Equipment selection for high selective excavation surface coal mining

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Synopsis

The choice of which mining method to use at many large surface coal mines is often dicated by what machinery is available or what experience the mine management can offer. One of the most significant surface coal mines in Turkey is owned and operated by the Turkish National Coal Board, located to the west of the city of Kütahya. The Seyitömer Lignite Enterprise (SLE) extracts low quality coal, the majority of which is supplied to an adjacent power station. The coal seems at SLE contain bands of ash which under normal mining conditions are extracted with the coal. This increases the ash content of the run of mine coal and results in lower efficiency at the power station and financial penalties for SLE.

In this paper, therefore, selection of the best possible equipment and production method was identified to achieve high selective mining at SLE. The research found that two different high selective mining methods were suitable for selective excavation of the B3 seam, which were hydraulic excavator and truck and surface miner and truck combinations. It was also found that high selective excavation could provide the desired coal quality at 52% lower costs when the whole process (excavation, transportation, processing, etc.) was considered.

Keywords: coal mining, surface mining, selective mining.

Introduction

One of the parameters that provide minimum cost for the targeted production in a mine is surely the suitability of the machines/equipment selected. Moreover, equipment selection directly affects the pit design and production planning. In open pit mining, equipment selection is made according to many factors related to the ore and mining conditions. These factors can be qualitative and quantitative in nature. The main purpose of equipment selection is to choose the optimum and cost-effective equipment by installing a decision-support system, which can analyse various and complex factors. The term optimum here reflects that the equipment selected must comply with the mining conditions/limitations and meet the basic requirements and preferences of the mine[1,2].

Various types of equipment selection models have been proposed to incorporate into a decision-support system for application to the selection of mining equipment. These models are life cycle cost analysis[3], net present value analysis[4], linear breakeven model[5], linear programming[6] and decision making tools such as reliability analysis, knowledge based expert systems and analytical hierarchy processes[7–9].

The most important factors for the selection of opencast mining equipment may be identified as site or deposit parameters, organizational culture, adaptability to change, technical features, production performance, operator capability, mine/machinery life, performance monitoring facilities, administration, financial consideration, manufacturer's reputation, delivery lead time and warranty, reliability of machinery, employee participation in the decision-making process (maintenance and operation), drive system (hydraulic/electric/mechanical), maintainability, power source required (diesel/electric), available training facilities, auxiliary machines required, general supervision required, logistics support or management, degree of automation, operating condition, level of safety, working environment and the ease of configuration[2].

The basic principle in equipment selection is to define the degree of priority or governing factors among the ones given above and then determining the matching equipment and the alternatives to these parameters comparatively. In most instances, however, it is difficult to determine the equipment meeting all the requirements stated.

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Seyitömer Lignite Enterprise of the Turkish National Coal Board (SLE) is one of the largest coal producers in Turkey and produces 7.5 million tonnes of lignite coal per year from an opencast mine close to the city of Kütahya (Figure 1).The most significant problem that the enterprise currently faces is the low quality run of mine coal (ROM), which is mainly sold to the nearby power station. The excavation of the partings in the seam together with coal increases the ash content of the coal produced, which in turn decreases the efficiency of the coal burning process at the power station and results in high penalty costs for the mine. Since the main problems at SLE were caused by the current coal quality not meeting the standards required by the power plant and the market, and the need for balanced pit development, an attempt was made at quality planning to meet the various requirements. Factors related to quality improvement for current and proposed production strategies were determined, according to the customers' quality demands and the saleable coal quality reserves. Afterwards, the necessity and the degree of selectivity for each strategy and determining of an optimum excavation configuration was defined. The result was high selective mining at the B_3 seam to increase the power plant coal quality up to 1761 kcal/kg using a production strategy based on maximum coal supply to the market[10].

Once a decision was made for quality improvement upon high selective excavation at the enterprise, it was then important to select suitable machinery/equipment and production methods that will result in the required coal quality improvement. In order to make the selective excavation applicable, the machinery to be selected must have highly selective and productive capabilities at reasonable costs. In fact, there are many examples of selective excavation applications in opencast mines to remove the partings from coal to be sold for power stations. The main reasons for these mines to employ selective excavation are the difficulties in solving the problems during the processing stage and that the selective excavation produces more economical solution[11–13].

Location and geology

The SLE lignite basin is located to the north-west of the city of Kütahya (Figure 1) and it consists of three main regions: Seyitömer, Aslanlı and Ayvalı as shown in (Figure 2). The Seyitömer region is divided into three sub-regions (districts), which are Seyitömer-East, Seyitömer-West and the Dragline District. The Aslanlı region consists of two separate districts called Aslanlı-1 and Aslanlı-2.

In the Seyitömer basin, there are two 0–70° dipped horizontal lignite seams, which are simply referred to as seam-A and seam-B and the vertical distance between the seams varies from 10 to 50 m. Both seams contain interburdens with thicknesses varying from 0.1 m to 2 m. The thickness of seam-A varies between 5 to 25 m but the average thickness is accepted as 10 m. This seam contains very intensive interburdens and has an average calorific value of 1820 kcal/kg[14].

Figure 1—Location of the Seyitömer coal field

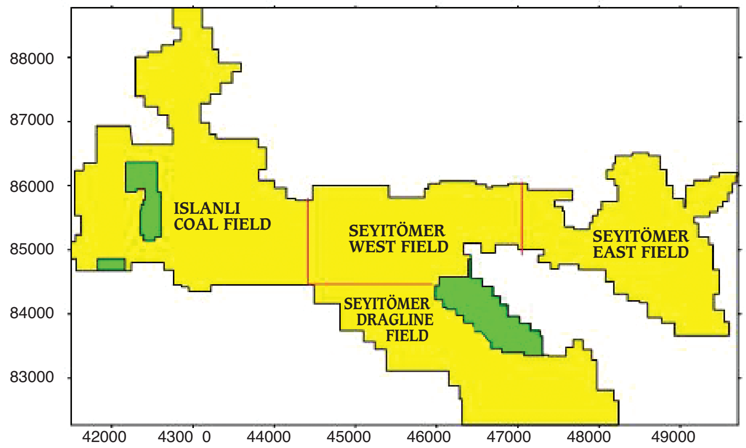

Figure 2—Reserve Boundaries and Production Fields of the Seyitömer-Aslanlı Region

Seam-B is located beneath seam-A and its thickness varies between 2 and 30 m with an average thickness of 20 m. Seam-B consists of three different sub-levels from top to bottom which are called B_1, B_2 and B_3 and the calorific values of these sub-levels decrease from top to bottom due to the intensified interburden sequencing. In particular the B_3 seam throughout the basin includes partings thinner than 0.5 m in thickness[14,15].

The coal produced from the Seyitömer lignite basin has high moisture content varying from 33% to 39% and they are classified as soft and mate lignite[14]. The coals of B_1 and B_2 seam levels have higher calorific values and are often sold as a domestic coal in the market. However, the coal of seam B_3 has lower calorific value and finer particle size (-200 mm) and therefore, it can be sold only to the nearby power plant. Approximately 12% of the total production in the coal field (850 000 tonnes) is sold in the market for domestic use and the remaining 88% of the production (6 250 000 tonnes) is consumed at the power plant. However, the income obtained per tonne of coal sold to the market is almost twice as much as the income from sale to the power station.

Optimum equipment and method selection for high selective excavation at SLE

Identification of main factors related to equipment selection

Firstly, three priority degrees of effective parameters were determined according to the mining and geological conditions in order to select optimum machinery and mining methods. These parameters were determined according to the purpose of the research, observation made at the mine and the discussions with the experts. After an overall assessment, three priority degree parameters were determined as follows:

- ➤ *First priority degree parameters*—ease of rock excavation, high selective ability of the machinery
- ➤ *Second priority degree parameters*—rate of production, capacity and productivity of machinery, capital and operating cost of machinery
- ➤ *Third priority degree parameters*—geological/mining features (faulting, bench width, seam dip, waste rock features, floor condition, material size after fragmentation), flexibility, maintainability (labour's skill and technical knowledge required, maintenance support, spare parts availability, back-up service).

High selective ability of the machinery is first priority since achieving a high selective excavation is directly dependent on the minimum separation thickness and separation accuracy of the machine or equipment used. The production method to be applied will also be determined according to the selected machinery having the capability of high selective excavation. This assumption actually makes the selection more straightforward and less complex.

