possible. Figures 7, 8 and 9 illustrate the overall paces, the paces excluding final waiting times and the paces excluding both types of waiting, respectively. The conclusions reached are:

a) For each dragline, the overall linear advance rate is computed by dividing the total distance moved by the total simulation time, which is inclusive of both types of waiting. Figure 7 reveals that for the 15 successful trials, the overall linear advance rate strolls around a reference value of 2.518 m/h, deviations from which are attributed to the stochastic nature of parameters in the optimization model.

b) The linear advance rates of all draglines during operations are continued, and are presented in Figure 8. The pace of ID continuously diminishes with the increasing size of the cut it excavates. SDD, whose advance is bound by ID, operates at its own pace for the first three pit configurations. At an upper bench thickness of 32 m (lower bench thickness of 33 m), the paces of ID and SDD are synchronized provided that the final waiting is ignored. Beyond this point, however, the pace of SDD is reduced to that of ID by operating intermittently, which is reflected as waiting during operations, in order to maintain the safety distance on the high-wall side. For all trials, FDD advances at a slower pace than SDD with which it is never synchronized. But it is synchronized with ID at an upper bench thickness of 45 m.

c) Figure 9 gives the net rates of linear advance, which excludes both waiting types for all draglines. The scene is clearly indicating that under the given conditions the triplet cannot be synchronized. The paces of ID and FDD are approaching each other at thicker upper bench values while SDD appears to be capable of excavating much larger volumes than it is assigned. However, a full synchronization requires the pace curves of all individual units to coincide at a specific configuration of bench allocation, which determines the work load of each dragline.

A thoroughly synchronous triplet is thus the one, in which all units have the rates of linear advance identical and the final waiting times as close to zero as possible. For this reason, the optimization model is run several times for determining the optimum triplet. At each run, the bucket capacity of SDD is gradually reduced by selecting smaller draglines. Quantitatively, the bucket capacity of SDD is reduced to 103 m³ at the 2nd run, 92 m³ at the 3rd run, 84 m³ at the 4th run, 76 m³ at the 5th run and 71 m³ at the 6th run. The optimum results are reached at the sixth run. The distribution of simulation time among the tasks is presented in Figures 10, 11 and 12 for ID, SDD and FDD, respectively. The conclusions derived are summarized below:

a) The triplet passed the production limit seven times for the upper-bench thickness values between 39 m and 45 m. Outside this interval, SDD and consequently FDD failed to realize the required volume. For all seven successful trials, the overall linear advance rate ranges between 2.518 m/h and 2.529 m/h as seen from Figure 13.

b) For all draglines, the minimum final waiting time is minimized at an upper bench thickness of 45 m.

c) For both SDD and FDD, the operational waiting time is minimized at an upper bench thickness in a range of 40 m – 41 m. Table 3 lists the percentage of the time periods elapsed by operational and final waiting.

d) At the upper bench thickness of 42 m (23 m for SDD), the pace of SDD is dropped to that of ID, which is reflected by consistently increasing waiting times during operations. Similarly, the pace of FDD catches that of SDD at an upper bench thickness of 41 m where its operational waiting time is minimized (Figure 14).

e) ID and FDD show the minimum total waiting times at an upper bench thickness of 45 m. On the contrary, SDD catches the minimum at 39 m. The incompatibility in the final waiting times of ID and SDD is encountered in all trials. It is caused by the imbalance between the workloads at a specific bench configuration, a situation which cannot be corrected unless the bucket capacity of SDD is adjusted every time the lower bench thickness is changed.

f) The difference between the linear paces of all draglines is minimized at the upper bench thickness of 41 m (Table 3, Figure 15). Since ID experiences no waiting during operations, the equalization of the linear pace of units in the triplet means that both dependent draglines have the minimum waiting times during operations, which satisfies the main objective of the simulation model. It should be noted that the operational waiting times of SDD and FDD cannot be zero as SDD waits for ID for two cuts and FDD waits for SDD for two cuts at the start of stripping operations.

