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A New Method for Haul Road Design in Open-Pit Mines to Support Efficient Truck Haulage Operations

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Abstract: The design of a haul road for an open-pit mine can significantly affect the cost associated with hauling ore and waste to the surface. This study proposes a new method for haul road design in open-pit mines to support efficient truck haulage operations. The road layout in open-pit mines was optimized by using raster-based least-cost path analysis, and the resulting zigzag road sections were simplified by applying the Douglas-Peucker algorithm. In addition, the road layout was modified by reflecting the radius of curvature suggested in the road design guides. Finally, a three-dimensional model reflecting the results of the road design was created by combining the road layout modification result with the slope of the open-pit mine and the bench design result. The application of the proposed method to an area containing gold deposits made it possible to design a haul road for open-pit mines such that it supported efficient truck haulage operations; furthermore, the time required for truck movement along the road could be estimated. The proposed method is expected to be useful for planning and designing open-pit mines and to facilitate the improvement of the road design function of existing mining software applications.

Keywords: haul road design; open-pit mine; least-cost path analysis; douglas-peucker algorithm; truck haulage operation

1. Introduction

Designing an efficient haul road for the movement of mining equipment in open-pit mines is of critical importance because the cost of transporting ore and waste can vary greatly depending on the road design results [1]. Many guides on road design in open-pit mines have been developed to date [1–5]. These guides describe the design of the width, slope, and curvature of haul roads to secure the safety of truck haulage operations, as well as road construction and maintenance procedures. However, one limitation of these guides is that they do not present a road design method capable of supporting efficient truck haulage operations over the entire lifecycle of an open-pit mine.

In recent years, computer designs have become generalized, and many software applications such as Autodes's AutoCAD Civil 3D (2017, San Rafael, CA, USA) [6], Dassault System's GEMS (2017, Paris, France) [7], Carlson's Civil and Mining Suites (2017, Maysville, KY, USA) [8], and Maptek's Vulcan (2017, Golden, CO, USA) [9] have been developed for the mining industry and are used for the design of open-pit mines. These applications provide features related to road design in open-pit mines. For example, AutoCAD Civil 3D can automatically design a road when design parameter values such as the topographic data of an open-pit mine, the road layout, the road width and slope, and the cut and fill slope are specified [10] (see Figure 1). GEMS enables the user to set the road slope, the horizontal and vertical distances, and the direction of progress (that is, in a direction to the left or right based on the selected bench) via the user interface, upon which the application designs the haul road segment interconnecting the top and bottom benches and presents the results in combination with three-dimensional (3D) topography [11]. Therefore, these software applications allow the haul road design of an open-pit mine to be performed more effectively and efficiently by applying the criteria suggested in existing guides. However, even when an open-pit mine is designed using these software applications, the user must determine the overall road layout, which is used as input data, by performing a separate analysis (see Figure 1). Since the mining software applications do not provide a feature for optimizing the road layout in open-pit mines to support efficient truck haulage operations, these tasks are mostly carried out by relying on the empirical and subjective judgment of mining engineers.

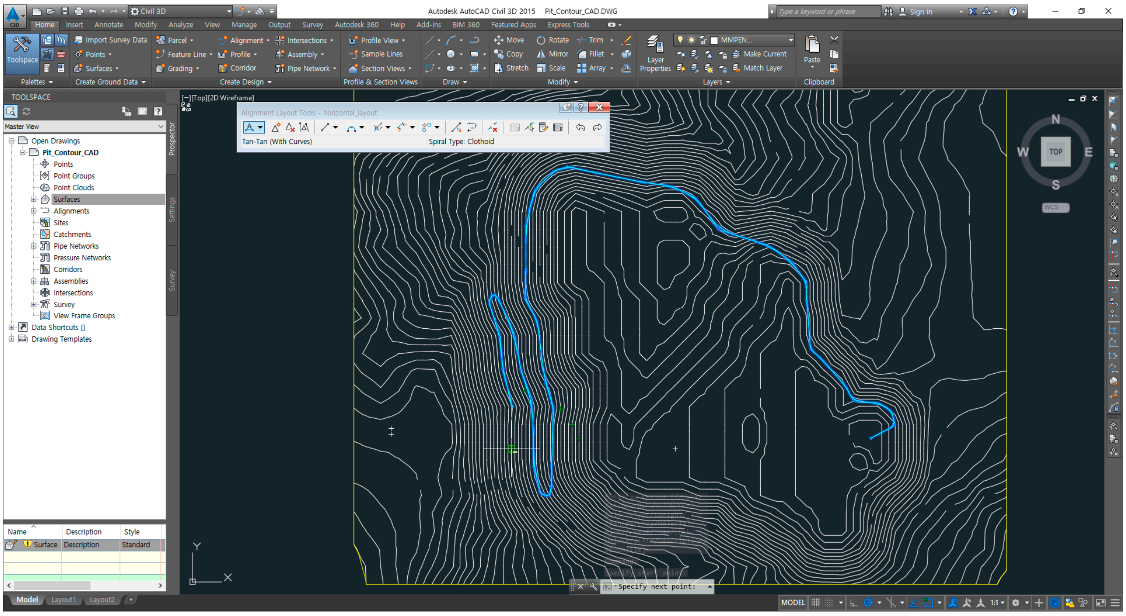

Figure 1. Example of haul road design for an open-pit mine using AutoCAD Civil 3D software.

The determination of the appropriate road layout in open-pit mines to support efficient truck haulage operations requires the application of a spatial optimization technique [12]. In this regard, raster-based least-cost path analysis (LCPA) is a representative spatial optimization technique used in a variety of fields [13]. This technique is useful for analyzing the optimum travel path that can minimize the cost (time, distance, resistance, fuel consumption, etc.) in an area with no travel path network such as roads and railroads [14,15]. The LCPA method consists of two steps [14]. First, the cost of passing every cell from the origin is calculated based on the cost surface data, which contains the cost of passing each cell, and these values are recorded in every cell [16]. Next, the least-cost path is derived using the back-link mechanism based on the calculation results of the accumulated travel cost recorded in all cells [17]. A detailed explanation of the raster-based LCPA method was published by Etherington [18].