Evaluation and selection of machines

After defining the governing parameters given above, it is then necessary to evaluate the alternative machinery for their suitability to the parameters in a comparative approach. In this evaluation, first priority parameters were regarded as non-flexible parameters and the equipment meeting these parameters will then be evaluated for the second and tertiary degree parameters. Finally, the equipment will all be reevaluated considering their suitability for all the whole parameters before the selection is made.

For the final selection, almost all classical mining (ripping, shovel digging) machinery and continuous surface miners (CSM) excavating with low operation height were considered.

First priority degree parameters

Ease of rock excavation

The determination of ease of rock excavation is one of the critical stages in surface mining projects. On many projects the ease of rock excavation is mainly based on the principle of whether the rock can be economically excavated by mechanical excavators or is drilling and blasting necessary[16]. In this research, the diggability index rating method and its classification chart were used to determine the ease of excavation at the B_3 seam. In this method, the index for the ease of excavation was determined according to the rock mass parameters such as weathering, uniaxial compressive strength (UCS), joint spacing and bedding spacing. The index was then used to define the rock classification and the related excavation method as well as the machinery to be used. In this method, the ease of rock excavation is classified into 7 groups as 'very easy', 'easy', 'moderately difficult', 'difficult', 'very difficult', 'extremely difficult' and 'marginal without blasting'[16,17].

The results of investigation and experiments carried out on the coal and clay of the B_3 seam using the ease of excavation approach explained are given in Table I. The compressive strengths of the coal layers in the B_3 seam were obtained as between 7.7 MPa and 17.9 MPa. The interburdens are mainly comprised of clay with white gray and black colours, and their strength values are liable to change according to the type of the mineral composition and vary between 0.81 MPa and 24.5 MPa. Also the SiO_2 content of these clay formations, which is a determining factor in production performance and excavation cost, varies between 55 and 61%[18].

As it is seen from Table I, the ease of excavation for coal layers and clayey interburdens were found to be 'easy' and 'moderately difficult', respectively. When whole layers were considered, it was seen that excepting ripper-scraper and loader excavation methods, both ripping and shovel digging methods were applicable. Therefore, excluding scraper and loader working as the main excavating unit, there is no limitation on the use of classical excavation machines and the surface miners working with ripping principles as far as diggability is concerned. In fact, it has been well known for 20 years that it is possible to employ CSMs directly or without using explosives for the ores or rocks having uniaxial compressive strength up to 118 MPa. CSMs are generally selected for the excavation of ores such as coal, bauxite, and gypsum[19,20].

Ability of high selective excavation

The possibility of extracting layers separately by a suitable machine/equipment during the excavation stage is the main

Table I

Determination of ease of digging and excavation method according to the diggability index rating method for B_3 seam level at SLE

Parameter and selection	Rock formations in B_3 level	
	Coal	Clay
Parameter		
Weathering	Slightly	Slightly
Rating	20	20
Strength UCS (N/m^2)	17 946 261	24 516 750
Rating	0	10
Joint spacing (m)	0.3–0.6	0.3–0.6
Rating	15	15
Bedding spacing (m)	0.3–0.6	0.3–0.6
Rating	10	10
Selection		
Index (total rating)	45	55
Ease of digging	Easy	Moderately difficult
Excavation method	Ripping, shovel digging	Ripping without scraper, shovel digging

goal of coal quality improvement. Extraction of the layers separately is related to the selective working ability of the excavation machines rather than the production method[21]. So, in the Seyitömer stratified coal deposit, to select a suitable machine providing coal production with the quality demanded, the most important criteria to be considered is the ability of the high selective operation of the machine to be used. At this point, the first consideration has to be given to the minimum separation thickness and the separation accuracy of the machines/equipment being selected. Machines with high cutting depth operate as a rule with low separation accuracy and vice versa. Also, inaccuracy of separation increases with increasing minimal separable thickness[22,23]. The selective working ability of different types of excavation and loading machines used in open pits shows great variations. The ability of the high selective operation of these machines under 0.5 m separation thickness should be investigated for the selection of the Seyitömer case.

The use of explosives should be avoided in the selective excavation since high material admixture is not avoidable in stratified deposits when explosives are used[23]. Rippers are used successfully in strata inclined up to 300 when the formations provide a satisfactory traction surface. Rippers that are used together with dozers and loaders in production could be successfully used in high selective operation because of their suitable cutting depth. The proportion of dilution by using a ripper is lower than excavation by explosives and by most of the other excavation methods[23]. Rope shovels are generally unsuitable for all degrees of selective excavation. The bucket motion, including its forward and upward circular arc, causes an unavoidable mixture of ore and waste in intercalated beds[23].

Front and backhoe shovels are successfully used in high selective excavation. Basic features of these machines are free motion of the bucket from the bucket boom, which makes the horizontal motion capability (parallel crowding) of the bucket higher[24]. However, only the shovels whose capacities are lower than 15 m^3 can be used for selective and high selective operation. In other words, higher capacity shovels cannot be used for a high degree of selective excavation[22]. There are some considerable superiorities and advantages of backhoes over front shovels in terms of excavating selectivity in deeper seams and upbench operation[22]. Wheel or track type loaders can be only used in a selective excavation if the formation is very soft or well fragmented[23]. Therefore, loaders alone cannot be regarded as a main excavating unit when the ease of digging is considered at the B_3 seam level. However, a combination of ripper-dozer-loader could be a suitable excavation method for a high selective operation at the B_3 seam level.

Bucket wheel excavators can be used only under semi-selective conditions with a layer thickness between 1 and 3 m[22]. Among the CSMs only the centrally positioned shearer drums can work in a high selective operation. So far, machines of this type manufactured by Wirtgen (Wirtgen Surface Miner) and Huron (Easy Miner) Manufacturing Company have been employed in surface mining operations. Other types of CSMs are less suitable for high selective excavation[22].

After the analysis of first priority degree parameters, it was concluded that the machinery alternatives to be used for a high selective excavation at the B_3 seam were ripper-dozer-loader combinations, shovels (front and backhoe type) and CSMs with centrally positioned shearer drums. Very high selectivity conditions necessitate a very low separation thicknesses (0.1 m–0.3 m) to achieve the required quality, and the Wirtgen surface miner was seen as more suitable in comparison to the other machines because it could operate with less mining loses and dilution.

Second priority degree parameters

Rate of production, capacity and productivity of the machinery

In order to accomplish maximum coal supply to the market and provide a balanced pit development, it was calculated that about 4.5 million tonnes of coal and 3 million tonnes of waste material had to be excavated separately annually from the B_3 seam level[10]. In other words, the selective machinery to be used has to posses a production capacity of 820 m^3/h (1350 tonne/h) at the B_3 seam level and it must be operated efficiently.

Operating efficiency of all mining machines used in a selective mining operation decrease rapidly as the degree of selectivity increases. Production losses and operation costs increase in connection with a considerable decrease in efficiency[22,23]. However the only mining machines that can be used in high selective operation with the highest capacity and efficiency are CSMs with centrally positioned shearer drums and small shovels. The Wirtgen and Easy Miner achieve the highest separation accuracy together with the highest capacity of all the other excavating machines. However, these advantages can be only obtained when they work in horizontal and nearly horizontal seams up to 12°. Depending on machine size, cutting thickness and other working conditions, an effective output of 225 m^3/h to 1 075 m^3/h is achievable[22]. The reason for this high efficiency is explained by its continuous cutting system, especially in a long length of cut. The other factor increasing the productivity when working with these CSMs is that the operation steps, such as loosening, crushing and loading, are all combined in one machine[19].

Hydraulic excavators also have high operational capacity in a high selective excavation, but the output achieved is less than those of CSM machines used in a high selective operation. Hydraulic shovels with a shovel capacity of up to 15 m^3 are suitable for selective and high selective operation as well. The hourly output of these machines varies from 110 to 1 050 m^3/h depending on machine size and digging height. Thin cutting slices lead to an increased length of single cut, a more complicated shovel movement control and a decrease of the filling factor. However, the short cycle time of shovels make these machines efficient in comparison to other traditional excavation machines, especially where the high selective excavation is required[22,23]. Hourly production capacity at the Seyitömer open cast mine was calculated as 1 050 tonne/h for the Wirtgen surface miner 4200 SM model; 442 tonne/h and 620 tonne/h for 4.59 m^3 and 7.65 m^3 capacity hydraulic excavators, respectively.

