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# Evaluation of Different In-Pit Haulage Patterns in an Oil Shale Mine Deposit

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## Abstract

*Diverse four patterns of mine face development have been implemented in this study; this includes continuous longitudinal single-sided mining development system (Dsl), continuous longitudinal double-sided mining development system (Ddl), continuous cross single-sided mining development system (Dsc) and continuous cross double-sided mining development system (Ddc). This study suggests a progressive development approach that involves the shortest in-pit transport approach from the face of the mine to the reloading station using three options, including a power plant consisting of one Circulating Fluidized Bed (CFB) boiler unit and one steam generator in the first 5 years (first option), two CFB units and two generators in the second 5 years (second option), and three CFB boiler units and three generators in the rest of the mine life (third option). The mineable reserve is estimated at 470,861,070 $m^3$, with a projected mine life of 57.4 years, an annual ore volume of 2,840,075$m^3$, and a total mining capacity (including ore and overburden) of 7,838,607$m^3$.*

***Major Findings:*** *The findings suggest that the minimum in-pit haulage distance of 858.7m for the first option can be attained through the implementation of a continuous cross-double-sided mining development system. The findings also suggest that the continuous cross double-sided mining development system is the optimal selection for the second option, while the continuous longitudinal double-sided mining development system is the optimal selection for the third option.*

**Keywords:** *Mineable Reserve, Mine Face Systems, Mine Life, Open Pit Mining, Reloading Station*

## 1.0 Introduction

The mining industry is presently in the process of adapting to specific obstacles and significant setbacks. On one hand, the expansion of the global economy, rapid urbanization, and lifestyle changes have contributed to an upsurge in the trade of products and commodities on a global scale. Demand is being hindered by a range of factors, including price volatility, resource scarcity, low-grade ores, environmental mandates, challenges related to pandemic closure, and the ongoing pursuit of sustainable development. These contradictory issues create supply

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and demand vulnerability in the market, which has compelled the mining industry to modify its methods of operation management.

Mining operations encompass all essential primary and auxiliary procedures that are necessary to extract valuable materials from minerals[1]. The fundamental operations of an open-pit production consist of access opening, blasting and drilling, excavation, and conveyance. Auxiliary operations consist of activities such as the elimination of overburden and topsoil, whereas secondary operations encompass logistical and maintenance functions[2].

Haulage of ore is a crucial aspect of mining operations as it represents a substantial portion of total capital and operational expenses[3]. It involves moving materials to certain locations such as mineral processing plants, spoiling regions, landfill areas, etc. It constitutes 30 to 75% of mines' operational expenses[4]. Various haulage systems are utilized for material transportation in mines, based on factors such as mine characteristics, output, haulage distance, inclination, topographical and geotechnical aspects of the mine ground, and physical properties of the ore[5]. Trucks, belt conveyors, rail haulage, and pipelines are popular haulage techniques used in open-pit mines.

The transportation of ore is the second most crucial operation in many mining companies, following the extraction of ore. The procedure can be executed utilizing four modes of transportation: wheeled vehicles, trains, conveyors (referring to horizontal transport), and shafts (referring to vertical transport)[6]. Every method of transportation possesses certain features that align with its efficiency, initial implementation effort, and cost of use, among other factors. Trucks are the most frequently utilized machinery in open-pit mining operations[2]. Truck haulage is preferred in developing nations and for small-scale production output because of its reduced investment cost in comparison to alternative systems, its rapid establishment time[7], its high level of productivity, its reliability, and its utilization of cutting-edge technologies[8]. Conversely, truck operations are characterized by relatively high operating costs and are contingent upon both climatic conditions and transport road conditions. Research and practical experience have demonstrated that while the conveyor belt method has drawbacks such as high initial costs, complex management, and limitations due to terrain and other factors, its long-term financial viability surpasses that of the traditional truck-shovel method[9].

Surface mining planning and design are influenced by a variety of factors, including but not limited to mine development, production rates, ore grade, mineral location; mining method employed, and transport system. Trucks are utilized in the majority of mining operations in Jordan to transport overburden (OB) and ore. This is attributed to the adaptability and capability of these machines to operate in various environments and materials, their exceptional manoeuvrability, and their optimal performance in mines with moderate production levels and brief haulage distances (less than 10 kilometres)[7].

Seeking enhanced efficiency in mining operations encompasses various facets. One component involves efficiently transporting the ore/overburden fleet to their destinations within the quickest possible timeframe. The relationship between hauling cost and mining cost is evident: as hauling cost decreases, mining cost also decreases[10]. The main waste/ore dump is a highly frequented location, thus when connecting the haul road, it is important to take into account the specific position. Given that Jordan relies on imports for almost 97% of its fuel, and has sizable oil shale reserves exceeding 50 billion tons which are capable of yielding 50 billion barrels of crude oil[11], it is imperative to utilize any available domestic fuel resources, such as oil shale. Jordan is beginning to exploit oil shale deposits; however, mining operations will be expensive, particularly if fuel prices are high. Hence, choosing the most efficient routes would significantly reduce transportation costs, while a shorter route length would lead to reduced transportation time and related factors such as fuel consumption, maintenance costs, and enhanced machinery efficiency.

As the haulage in-pit distance depends on many factors as explained earlier, then an optimizing approach will be employed to estimate the optimal distance at different situations. An examination will be conducted on the in-pit haulage distance subsequent for four proposed mine face advancements for the Al-Sultani oil shale deposit. These four proposed mine face systems are[12]:-

- Continuous longitudinal single-sided mining development system ($D_{sl}$).
- Continuous longitudinal double-sided mining development system ($D_{dl}$).
- Continuous cross-single-sided mining development system ($D_{sc}$).

- Continuous cross-double-sided mining development system ($D_{dc}$).

Increasing the depth of open pits has made raw material extraction more complicated, which in turn, has required the building of haulage systems consisting of various mining and transportation vehicles[13]. As stated by Namin *et al.*,[14] establishing an efficient transportation system within the mine is crucial to minimize expenses and mitigate the negative effects on the environment. Optimization methods are highly used in mining industry to enhance mine design, improve operations, and significantly reduce cost as well as risk associated with mining industries[15]. Maximizing mining operations' profits necessitates the optimization of mining development and working face advancements throughout the mine's existence. Diverse patterns of mine face development could be implemented. Previously, four mine face systems have been suggested, in which a continuous longitudinal or transverse mining system might function in either a single or double-moving direction. These choices have an impact on the distance and paths taken by vehicles used for in-pit transportation.

To determine the ideal transport route for each system, we have computed the mine life and annual production rate (including both ore and overburden) by determining the total mineable reserves. The proved reserves were determined by splitting the study region into 13 sub-areas surrounding the drilled boreholes, taking into account the lithology, thickness, and distribution. Various mine development alternatives have been computed and the impact of the minefield's size has been examined.

In-pit haulage distance for the four mine development patterns was investigated. These four mine face systems were analysed for different scenarios. The first scenario involves a progressive development approach that involves the use of a power plant consisting of one Circulating Fluidized Bed (CFB) boiler unit and one steam turbine generator in the first 5 years, the second scenario involves two CFB boiler units and two steam turbine generator in the second 5 years and the third scenario involves three CFB boiler units and three steam turbine generator in the rest of the mine life. These four mine face systems have been examined for a rectangular minefield region. Additionally, a square-shaped minefield has been proposed to determine if there are any variations in the outcomes. The paper is divided into several sections. The first section provides an introduction. The second section focuses on the oil shale deposits in Jordan and provides a brief description of the study area. The third section analyzes the methodology and presents detailed equations for mine reserve calculations and productivity, as well as equations for each of the four mine face systems. The fourth section presents the results and discussion. Finally, the fifth section concludes the paper.