The raster-based LCPA method has mainly been used to analyze and determine the optimum path at the local scale such as paths for a pipeline [19], mountain climbing [20], a temporary haulage road interconnecting a mine and a port [21], a power line [22], material transportation at a construction site [23], and an expressway [24]. Recently, studies were conducted to optimize truck haulage paths by applying the raster-based LCPA to open-pit mines. Choi et al. [12] determined the optimum travel path of waste haulage trucks by considering the speed, closeness to water bodies and ore bodies, visibility, etc. in a complex manner through LCPA. Choi and Nieto [25] developed a new LCPA algorithm to analyze the travel path that minimizes the movement time or fuel consumption of trucks in open-pit mines. However, studies of methods to optimize the road layout by applying the raster-based LCPA method to open-pit mines in which a road does not yet exist and the application of the results to road design in the planning or design stage have not yet been reported.

The purpose of this study is to propose a new method for designing a road capable of supporting efficient truck haulage operations in open-pit mines that are in the planning or design stage, i.e., for situations in which physical roads are entirely absent. To that end, an efficient road layout to minimize the truck movement time is determined by applying the raster-based LCPA method to the final pit analysis and bench design data for open-pit mines. The zigzag-shaped travel path obtained by the LCPA is simplified using the Douglas-Peucker algorithm [26], in line with the actual road, and the road layout is modified by applying the radius of curvature limitations of the roads presented in existing guides [1–5]. Finally, a 3D model, which reflects the road design results, is created by combining the topographic model and the result of the road layout design that reflects the final pit analysis and bench design results. This paper presents the principles and application procedure of the developed road design method and the results of a case study of a haul road that was designed for an open-pit gold mine in the OO area.

2. Problems with the Determination of Road Layout by Raster-based Least-Cost Path Analysis

Analyzing a road layout by applying the raster-based LCPA method to the final pit analysis and bench design results of an open-pit mine can lead to the following problems. First, zigzag-shaped travel paths can be generated from the road layout analysis (see Figure 2). When the least-cost path is analyzed in a raster structure, the layout is determined by connecting adjacent cells in the orthogonal direction (i.e., in the horizontal and vertical directions) and diagonal direction from the cell at the origin to that at the destination, which results in a zigzag-shaped travel path. This problem was described in detail by Tomlin [27]. Second, the result of the road layout analysis does not reflect the radius of curvature condition of the road, presented in existing mining design guides. Haulage roads that do not consider the radius of curvature reduce the efficiency of haulage operations and pose safety problems. Therefore, the above-mentioned problems should be solved before applying the raster-based LCPA method to analyze the haul road layout in open-pit mines.

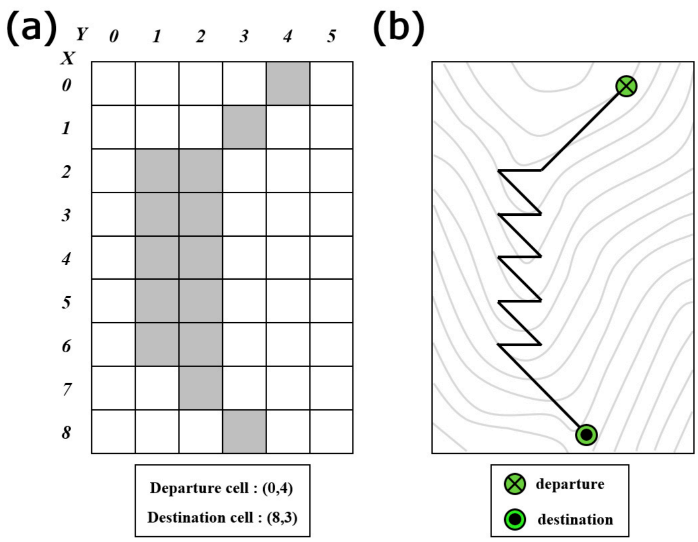

Figure 2. Example of a zigzag-shaped path obtained by least-cost path analysis. (**a**) Least-cost travel path analyzed with a raster surface; (**b**) Result of converting the travel path with a raster structure into a path with a vector structure.

3. Methods

The method that was developed in this study for designing roads for open-pit mines consists of five steps in total (see Figure 3). First, the final pit of the open-pit mine is analyzed, and the bench is designed. The 2D road layout is analyzed through the LCPA using the mine design data, and the zigzag-shaped road layout is simplified appropriately for the actual road design using the Douglas-Peucker algorithm. Next, the road layout is modified considering the limiting condition of the radius of curvature suggested in the existing guides. Finally, a 3D mine topographic model is produced by combining a 3D topographic model of the open-pit mine, including a bench design with a 2D road layout design result.

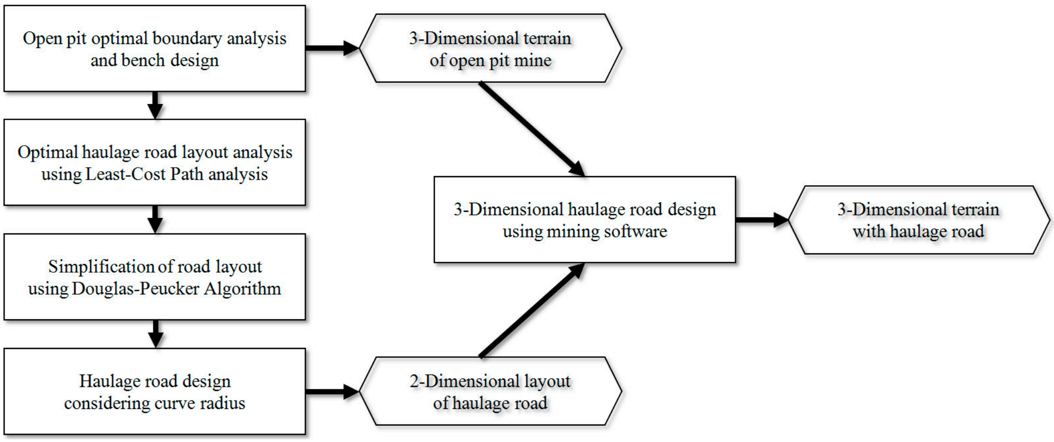

Figure 3. Study process of haul road design for open-pit mines using the proposed method.