g) The model has provided a 41 per cent reduction in the bucket capacity of SDD, which was reduced from an initial value of 120 m³ to 71 m³. But still the required yearly stripping volume is realized.

h) The final pit geometry, by which all draglines are synchronized, is plotted in Figure 16 with significant dimensions indicated. As the study is based on average coal and overburden thicknesses, part of the material overlying the dragline benches, which may rise up to 50 m in thickness, should be dug and transferred to the spoil side using a BWE-XPS system, which must advance at an identical linear rate as the draglines. Since this material is to be deposited beyond dragline spoil ridges, it is clearly seen from Figure 16 that the XPS must cover the horizontal span not less than 184 m.
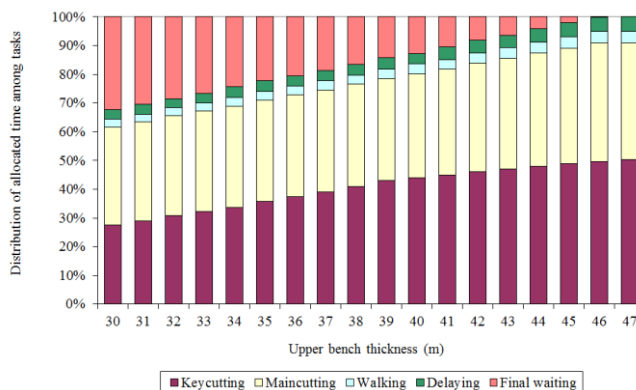
Fig. 4 Percentage of time elapsed during operations as a function of upper bench thickness for ID (first run).
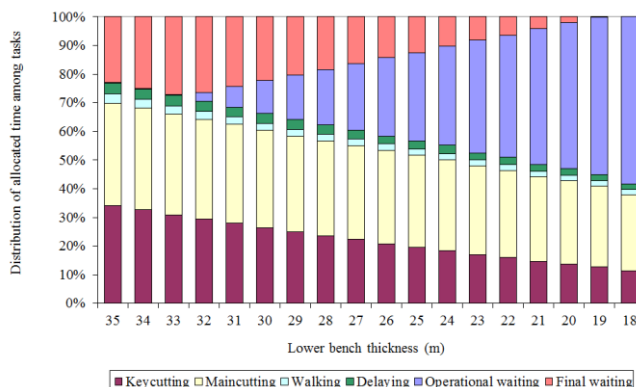
Fig. 5 Percentage of time elapsed during operations as a function of lower bench thickness for SDD (first run).
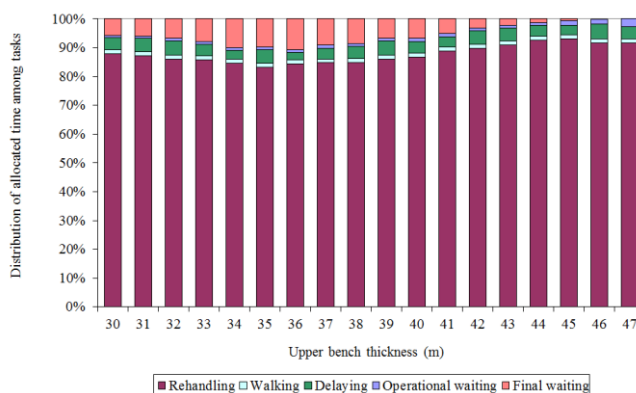
Fig. 6 Percentage of time elapsed during operations as a function of upper bench thickness for FDD (first run).
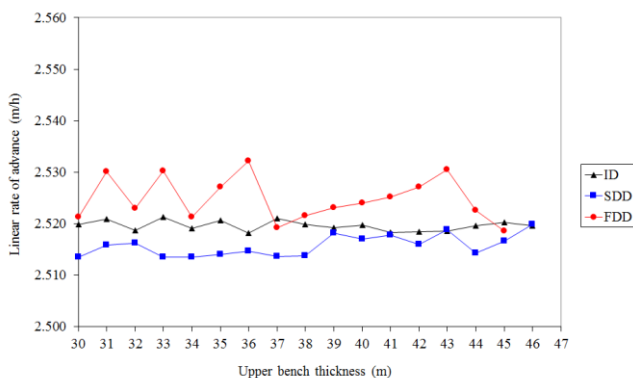
Fig. 7 Linear pace as a function of upper bench thickness (inclusive of both waiting types) (first run).
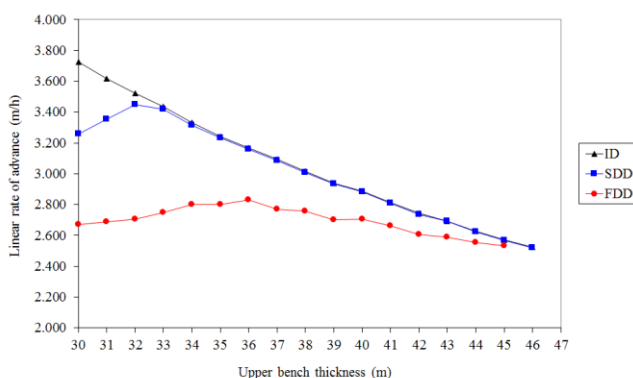