The ripper-dozer-loader combination adapts easily to high selective digging in terms of their working patterns. However, the use of this combination will result in an unproductive excavation operation resulting from the three-stage excavation procedure (ripping, dozing and loading). According to SLE operational data, the average capacity of the ripper-dozer-loader (7.65 m^3) combination used for a selective excavation at the B_3 seam level down to 0.5 m was 250 m^3/h (410 tonne/h). This value would be reduced to 326 tonne/h for a high selective excavation condition. Therefore, for the Seyitömer case, even though the use of dozers and loaders met the quality requirements, it would result in a considerable unproductive output in terms of meeting the capacity compared to Wirtgen surface miners (WSM) and shovels.

Capital and operating cost of machines

When the production demand is considered, it is seen that the mine requires 4 machines of 4.59 m^3 or 3 machines of 7.65 m^3 in a shovel operation, 2 WSMs (4200 SM) in a surface miner operation and 5 rippers-dozers and 5 loaders (7.65 m^3) in a riper-dozer-loader operation. Shovel alternatives with 4.59 versus 7.65 m^3 capacity machines have almost similar investment costs (US$4 million) and this corresponds to 10% of the annual profit. WSM investment cost is much higher than shovel investment and is almost US$7 million corresponding to 18% of the annual profit. Although the mine already has rippers, dozers and loaders in adequate numbers, the operational consistency or reliability may be very low owing to their age. If the machines are renewed then the cost will be around US$4 million for 10 machines of this alternative. Considering the annual profit and the reserve available (250 million tonnes) at the mine, investment costs for any excavation alternatives are seen to be feasible.

Investigation has shown that the operation costs of surface miners and hydraulic shovels are in the range of $0.2 /tonne and $0.6/tonne. Although these machines accomplish the selectivity in the face, the excavation cost increases massively with decreasing separation thickness and low efficiency. In particular, the use of high capacity hydraulic shovels in too thin slices leads to extremely high costs, which may even exceed $1.2/tonne[22]. Three-stage excavation process at ripper-dozer-loader combination leads to a reduced production capacity which, in turn, increases the production cost compared to other alternatives[23].

At SLE conditions, excavation costs of a high selective operation (including depreciation and interest) for the hydraulic excavator and WSM versus ripper-dozer+loader combination were calculated as $0.13/tonne, $0.27/tonne and $0.625/tonne, respectively. Investment costs for each alternative affects the excavation costs evenly, which are in the range of 15% to 25%. In other words, if investment costs are excluded from the operational costs, the actual operational or excavation costs for hydraulic excavator and WSM versus ripper-dozer-loader combination are $0.10/tonne, $0.20/tonne and $0.52/tonne, respectively. In short, the hydraulic excavator alternative was found to be the most advantageous alternative considering both investment and total operational costs.

When the alternatives were compared according to the second priority degree parameters, shovels (front and backhoe) and CSMs with centrally positioned shearer drums (WSM) were found to be more advantageous than the ripper-dozer-loader combination. Among these alternatives, WSMs have higher production capacity in horizontal deposits found at SLE than a hydraulic shovel; however, hydraulic excavators are much more economical considering their investment and operation costs.

Tertiary priority degree parameters

These parameters were determined as the mine features (faulting, bench width, seam dip, waste rock features and floor condition, material size after fragmentation), flexibility, maintainability (labour's skill and knowledge, maintenance support, spare parts availability, back up service). Therefore, WSM, shovel and ripper-dozer-loader combination alternatives had to be compared according to the parameters determined in this category.

Mine features

There are many oblique faults in the district which are mainly in the south-north direction dividing the coal-seam into blocks[14]. This is a limiting factor for each alternative in terms of production capacity. In this respect, hydraulic excavators are seen to be more advantageous since they can operate at a narrow excavation face. However, for such conditions, it is advisable for the WSM to continue cutting with the selected cutting depth and change the truck when the material changes in the fault.

The disadvantage of the WSM is that it requires a 50–60 m bench width, whereas 15–20 m bench width is sufficient for a hydraulic excavator. Increased working inclination affects operational conditions of WSM more negatively. Nevertheless, there are applications of WSMs in dipped and steep seams. Up to a certain angle in cross direction (8%) and length direction (12°) the WSM can follow the dipping seams if wished[13]. Regarding the basin conditions at Seyitömer, the low formation dip (5–7°) will not cause a problem or bring in any limits in terms of WSM operation.

Waste rock or base formation properties such as plasticity, sticky nature and silt content especially affect machine performance. As a result of the particle size analysis of waste rocks in the B_3 level, it was determined that the rocks contained 16–33% clay; 49–74% silt; and 9–26% sand. As it is clearly seen from the analysis, the formations primarily contain silt. Clay analysis was achieved using the X-ray diffraction (XRD) method; illite and chlorite were found to be the major minerals[18]. Moreover, it was determined that green clay, which is the floor formation, had high plasticity and contains the montmorillonite type of swelling clay[25]. In the other levels, swelling type clays are rare and, therefore, swelling is not an important problem except for floor formation. In swelling formation, the performance of the WSM and ripper-dozer-loader is reduced; however, this problem can be overcome by using a backhoe type of shovel. Hydraulic backhoes have an advantage if there is an inability to work on sticky or swelling footwall materials, because it operates on the hangingwall of the seam[23].

For the waste rocks at the B_3 seam level, stickiness is unavoidable on rainy days. There will be a certain amount of decrease in the performance of the three alternatives when operating on these sticky clay formations. Performance reduction will be much higher with ripper-dozer-loader and WSM alternatives since they continuously operate on this sticky formation. For the WSM, cutting of plastic, sticky material can also be difficult. In this case the cutting drum starts to clog and production will decrease. In some instances, this problem could be overcome by increasing the cutting drum's rpm, spraying water into the cutting drum housing and cutting nonsticky material together with sticky material[13]. Moreover, using a track type of WSM is much more advantageous than a ripper-dozer-loader in a sticky formation.

As a result of the chemical analysis done by the X-ray fluoresence (XRF) method, it was mainly found that Al, Si, K, and Ca were the primary elements. From the chemical analysis, on the other hand, it was found that the SiO_2 content of the waste rock formations varies from 55% to 61%[18]. This obviously causes a negative effect on the performance of the machinery to be used in these formations and increases the bit cost compared to the coal formations. This fact was considered in the cost analysis for each operation.

When material size after fragmentation is considered, the WSM was found to be much more advantageous than hydraulic excavators and the ripper-dozer-loader. Smaller sized materials increase the capacity of trucks for material transportation and, therefore, reduce transportation cost[13].

Flexibility

Hydraulic shovels are much more flexible and more easily adaptable compared to CSMs with respect to their connection to the hauling system and different mining and deposit conditions. Although a direct connection of a hydraulic shovel to a conveyor system is not possible, the material transfer problems can be solved easily via mobile crusher and intermediate conveyor because of the low advancing speed compared to CSMs[22,26]. The ability to easily respond to changing production requirements is also a feature of hydraulic shovels as moving them from one region to another as a result of changes in short-term planning is more rapid[26]. This is also the case for SLE and only the ripper-dozer-loader alternative has similar advantageous of hydraulic excavators in this sense.

Maintainability

One of the most important factors that will affect the productive operation of a production system based on the WSM at SLE is the training of the technical staff. It will not be easy to adapt the technical staff who for years have been used to only a production system based on machines such as shovel, ripper, dozer and loader. Therefore, the adaptation of the WSM to SLE conditions ideally will also depend on the conforming of the technical staff to this production system. In this respect, it will be necessary to have an intensive training course for the technical staff, when the utility of this machinery will be decided. The use of the production system upon these machines in many of the metal and coal enterprises has caused the growth of maintenance support, spare part supplying and services of the manufacturer of these machines. Continuous excavation systems in open mines are a technology that has been developing only recently in the world. For this reason, spare part supply and available servicing of WSMs have not been developed as much as the machines themselves. This difficulty is also the case for SLE. This subject is important in terms of a productive operation of the enterprise although it is a criterion considered only in the last stage.