3.1. Optimal Boundary Analysis and Bench Design in Open-Pit Mines

The optimal boundary analysis of an open-pit mine consists of two steps. First, the economic value of every block comprising the model of the ore body is calculated by considering various parameter values such as the mineral cost, recovery, and production cost. Next, the pit boundary that maximizes the production profit is analyzed by entering the calculated economic value of every block into an open-pit mine boundary optimization algorithm such as the Lerchs-Grossmann [28], Korobov [29], and Floating Cone [30,31] algorithms. After analyzing the optimal boundary of the open-pit mine, the bench of the open-pit mine is designed. The design parameters for the bench include the height, width, and face angle of the bench (see Figure 4). The bench height should be designed by considering the workable height of the excavation equipment used in mines, which is typically designed in the range of 10–18 m in large mines. The bench width should be designed to be sufficiently wide enough to prevent stones from the top bench from continuously falling onto the bottom bench. Equation (1) represents the correlation between the bench width and height empirically [32].

$$\text{Bench width (m)} = 0.2 \times \text{Bench height (m)} + 4.5\ \text{(m)} \tag{1}$$

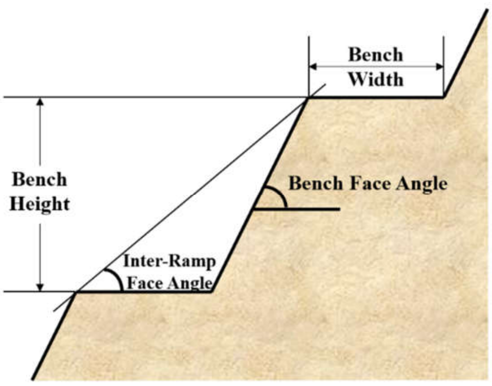

Figure 4. Bench geometries used in bench design.

3.2. Road Layout Analysis Using LCPA

Researchers have developed various LCPA methods to derive the least-cost path between the point of departure and the destination. Representative examples include methods for deriving the least cost path by integrating multiple influencing factors [16,33], for deriving a new optimal path considering existing physical roads [15,34], for increasing the number of movable cells to avoid the formation of zigzag-shaped roads [35], and for searching for the optimum path by considering vertical influencing factors such as terrain slope and horizontal influencing factors such as wind direction and strength [13,14,36,37]. The present study analyzes the road layout in open-pit mines by using the LCPA algorithm proposed by Choi and Nieto [25]. This method is appropriate for the road layout optimization in open-pit mines or construction sites because it allows for consideration of the terrain slope (vertical friction) and the rotational angle of trucks, both of which greatly affect the travel time and fuel consumption of dump trucks.

The input data required for the LCPA method include the topographic data of the mine, the point of departure and destination, the cost map, and the vertical and horizontal factor models. The final pit analysis and bench design data can be used as the topographic data of an open-pit mine in the planning and design stage. The input type of the mine terrain is a digital elevation model (DEM) that assigns the terrain altitude to grids divided into the same size. The departure point of the truck was set as the area at the bottom of the open-pit mine, and the destinations of the truck were set as the respective entrances to the stockpile and the waste dump, where the ore and waste are unloaded. The place of departure and the destination are entered as points. The cost map takes the form of raster data, which is the cost of moving by a unit of distance recorded in every grid. The types of costs generated when the trucks move include the truck travel time, physical distance, fuel consumption, risk, and resistance.

The Vertical Factor model calculates the weights for terrain slopes (see Figure 5a). Haul roads with a slope greater than the slope limit make it difficult to run trucks stably and increase the travel time and fuel consumption of trucks. Therefore, the terrain slope must be considered in order to design a haul road with a slope that does not exceed the slope limit. The appropriate slope limit for haul roads is 8% to 11% (approximately 5° to 6°) and should be determined by considering the performance and efficiency of trucks used in the mine [5]. The Vertical Factor model assigns an infinite weight to terrain slopes exceeding the slope limit (see Figure 5b). The Horizontal Factor model calculates weights for the rotational angle of trucks (see Figure 5c). The weight of a rotational angle is determined by considering the difference between the angle of the path entering Cell C and the angle of the path leaving Cell C. The Horizontal Factor model assigns an infinite weight when the angle difference exceeds the angle limit (see Figure 5d).

The 2D haul road layout is analyzed through the LCPA using the generated input data (see Figure 6).

First, the cell containing the departure point is set as the current processing cell, and the travel costs incurred when the truck moves from the current processing cell to the neighboring cells in the orthogonal and diagonal directions are calculated using Equation (2). The travel cost calculations are divided into the orthogonal and diagonal directions when moving to the neighboring cells.

$$Cost_{C\to N} = \begin{cases} 0.5 \times \sqrt{{D_0}^2 + (Elv_N - Elv_C)^2} \times VF_{C\to N} \times (C_C \times HF_{C\to N} + C_N) & \textit{Orthogonal connection} \\ 0.5 \times \sqrt{\left(D_0 \times \sqrt{2}\right)^2 + (Elv_N - Elv_C)^2} \times VF_{C\to N} \times (C_C \times HF_{C\to N} + C_N) & \textit{Diagonal connection} \end{cases} \quad (2)$$

In the above equation, $Cost_{C\to N}$ is the cost for moving from the current processing cell to the neighboring cell, $C_C(C_N)$ is the cost for passing the current processing cell (neighboring cell), D_0 is the cell size (m), $Elv_C(Elv_N)$ is the altitude of the current processing cell (neighboring cell) (m above sea level), $VF_{C\to N}$ is the vertical factor for moving from the current processing cell to the neighboring cell, and $HF_{C\to N}$ is the horizontal factor for moving from the current processing cell to the neighboring cell.