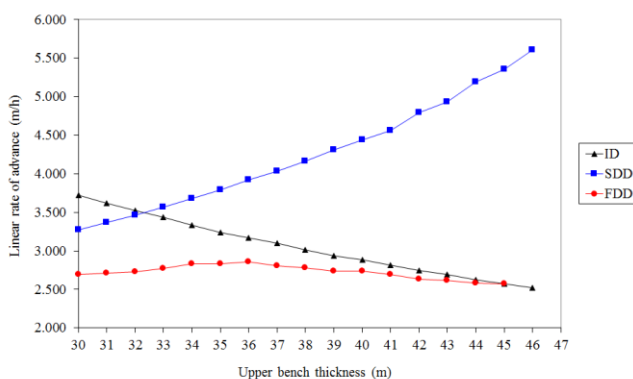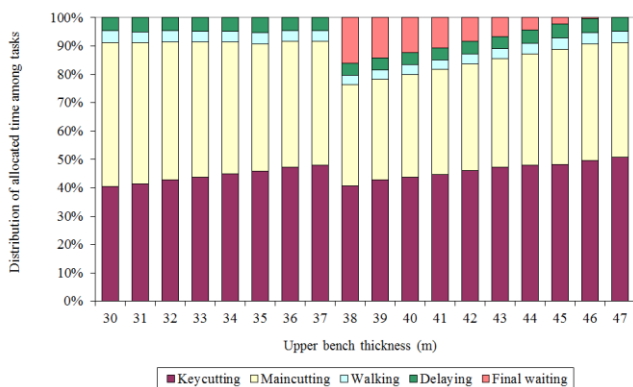**Fig. 8 Linear pace as a function of upper bench thickness (exclusive of final waiting) (first run).**