## 2.0 Oil Shale Deposits in Jordan

Jordan is highly reliant on external sources to meet its hydrocarbon and gas requirements. Diversifying energy sources, transitioning to more sustainable energy options, constructing renewable energy projects, modernizing local oil and gas fields, and liberalizing energy markets are some of the measures taken to mitigate this effect. Nonetheless, average imports of oil and gas products have remained elevated from 2017 to 2021, reaching around 97%[16].

Jordan may find oil shale to be one of its energy alternatives. More than 70 billion tons of oil shale deposits are dispersed throughout the kingdom[17]. The sole substantial indigenous resources could potentially be exploited via direct combustion to generate electricity or retorting processes to produce oil. This has the potential to decrease the Kingdom's reliance on energy imports,

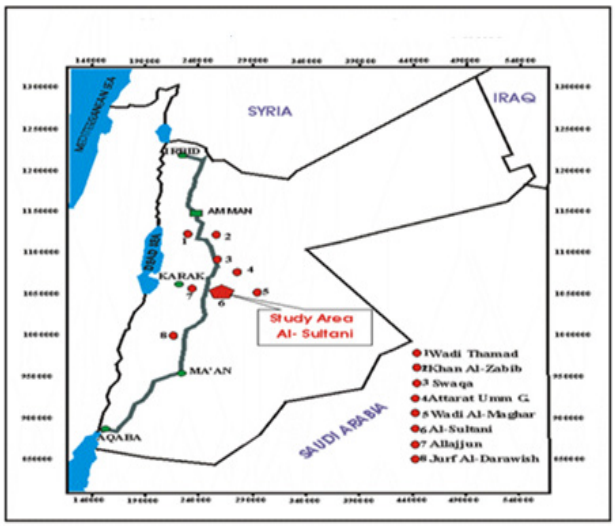



**Figure 1.** Shale Occurrences in Jordan[17].

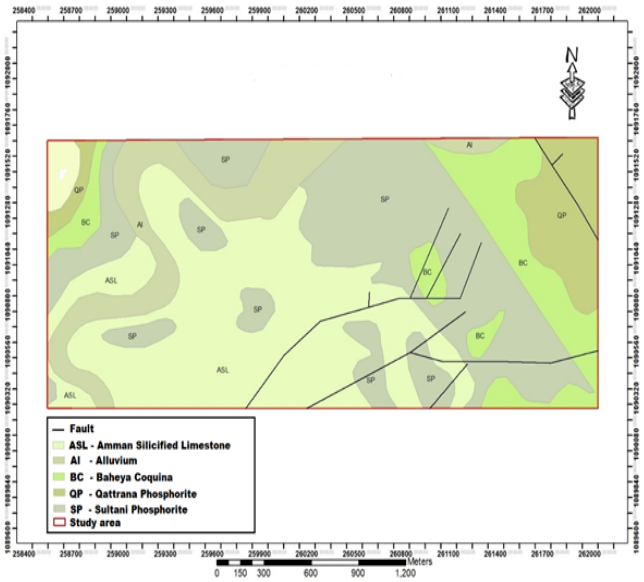



**Figure 2.** Geological map of the study area.

thereby alleviating a portion of the strain on the domestic economy.

According to research conducted by the Jordanian Ministry of Energy and Mineral Resources (MEMR), approximately 60% of the nation is covered by oil shale[17]. Enefit, a globally recognized energy producer and a pioneer in oil shale technology, was awarded the initial permit for surface mining of oil shale after conducting thorough exploration and geological studies to evaluate the volume and quality of oil shale in various locations across the country. A comprehensive investigation revealed eight of these locations, namely Al-Lajjun, Al-Sultani, Jurf Al-Darawish, Attarat Umm Al-Ghadran, Wadi Al-Maghar, Swaqa, Khan Al-Zabib, and Al-Thamd. Figure 1 illustrates the locations of oil shale deposits in Jordan including our study area (Al-Sultani) and Figure 2 demonstrates the geological map of the study area.

Jordan's oil shale is generally of good quality, with relatively low ash and moisture content. The gross calorific value ranges between 6 and 8 MJ/kg and the average oil yield is about 8 – 12%, similar to values from western Colorado (USA) shale[18]. The geologic conditions, such as the thickness and the structural setting as well as the chemical and mineralogical composition, are favourable for open-pit mining. All these factors, together with the low mining and infrastructure costs, render the deposit quite suitable for industrial utilization. The production of oil and electricity using oil shale could be a viable option even at today's oil prices[11].

Enefitwas granted the responsibility of developing the Attarat Um Ghudran oil shale deposit (equivalent to the first oil shale power plant and mine in Jordan). The deposit is situated approximately 110 kilometers south of Amman, the capital city of Jordan. Enefit, in collaboration with Malaysian and Chinese counterparts, has successfully constructed an oil shale-fired power plant. The facility is composed of two Siemens Steam Turbine Generators and two Sumitomo Foster Wheeler Circulating Fluidized Bed (CFB) Boilers, each unit with a net generation capacity of 235 MW, for a combined output of 470 MW. The power plant can receive an estimated annual output of 10 million tonnes (5,681,818 m3) from the mining area, which spans an approximate area of 11 km$^2$, for duration of 40 years. This development represents the most advanced oil shale undertaking beyond Estonia[19].

## 2.1 Al-Sulatani Area

### *2.1.1. Drilling and Sampling*

Approximately a total of 44 boreholes were drilled in the Al-Sultani area. Samples of the oil shale were collected, stored in polythene bags, documented in terms of lithology on-site, and examined in the Natural Resources Authority (NRA) laboratories[20]. In our designated study region, there are a total of 13 boreholes. Table 1 displays the comprehensive data of the boreholes. As can be noticed, the mine has an average stripping ratio of 1.76, a total study area of 344615.4 m$^2$, an average overburden thickness of 63.1m, and an average oil shale thickness of 24.9m.

