The optimal location of the distribution point of the belt conveyor system in continuous surface mining operations

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\textbf{A B S T R A C T}

Continuous surface mining projects are dynamic and quite complex. They are characterized by geological and spatial variability and several stochastic parameters that affect initial planning and final design. In strategic mine planning and operations management of such projects, the location of the distribution point of the belt conveyor system (BCDP) is of high importance as it directly influences mine development and the production schedule. In addition, the spatial location of the BCDP directly affects project cash flow including investment and operating costs and, as a result, the economic viability of the mining project. Therefore, the problem of the optimal location of BCDP could be defined as an economic optimization problem focusing on the material transportation cost. In this paper a model for the optimal location of BCDP in continuous surface mines is formulated based on the minimization of the transportation cost within the lifetime of the mine. A computer model was developed based on a methodological approach and was verified utilizing an actual lignite deposit which was simplified in terms of geometry and geology. Simulation results compare well with actual data available for the specific lignite mine.

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1. Introduction

It is estimated that coal reserves in the world exceed the reserves of oil and natural gas. Today, in Greece, about 50% of the produced electric power is generated by thermal power plants using lignite as fuel. Furthermore, approximately 3 billion tonnes of proven, exploitable lignite reserves are located throughout Greece. Approximately 97% of the mined lignite is used to supply the lignite power plants with a total installed capacity of 5180 MW. In Greece lignite is mainly produced in two locations, one in western Macedonia in northern Greece and one in Peloponnese in the South. The majority of the currently operating surface lignite mines utilizes the continuous mining method\textsuperscript{[5]}.

Continuous surface mining is widely applied for the exploitation of multiple-layered lignite deposits. Mining equipment include high capacity and continuously operating bucket wheel excavators for excavation, belt conveyors for transportation of the excavated material and spreaders for dumping the material to the dumping sites. This procedure ensures selective mining of lignite and waste layers and high lignite production rates even when the deposit contains several lignite seams of varying thickness alternating with waste seams (zebra type deposits). In cases where the overburden or interburden...
includes hard rock material (sandstones, marls and conglomerates) that cannot be excavated by bucket-wheel excavators or
when the geometry of the deposit restricts the application of continuous mining equipment, diesel mobile equipment is
used, consisting of blast hole drills, bulldozers, shovels, wheel loaders, dumpers and other auxiliary units. Furthermore, a
continuous surface mining system may operate in a parallel or a slewing pattern or in a combination of both. The selection
of the operation mode depends on various parameters and mainly on (a) the available reserves, (b) the geometry of the final
pit, (c) land acquisition or other constraints, (d) the waste to lignite ratio and (e) the centroid of the overburden and of lignite
deposit (interburden and lignite).

Such mining projects are dynamic and quite complex. They are characterized by geological and spatial variability and sev-
eral stochastic parameters that affect initial planning and final design. Optimization during the mine planning and design
phases of such projects, utilizes methodologies based on operations research concepts, which include but are not limited
to the following [15,10,4,16]:

(1) determination of the optimum utilization of the lignite deposit
(2) determination of the ultimate pit limit design and mine layout
(3) development of the sequence of the mine exploitation phase, from the opening up of the mine to the end of its life
(4) design of the geometrical characteristics of each bench
(5) short term block sequencing
(6) determination of equipment specifications for short term and operational equipment-allocation
(7) lignite production schedule, incorporating quantity and quality requirements according to the specific energy
consumption of the power plant, integrating technological, economic, environmental or social parameters
(8) uncertainty and risk analysis of all stages of mining activities.

Strategic surface mine planning, incorporating stochastic optimization techniques in mine design and production sched-
uling, allows modeling and direct integration of the project uncertainties and provides a framework for the optimization of
the life-of-mine planning [4]. Such planning is essential for surface lignite mines with extensive horizontal development and
a long life span [12,14]. Modeling and evaluation of the exploitation strategy of such projects could be based on indicators
connected with activities that take place throughout the whole mine life cycle, from the first exploratory stages to the post

One of the main objectives of optimization which dominates the long term mine planning is the minimization of the pro-
duction life cycle cost. Transportation cost (investment and operating) represents a significant percentage (usually more than
50%) of the total production cost in continuous surface mining systems that have less flexibility than the non-continuous min-
ing systems. Modeling of transportation costs for alternative life-of-mine plans of such lignite mines allows a more accurate
economic evaluation model of the corresponding deposit [8]. It can be mainly based on the location of the belt conveyors dis-
tribution point (BCDP) with respect to the locations of the power plant and external waste dumping site(s) and on the sequence
of mine operations through time that begins with the initial access of the deposit and ends when the deposit is fully exploited.