General assessment of the three excavation alternatives according to the three priority degree parameters is also given in Table II. In this table, different percentages representing the priority degree, which are attached to each parameter, are multiplied byh certain points (from 0 to 5) representing the appropriateness of the machine, to find out the machine's degree of suitability. The sum of this procedure yields the overall rating of the machine and the classification for optimum equipment selection. As seen from Table II, the WSM and hydraulic excavators perform 'very good' while the ripper-dozer-loader combination only performs 'good'.

The percentages attached to each parameter were determined according to expert opinion, past experience, related literature and information gathered from the producer companies, etc. It was decided that the hydraulic excavator

Table II

General evaluation of machine alternatives and the overall results

Parameters	Priority of parameters (PP) (%)	Priority of machine alternatives (PMA)*		
		Ripper dozer loader	Hydraulic shovel	WSM
Ability of high selective mining	0.45	4	4	5
Production performance in high selective operations at horizontal deposits	0.20	2	4	5
Advantage of capital and operational costs	0.15	2	5	3
Operational advantages when working in faulty zones	0.05	3	5	3
Adaptability to changing floor conditions	0.02	2	5	4
Advantage of material size after fragmentation	0.02	3	3	5
Flexibility	0.05	5	5	3
Adaptability of staff	0.02	5	5	2
Maintainability	0.04	5	5	2
Overall rating (∑ PP×PM*)		3.30	4.31	4.30
General suitability**		Good	Very good	Very good

*Priority of machine alternatives (PMA): 0=Insufficient, 1=Very bad, 2=Bad, 3=Moderate, 4=Good, 5=Very good
**General suitability: (0–1)=Very bad, (1–2)=Bad, (2–3)=Moderate, (3–4)=Good, (4–5)=Very good

and the WSM were the optimum alternatives for a high selective excavation at SLE. Ripper-dozers and track or wheel type loaders available in the mine (being used in the B_3 level) can also be used as auxiliary machines whichever method is chosen since they easily adapt to selective mining conditions. In addition, their good mobility and usefulness for bench maintenance make them important in excavation.

Method selection and production planning

For complete production planning, transportation of the excavated ore also has to be considered. In a previous study on transport planning, it was decided to use trucks, although rate of production and large coal reserves facilitate the use of a conveyor and railway transportation system too. The reason for choosing truck transportation was explained as given below[27,28]:

- Irregularities and discontinuities in the coal-seam due to major faults cause problems for continuous transport systems
- The need for a flexible production method according to market and power plant demands necessitates production from different parts of the mine and this requires a more mobile transport system
- The inclination of the transport roads is not suitable for railway systems
- Railway and conveyor systems are not flexible enough for SLE conditions
- Possible interruptions in the transportation due to breakdowns in the railway or conveyor systems are possible
- The higher investment costs and longer time needed for the construction of railway and conveyor systems are disadvantageous.

From these reasons, only trucks have been employed for the waste rock and ore transportation at SLE. Truck transportation still seems to be advantageous even if WSM or hydraulic excavators are used for a high selective excavation at B_3 seam level for the following additional reasons:

- In selective mining, coal layers and the interburden layers have to be excavated and transported separately. In order to accomplish this, the most flexible and easily adaptable system is truck transportation[29].
- Direct connection of a hydraulic shovel to a conveyor system is not possible; the material transfer problems can be solved only via mobile crusher and intermediate conveyor[22].

Consequently, it was found that there are two alternative high selective production methods applicable to the B_3 level, namely: hydraulic excavator truck or WSM truck combinations.

As explained before, coal quality distributions in the field make it necessary to apply high selective mining in the B_3 seam level[10]. However, the use of the rope shovel excavators available seems to be possible in the B_1 and B_2 levels since the coal has a massive structure and the quality of coal produced is suitable to meet market demand. For the current production, 3 rope shovel excavators with 7.65 m^3 shovel capacity were calculated as adequate in the B_1 and B_2 levels. Therefore, general production planning was made according to the assumption that the conventional method with rope shovel excavators could remain operational in the B_1 and B_2 levels, and a high selective mining method be employed in the B_3 level with new machines. In this research, production planning for both WSM and hydraulic excavators were made to carry out high selective excavation of the B_3 seam level.

The production strategy for SLE was based on 'maximum coal supply to the market' by selling +0.1 m fraction of B_1 and B_2 seam levels only to the market[10]. According to this strategy, annually, 6.5 million tonnes of coal with an average calorific value of 1 711 kcal/kg and particle size of (-0.2 m) are sold to the Seyitömer power plant. About 2 million tonnes of this amount comes from the coal preparation plant as a fine coal (-0.1 m) and its calorific value varies between 1 600 and 1 718 kcal/kg, depending on the rate of production from the B_1 and B_2 levels. The rest of the coal, which is about 4.5 million tonnes, is produced from the B_3 level. The required minimum calorific value of the coal produced from the B_3 level changes between 1 707 and 1 761 kcal/kg, depending on the average calorific value of the fine coal from the preparation plant. In other words, the calorific value of the coal to be produced from the B_3 level should be raised from 1 462 kcal/kg to 1 761 kcal/kg, which necessitates an ideal selective excavation in order to obtain balanced mine planning. To achieve this goal, about 4.5 million tonnes of coal and 3 million tonnes of waste material have to be excavated separately per year from the B_3 seam level[10].

Hydraulic excavator-truck method

The excavation at the B_3 level can be accomplished by using a hydraulic excavator-truck combination and ripper-dozer-loader can be operated for auxiliary works together with hydraulic excavators. The separated waste is transported to the dumping area and the coal is sent either to the preparation plant or directly to the power plant by trucks of 85 short tonne capacity. The selectivity of a hydraulic excavator is related to the shovel capacity selected. Generally, small shovel capacities increase the selectivity, but at the same time reduce both productivity and efficiency of the mine[22].

The short cycle time of shovels makes these machines efficient in comparison to other traditional excavation machines, especially where high selective excavation is required[22,23]. However, the production planning based on the use of an hydraulic excavator was made according to shovel capacities with 4.59 m^3 and 7.65 m^3. In fact, larger shovel capacities (>20 yd^3) are not suitable for high selective excavation[22]. Moreover, the stated capacity shovel can operate more precisely and accommodate changing seam height down to 5–6 m at the B_3 seam level.

The parameters used in the analysis and the number of machines required in this method are summarized in Table III. The data except bucket period in this table are derived from the mine, and the bucket period derived from manufacturer's data. Since there is a possibility of having a swelling floor, one or two of the hydraulic excavators to be bought should be back hoe type and the other should be of the front shovel type.

Wirtgen surface miner-truck method

The excavation at the B_3 level can be accomplished by using a WSM 4200-truck combination and ripper-dozer-loader can be operated for auxiliary works together with the WSM system. The separated waste is transported to the dumping area and the coal is sent directly to the power plant by trucks of 85 short ton capacity. The surface miner has a continuous excavation system and the excavation is accomplished with the movement alongside the horizontal axis of the layer. This horizontal movement of the surface miner on the layer increases the selectivity and in this respect, they are considered to be the best excavation machines of all. WSM look like large pavement strippers and operate basically on the same principle. They can cut layers even if they are too thin (down to 0.025 m) and these machines have the best selective excavation capability among CSMs. While the machine moves on the formation, the formation is crumbled by excavating with a continuously rotating cutting drum. The material that is under specific size is transferred to a primary conveyor and then onto a discharge conveyor in the machine. The material finally is dumped to trucks, conveying system or working field (Figure 3). In other words, in this operation system, cutting, primary crushing and loading are performed

Figure 3—Operational system of Wirtgen surface miner[13]

Table III

Operational parameters and the equipment list for selective excavation with hydraulic excavator

Parameters	Hydraulic excavator with 4.59 m^3	Hydraulic excavator with 7.65 m^3
Daily working period (hour)	18	18
Annual working period for 300 days (hour)	5 400	5 400
Bucket period (s)	26	28
Bucket efficiency (%)	0.85	0.75
Bucket capacity (m^3)	4.59	7.65
Truck capacity (st)	85	85
Working efficiency for coal (%)	0.80	0.80
Working efficiency for interburden (%)	0.75	0.70
Rate of working order	0.80	0.80
Working time per hour (min/h)	50	50
Coal density (t/m^3)	1.35	1.35
Interburden density (t/m^3)	2.5	2.5
Swelling factor for coal	1.40	1.40
Swelling factor for interburden (clay)	1.55	1.55
Coal production (tonne/year)	4 467 742	4 467 742
Interburden tonnage separated (tonne/year)	3 032 443	3 032 443
Total number of machines required	**4**	**3**