Fig. 9 Linear pace as a function of upper bench thickness (exclusive of both waiting types) (first run).
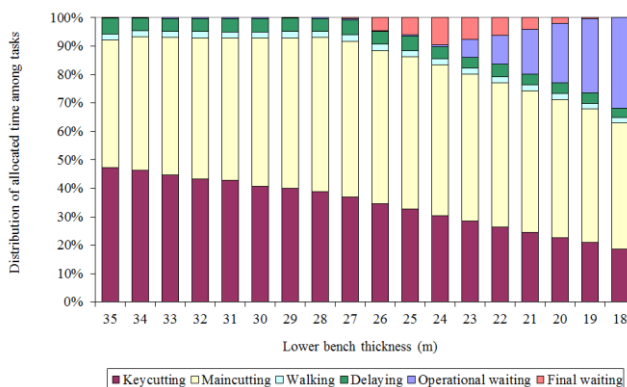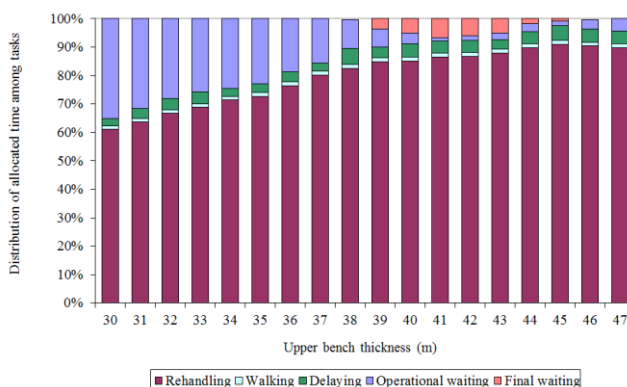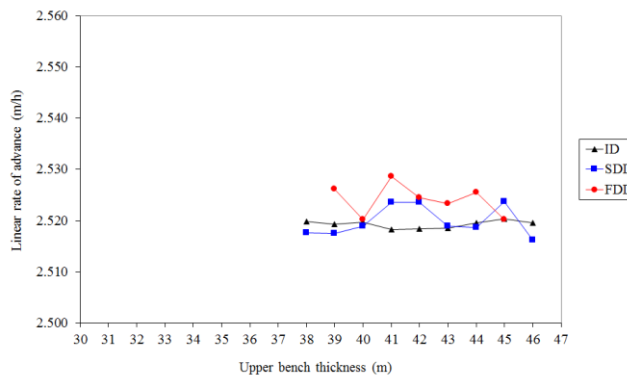

Fig. 10 Percentage of time elapsed during operations as a function of upper bench thickness for ID (sixth run).
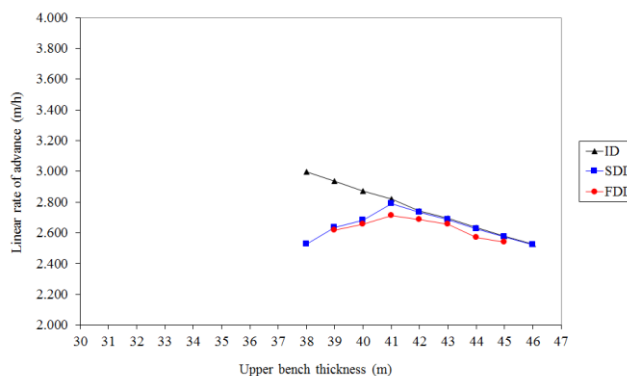
Fig. 11 Percentage of time elapsed during operations as a function of lower bench thickness for SDD (sixth run).

Fig. 12 Percentage of time elapsed during operations as a function of upper bench thickness for FDD (sixth run).

Fig. 13 Linear pace as a function of upper bench thickness (inclusive of both waiting types) (sixth run).