Once the travel cost is calculated, the least accumulated travel cost of the neighboring cells is calculated with Equation (3). If the calculated accumulated travel cost is smaller than the previously recorded accumulated travel cost, it is recorded again with the new calculated value. Otherwise, the previously recorded accumulated travel cost is maintained.

$$acCost_N = \begin{cases} acCost_C + Cost_{C\to N} & \text{if } acCost_C + Cost_{C\to N} < acCost_N \\ acCost_N & \text{if } acCost_C + Cost_{C\to N} \geq acCost_N \end{cases} \quad (3)$$

In the above equation, $acCost_N(acCost_C)$ is the accumulated travel cost of the neighboring cell (current processing cell). The cell that has the smallest value for the accumulated travel cost among all cells is selected as the new current processing cell, and then the accumulated travel costs of the neighboring cells of the current processing cell are calculated. The calculation of accumulated travel cost is repeated until the least accumulated travel cost is determined for every cell.

The least cost path is traced through the back-link mechanism proposed by Xu and Lathrop [17] using the least accumulated travel cost data calculated in the previous step, back-link data, and the destination. The 2D haul road centerline is formed by converting the analyzed road layout into a vector structure.

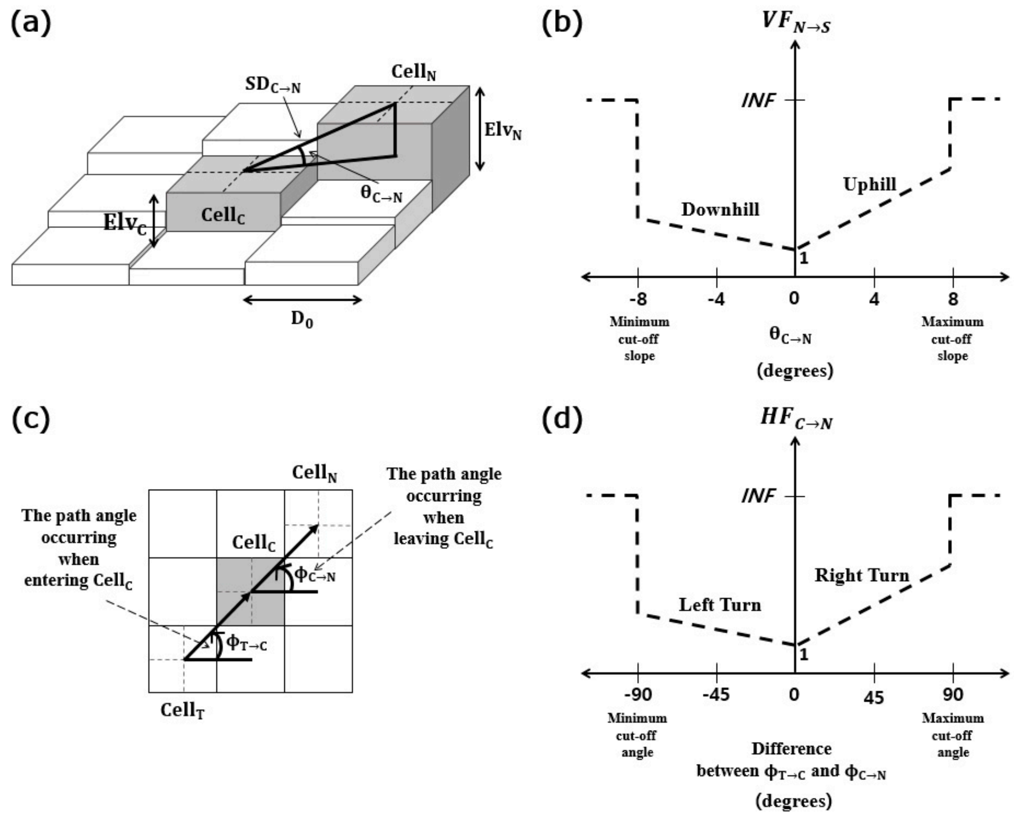

Figure 5. Concept of factors used for calculating travel cost. (**a**) Example of calculating slope gradient occurring when connecting the center cell ($Cell_C$) and a neighboring cell ($Cell_N$). $SD_{C\to N}$ is the 2,5-dimensional physical distance (m) between the centers of Cell C and Cell N. Elv_C (Elv_N) is the elevation (m above sea level) of Cell C (Cell N). $\theta_{C\to N}$ is the slope-gradient (degrees or percent) occurring when connecting the center of the Cell C and the center of the Cell N. D_0 is the cell size (m); (**b**) Vertical factor graph according to the slope gradient; (**c**) Example of calculating the difference between the path angle ($\phi_{T\to C}$) occurring when entering Cell C and the path angle ($\phi_{C\to N}$) occurring when leaving Cell C; (**d**) Horizontal factor graph according to the difference between $\phi_{T\to C}$ and $\phi_{C\to N}$.