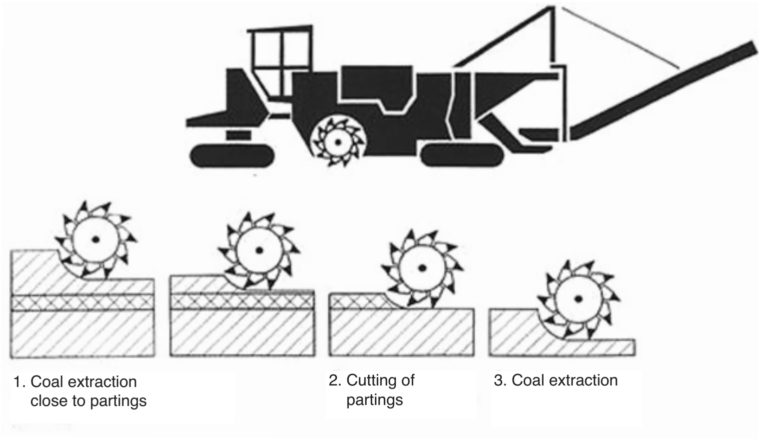

Figure 4—High separation accuracy of Wirtgen surface miner[13]

Table IV

Operational parameters of WSM 4200

Parameters	Value			
Mining Related Parameters				
Daily working Period (hour)	18			
Annual working day	300			
Annual working period (hour)	5400			
Material related parameters	Coal		Clay	
Density, δ, (tonne/m³)	1.35		2.5	
Abrasiveness	None		Low	
Compressive strength (N/m²)	14 700 000		19 600 000	
Tensile strength (MPa)	2.18		3	
Length of cut, L, (m)	50		50	
Width for operation (m)	60		60	
Truck capacity, T, (ston)	85		85	
Truck filling factor, F, (%)	100		100	
Machine parameters				
Width of cut, W, (m)	4		4	
Depth of cut, D, (m)	0.7	0.2	0.5	0.2
Forward speed, S, (m/min)	14	18	6	10
Production related parameters				
Theoretical cutting performance (m³/h)	2 352	864	720	480
Truck loads (N) per cut	2.45	0.70	3.24	1.29
Truck exchange time, e, (sec)	20	20	20	20
Total exchange time per cut (E), (min)	0.48	0	0.74	0.09
Maneuver time, M, (min)	8	8	8	8
Operator efficiency, O, (%)	90	90	90	90
Effective production (m³/h)	627.3	200.5	317.0	165
Effective tonnage (tonne/h)	846.8	270.6	792.5	412.5

rapidly by one machine[26,13]. When a WSM is used in a stratified surface coal mine, it has important features and advantages; as the WSM achieves small aggregate size (<0.3 m), primary crushing is not necessary. With the WSM, as the waste material in the ROM product decreases, there will be no need to transport this waste material. Besides, since seams or partings as thin as 0.025 m are mined selectively with 0.01 m exceptional separation accuracy as seen Figure 4, both clean and high quality run of mine ore production is achieved and utilization of mineral seams and recoverable of reserve are improved[13].

The operational parameters of the WSM 4200 model at the B_3 level of Seyitömer field are given in Table IV. The data in Table IV were obtained both from the mine (material related parameters) and from the manufacturer's (machine related parameters) catalogue[13]. Production parameters were determined by using the following equations:

Theoretical cutting performance = W × D × S × 60

Truckloads (N) per cut = (W × D × L ×) /(T × F)

Total exchange time per cut (E) = (e/60) × (N–1)

Effective tonnage = W × D × L × 60 × O × /(L/S + M + E)

The variables such as depth of cut (*D*), forward speed (*S*) and length of cut (*L*) as seen in Table IV are varied according to the production design, ease of excavation, layer thickness, rate of production and need for selectivity.

The two important factors that affect the productivity of a surface miner during the excavation are the cutting length and the cutting depth, which are dependent on production (panel) design, layer thickness, rate of production and need for selectivity. The productivity and the capacity of the machine can be increased as the cutting length increases. Cutting depth is the key criterion for the selection efficiency at coal-clay sequencing. In places where the selectivity requirement is high, the only way to increase the productivity is to increase the length of the cut. Another production parameter, forward speed (*S*), is dependent on formation thickness to be excavated and the physical and mechanical properties of formation; the values were obtained from the manufacturer's catalogue.

Production parameters given in Table IV were calculated using the assumption that length of cut is 50 m, depth of cut for coal is 0.7 and 0.2 m, and depth of cut for clay is 0.5 m to 0.2 m (the numbers show the highest and the lowest selectivity).

Table V explains the effective capacities and annual working hours calculated for various lengths of cut depending on highest selectivity conditions (0.2 m for coal and 0.2 m for clay) and lowest selectivity conditions (0.7 m for coal and 0.5 m for clay) for a production of 4 467 742 tonnes of coal and 3 032 443 tonnes of clay from the B_3 level in the mine.

As can be seen from Table V, the required excavation time decreases as the length of cut increases. When considering SLE conditions, the maximum length of cut was assumed to be 300 m. Afterwards, the production capacities for coal and the clay were calculated as 1 000 tonne/h and 1 125 tonne/h, respectively, assuming the maximum length of cut was 300 m and the average depth of cut was 0.3 m. As given in Table IV, the annual operational time was assumed to be 5 400 hours with 300 working days a year and 18 working hours a day with 3 shifts. Using this annual operational time, two surface miners were found to be sufficient to fulfil the annual demand.

Scheduling

There must be adequate production scheduling for the excavation to be done by either of the machines at the B_3 seam level. In the mine, in order to produce B_3 seam level coal which is sold to the power plant, the upper levels of the B_1 and B_2 coals which are sold to the market must be firstly produced (Figure 5). In regions where the ratio of the B_3 seam thickness to total seam thickness is lower than 58%, the production at the B_3 seam level will reduce owing to the late advance in the upper levels. For this reason, in the first years the production should not be made as dual face, and B_1 and B_2 seam production and B_3 seam production should be accomplished at different panels. The ideal scheduling could be to produce B_1 and B_2 seam coals where the B_3 seam thickness is lower (where the lowest block calorific value exists, see Figure 5), and to produce B_3 coals where B_1 and

Table V

Effective production capacity of WSM 4200 and the required excavation time for different cutting lengths

Length of cut (m)	Lowest selectivity (separation thickness=0.7 m for coal and 0.5 m for clay)			Highest selectivity (separation thickness=0.2 m for coal and 0.2 m for clay)		
	Production capacity (tonne/h)		Required excavation time, (h)	Production capacity (tonne/h)		Required excavation time, (h)
	Coal	Clay		Coal	Clay	
50	846.8	792.5	9 102	270.6	412.5	23 861
100	1240.0	1022.3	6 570	425.2	583.1	15 086
200	1621.2	1194.6	5 293	592.1	724.8	11 735
300	1804.7	1263.8	4 874	680.7	805.1	10 327
400	1914.0	1303.7	4 661	735.8	845.5	9 667
500	1982.0	1328.7	4 537	772.4	871.6	9 286

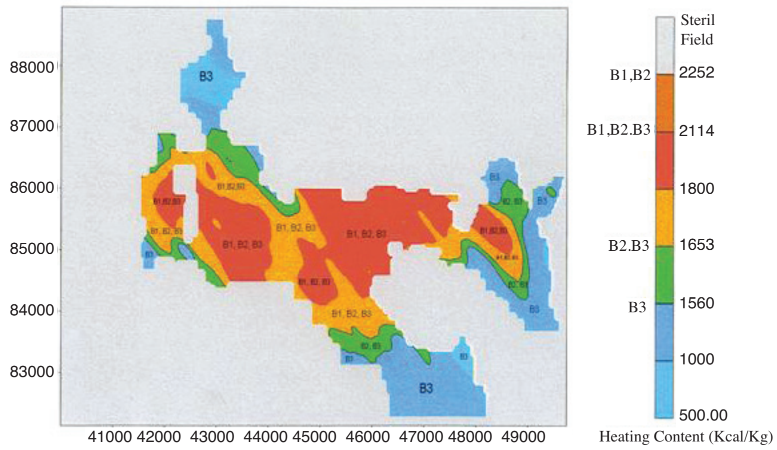

Figure 5—Distribution of the Levels according to the regions

B_2 seam thickness are very low or B_1 and B_2 levels were already removed (regions where block calorific values are less than 1 560 kcal/kg, see Figure 5). This type of a scheduling also provides enough working space for WSM application which requires a bench width of 60 m.