### *2.1.2 Lithology of the Oil Shale Deposit.*

Figure 3 displays the lithological column of the studied area. Oil shale is located under the Muwaqqar Chalk Marl Formation. The upper part of this formation contains the overburden. The overburden exhibits a variation in depth, ranging from 43.8 to 90 m. It consists, in ascending order, of a non-Bituminous marly limestone bed, a chalky yellowish marly bed, and a layer of alluvium, soil, and gravel. The bottom part of the Muwaqqar Chalk Marl primarily contains the oil shale bed which is bituminous

**Table 1.** Data borehole in the study area[20]

| BH_N | Coordinates | | Elevation m | Influence area $m^2$ | O.B Thickness m | Oil Shale Thickness m | Total depth m | Stripping ratio |
|---|---|---|---|---|---|---|---|---|
| | East | North | | | | | | |
| BH_51 | 247325 | 1059820 | 824.7 | 425500 | 43.8 | 25.8 | 69.6 | 1.7 |
| BH_58 | 24902 | 1059700 | 843.14 | 259157 | 56.1 | 25.1 | 81.2 | 2.24 |
| BH_59 | 248725 | 1059790 | 838.52 | 47000 | 54 | 23.5 | 77.5 | 2.3 |
| BH_510 | 249725 | 1059375 | 852.14 | 323892 | 55 | 24 | 79 | 2.3 |
| BH_511 | 24796 | 1058350 | 828.51 | 341000 | 69.5 | 29.4 | 98.9 | 2.3 |
| BH_513 | 24985 | 1058000 | 833.31 | 59040 | 60 | 9 | 69 | 6.66 |
| BH-514 | 249000 | 1058530 | 827.18 | 249567 | 60 | 39.7 | 99.7 | 1.51 |
| BH_516 | 250.82 | 1058355 | 842.27 | 646000 | 68 | 10.7 | 78.7 | 6.36 |
| BH_517 | 251925 | 1058360 | 859.19 | 659000 | 90 | 65 | 155 | 1.38 |
| BH_518 | 251080 | 1058200 | 844.83 | 625130 | 54 | 56 | 110 | 0.96 |
| BH_519 | 249950 | 1058289 | 837.84 | 555354 | 84 | 45.6 | 129.6 | 1.84 |
| BH_520 | 249100 | 105259 | 833.46 | 22045 | 60 | 53 | 113 | 1.13 |
| BH_521 | 252525 | 105182 | 870.22 | 267315 | 66 | 54 | 120 | 1.22 |
| Total area | | | | 344615.4 | | | | |
| Average | | | | | 63.1 | 24.9 | | 1.76 |

calcareous marl with a thickness that ranges from 9 to 65 m. Phosphatic marl is found in the lower section of the oil shale bed in Al-Hisa phosphorite formation.

### *2.1.3 In-pit Haulage Distance in Sultani Mine*

Transport systems are usually used to haul overburden (OB), ore, workers, materials, supplies etc. In this paper, trucks are considered as a means to transport OB and ore in the proposed Al-Sultani mine. When determining a judicious mode of transportation for the Al-Sultani oil shale mine, it is important to consider that road haulage is conventional for quarries in Jordan and neighbouring countries. Mining the Al-Sultani oil shale deposit via conveyor or rail is challenging due to the absence of a reliable supply chain, repair infrastructure, and technical expertise for the necessary equipment and components. There is a possibility of establishing connections for the importation of components from other nations, however, doing so will significantly increase the capital cost and construction time required to complete the mine. Automobile haulage is the most logical method for transporting oil shale because of its high manoeuvrability and optimal performance in quarries with medium production and short-distance haulage. By employing road haulage, as opposed to rail, it is claimed by[21] that the longitudinal slope of the trenches is reduced, mining and building activities are curtailed, and as a result, the time and expense required to construct quarries are lowered by 20 to 25 %. When there are no rail tracks or contact

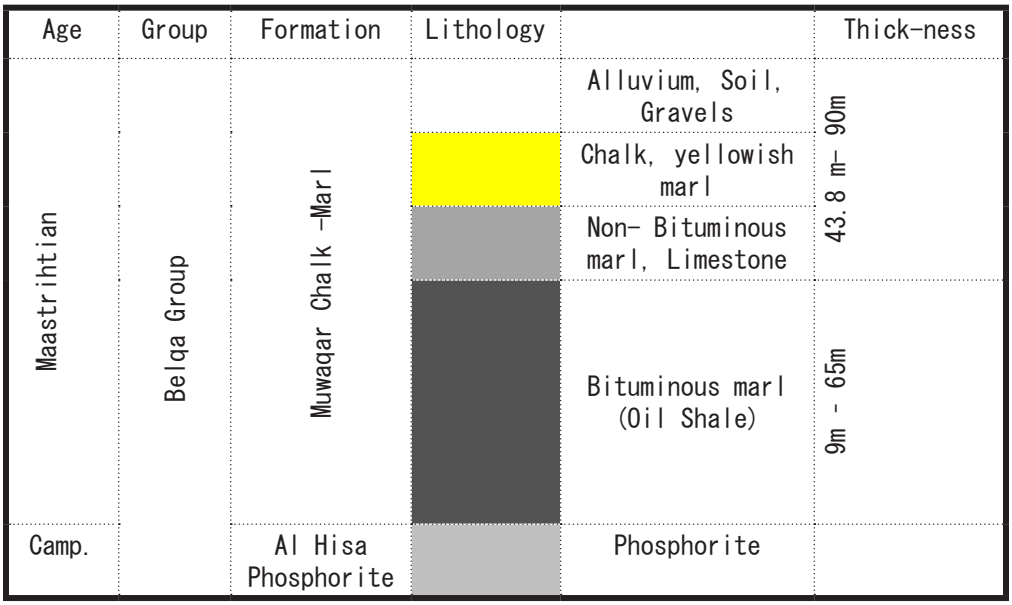



**Figure 3.** Lithological columnar section of the study area[20].

networks, work organization is made easier and excavator productivity rises by 20-25 % compared to when rail haulage is used.

Truck haulage is also utilized because the selection of the Al-Sultani mine for development permits the maintenance and technical foundation of domestic mining equipment. When considering mining transportation for mineral deposits characterized by semi-hard rock formations and thick seams, such as the oil shale deposits found in the Sultani area in Jordan, a combination of conveyor transport and trucks is a logical solution. The primary benefit of this system is that each mode of transportation is utilized under optimal conditions, resulting in the most favourable economic outcomes. It allows for a decrease in transportation charges and haulage costs, resulting in a reduction of over 50% of mining costs and potentially reaching 25% of total mineral production costs[22]. As Purhamadani *et al.*,[23] claimed, the conventional truck-based haulage system has long been a major energy consumer in the haulage industry, especially in open-pit mines and one practical way to drastically cut energy use in this industry is to implement continuous In-Pit Crushing and Conveying (IPCC) systems.

When utilizing mining haul trucks and conveyor transport, the location of the reloading station or crusher must be justified and its parameters must be determined. The rationale for the placement and type of the reloading station concerning field development conditions and the utilization of mining haul trucks and conveyor transport can enhance the economics of mineral resource production. In the process of determining whether to utilize a stationary or mobile reloading station or crusher, consideration was given to the scientific research of Yakovlev[24], which identified a notable drawback of stationary reloading stations as their failure to align with the evolving dynamics of mining operations and the requirements for coordinating technological haul flows. However, using a stationary reloading station in a continuous system for developing the Jordan oil shale deposit in Sultani eliminates the need for relocating it as the mining front decreases. This reduces additional capital costs associated with constantly moving the reloading station as the mining front lengthens. The most effective mode of transportation is using fixed crushers and trucks, compared to other options such as semi-mobile crushers and trucks, and mobile crushers and trucks. This option is favoured since the expenses associated with transporting materials in mining activities have significantly risen as a result of the recent surge in fuel prices. In determining the reloading station location relative to the pit floor, there are three methods[25]:

- Locating the reloading station in the center of the pit floor; is not applicable.

- Locating the reloading station near the main access ramp; is preferable.

- Locating of the reloading station inside the open pit; not considered.