In surface mining projects material transportation is mainly accomplished using belt conveyor systems. One such system
is needed for every active excavation bench. In most cases, all incoming conveyor systems, i.e. originating from the pit, con-
verge to a single location, the BCDP location where the material is redistributed to the outgoing conveyor systems which
transport waste material to the external or internal dump areas and lignite to the power plant or the coal bunker. Selecting
the optimum location for the BCDP definitely reduces the total cost (i.e., investment and operating) related to materials han-
dling, while it has a direct impact on the economic viability of the mining project. The importance of location optimization is
further justified considering the lifespan of such mines, which in many cases spans several decades. Therefore, the problem
of the optimal location of BCDP could be defined as an economic optimization problem concerning the transportation cost.
The objective of this paper is the development of a model for the optimal location of BCDP in continuous surface mines.
The model is applied to examine different scenarios for a lignite deposit with simplified geometry and geology considering a
spatial analysis perspective.

2. Problem definition

It is assumed that for a given surface lignite mine, operating with continuous mining equipment, the following para-

ters have already been determined:

- the spatial distribution of lignite deposit and overburden material,
- the final pit limits and the geometry of the excavation site,
- the geometry of the mining benches and dumping areas which are usually determined by the characteristics and the
capacity of the equipment utilized,
- the annual schedule of lignite production and the corresponding waste material,
- the boundaries of the excavation sectors, which are directly related to the parallel or slewing mode of operation of the
  continuous system,
- the location of the power plant and the external dumping site of waste material.
The optimization problem refers to the determination of the optimal location of BCDP which minimizes the total production cost (investment and operating). The selection of the optimal location of BCDP is an integral part of the strategic development of a continuous surface mine.

Fig. 1 shows a plan view of the final pit limits of a surface mine with six alternative locations for the BCDP and three alternatives for mine development using parallel, slewing and combined operation [1].

Furthermore, the basic assumptions for the BCDP optimization model include the following:

(a) Only one BCDP location will be selected for the whole lifetime of the mine.
(b) Only continuous mining equipment is used for mining and transporting both lignite and waste.
(c) The location of the BCDP cannot be inside the mine excavation perimeter for obvious reasons.
(d) Lignite production is fed to only one power plant or directed to one storage location (i.e., fuel bunker).
(e) There may be multiple waste dump locations (external and internal).

The optimization model should also incorporate the following data:

- the development of the internal dumping procedure of the mine
- the mass balance ratio concerning the lignite to the power plant and the waste to the external and internal dumping sites through the distribution point
- the time evolution of the length of the conveyor belts
- investment and operating cost data for belt conveyors

3. Optimal location methodology

3.1. BCDP location optimization

Within a spatial analysis perspective, location/allocation practices refer to the determination of an optimal spatial positioning of \( p \) facilities towards the satisfaction of \( n \) locations (where \( n > p \)). The associated family of location problems is also referred as \( p \)-median problems [6].

A classification for location/allocation problems is presented in Daskin [3]. Depending on whether demand is uniformly spaced throughout the search area or resides in specific points, models are characterized as analytic or continuous.

![Fig. 1. Plan view of the final pit limits of a surface mine with six alternative locations of BCDP (a) and three alternatives for mine development with parallel (b), slewing with BCDP in location 3 (c) and combined operation (initially slewing and then parallel) with BCDP in location 2 [1].](image-url)
respectively. Network types of optimization techniques solve fundamental routing service applications with established algorithms (Traveling Salesman Problem, Minimum Spanning Trees, etc.). More generally, location analysis optimizes positioning according to a series of defined criteria expressed by objective functions [2]. Various design alternatives according to application at hand include demand patterns, travel costs and weights, dynamic changes in costs, single or multi-objective criteria, local policies governing the area at hand, desirable/undesirable spatial constraints, human based criteria [7].

In spatial analysis scenarios, cost is mainly a function of sets of distances between facility and demand domains. Distance cost may be computed in terms of Euclidean, raster, network or vector schemes. Additional objectives include time, legislation, environmental and user – application defined metrics.