Figure 6 shows the WSM-truck application at the B_3 level whose upper level coals were extracted before in the Aslanlı district. In this production 4 467 742 tonnes of coal and 3 032 443 tonnes of clay will be produced in a year by two WSMs and with 0.3 m depth of cut and 300 m length of cut at the B_3 level.

Effects of selective excavation on the overall process—comparison of the methods

First of all, high selective excavation will affect the quality and the quantity of the coal produced at the B_3 seam level. The effects of selective excavation on coal quality were examined by analysing and comparing 3 different conditions, namely; non-selectivity, current selectivity requiring 0.5 m separation thickness and average coal quality of 1 462 kcal/kg, and ideal selectivity (high) requiring an average 0.3 m separation thickness and average coal quality of 1 761 kcal/kg in the B_3 level of the mine[10]. In this comparison, annual production was assumed to be 7.5 million tonnes at the B_3 seam level, the amount of interburden and recoverable coal, coal quality and selectivity were calculated considering the dilutions and mining losses. While the results of these comparisons are presented in Table VI, detailed features of the table and the calculation of parameters are presented in Appendix 1. As it is seen from Table VI, ROM coal quality increases due to the increase in selectivity.

For ideal selectivity conditions which also require balanced mine planning, the composite calorific value of the B_3 level coal given to the power plant should have an average calorific value of 1 900 kcal/kg to comply with the required calorific value of 1 761 kcal/kg in the ROM coal as seen from Appendix 1. In this ideal selective mining condition, almost 7.5 million tonnes of coal and interburden will be excavated and 3 million tonnes (~1.2 million m^3) of this production will be separated as waste in the B_3 level. The remaining 4.46 million tonnes will be sent to the power plant as ROM coal. In the current selectivity conditions, on the other hand, 7.5 million tonnes of coal and interburden are excavated and 2.11 million tonnes of this production is separated as waste in the B_3 level. The remaining 5.38 million tonnes are sent to the power plant as ROM coal.

High selective mining will not only affect the production cost but also affect the transportation and coal processing costs. In this research, the total costs of the current selective mining (excavation down to 0.5 m separation thickness) and high selective mining using hydraulic excavator-truck and WSM-trucks down to 0.3 m separation thickness were compared and analysed. In the total cost calculations, excavation, transportation and processing costs were all considered for the mining operations using the current selectivity and the high selectivity at the B_3 seam level.

The excavation costs of coal and the waste in the B_1 and B_2 levels were found to be \$0.124/tonne and \$0.067/tonne, respectively, assuming a production of 3.22 million tonnes of coal and 1.7 million tonnes of interburden materials. The unit stripping cost for overburden was taken as \$0.156/m^3. However, these values were not used in the comparisons of high selective mining alternatives since the proposed high selective excavation will be only applied at the B_3 seam level.

In order to determine the excavation costs at the B_3 seam level, firstly hourly production capacity of the selected excavation machines to be used at the present and at ideal (high) selectivity conditions was determined, and the results are summarized in Table VII. For the hourly production capacity of hydraulic excavator at coal and clay excavation, a shovel capacity of 4.59 m^3 was considered and the calculations were made using the parameters in Table III. The parameters given in Table III represent the ideal selectivity conditions and the production capacities were found to be 347 tonne/h and 543 tonne/h for coal and clay, respectively. For the current selective excavation, the production capacities were found to be 442 tonne/h and 693 tonne/h for coal and for clay, respectively, assuming that bucket efficiency will rise but bucket period will reduce. In these calculations, bucket efficiency and the bucket period were taken as 0.90 and 23 seconds for both coal and the clay; working order parameters, on the other hand, were taken as 0.85 and 0.80, respectively. The other parameters are given in Table III.

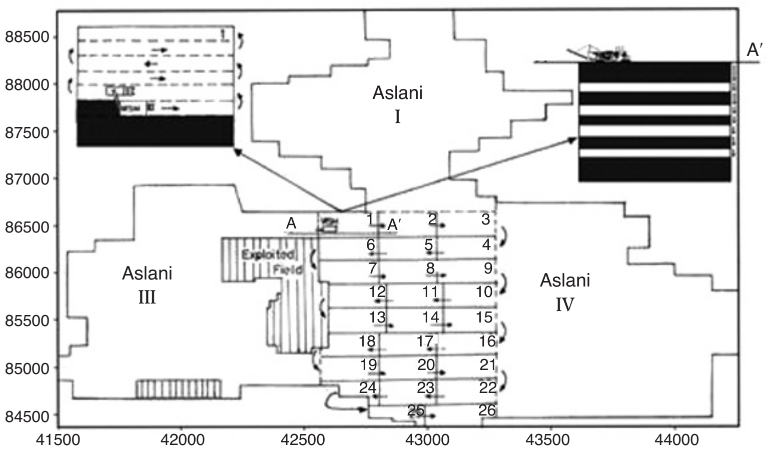

Figure 6—Application of WSM-truck method at Aslanlı region

Table VI

Comparison of non-selective, current selective and ideal selective conditions

Parameters	Selectivity		
	Non	Current (>0.5 m separation thickness)	Ideal (0.3–0.5 m separation thickness)
Average calorific value of seam (kcal/kg)	1049	1 049	1049
Average coal seam thickness (m)	12	12	12
In situ coal thickness (m)	7.689	7.689	7.689
In situ parting thickness, (m)	4.311	4.311	4.311
Calorific value of *in situ* coal, (kcal/kg)	2098	2098	2098
In situ coal volume (m³/year)	2 602 599	2 602 599	2 602 599
In situ partings volume (m³/year)	1 459 335	1 459 335	1 459 335
Total excavated tonnage (tonne/year), M	7 500 185	7 500 185	7 500 185
Total excavated volume (m³/year), V=M/yt	4 061 934	4 061 934	4 061 934
Compositing			
Amount of dilution in composite ore (tonne/year)		1 280 744	3 78 244
Amount of mining losses in composite ore (tonne/year)		89 199	89 199
Composite coal tonnage (tonne/year)	-	5 043 393	4 140 891
Composite partings tonnage (tonne/year)	-	2 456 792	3 359 294
Calorific value of composite coal (kcal/kg)	-	1 560	1 900
Selective mining	No	Yes	Yes
Amount of dilution in ROM coal (tonne/year)	3 648 337	1 618 810	7 05 095
Amount of mining losses in ROM coal (tonne/year)		89 199	89 199
Separated interburden tonnage (tonne/year)	0	2 118 726	3 032 443
ROM coal production (tonne/year)	7 500 185	5 381 459	4 467 742
Calorific value of ROM coal (kcal/kg)	1 049	1 462	1 761
Selectivity, S	64	77.78	87.84

Table VII

Capacity of the machines for different selective conditions

Alternatives	Selective conditions	Capacity (tonne/h)	
		Coal	Clay
WSM 4200 (recommended)	Current (1 462 kcal/kg)	1 425	1 295
	Ideal (1 761 kcal/kg)	1 000	1 125
Hydraulic excavator (4.59 m³) (recommended)	Current (1 462 kcal/kg)	442	693
	Ideal (1 761 kcal/kg)	347	543
Ripper-dozer-loader (7.65 m³) (in use)	Current (1 462 kcal/kg)	318	502
	Ideal (1 761 kcal/kg)	250	406

The capacity of the WSM for ideal and the current selectivity was determined by using the parameters in Table III. For the ideal selectivity, the capacities were found to be 1 000 tonne/h and 1 125 tonne/hour for the coal and the clay, respectively, assuming the average length of cut as 300 m and the average depth of cut as 0.3 m. For the current selectivity, the capacities were determined as 1 425 tonne/h and 1 295 tonne/h for coal and the clay, respectively, assuming the average length of cut as 200 m and average depth of cut as 0.5 m. Since compressive strength for clay formations is higher than coal, the speed and m³ performance of the WSM in this formation will be lower than in coal. Optimum operational speed of the WSM increases as the thickness of the layer excavated decreases, as obtained from the manufacturer's catalogue.