The prevailing system employed at Sultani Mine entails a reloading station close to the primary access ramp. According to Yakovlev, after analyzing effective alternatives for implementing combined transportation, it is recommended to locate the reloading station for mine development of the examined deposits on the surface of the open pit, next to the main access ramp[24].

## 3.0 Methodology

After calculating the mineable reserves, annual output, and the expected lifespan of the mine, these factors can be utilized to determine the distances for in-pit hauling in continuous mining systems and truck-conveyor transport. The following systems can be considered for this purpose[26]:

- Continuous longitudinal single-sided mining development system ($D_{sl}$).

- Continuous longitudinal double-sided mining development system ($D_{dl}$).

- Continuous cross-single-sided mining development system ($D_{sc}$).

- Continuous cross-double-sided mining development system($D_{dc}$).

### 3.1 Mineable Reserve, Mine Life and Production Rate Calculations

To calculate the annual production of the mine, geological reserves were calculated. Ore reserve estimation is based on the principle of calculating volume using the method of multiplying the influence areas of the boreholes by the average thickness of each block. The unit of estimation is ($m^3$) and the formula is written as:

Total Volume of ore= Total exploitation area *Average Thickness (1)

Where the influence area and thickness of boreholes (BH) are extracted from[20]. Once we calculate the volume, we need to calculate the mineable reserve by taking into consideration the recovery rate and the dilution factor is given by Camm as demonstrated in Equation (2)[27].

$$T_{d=}(rv) \text{ x } (rf)x(1+df) \quad (2)$$

$T_{d:}$ Total volume of ore to be mined (mineable reserves);

*rv*= Total ore volume;

*rf*= Recovery factor for the particular mining method;

*df* = Dilution factor.

After we compute mineable reserves, we can compute the life of mine as following[27]:

Life of mine (yrs.) LOM = Ore reserves ($m^3$) /Ore production rate ($m^3$ p.y.) (3)

It is possible to compute the daily mining capacity by applying equation 4 below, depending on whether there are 350 operational days in a year (corresponding to operating 7 days a week). In our case, we assumed operating days to be 350 days[27].

$$C_{Ore} = (T_d)/(LOM.dpy) \quad (4)$$

$C_{ore}$: Daily ore mining capacity ($m^3$/day)

LOM: Life of mine (in years)

$T_d$: Total volume of ore to be mined

$d_{py}$: Number of working days per year, assumed 350 days in this work.

By substituting LOM in Equation (3) into Equation (4), the resulting formula will be Equation (5) with the following form:

$$C_{Ore} = (T_d)/((\text{LOM } x\ dpy) \quad (5)$$

We can also calculate the total capacity of mining (ore + waste) using the following equation (Equation (6))[21]:

$$C_m = [(SR+1)x\ C_{Ore}] \quad (6)$$

Where, $C_m$ is the total capacity of mine (Ore + waste) in cubic meters; SR is the stripping ratio.

### 3.2 Justification of a Rational Type of Mining Transportation

In this work, patterns of changes in intra-pit transportation distances from the mining front to the reloading station using a trucks-conveyor transport system will be studied.

Each pattern will be explained and parameters affecting intra-pit transporting distance will be discussed. It is considered that in-pit distances of truck transportation at each system of development consist of uniform and temporal segments. The uniform segment is determined by the length of the mining front, while the movement of the mining front per year represents the variable segment. These segments are summed up during the operation of the open pit mine. On this basis, the distances of the transportation road to the reloading station, which is located on the board of the open pit near the exit trench, are determined. The method for determining in-pit hauling distances for continuous mining systems and truck-conveyor transport is as follows:

### 3.2.1 Continuous Longitudinal Single-sided Mining Development System ($D_{sl}$)

Let the area of the minefield ABCD be developed according to a continuous single-side development system with a mining front length in the longitudinal direction ($L_l$). The reloading station is located on the surface near the midpoint between A and D, as shown in Figure 4, then, the uniform distance of truck transportation along the mining front is 0.5 $L_l$.

Due to work front movement in the transverse direction (i.e. along line AB), the distance of transportation will increase by the amount of the annual movement Q/($HL_l$), where Q (the total mining capacity (ore + O.B) per year, $m^3$), and H is the deposit thickness. The temporal change can be expressed by TQ/($HL_l$), where T is the time of my life in years[12]. The hauling distance to the reloading station with a continuous longitudinal single-side mining development system ($D_{sl}$), is given by Altiti and Pcholkin[12], as in Equation (7)

$$D_{sl} = 0.5L_l + \frac{TQ}{HL_l} \quad (7)$$

Similarly, the hauling distances of trucking to the reloading station are determined for other types of continuous open-pit mining systems.

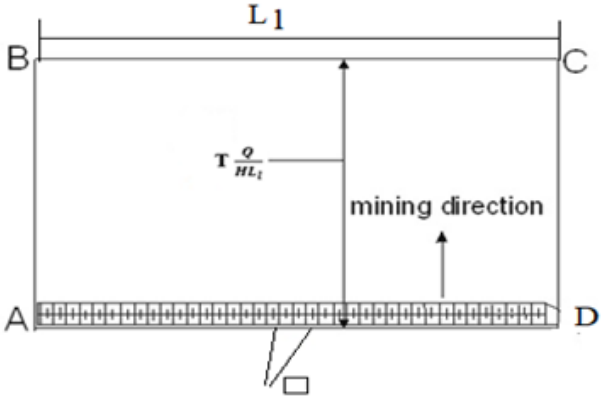



**Figure 4.** Continuous longitudinal single-sided mining development system.

### 3.2.2 Continuous Longitudinal Double-sided Mining Development System ($D_{dl}$)

In this case, mining operations occur in two directions simultaneously, with the reloading station located midway of the mining field width (line CD) as illustrated in Figure 5. The hauling distance for continuous longitudinal double-sided mining development system ($D_{dl}$) is given by Altiti and Pcholkin[12] as demonstrated in Equation (8)

$$D_{dl} = 0.5\left(L_l + \frac{TQ}{HL_l}\right) \quad (8)$$

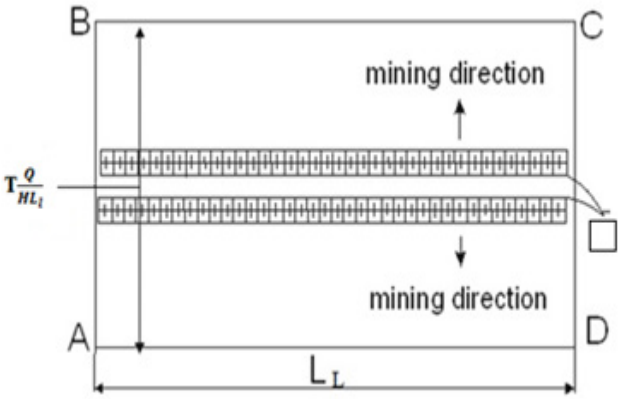



**Figure 5.** Continuous longitudinal double-sided mining development system.

### 3.2.3 Continuous Cross Single-sided Mining Development System ($D_{sc}$)

In a continuous transverse single-side mining development system, the mining front length in the transverse direction ($L_c$) is replacing $L_l$ as depicted in Figure 6. The hauling distance to the reloading station with a continuous transverse single-side mining development system ($D_{sc}$),