The design and scheduling phase in mine-planning is a multi-criteria, region and application-specific process, which may include temporary production increases as well as unexpected delays due to technical, environmental or other constraints. In this study, a generic optimization methodology is proposed which aims to involve a significant set of objectives and design parameters as described in the next sections.

For the purpose of this study, a simplified typical continuous surface mine setting includes the geometrical model of the surface mine, the belt conveyor system which transfers material from the excavation sites, through the BCDP towards the internal and external dumping sites and the power plant. The performance measure of the BCDP location is expressed mathematically by the definition of the operation and investment costs. The operation cost is a function of the quantity of the material transferred through the belt conveyors. The power $N_a$ (PS) consumed is given by Eq. (1) for each belt conveyor segment.

$$N_a = \frac{C \cdot f \cdot L}{270} \cdot (3 \cdot 6 \cdot G_m \cdot v + Q_t) \pm \frac{Q_t \cdot H}{270}$$

(1)

where $C$ is a coefficient dependent on the transfer distances $L$ (m) ranging from 1.0 to 1.2, $f$ is the friction factor, $v$ (m/s) is the conveying speed, $H$ (m) is the elevation difference between the points of transfer, while $G_m$ is the weight of the conveyor belt (kp/m) and $Q_t$ (t/h) is the rate of the transferred material. The parameters $f$, $v$ and $G_m$ are considered invariable.

Accordingly, the investment cost which represents the acquisition cost of the belt conveyors is linearly related to the total length of the belt conveyor system.

Given the operating and investment cost functions the optimization procedure aims to minimize their combined objective function upon the spatial two-dimensional coordinates ($x$, $y$) of the BCDP. The objective function depends on the transportation length which is given as the Euclidean distance between two points. This distance is a convex function and therefore the objective function is also convex. Thus, by definition it exhibits a single global minimum (i.e. the optimal location) which can be determined by differentiating with respect to $x$ and $y$ coordinates. The investment function is linear and relative to the distance measures between the BCDP and the excavation, waste dumping and power plant sites. The optimal solution is derived by minimizing the total cost which is calculated as the sum of the operating cost (using Eq. (1)) and the investment cost.

The location of the BCDP depends on the number of belt conveyors that transfer material towards and away from the BCDP. Since in most cases the belt segments exiting from the mine are comparable in quantity to these distributing the material towards the external dumping sites and power plant, the BCDP location remains close to the mine perimeter. In addition, according to the overall waste to lignite mining ratio, the BCDP optimal location slightly shifts towards the power plant or the waste disposal area.

It is noted that depending on the type of cost function utilized, the optimization methodology presented above may need to employ algorithms that can negotiate multiple local minima, i.e. heuristic algorithms.

3.2. Optimization algorithm

To address this optimization problem, an algorithm was developed and implemented under MATLAB [9]. The basic MATLAB package without any additional toolboxes as well as the GUI programming capabilities (GUIDE), were used. As already discussed, input parameters include mine geometry, mine sector allocation and extraction sequence, the location of the external destination sites as well as mine planning and scheduling parameter, e.g. polygon coordinates of mine perimeter, point coordinates of power plant site, point coordinates of internal–external waste dumping sites and excavations for every time period, transferred material quantity rates and waste to useful material ratios.

The procedure returns the optimal BCDP position in three dimensions as described in the following steps:

Step 1: The procedure initiates by navigating around the final mine perimeter and estimating at each sampling point the total Euclidean length of the belt conveyor system (Eq. (2)).

$$D_i = \sum_{k} (dw_i + df)$$

(2)

where $D_i$ is the total belt conveyor length for perimeter point $i$, $k$ is the number of the mine scheduling increments (e.g. annual), $dw_i$ and $df$ are the distances between mine perimeter point $i$ and waste dumping and excavation respectively during the time period $j$ and $df$ is the distance between point $i$ and the power plant site. After a full perimeter scan,
the perimeter point with the minimum distance \( (p_{\min}) \) is selected as a temporary hub for the belt conveyor system \((x_{\text{hub}}, y_{\text{hub}}, z_{\text{hub}})\), i.e., the point where the belt conveyor system exits the mine.