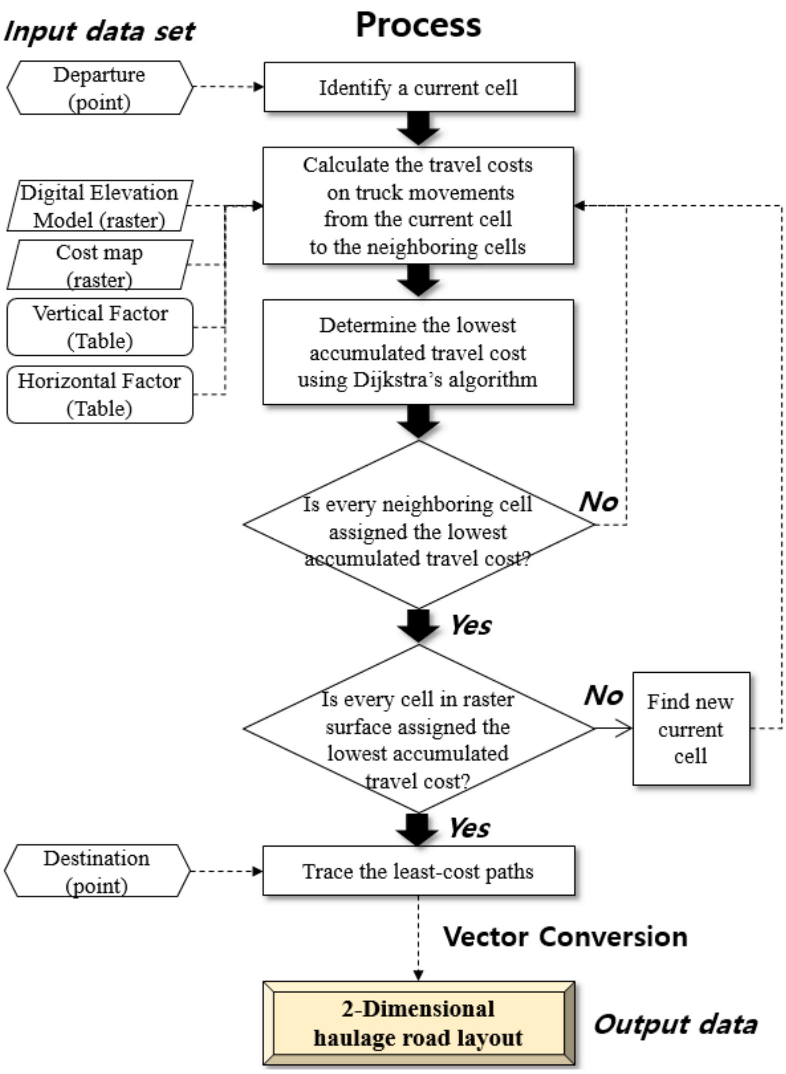

Figure 6. Procedure for generating 2D haulage road layout using the least-cost path analysis (LCPA) technique.

3.3. Simplification of Road Layout Using the Douglas-Peucker Algorithm

The application of line simplification algorithms is needed to convert the zigzag-shaped travel path into a form that is appropriate for actual road design. The representative line simplification algorithms include the Lang simplification algorithm [38], the Reumann-Witkam routine [39], the Opheim simplification algorithm [40], the Visvalingam and Whyatt algorithm [41], and the sleeve-fitting polyline simplification algorithm [42]. In the present study, the layout of the haul road is simplified by applying the Douglas-Peucker algorithm [26], which is regarded as having the least errors and the highest accuracy among the many algorithms [43].

The Douglas-Peucker algorithm, which is a representative global simplification algorithm that simplifies lines by considering them globally, is implemented in many Geographic Information System (GIS) software packages and cartography software applications [43]. The principle of this algorithm is as follows (see Figure 7). The original line consists of nine vertices in total (see Figure 7a), and V, which is a set of vertices, can be expressed as follows:

$$V = \{v_0, v_1, v_2, \cdots, v_8\} \quad (4)$$

First, among the vertices comprising the line, the initial simplified line is formed by interconnecting the first vertex v_0 and the last vertex v_8 (see Figure 7b). Next, the perpendicular distance between every vertex, the initial simplified line, and every calculated value is compared with the user-defined tolerance (ε) (see Figure 7c). If every calculated perpendicular distance is smaller than the tolerance, the vertices excluding the first vertex and the last vertex are deleted, and the initial simplified line becomes the final simplified line. If any perpendicular distance exceeds the tolerance, the vertex (v_3) that has the largest perpendicular distance is set as the new vertex of the initial simplified line (see Figure 7d), and a new simplified line passing the vertex v_3 is formed (see Figure 7e). The above-mentioned procedure is repeated for the newly formed simplified line (see Figure 7f). The simplification process finishes when the perpendicular distance calculated at every vertex is smaller than the tolerance (see Figure 7g). The final simplified line becomes the current simplified line and includes four vertices; v_0, v_3, v_4, and v_8 (see Figure 7h).