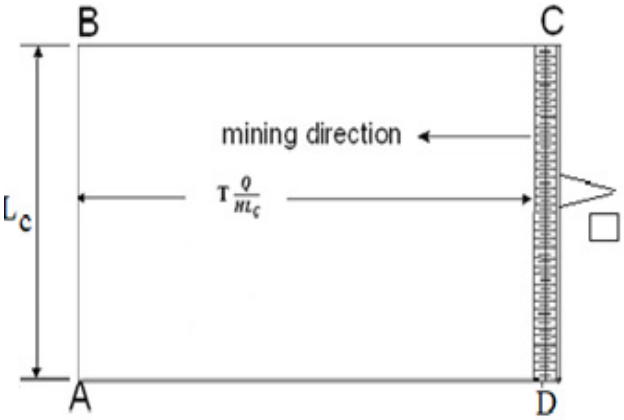



**Figure 6.** Continuous transverse single-side mining development system.

is given by Altiti and Pcholkin[12] as demonstrated in Equation (9).

$$D_{sc} = 0.5L_c + \frac{TQ}{HL_c} \quad (9)$$

### *3.2.4 Continuous Cross Double-sided Mining Development System ($D_{dc}$)*

Figure 7 shows the development system when using transverse double-side mining pattern. Similarly, the hauling distance for a transverse double-sided mining system ($D_{dc}$) can be obtained using: Equation (10) by Altiti and Pcholkin[12]:

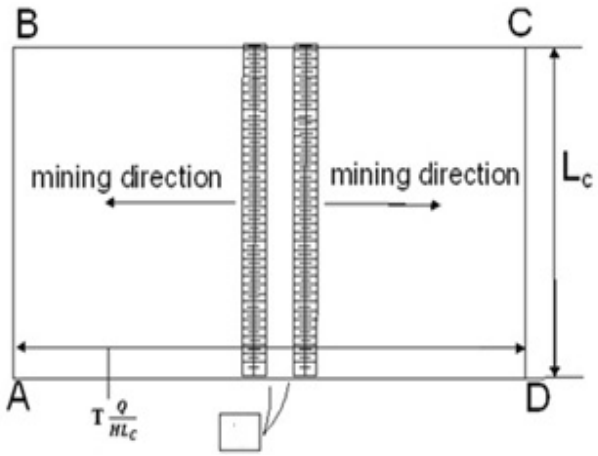



**Figure 7.** Continuous transverse double-sided mining development system.

$$D_{dc} = 0.5\left(L_c + \frac{TQ}{HL_c}\right) \quad (10)$$

## 4.0 Results and Discussion

To compensate for the eroded amounts of Oil Shale in the site, the proved reserve was calculated by subdividing the area into 13 influences sub-areas around the drilled boreholes based on the lithology, thickness and distribution. The volume of the overburden encountered in the project mining site is also considered. Table 2 shows the details of total ore reserve calculations. The volume of the oil shale is 172,507,236m$^3$ and the volume of the overburden is 298,353,833.7m$^3$, the total volume of the deposit (ore waste) is 470,861,070m$^3$.

The diluted reserves depend on the mining method used. Here, the open pit mining method is proposed with an assumed recovery rate and dilution factor of 90% and 5% respectively[27]. Diluted reserves can be calculated using Equation (2). Since we are using open pit mining, to find the diluted reserves $T_d$, we need the recovery rate and the dilution factor for the mining method which can be taken from Appendix 1; Equation (2) is applied as:

$T_d$ = 172,507,236 x 0.9 x1.05 = 163,019,338 m$^3$

To calculate the life of mine (LOM), we will use a single unit of Circulating Fluidized Bed (CFM) which requires 2,840,909 m$^3$ of Oil Shale per year. LOM can be calculated as

LOM = Total ore volume / annual power plant requirements

LOM = 163,019,338 m$^3$/2,840,909 m$^3$ = 57.4 years

To calculate the quantity of ore, Equation (5) can be used

$$C_{Ore} = (T_d)/(\text{(LOM } x\ dpy)$$

= 163,019,338 /57.4 x 350 = 8,114.5 m$^3$/day.

As can be deducted from Table 1 (previously explained in section 2.1.2), the stripping ratio is 1.76; then we can use it to estimate Equation (6), the daily mining output (ore + waste) becomes as:

$$C_m = [(SR + 1)x\ C_{ore}$$

= (1.76+1) $x$ 8,114.5 = 22,396 m$^3$ per day which is equivalent to 7,838,607m$^3$per year (22,396 m$^3$ /day x350 days). Table 3 shows the summary of our main results.

**Table 2.** Estimated reserve of the study area

| *BH-NO* | *Overburden depth (m) 1* | *Ore depth (m) 2* | *Influence Area ($m^2$) 3* | *O.B volume ($m^3$) 4=1x3* | *ore reserve volume ($m^3$) 5=2x3* | *Total volume Reserve ($m^3$) 6=4+5* |
|---|---|---|---|---|---|---|
| BH-51 | 43.8 | 25.8 | 425,500 | 18,636,900 | 10,977,900 | 29,614,800 |
| BH-58 | 56.1 | 25.1 | 259,157 | 14,538,708 | 6,504,841 | 21,043,549 |
| BH-59 | 54 | 23.5 | 47,000 | 2,538,000 | 1,104,500 | 3,642,500 |
| BH-510 | 55 | 24 | 323,892 | 17,814,060 | 7,773,408 | 25,587,468 |
| BH-511 | 69.5 | 29.4 | 341,000 | 23,699,500 | 10,025,400 | 33,724,900 |
| BH-513 | 60 | 9 | 59,040 | 3,542,400 | 531,360 | 4,073,760 |
| BH-514 | 60 | 39.7 | 249,567 | 14,974,020 | 9,907,810 | 24,881,830 |
| BH-516 | 68 | 10.7 | 646,000 | 43,928,000 | 6,912,200 | 50,840,200 |
| BH-517 | 90 | 65 | 659,000 | 59,310,000 | 42,835,000 | 102,145,000 |
| BH-518 | 54 | 56 | 625,130 | 33,757,020 | 35,007,280 | 68,764,300 |
| BH-519 | 84 | 45.6 | 555,354 | 46,649,736 | 25,324,142 | 71,973,878 |
| BH-520 | 60 | 53 | 22,045 | 1,322,700 | 1,168,385 | 2,491,085 |
| BH-521 | 66 | 54 | 267,315 | 17,642,790 | 14,435,010 | 32,077,800 |
| Average | 63.1 | 25 | | | | |
| Total | | | 4,480,000 | 298,353,833.7 | 172,507,236 | 470,861,070 |

## 4.1 Generating Electricity from Sultani Mine

According to Enefit, a power plant that is comprised of one unit of Circulating Fluidized Bed (CFB) boilers and one unit of steam turbine generator would generate a net capacity of 235 MW; this requires extracting 5 million tonnes of oil shale per year (2,840,909 $m^3$). However, to extract this amount of oil shale, an annual mining output (including ore and waste) of approximately 7,840,909 $m^3$ is necessary. From this number, we conclude that the total volume of the reserve (O. B+ Ore) for the whole life of the mine (57 years) is 470,861,070$m^3$.

This study suggests a progressive development approach that involves the use of a power plant consisting of one Circulating Fluidized Bed (CFB) boiler unit and one steam turbine generator unit in the first 5 years, two CFB boiler units and two steam turbine generator units in the second 5 years and three CFB boiler units and three steam turbine generator units in the rest of the mine life. The details for each scenario are presented in Table 4.