Step 2: Using point \((x_{\text{hub}}, y_{\text{hub}}, z_{\text{hub}})\) as the exit point from the mine, the global minimum solution of Eq. (3) is used to determine the point coordinates \((x_{\text{BCDP}}, y_{\text{BCDP}}, z_{\text{BCDP}})\) of the BCDP location:

\[
f = \sum_{j=1}^{k} (cw_j + ce_j + cf) + ci
\]

where \(cw_j\) is the operating cost for the belt conveyor segment between the BCDP and waste dumps, during time period \(j\). Accordingly, \(ce_j\) is the operating cost for the belt conveyor segment between BCDP and the excavation point, \(cf\) represent the operating costs for the belt conveyor segments between BCDP and power plant site and finally \(ci\) is the investment cost. The energy consumption is calculated using Eq. (1) by multiplying the power consumption of the system with the annual operation time. The operating cost is derived by multiplying the energy consumption with the corresponding unit cost. This solution is not considered optimal, since perimeter sampling of the first step is not spatially fine tuned.

Step 3: This step iteratively refines the BCDP location by changing the exit point of the belt conveyor system \((x_{\text{hub}}, y_{\text{hub}}, z_{\text{hub}})\) by vertically projecting the BCDP point to the closest arc of the mine perimeter polygon. Steps 2 and 3 are repeated until there is no more reduction of the estimated cost or the exit point of the belt conveyor system does not change.

Step 4: If the BCDP is placed inside the open cast mine area, then it is moved to the point that corresponds to the vertical projection of BCDP to the closest arc of the mine perimeter polygon. The mine perimeter polygon is assumed to be convex.

Step 5: While the coordinates of the various point positions and related distances are estimated in three dimensions, the optimum BCDP location is initially estimated using only the surface plane coordinates \((x, y)\) as the \(z\) coordinate is derived by the actual landscape. Since small scale excavations may be feasible for the actual construction of the BCDP system, the optimal \(x, y\) solution is determined by modifying the \(z\) coordinate (in the range of a few meters) and minimizing the cost function in three-dimensions. A generalized flowchart of this algorithm is shown in Fig. 2.

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**Fig. 2.** Generalized algorithmic flowchart.
4. Simulation and results

A lignite surface mine with simplified geometry and geology operated by a continuous surface mining system closely approximating an actual mine was selected as a case study. This mine model was adopted in order to check the robustness and validity of the optimization. Fig. 3 shows the plan view and a longitudinal cross-section of the mine. Mine scheduling includes four excavation sectors sequentially mined from west to east. Under this simulation scenario, each bench within a sector needs to be fully excavated before operations commence in the following sector.

The dimensions of the rectangle representing the bottom of the pit of the mine are $2\text{km} \times 5\text{km}$ and the technical parameters for this mine are the following:

- Surface elevation: 80 m a.s.l.
- Mine depth: 80 m.
- Bench height: 20 m.
- Lignite content: Sectors 1 and 2: 40% and sectors 3 and 4: 60%.
- Density of materials: Lignite: 1.2 t/m$^3$, waste: 1.8 t/m$^3$.
- Equipment capacity: Benches 1 and 2: 10 Mm$^3$/y, bench 3: 9 Mm$^3$/y, bench 4: 8 Mm$^3$/y.
- Final overall excavation pit slope: 1:3.
- Operational overall excavation pit slope: 1:5.
- Excavation bench pit slope: 1:1.

For every phase of mine development, the volumes of the handled materials and the corresponding centroids of the excavation and dumping sites are calculated based on the geometry of the excavations and on the relative assumptions for the dumping areas. The operating transportation cost is calculated by the application of Eq. (1), assuming continuous operation, as a function of the locations of BCDP and of dumping sites, for a certain location of the power plant, taking into account the values of the invariable parameters $f = 0.028$, $G_m = 100kN/m$, $v = 5.4 \text{m/s}$ and an electricity consumption cost of 0.06 €/kW h. A price of 3520 €/m was assumed for calculating the corresponding investment cost of the belt conveyors.

The BCDP location optimization algorithm is implemented under a program developed in Matlab which features a user-friendly interface. The input data are organized in excel files including mine perimeter and power plant coordinates, excavation and waste dumping coordinates for each temporal increment, and excavation volumes along with lignite to waste ratios for the mine life cycle. The program is divided in two sections, namely a data input/output area and a plot area, as shown in Fig. 4. The following features are supported through the respective buttons:

![Fig. 3. Plan view and longitudinal cross-section A–A′ of the surface mining operation used in the simulation runs.](image-url)
Initialize: Upon clicking on the “initialize” button, the program plots the mine perimeter, along with the excavation, deposit and power plant locations in the plot section. “Ai” and “Ei” denote the waste dump and excavation locations respectively for each temporal increment i. At the same time, quantitative data are uploaded in the data section, including the excavation and waste coordinates with the corresponding volumes and lignite to waste ratios for each temporal increment.