The capacity calculations of ripper-dozer-loader (7.65 m³) combination were made by using the parameters in Table III and 410 tonne/h and 328 tonne/h capacities were determined for the current and ideal selectivity, respectively. Although the bucket capacity of the loader was selected as 7.65 m³, the hourly capacity was found to be lower than the WSM and hydraulic excavator. The reason for that was the high time losses for loosening, gathering and loading operations in this combination. Among the three alternatives, the WSM provides the highest capacity due to the continuous system of operation. However, as the selectivity increases, production capacity for each system decreases.

After hourly capacities of each alternative were determined, hourly costs of the machines were found for the current and high selectivity in order to calculate cost per tonne of coal and clay excavation. The results are given in Table VIII. In the calculation the parameters such as capital cost, fuel cost, lubrication cost, repair and maintenance cost, spare part cost and operator cost were counted. Most of the parameters in Table VIII were obtained from both the mine and the machine manufacturers. As seen from Table VIII, the classification of the systems according to the hourly cost advantages is as follows: hydraulic excavator, ripper-dozer-loader combination and WSM. Cost constituents for the WSM are much higher than the others except for operator cost. Additionally, within spare part cost, the excavating bit cost for the WSM becomes higher in clay formations due to silt content and the higher compressive strength values of clay.

Table VIII

Hourly investment and operation cost of machines

Costs	Investment and operational costs ($/h)					
	WSM 4200		Hydraulic excavator (4.59 m³)		Ripper-dozer-loader (7.65 m³)	
	Coal	Clay	Coal	Clay	Coal	Clay
Capital cost (depreciation+interest)	58.7	58.7	14.01	14.01	32.05	32.05
Fuel cost	88.6	93.3	16.52	21.02	84.21	92.1
Lubrication cost	13.29	13.99	2.428	3.453	12.6	13.8
Repair and maintenance cost	65.44	65.44	1.675	2.01	6.64	7.095
Spare part cost	12.45	74.32	1.675	2.01	18.10	20.2
Operator cost	18	18	18	18	36	36
Total cost	256.5	323.75	53.04	60.30	189.6	201.24

Table IX

Unit excavation and annual operational costs of selective excavation alternatives

Alternatives	Selective conditions	Excavation cost ($/tonne)		Annual operation cost ($/year)
		Coal	Clay	
WSM	Current (1 462 kcal/kg)	0.180	0.250	1 498 344.1
	Ideal (1 761 kcal/kg)	0.256	0.287	2 014 053.1
Hydraulic excavator (4.59 m³)	Current (1 462 kcal/kg)	0.122	0.086	838 748.3
	Ideal (1 761 kcal/kg)	0.156	0.110	1 030 536.5
Ripper-dozer-loader (7.65 m³)	Current (1 462 kcal/kg)	0.592	0.393	4 018 483.1
	Ideal (1 761 kcal/kg)	0.761	0.494	4 897 978.4

Table X

General production cost evaluation for different selective conditions

Cost bearing processes		Costs for current selective condition ($/year)	Costs for ideal selective condition ($/year)	
		Ripper-dozer-loader -truck method	Hydraulic excavator (4.59 m³)-truck method	WSM 4200-truck method
Excavation		4 018 483.1	1 030 536.5	2 014 053.1
Coal and interburden transportation	Transportation to the plant	1 646 726.4	1 367 129	1 228 629
	In situ dumping	33 899.6	49 365.3	49 365.3
	Total transportation	1 680 626	1 416 494.3	1 277 994.3
Processing		524 692.2	223 387.1	38 422.5
Total		622 3801.3	2 670 417.9	3 330 469.9

The reason why the investment and operational costs are higher for the ripper-dozer-loader combination than the hydraulic excavator is that it requires two machines and more operations for the excavation/transportation of the same amount of material. For each alternative, the excavation cost in clay was found to be higher than in coal owing to excavation difficulties.

Cost per tonne was determined by dividing the calculated hourly cost to hourly capacities for coal and clay in both the current and the ideal (high) selectivity conditions. Afterwards, annual excavation costs were calculated by multiplying the costs per tonne by annual coal or clay productions; the results are summarized in Table IX. As seen from Table IX, the classification of excavation alternatives according to the cost advantages per tonne or for annual excavation is as follows:

- hydraulic excavator ($0.133/tonne)
- WSM ($0.27/tonne)
- ripper+dozer+loader combination ($0.625/tonne).

As can be seen from Table VIII and Table IX, the capacity of the machines decreases and the cost of operation increases as the rate of selectivity increases.

The overall cost evaluation of the present and high selective mining was made by considering the cost of excavation, transportation and processing for the coals from the B_3 level and these evaluations and comparisons are summarized in Table X. As seen from Table X, if the coal excavation is considered alone, the annual production cost at the B_3 level with the WSM-truck method is higher than the cost of the hydraulic excavator-truck method at ideal selectivity conditions and than the loader-dozer-truck method at present selectivity conditions. In general, the annual excavation cost for high selectivity was found to be 21% higher than the one for the current selectivity.

For the transportation cost calculation, data were gathered from the mine and the cost of material transportation to both coal processing unit and the dumping area were considered for each selectivity condition. In the high selective excavation, annually 4.47 million tonnes of coal will be transported to the coal processing unit and 3.03 million tonnes of interburden materials will be transported to the waste area. However, in the current selective excavation, annually 5.38 million tonnes of coals are transported to the coal processing unit and 2.12 million tonnes of waste material are transported to the dumping area. The unit transportation costs for the coals to the processing unit and for the waste to the dumping area were calculated as $0.306/tonne and $0.275/tonne, respectively.

Since the average particle size of the coals produced by an hydraulic excavator, the WSM system has higher efficiency because of the high filling factor resulting from the lower lump size and lower cost in transportation to the plant over the hydraulic excavator. The unit transportation costs for the ripper-dozer-loader combination at the current selectivity is $0.306/tonne. Internal waste dumping cost for the current and ideal selectivity was calculated as $0.016/tonne.

Annual transportation costs were calculated using these results and summarized in Table X. As can be seen from Table X, total annual transportation cost is 20% lower than that of the current selectivity since most of the waste material is separated before ROM coal is transported to the processing unit. Briefly, the cost of transportation is decreased as the selectivity in the excavation increases.

Processing costs were also calculated from the data obtained from the mine. In the high selective mining, 4.47 million tonnes of ROM coal having an average calorific value of 1761 kcal/kg will be processed by three crushing-screening units, each with 800 tonne/h capacity. Since the coal quality for the power station is ROM there will be no further sorting or processing needs. Under these circumstances, the processing costs for hydraulic excavator-truck and WSM-truck systems will be $0.050/tonne and $0.0086/tonne, respectively, in high selective mining. The reason why the processing cost for the WSM-truck method is so low that particle size of the coals produced in this method is quite small (-150 mm) and requires no further crushing at the units.

In the current selective mining, 5.38 million tonnes of ROM coal having an average calorific value of 1 462 kcal/kg is processed by three crushing-screening units, each with 800 tonne/h capacity. Under these conditions, the coal quality does not meet the requirements of the power station and therefore, ROM coal has to be crushed, screened and processed by sorting. The unit processing cost in this case was calculated as $0.097/tonne. The cost is high owing to material that has to be more highly processed, which requires more energy and intensive labour.

Processing costs for both methods are given in Table X. As seen from Table X, the cost of processing decreases as the selectivity in the excavation increases. In fact, the annual processing cost for high selectivity is reduced by 75% compared to the current selectivity.

If all the production processes are considered, the overall production cost of the present selective excavation method was found to be 52% higher than the cost of the high selective excavation alternatives because of the transportation and preparation costs of less-selected B_3 coal. In addition, the hydraulic excavator-truck method, which is used for ideal selective excavation, has the minimum production cost.

Conclusion

Improving coal quality at SLE can be only achieved by the application of high selective mining methods. In order to apply high selective mining, suitable machines/equipment have to be selected and the technical and financial effects of high selective excavation should be determined. In the selection process, parameters such as ease of rock excavation, ability of high selective excavation, rate of production and productivity demands, capital and operational cost and mine features were determined to be critical. The selection was then made according to the appropriateness of the equipment/method alternatives to these parameters. Among the parameters, ease of rock excavation and ability of high selective excavation were the dominant (first priority degree) parameters.