## 4.2 In-Pit Haulage Distance with Different Mine Development Options

In-pit haulage distance for different mine development patterns were investigated. These were calculated based on the baseline case of proposed mine parameters ($L_l$ = 3200 m, $L_c$ = 1400 m). As illustrated in Table 5, the power plant installation is proposed to begin with one unit for the first five years, followed by two units for the next five years, and finally three units for the remaining lifespan of the

**Table 3.** Summary of the results

| Item | Result |
|---|---|
| Total influence area, $m^2$ | 4,480,000 |
| Average thickness of overburden, m | 63.1 |
| Average thickness of ore, m | 25 |
| Total overburden (O.B) volume, $m^3$ | 298353833.7 |
| Total ore reserve volume (*rv*), $m^3$ | 172,507,236 |
| Total volume of ore to be mined (mining reserve) ($T_d$), $m^3$ | 163,019,338 |
| Total volume of the deposit (*O.B+ Ore*) , $m^3$ | **470,861,070** |
| Average stripping ratio | 1.76 |
| Life of mine, year | 57.4 |
| Total volume of ore per day ($C_{ore}$), $m^3$ | 8,114.5 |
| Total volume of ore per year ($C_{ore}$), $m^3$ | 2,840,075 |
| Total mining capacity (*Ore + O.B)* per day ($C_m$), $m^3$ | 22,396 |
| Total mining capacity (*Ore + O.B*) per year ($C_m$), $m^3$ | 7,838,607 |

mine and its reserve. This plan takes into consideration the electricity demand and installation costs.

In-pit haulage distance Vs Time:

**$D_{sl}$, $D_{dl}$, $D_{sc}$, and $D_{dc}$**

Baseline case ($L_l$ = 3200 m, $L_c$ = 1400 m)

Where: Dsl- is a continuous longitudinal single-sided mining development system.

Ddl- is a continuous longitudinal double-sided mining development system.

Dsc- is a cross-single-sided mining development system.

Ddc- is a cross-double-sided mining development system.

Table 5 shows that the shortest in-pit haulage distance of the first option is 858.7m by using a continuous cross double-sided mining development system at the end of the first five years. The shortest in-pit haulage distance in the second option (the second five years) is 1,017.8m by using a continuous cross-double-sided mining development system at the end of the second five years. The shortest in-pit haulage distance in the third option (the remaining life of reserves) is 3,560.2m by using a continuous longitudinal double-sided mining development system at the remaining mine life.

The results are summarized in Figure 8. The shortest in-pit haulage distance for the total three options has been calculated, as indicated in the black colour column. This distance is 6,968.8m and was accomplished by utilizing a continuous longitudinal double-sided mining development system. The results in Figure 8 also indicate that $D_{dc}$ is the shortest route during the initial years (the first five years and the second five years), however,

**Table 4.** Annual mining output (ore + waste), remaining reserve (in $m^3$) and mine life mine (in years)

| | | **Annual mining output (ore +waste)$C_{m,}$ $m^3$** | **Output in first 5 years $m^3$** | **Remaining reserve $m^3$** | **Remaining mine life in years** |
|---|---|---|---|---|---|
| | | | | 470,861,070 | 57 |
| Option 1 | Using one unit | 7,838,607 | 39,193,545 | 431,667,525 | 57 |
| Option 2 | Using two units | 15,677,214 | 78,386,070 | 353,281,455 | 52 |
| Option 3 | Using three units | 23,515,821 | 117,579,105 | 235,702,350 | 47 |

**Table 5.** Calculations of in-pit haulage distance for a rectangular area using one unit, two units and three units options

| Option (No. of units) | Equations | Results |
|---|---|---|
| 1 | $D_{sl} = 0.5L_l + \frac{TQ}{HL_l}$ | $D_{sl} = 0.5x3200 + \frac{5x7,838,607}{88.1x3200} = 1,733.8m$ |
| | $D_{dl} = 0.5\left(L_l + \frac{TQ}{HL_l}\right)$ | $D_{dl} = 0.5\left(3200 + \frac{5x7,838,607}{88.1x3200}\right) = 1,669.4m$ |
| | $D_{sc} = 0.5L_c + \frac{TQ}{HL_c}$ | $D_{sc} = 0.5x1400 + \frac{5x7,838,607}{88.1x1400} = 1,017.4m$ |
| | $D_{dc} = 0.5\left(L_c + \frac{TQ}{HL_c}\right)$ | $D_{dc} = 0.5\left(1400 + \frac{5x7,838,607}{88.1x1400}\right) = 858.7m$ |
| 2 | $D_{sl} = 0.5L_l + \frac{TQ}{HL_l}$ | $D_{sl} = 0.5x3200 + \frac{5x15,677,214}{88.1x3200} = 1,878m$ |
| | $D_{dl} = 0.5\left(L_l + \frac{TQ}{HL_l}\right)$ | $D_{dl} = 0.5\left(3200 + \frac{5x15,677,214}{88.1x3200}\right) = 1,739m$ |
| | $D_{sc} = 0.5L_c + \frac{TQ}{HL_c}$ | $D_{sc} = 0.5x1400 + \frac{5x15,677,214}{88.1x1400} = 1,335.5m$ |
| | $D_{dc} = 0.5\left(L_c + \frac{TQ}{HL_c}\right)$ | $D_{dc} = 0.5\left(1400 + \frac{5x15,677,214}{88.1x1400}\right) = 1,017.8m$ |

| | | |
|---|---|---|
| 3 | $D_{sl} = 0.5L_l + \frac{TQ}{HL_l}$ | $D_{sl} = 0.5x3200 + \frac{47x23,515,821}{88.1x3200} = 5,520.4m$ |
| | $D_{dl} = 0.5\left(L_l + \frac{TQ}{HL_l}\right)$ | $D_{dl} = 0.5\left(3200 + \frac{47x23,515,821}{88.1x3200}\right) = 3,560m$ |
| | $D_{sc} = 0.5L_c + \frac{TQ}{HL_c}$ | $D_{sc} = 0.5x1400 + \frac{47x23,515,821}{88.1x1400} = 9,661m$ |
| | $D_{dc} = 0.5\left(L_c + \frac{TQ}{HL_c}\right)$ | $D_{dc} = 0.5\left(1400 + \frac{47x23,515,821}{88.1x1400}\right) = 5,180.5m$ |

$D_{dl}$ is the shortest distance thereafter (at the end of the mine life).