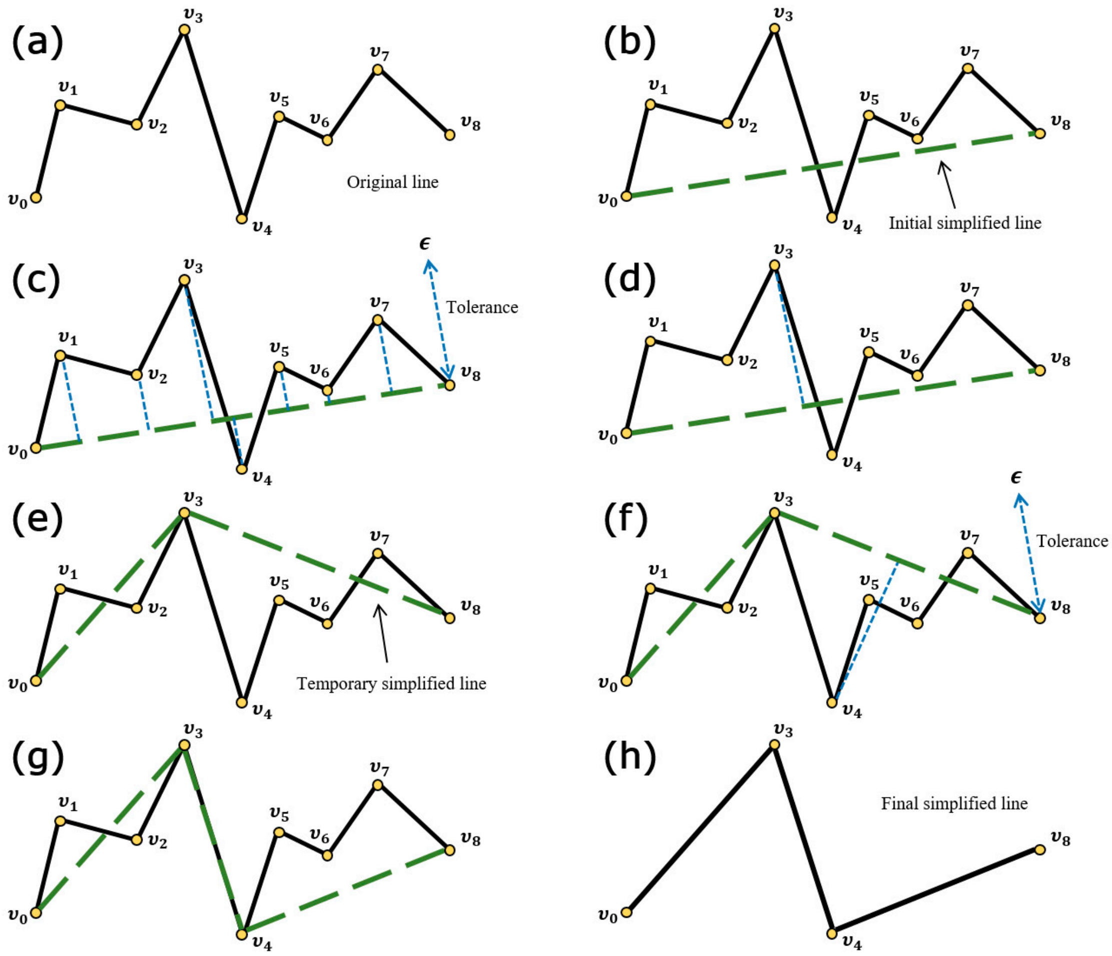

Figure 7. Procedure of line simplification using the Douglas-Peucker algorithm.

3.4. Modification of Road Layout Considering the Radius of Curvature Constraints

The radius of curvature must be considered when determining the horizontal layout of the haul road. If a sufficient radius of curvature is not considered, the travel time and cost could be increased due to a decrease in the operational stability of a truck. If a sufficient radius of curvature is obtained, a stable truck speed can be maintained and the wear of truck wheels can be reduced, thereby enabling an efficient haulage operation.

The radius of curvature should be designed in such a manner that the centrifugal force on the truck during rotation and the friction between the truck tire and road surface are balanced (see Figure 8a).

The equation for the minimum radius of curvature that should be considered when designing a road is as follows [2]:

$$R = \frac{V^2}{127(e+f)} \quad (5)$$

where R is the radius of curvature (m), V is the vehicle speed (km/h), e is the super-elevation rate (m/m), and f is the friction coefficient between the tire and road surface. The vehicle speed means the maximum speed when the truck runs on a downward slope without a load. Super-elevation refers to the degree of banking along one edge of a road (see Figure 8b). Applying the difference in altitude at both edges of the road decreases the centrifugal force on the truck during rotation and allows the truck to rotate stably. The super-elevation should be designed not to exceed 5%–7% (approximately 3°–4°) [5]. Kaufman and Ault [2] proposed super-elevation on a haul road according to the radius of curvature and vehicle speed (see Table 1). The friction coefficient varies according to the road surface and is assumed as 0.3 if the surface is sandy and soft or muddy or as 0.45 if the road surface partially consists of gravel [5].

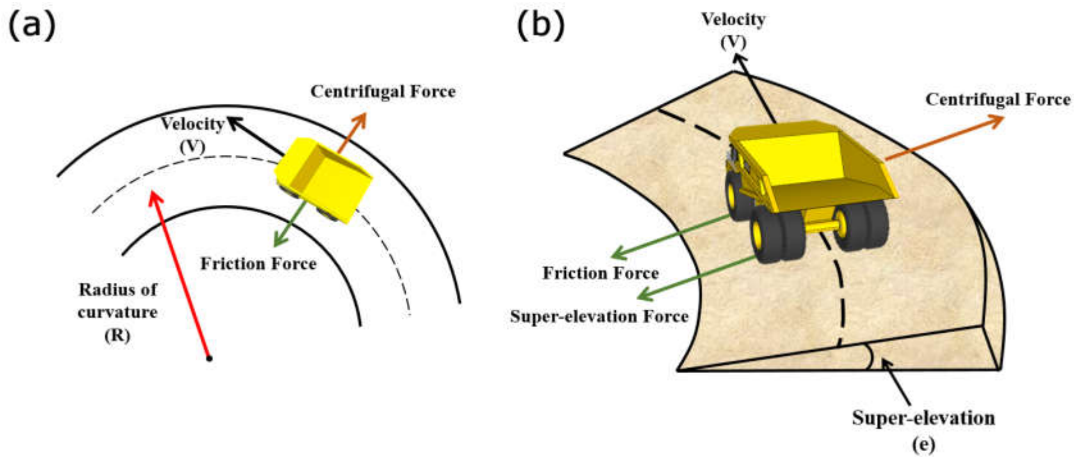

Figure 8. Schematic representation of road geometries showing the (**a**) radius of curvature when the dump truck turns and (**b**) cross-sectional view of the road showing the super-elevation.

Table 1. Super-elevation of the haul road according to the radius of curvature and the vehicle speed [2].

Radius of Curvature (m)	Speed (km/h)				
	24	32	40	48	>56
15	4% (≈2°)				
30	4% (≈2°)	4% (≈2°)			
45	4% (≈2°)	4% (≈2°)	5% (≈2°)		
75	4% (≈2°)	4% (≈2°)	4% (≈2°)	6% (≈3°)	
90	4% (≈2°)	4% (≈2°)	4% (≈2°)	5% (≈3°)	6% (≈3°)
180	4% (≈2°)	4% (≈2°)	4% (≈2°)	4% (≈2°)	5% (≈3°)
300	4% (≈2°)	4% (≈2°)	4% (≈2°)	4% (≈2°)	4% (≈2°)

3.5. Three-Dimensional Haul Road Design Using Mine Design Software

Mine design software is used to integrate the vertical alignment and sectional elements of the haul road to form a 3D haul road. The vertical alignment design of a haul road is conducted to analyze the profile of the terrain on which the haul road is to be formed and to design the optimum vertical layout (see Figure 9a). The sectional element design of a haul road is carried out to design the road width, super-elevation, cut and fill slope, safety berm, and ditch (see Figure 9b). The road width should be designed on the basis of the equipment with the largest width among the haulage equipment used in a mine and may vary by the number of lanes. The equation used to determine the haul road width is as follows [3]:

$$W = (1.5 \times L + 0.5) \times X \quad (6)$$

where W is the width of the haul road, L is the number of lanes, and X is the width of haulage equipment. The safety berm prevents trucks from careering over the edge, which may occur when a truck filled with ore or waste runs at a fast speed, and it also enables the driver to recognize the lanes. The minimum height of the safety berm should be at least two thirds of the tire diameter of the haulage equipment, and the appropriate slope gradient is 3H:1V. The ditch is a structure to facilitate the drainage of water in the mine to allow the safe operation of trucks. The most appropriate slope gradient is 4H:1V [5].