The diggability studies of the coal-seams and the interburden material based on the diggability index rating method showed that the formation is quite suitable for excavation with a shovel digging method or ripping methods, which are applied with a ripper-loader and continuous miner. Excavation with loader or ripper scraper is not suitable for the formations.

When the first priority parameters were considered, it was found that ripper-dozer-loader combinations, shovels (front and backhoe) and CSMs with centrally positioned shearer drums were the possible alternatives to be used for a selective excavation at the B_3 seam level. When all the parameters were considered, hydraulic excavator and WSM (CSM) were decided to be better alternatives for high selective excavation at SLE. After consideration was given to the material transportation, WSM-truck or hydraulic excavator-truck combinations were found to be suitable for this particular case. As the excavation at the B_1 and B_2 levels was considered, it was decided that the excavation could still be made by available rope shovels and the production be transported by trucks at these seam levels.

After the analysis, it was seen that high selective excavation at the B_3 seam level would affect the amount and the quality of the coal produced, which in turn changes the production and processing costs. While 5.38 million tonnes of ROM coal with a calorific value of 1 462 kcal/kg are produced in the current selective excavation at the B_3 seam level, 4.46 million tonnes of ROM coal with a calorific value of 1 761 kcal/kg will be produced in the high selective excavation. Whichever high selective excavation alternative is used, the capacity will be reduced compared to the current selective excavation, which can be as high as 20%.

Among the high selective excavation machines considered, the WSM and hydraulic excavators were found to have larger capacities to work at SLE conditions. Production capacity of the WSM method was calculated as 2.5 times higher than the hydraulic excavator.

The unit excavation cost for a high selective excavation was found to be 22% higher than the current selectivity; the annual excavation costs, on the other hand, were determined to be 21% higher than the current selectivity. From the cost analysis, the average unit excavation costs were found to be \$0.133/tonne, \$0.27/tonne and \$0.625/tonne for hydraulic excavator, WSM, and ripper-dozer-loader alternatives, respectively, which means hydraulic excavators have 50% cost advantages over the WSM method on unit and annual excavation costs.

The degree of selectivity directly affects the transportation and processing costs. In the high selective excavation, annual transportation cost was calculated to be 20% lower and the processing cost was 75% lower than those of the current selectivity. The transport and processing costs with the WSM method will be 10% and 83% lower than with hydraulic excavators, respectively.

When the whole mining process is taken into account, the production costs of the high selective excavation methods were found to be on average 52% lower than the cost of the current production method at the B_3 seam level. Among the selective excavation methods, the hydraulic excavator-truck method has the minimum production cost and the cost is 20% lower than the WSM-truck method. The WSM system, on the other hand, has higher flexibility in adjusting to changing mining conditions and, therefore, gives the highest selectivity.

Finally, the hydraulic excavator system can be recommended as the optimum selective excavation method in terms of parameters such as formation characteristics, ability of high selective excavation, rate of production and productivity, capital and operational cost, operational conditions and mine features. The use of a high selective excavation method by either employing the WSM or a hydraulic excavator at the given conditions could reduce the cost of operation by increasing the quality of coal to be produced at the B_3 seam level.

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Appendix 1

Comparison of non-selective, current selective and ideal selective conditions

Parameters	Selectivity		
	Non	Current (>0.5m st)	Ideal (<0.5 m st)
Average calorific value of seam (kcal/kg)	1 049	1049	1 049
Average coal seam thickness (m), T	12	12	12
In situ coal thickness (m), t_{ic}	7.689	7.689	7.689
In situ parting thickness, (m), t_{ip}	4.311	4.311	4.311
Calorific value of *in situ* coal, (kcal/kg)	2 098	2 098	2 098
Density of *in situ* coal (tonne/m^3), y_{ic}	1.48	1.48	1.48
Density of *in situ* parting (tonne/m^3), y_{ip}	2.5	2.5	2.5
In situ coal volume (m^3/year), $V_{ic}=(t_{ic}/T)\times V$	2 602 599	2 602 599	2 602 599
In situ partings volume (m^3/year) $V_{ip}=(t_{ip}/T)\times V$	1 459 335	1 459 335	1 459 335
Density of excavated material, (tonne/m^3), y_t	1.846	1.846	1.846
Total excavated tonnage (tonne/year), M	7 500 185	7 500 185	7 500 185
Total excavated volume (m^3/year), $V=M/y_t$	4 061 934	4 061 934	4 061 934
Compositing			
Dilution in composite ore (m), d_{cd}	-	1.513	0.446
Mining losses in composite ore (m), d_{cm}	-	0.185	0.185
Total composite coal thickness (m), $t_{cc}= t_{ic}+d_{cd}–d_{cm}$	-	9.017	7.950
Total comp. Parting thickness (m), $t_{cp}=t_{ip} –d_{cd}+d_{cm}$	-	2.983	4.04
Composite coal volume (m^3/year), $V_{cc}=(t_{cc} /T)\times V$	-	3 052 081	2 691 081
Composite parting volume (m^3/year), $V_{cp}=(t_{cp}/T)\times V$	-	1 009 853	1 406 853
Volume of dilution in composite ore (m^3/year), $V_{cd}=(d_{cd}/T)\times V$	-	5 12 298	1 51 298
Amount of dilution in composite ore (ton/year), $M_{cd}=(d_{cd}/T)\times V\times y_{wp}$		1 280 744	3 78 244
Volume of mining losses in composite ore (m^3/year), $V_{cm}=(d_{cm}/T)\times V$	-	62816	62 816
Amount of mining losses in composite ore (t/year), $M_{cm}=(d_{cm}/T)\times V\times y_{wc}$		89 199	89 199
Composite coal tonnage (ton/year), $M_{cc}=(V_{ic}\times y_{ic})+M_{cd}-M_{cm}$	-	5 043 393	4 140 891
Composite partings tonnage (ton/year), $M_{cp}= (V_{ip}\times y_{ip})–-M_{cd} +M_{cm}$	-	2 456 792	3 359 294
Calorific value of composite partings (kcal/kg)	-	100	100
Calorific value of composite coal (kcal/kg)	-	1560	1 900
Selective mining	No	Yes	Yes
Total coal loss (compositing+excavation) (m), D_{rm}	0	0.185	0.185
Total dilution (compositing+excavation) (m), D_{rd}	4.311	1.912	0.833
ROM coal thickness (m), $t_{rc}=t_{ic}+D_{rd}–D_{rm}$	12	9.416	8.337
Waste-parting thickness (m),t_{rp} = T–t_{rc}	0	2.584	3.663
Volume of dilution in ROM coal (m^3/year) $V_{rd}=(D_{rd} /T)\times V$	1 459 335	6 47 524	282038
Amount of dilution in ROM coal (ton/year) $M_{rd}=(D_{rd} /T)\times V\times y_{wp}$	3 648 337	1 618 810	705095
Volume of mining losses in ROM coal (m^3/year), $V_{rm}= (D_{rm}/T)\times V$	0	62 816	62816
Amount of mining losses in ROM coal (ton/year), $M_{rm}= (D_{rm}/T)\times V\times y_{wc}$		89 199	89199
Separated interburden volume (m^3/year) $V_{rp}= V_{ip}–V_{rd} +V_{rm}$	0	8 74 627	1 240 113
Separated interburden tonnage (ton/year) $M_{rp}= (V_{ip} \times y^{ip})–(V_{rd}\times y_{W}p)+ (V_{rm}\times y_{wc})$	0	2 118 726	3032.443
ROM coal production (m^3/year) $V_{rc}=(V_{ic} + V_{rd} –V_{rm})$	4 061 934	3 187 307	2 821 821
ROM coal production (ton/year) $M_{rc}=(V_{ic}\times y_{ic}) + (V_{rd} \times y_{wp}) –(V_{rm}\times y_{wc})$	7 500 185	5 381 459	4 467 742
Calorific value of ROM coal (Kcal/kg)	1049	1462	1 761
Selectivity, S, $(100–(D_{rd}/t_{rc})\times 100)\times(100–(D_{rm}/t_{ic})\times 100)/100$,%	64	77.78	87.84

st=separation thickness, y_{wp}= density of diluted partings, y_{wc}= density of mining losses