Excavation/Waste: The “Excavation” and “Waste” buttons facilitate manual input of additional temporal increments with corresponding coordinate and volume values.

Start Simulation: The “Start Simulation” button estimates the initial belt conveyor system exiting point on the mine perimeter, as computed in the first step of the optimization algorithm. This is an initial rough estimation of the BCDP location.

Refinement: The “refinement” button executes additional iterative steps of the algorithm, providing the final optimized location of the BCDP along with the corresponding overall cost.

Additionally, the program allows manual coordinate input of the power plant and the BCDP locations, providing automatic calculation of the new cost by selecting the “compute cost” button. Thus, the procedure supports the assessment of various user-based scenarios in real time, facilitating a quick visual and economic estimation of the system’s response.

A series of several model scenarios are depicted in Fig. 5, demonstrating the placement of the BCDP and the corresponding cost. Scenario (b) corresponds to the arrangement in Fig. 4. The input parameters apart from the waste dump site placement remain the same, according to the above-mentioned mine setting. The total operating and investment costs are presented in Table 1, while the optimal elevation of BCDP in all scenarios is computed as 49 m a.s.l. (or 31 m below the original surface).

The cost estimation data presented in Table 1 verify that the total transportation cost is directly related to the optimal location of the BCDP and thus, the location of the external dump site(s). The total transportation cost increases when the distance between the centroids of the two external dumping locations (1 and 2) and the centroid of the excavated volume increases. In the worst-case scenario presented (Fig. 5f), the total transportation cost may increase by about 15% with respect to the cost shown in Table 1.

The results of sensitivity analysis concerning the optimal elevation of BCDP, show that for a 10 m change of the elevation, the increase in the total transportation cost is less than 1%. This result should be co-evaluated with the excavation construction cost required for the installation of BCDP to its location, in order to find the optimum elevation of BCDP. In addition, other parameters related to the location BCDP should be taken into account. Such parameters include the geotechnical investigation of the excavations slope in the area of the BCDP, the environmental impact (mainly dust and noise emission) of the BCDP, the location of intermediate stockpile, the geometry of internal dumping sectors, the geometry of access ramps to excavation and dumping sites and the corresponding geometry of the required connecting conveyors, hydrogeological parameters or other parameters related to specific surface and mining characteristics.

Using the formulated algorithm, more complex cases can be examined regarding the lignite deposit, the geometrical characteristics of the surface mining, the mining equipment and other parameters (economic, environmental etc.). Such cases may include the incorporation of the spatial variability of the mineral deposit regarding quantity and quality characteristics, the parallel use of continuous and non-continuous mining equipment, the application of the dynamic criterion of Net Present...
Value as an objective function incorporating the revenue as well as the excavation cost (investment and operating) for the whole lifetime of the mine or the case that lignite production is fed to multiple power plants.

5. Conclusions

This paper proposes a formulation of a model for the optimal location of BCDP in continuous surface mines based on the minimization of the transportation cost when considering the full lifetime of the mine. A methodological approach and a Matlab based code were developed to solve this optimization problem. Computationally wise, the algorithm follows a simple iterative non-greedy process and achieves a fairly fast result. The program is easy to use and provides a concise visualization of mine geometry and transported volume centroids. The user can modify the centroid locations of the excavated volumes, the dumping and power plant locations and adjust the extraction volumes, developing various test scenarios. The calculated optimized location of the BCDP and the corresponding total transportation cost are extremely important for BCDP placement decision.
By the application of the model it is verified that the location of the external dump affects significantly the total transportation cost and as a consequence the optimal location of the BCDP. Furthermore, the sensitivity analysis results show that for a 10 m change of the elevation of the BCDP, the increase in the total transportation cost is less than 1%.

In addition this algorithm can also be applied to more complex continuous surface mining operations, e.g., where the geometrical characteristics are irregular, the temporal production characteristics vary considerably, production rates vary by bench and sector, etc. A dynamic economic criterion can be also applied for the objective function, incorporating the revenue as well as the excavation cost (investment and operating) for the full lifetime of the mine.

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