## 4.3 Effect of Minefield Area

The shape of the minefield and its geometry influence the haulage distance. Different scenarios are presented to investigate this effect: namely the shape and size of the minefield area. Firstly, a square shape of minefield ($L_l$ = $L_c$ supposing 2000m) having the same baseline case area is introduced. The haulage distance is shown in Table 6 and Figure 9 for single and double patterns. The double pattern has the shortest distance for all productivities i.e. $D_{dl} < D_{sl}$; $D_{dc} < D_{sc.}$ However, comparing the haulage distance in a square minefield with that of a baseline case, i.e. rectangular shape, it is found that the haulage distance for the square field is longer for the corresponding cross-mining patterns for all productivities to a certain time (i.e. $D_{sc}$ *and* $D_{dc}$ for a square minefield area are higher than $D_{sc}$

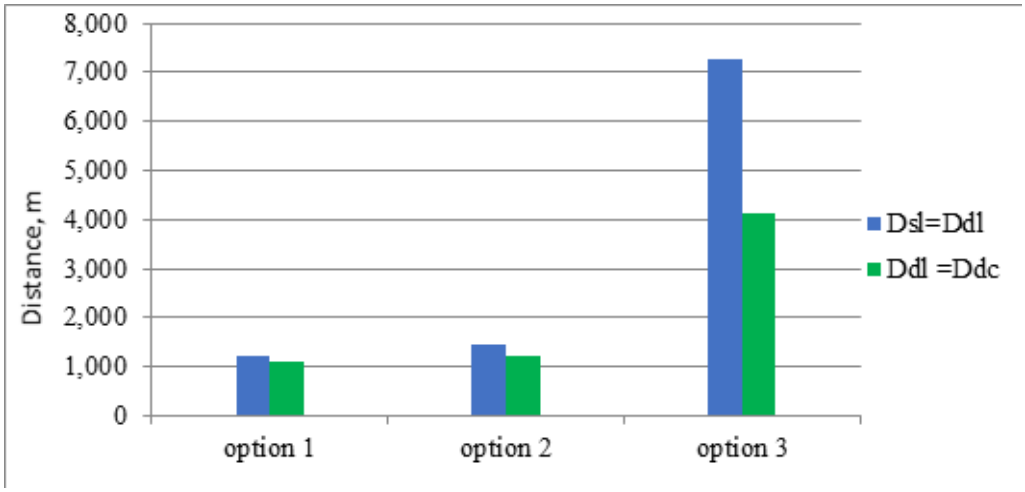



**Figure 9.** In-pit haulage distance for different mine development pattern of square minefield area.

**Table 6.** Calculations of in-pit haulage distance for a square shape area using one unit, two units, and three units' options

| Option (No. of units) | Equations | Results |
|---|---|---|
| 1 | $D_{sl} = 0.5L_l + \frac{TQ}{HL_l}$ | $D_{sl} = 0.5x2000 + \frac{5x7,838,607}{88.1x2000} = 1,222.4m$ |
| | $D_{dl} = 0.5\left(L_l + \frac{TQ}{HL_l}\right)$ | $D_{dl} = 0.5\left(2000 + \frac{5x7,838,607}{88.1x2000}\right) = 1,111.2m$ |
| | $D_{sc} = 0.5L_c + \frac{TQ}{HL_c}$ | $D_{sc} = 0.5x2000 + \frac{5x7,838,607}{88.1x2000} = 1,222.4m$ |
| | $D_{dc} = 0.5\left(L_c + \frac{TQ}{HL_c}\right)$ | $D_{dc} = 0.5\left(2000 + \frac{5x7,838,607}{88.1x2000}\right) = 1,111.2m$ |
| 2 | $D_{sl} = 0.5L_l + \frac{TQ}{HL_l}$ | $D_{sl} = 0.5x2000 + \frac{5x15,677,214}{88.1x2000} = 1,444.8m$ |
| | $D_{dl} = 0.5\left(L_l + \frac{TQ}{HL_l}\right)$ | $D_{dl} = 0.5\left(2000 + \frac{5x15,677,214}{88.1x2000}\right) = 1,222.4m$ |
| | $D_{sc} = 0.5L_c + \frac{TQ}{HL_c}$ | $D_{sc} = 0.5x2000 + \frac{5x15,677,214}{88.1x2000} = 1,444.8m$ |
| | $D_{dc} = 0.5\left(L_c + \frac{TQ}{HL_c}\right)$ | $D_{dc} = 0.5\left(2000 + \frac{5x15,677,214}{88.1x2000}\right) = 1,222.4m$ |

| | | |
|---|---|---|
| 3 | $D_{sl} = 0.5L_l + \frac{TQ}{HL_l}$ | $D_{sl} = 0.5x2000 + \frac{47x23,515,821}{88.1x2000} = 7,272.7m$ |
| | $D_{dl} = 0.5\left(L_l + \frac{TQ}{HL_l}\right)$ | $D_{dl} = 0.5\left(2000 + \frac{47x23,515,821}{88.1x2000}\right) = 4,136.3$ |
| | $D_{sc} = 0.5L_c + \frac{TQ}{HL_c}$ | $D_{sc} = 0.5x2000 + \frac{47x23,515,821}{88.1x2000} = 7,272.7m$ |
| | $D_{dc} = 0.5\left(L_c + \frac{TQ}{HL_c}\right)$ | $D_{dc} = 0.5\left(2000 + \frac{47x23,515,821}{88.1x2000}\right) = 4.136.3m$ |

*and* $D_{dc}$ for a rectangular minefield area for all options). One can also notice that in the case of a square minefield area, $D_{sl}$ and $D_{sc}$ are similar and $D_{dl}$ *and* $D_{dc}$ are similar for all options ($D_{sl}$ and $D_{sc}$= 1,222.4 and $D_{dl}$ *and* $D_{dc}$= 1,111.2, for option 1; $D_{sl}$ and $D_{sc}$ = 1,444.8 and $D_{dl}$ *and* $D_{dc}$= 1,222.4, for option 2; $D_{sl}$ and $D_{sc}$= 7,272.7 and $D_{dl}$ *and* $D_{dc}$= 4,136.3, for option 3).

## 4.4 Economic Impact of the Proposed Model

One of the challenges faced by mining and processing industries in their transport is the issue of transport routing. Mining companies must focus on devising an efficient transportation route that minimizes expenses. The route is determined by various factors including the fuel efficiency of the transport, the distance covered by the transport, the speed of the transport, and the time required for loading and unloading activities. By considering these parameters, it is feasible to create an ideal transportation route that minimizes losses.

The transportation distance in a mining operation significantly impacts both the income and operational cycle of the mine, as it is a crucial component of the overall mining expenses. A significant amount of truck transportation occurs within the mining region, mostly to transfer materials to crushers or processing plants (such as concentrators) before their removal from the mine. The primary catalyst for innovation in transportation continues to be efficiency, achieved through the decrease of costs. It encompasses any activity, investment, or novel procedure that might decrease production expenses and enhance the competitiveness of mining. The objective of enhancing efficiency focuses on reducing both direct costs, such as the expenses associated with transportation inputs like fuel, and indirect costs, such as minimizing energy consumption of vehicles or optimizing routing.

Our model has the potential to either decrease the duration of delivering the raw materials to the client lower the associated expenses, or potentially impact both by delivering a larger quantity of raw materials in a single shipment. The energy-intensive characteristics of mining operations, including activities such as drilling, blasting, haulage, and ore processing, necessitate a consistent and dependable source of power. In regions such as Jordan, where fuel costs are already inadequate or expensive, this would make the mining industry uncompetitive. Therefore, the implementation of new mining transport routes and creative processes can result in decreased costs and increased profitability.