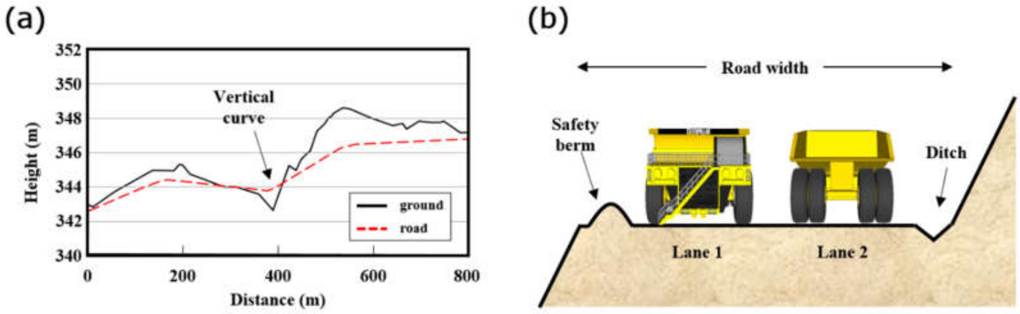

Figure 9. Conceptual view of factors to be considered when generating a 3D haul road. (**a**) Cross section of a haul road showing the height (solid line) of the ground and the vertical layout (dashed line); (**b**) Road geometry showing a cross section of the road

4. Case Study

4.1. Study Area and Data

The proposed road design method for open-pit mines was tested by designing the road for an open-pit mine. Land containing a gold deposit located in the OO area was selected as the study area. The size of the study area was 430 m × 980 m, and the gold-carrying ore body existed in an elongated shape in the N-S direction (see Figure 10). The average altitude above sea level is approximately 564 m, the terrain is relatively flat, and there is a mining town nearby. Thus, the area has the optimal infrastructure facilities required for mine development.

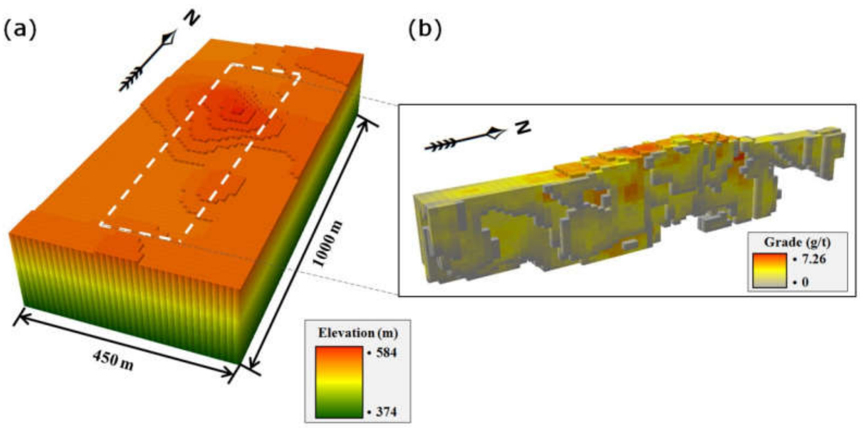

Figure 10. Three-dimensional view of the study area. (**a**) Block model of gold deposits; (**b**) Gold ore body marking the grade of gold.

The block model of the ore body that exists in this area is composed of blocks with the size of 12.5 m × 12.5 m × 6 m. The number of blocks is 36 in the x-axis direction (easting), 80 in the y-axis direction (northing), and 31 in the z-axis direction (elevation). The blocks are divided into ore and waste and include information about the mass and grade of the ore. The average grade of the gold ore body is 0.073 g/ton.

4.2. Creation of Input Data

Assuming that the gold ore body is to be developed as an open-pit mine, the optimum boundary of the open-pit mine was analyzed by applying the Lerchs-Grossmann algorithm, which is a representative boundary optimization algorithm for open-pit mines (see Figure 11a). Table 2 lists the factors and costs considered when calculating the economic values of all blocks comprising the gold ore body.

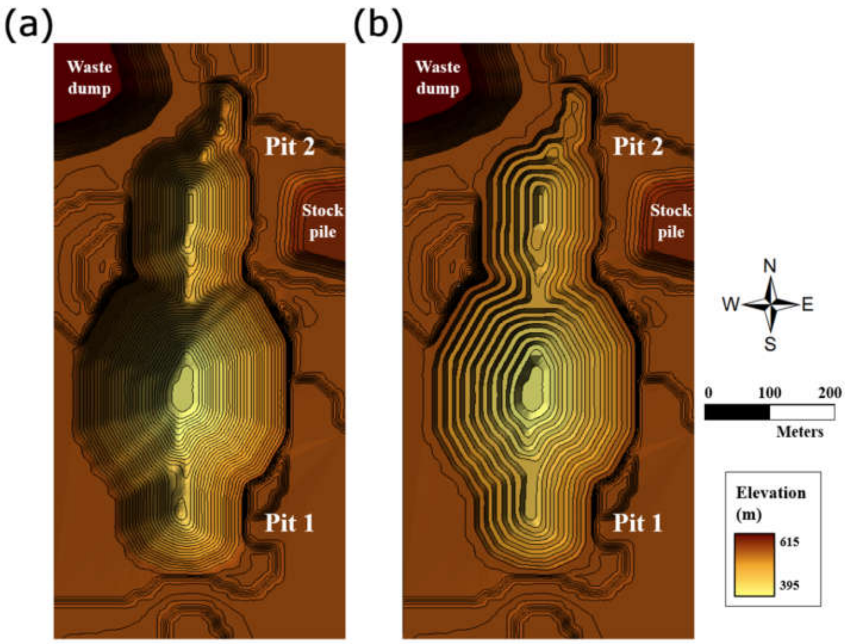

Figure 11. Result of the open-pit boundary analysis. (**a**) Optimum boundary showing the lower and upper zones (denoted Pit 1 and Pit 2); (**b**) Result of designing the bench, waste dump, and stockpile.