Fig. 14 Linear pace as a function of upper bench thickness (exclusive of final waiting) (sixth run).
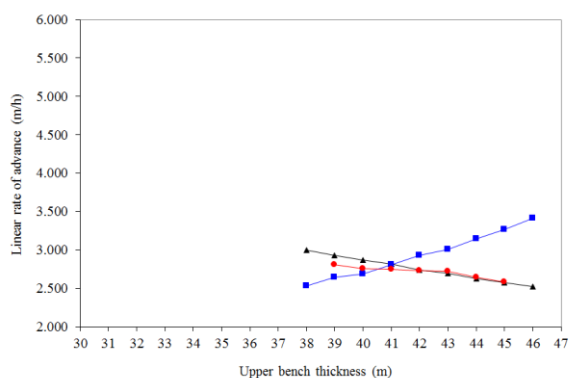
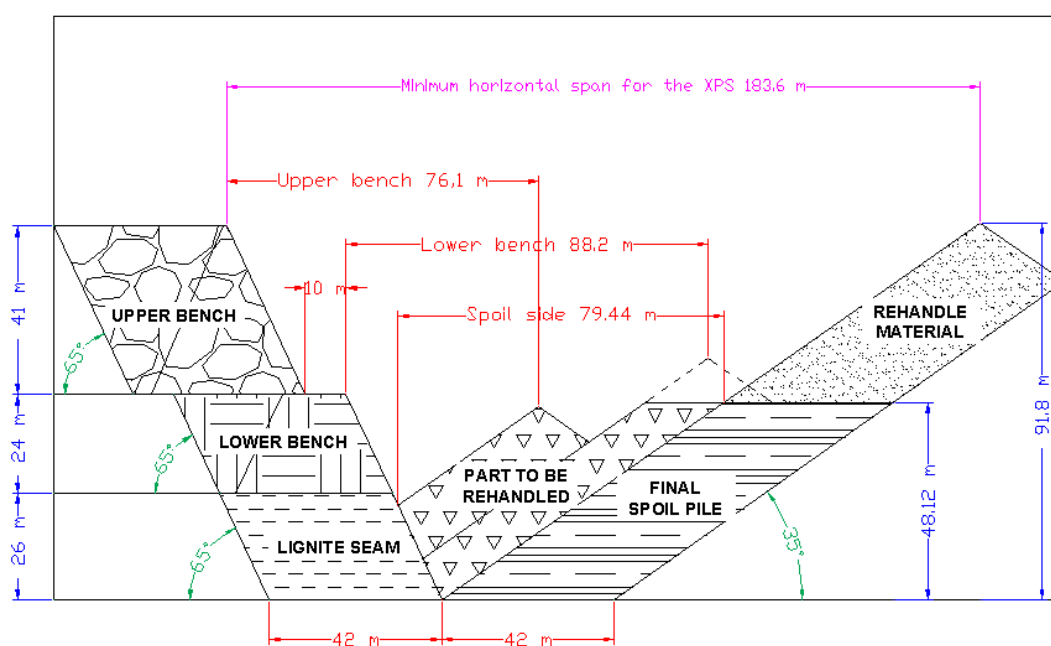**Fig. 15 Linear pace as a function of upper bench thickness (exclusive of both waiting types) (sixth run).**

Fig. 16 Final pit configurations at the optimum synchronization level (sixth run).

Tab. 3 Percentages of time periods elapsed by waiting at the 6th run and linear rate of advance of draglines in the fleet.

Upper bench thickness (m)	ID			SDD				FDD				Diff
	2	Σ	3	1	2	Σ	3	1	2	Σ	3	
39	14.17	14.17	2.935	0.34	4.49	4.83	2.645	6.50	3.53	10.03	2.808	0.290
40	12.32	12.32	2.874	0.33	6.08	6.41	2.692	3.58	5.16	8.74	2.762	0.182
41	10.68	10.68	2.819	0.62	9.51	10.13	2.808	1.24	6.74	7.98	2.748	0.071
42	8.23	8.23	2.744	6.30	7.71	14.01	2.935	1.50	6.09	7.58	2.732	0.203
43	6.58	6.58	2.696	10.15	6.28	16.43	3.014	2.41	5.05	7.46	2.727	0.318
44	4.32	4.32	2.633	15.78	4.13	19.92	3.145	2.92	1.73	4.65	2.649	0.512
45	2.22	2.22	2.578	20.88	1.91	22.79	3.269	1.73	0.76	2.49	2.584	0.691

1   Waiting time during operations [per cent]
2   Final waiting time [per cent]
Σ   Total waiting time [per cent]
3   Linear rate of advance that is exclusive of both waiting types [m/h]
Diff   The difference between the maximum and minimum rates of linear advance [m/h]

4 CONCLUSIONS

An optimization model is developed using which a fleet consisting of three draglines employed on a deep overburden stratum overlying a thick coal seam can be simulated. It assists in selecting the optimum triplet in terms of synchronization with employing three objective functions, which aim to select a triplet with identical rates of linear advance and the minimum waiting time after the operations are completed. It must be noted that when selecting the triple system, these indicators must be considered together as the individual consideration of a particular indicator may lead to an inefficient selection. The model is tested in the Afşin-Elbistan coal basin Sector-D, which covers a lignite reserve of some 750 million metric tons. The model achieved a size reduction of some 40 % in the bucket capacity of semi-dependent dragline. The model outcomes reveal that the fleet of three large-sized draglines with an optimized bucket capacity can realize the yearly production figures, with the top portions of the overburden stratum to be moved by BWE-XPS systems.

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