## 5.0 Conclusion

This study proposes a progressive development strategy for transporting materials from the mine face to the reloading station. The strategy involves three options: the first option is to use a power plant with one Circulating Fluidized Bed (CFB) boiler unit and one steam turbine generator unit for the first 5 years, the second option is to use two CFB boiler units and two steam turbine generator units for the next 5 years, and the third option is to use three CFB boiler units and three steam turbine generator units for the remaining life of the mine. The results showed that the mine has a reserve of 470,861,070 $m^3$, a mine life of 57.4 years, an annual volume of ore of 2,840,075 $m^3$, and a total mining capacity of 7,838,607 $m^3$. The results also showed that the shortest distance for transporting materials within the mine is 858.7 m for option one, which can be achieved by using a continuous cross-double-sided mining development system. The continuous cross double-sided mining development system was utilized to achieve the lowest distance for in-pit haulage 1,017.8m during the second option. The third option, which involves the remaining life of reserves, has a haulage distance of 3,560.2m within the pit and this has been achieved by implementing a continuous longitudinal double-sided mining development system.

The results also showed that by using a square shape area, the double pattern has the shortest distance for all productivities. However, comparing the haulage distance in a square minefield with that of the baseline case, i.e. rectangular shape, it is found that the haulage distance for a square field is longer for the corresponding cross-mining patterns for all productivities to a certain time. In reality, there may still be numerous types of obstacles, such as hydrogeological circumstances, protective structures, and rock engineering constraints. Hence, in future endeavours, it would be intriguing to enhance the suggested approach by taking into account factors such as the river, protective structures, rock quality, and other relevant aspects while determining the most efficient path for the primary haul routes.

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## 7.0 References

1. Hartman H . Mutmansky M. Introductory mining engineering 2nd edition. Hoboken, NJ: J Wiley; 2002. p. 592.
2. Wetherelt A, Wielen K. Introduction to Open-Pit Mining, in: Peter Darling (ed.): Mining Engineering Handbook, 3rd edition, Soc Min Metall Explor Inc (SME). 2011. p. 857.
3. Kluge P, Limpitlaw D, Swanepoel W. Ore transport system selection for the Sintoukola potash project in the Republic of Congo. J South Afr Inst Min Metall. 2017; 117(11); 1073-1080. https://doi.org/10.17159/2411-9717/2017/v117n11a12
4. Karande P, Chakraborty S. Material handling equipment selection using weighted utility additive theory. J Ind Eng. 2013; 1-9. https://doi.org/10.1155/2013/268708
5. Offei K, Checkel D, Nasab A. Evaluation of belt conveyor and truck haulage systems in an open pit mine using life cycle assessment. The Canadian Institute of Mining, Metallurgy and Petroleum (CIM). 2009; 102:1-6.
6. Skoczylas A, Rot A, Stefaniak P, Śliwiński P. Haulage cycles identification for wheeled transport in underground mine using neural networks. Sensors. 2023; 23(3):1331.
7. https://doi.org/10.3390/s23031331 PMid:36772371 PMCid:PMC9921929
8. Ozfirat P, Ozfirat M., Malli T. Selection of coal transportation mode from the open pit mine to the thermic power plant using Fuzzy Analytic Hierarchy Process. Transport. 2017; 33(2):502–509. https://doi.org/10.3846/16484142.2017.1295278
9. Vishnyakov Y, Pushkarev A, Botyan E, Khloponina V. Justification of rational modes of operation of quarry dump trucks in case of over-normative operation. MIAB. Mining Inf Anal Bull. 2023; (11-1):24-37. https://doi.org/10.25018/0236_1493_2023_111_0_24
10. Bao H, Knights P, Kizil M, Nehring M. Electrification alternatives for open pit mine haulage. Mining. 2023; 3(1):1-25. https://doi.org/10.3390/mining3010001
11. Hajarian A, Osanloo, M. A new developed model to determine waste dump site selection in open pit mines: An approach to minimize haul road construction cost. Int J Eng. 2020; 33(7):1413-1422. https://doi.org/10.5829/ije.2020.33.07a.29

12. Abu-Hamatteh Z, Al-Shawabkeh A. An overview of the Jordanian oil shale: Its chemical and geologic characteristics, exploration, reserves and feasibility for oil and cement production. Cent Eur Geol. 2008; 51(4):379-395. https://doi.org/10.1556/CEuGeol.51.2008.4.6
13. Altiti A, Pcholkin G. Rationale open cast mining technology for fields with large reservoir thickness, "extracting oil shale deposit of El-Lajjun area". PhD Thesis, National Mining University of Ukraine, Dnepropetrovsk; 2006. p. 290.
14. Anylogic. Productivity improvement in mining haulage system with simulation; 2024. Available from: https://www.anylogic.com/resources/case-studies/productivity-improvement-of-mining-haulage-system-using-simulation/
15. Namin S. Ghasemzadeh H, Aghajari A. A comprehensive approach to selecting mine transportation system using AHP and FUZZY-TOPSIS. Decision Making and Analysis. 2023; 1(1):23-39. https://doi.org/10.55976/dma.12023117323-39
16. Whittle J. Open Pit Optimization', in Kennedy, BA. (ed.) Surface Mining. 2nd ed., Colorado, USA: Soc Min Metall Explor Inc. (SME); 1990. p. 470-475.
17. MEMR. Jordan Energy Balance- facts and figures; 2022. Available from: https://www.memr.gov.jo/EN/List/Studies_and_Statistics
18. MEMR. Jordanian Oil Shale; 2020. Available from: https://www.memr.gov.jo/EBV4.0/Root_Storage/EN/Project/projects-Investment_Opportunities-_15-6-2020.pdf
19. Abu-Hamatteh Z, Jaber J, Besieso M, Al-Jufout S, Al-Azab T, Al-Shawabkeh A. Jordanian oil shale: A promising strategic source of energy. – In: White, J, Robinson, W (Eds): Natural Resources: Economics, Management and Policy. New York, Nova Science Publishers, Inc.; 2008. p. 89–129.
20. Enefit. Enefit Technology; 2022. Available from: https://www.enefit.com/
21. Hufnagel H. Investigation of the oil shale deposits at Jurf Ed Darawish, El Hasa and Sultani, Bundesanstalt fur Geowissenschaften und Rohstoffe, Hannover. Technical Cooperation Project No. 78.2165.5; 1985.
22. Khokhryakov V. Open-pit mining of mineral deposits: a textbook for technical schools. – 5th ed., Revised and Additional – M. Nedra; 1991. p. 336.
23. Dessureault S. Equipment Operations Technology, University of Arizona Mining and Geological Engineering, Course Notes – Fall; 2005.
24. Purhamadani E, Bagherpour R, Tudeshki H, Bagherpour R. Energy consumption in open-pit mining operations relying on reduced energy consumption for haulage using in-pit crusher systems. J Clean Prod. 2021; 291(1):125228.
25. https://doi.org/10.1016/j.jclepro.2020.125228
26. Yakovlev V. Promising solutions in the field of cyclic-flow technology of deep quarries. Mining Journal. 2003; 4(5):51-57.
27. Rahimdel M, Bagherpour R. Haulage system selection for open pit mines using fuzzy MCDM and the view on energy saving. Neural Computing and Applications. 2018; 29:187–199. https://doi.org/10.1007/s00521-016-2562-7
28. Tomakov P, Naumov I. Technology Mechanization and Organization of Surface Mining. 2nd ed. NEDRA: Moscow; 1986. p. 241.
29. Camm T. Simplified Cost Models for Prefeasibility Mineral Evaluations U.S. Bureau of Mines, Information Circular 9298; 1991.