Table 2. Economic parameters and values for calculating the economic value of a block.

Economic Parameters	Value
Price of gold ($/ounce)	1300
Recovery (%)	90
Mining cost ($/tonne)	2.5
Selling cost ($/ounce)	35
Processing cost ($/ounce)	18
Revenue factor	1

The optimum boundary was analyzed as the connection of two mines. In addition, due to the shape of the ore body, a small mine was formed with a large vertical width in the N-S direction and a small horizontal width in the E-W direction. The maximum depths of Pit 1 and Pit 2 are 156 m and 96 m, respectively, and the overall slope of the mine is 45° (100%).

The bench inside the mine was designed by using the analysis result obtained for the optimum boundary of the mine. According to the mine design guide, the bench width was designed as 7.5 m, the bench height as 15 m, and the bench face angle as 63.4° (approximately 200%) (see Figure 11b).

In addition, the design located a stockpile on the eastern side of the mine to store the ore moved by trucks and a waste dump to the northwestern side of the mine.

The bench design result was converted to a DEM with a 5-m resolution (see Figure 12a). Two departure points were selected for the trucks: the working areas at the bottom of Pit 1 and Pit 2. Furthermore, two destinations were selected for the trucks: the respective entrances to the stockpile and the waste dump. The cost map was calculated by considering the time the dump trucks required to travel 1 m. We calculated the truck travel time by using the approximate change in the travel speed of a truck for the haul road slope in a large open-pit mine reported by Choi et al. [12] (Table 3). When the bench and haul road are constructed, the ground surface is excavated first based on the mine design results. Thus, the terrain slope was assumed as 0% (0°) and the truck speed as 25 km/h in the initial excavation step of the haul road. Therefore, the cost of all terrains was calculated as 0.14 s/m. When setting the road slope limit, the local characteristics of the mine and the gross vehicle weight used in the mine should be considered [3].

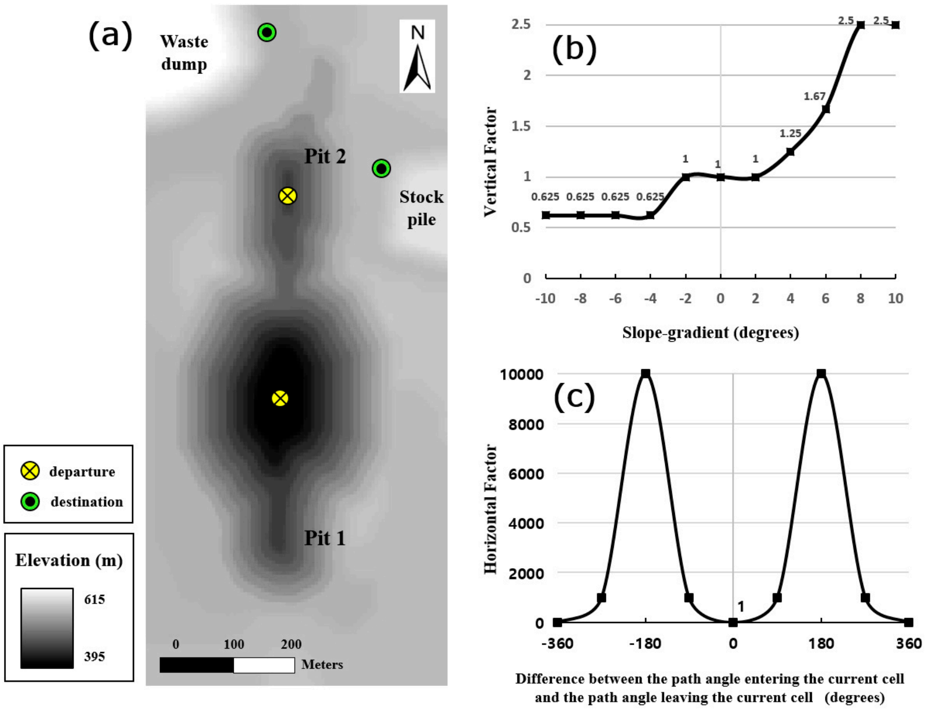

Figure 12. Input data set for least-cost path analysis. (**a**) Digital elevation model of the study area (resolution = 5 m). (**b**) Vertical factor graph. (**c**) Horizontal factor graph.

Table 3. Approximate speed of dump truck (100 ton) according to the slope-gradient of the haul road in an open-pit mine [12].

Haul Type	Grade (%)	Approximate Speed (km/h)
Full haul moving uphill	0–4 (≈0°–2°)	25
	4–8 (≈2°–5°)	20
	8–12 (≈5°–7°)	15
	over 12 (≈over 7°)	10
Empty haul moving downhill	0–4 (≈0°–2°)	25
	over 4 (≈over 2°)	40

The gold mine excavated in the study area is a small mine, the horizontal width of which is not large. Due to the local characteristics of the mine, a haul road with a relatively high slope should be designed to interconnect the bottom work site of the mine and the waste dump or the stockpile.

The small-sized haulage equipment used in a small mine has a lower maximum load weight compared to large haulage equipment. Thus, smaller equipment can be operated on a haul road with a higher slope. In this study, therefore, the road slope limit was set at 10° (approximately 18%) considering the local characteristics of the mine and the maximum load weight of small equipment. Furthermore, the Vertical Factor Model was formed, which has infinite weight in a terrain slope less than −10° and a terrain slope exceeding 10° (see Figure 12b). The weight for a terrain slope within the road slope limit is identical to the rate at which the travel time of the truck increases. The Horizontal Factor Model is set to assign infinite weight when the truck is moving in the direction opposite to the progress direction (that is, either −180° or 180°) (see Figure 12c). The weight was set as 1 if the truck continued to run in the same direction as before.

4.3. Optimization and Modification of Road Layout

Figure 13 shows the result of analyzing the 2D haul road layout with a slope limit of 10° (approximately 18%) through LCPA. It shows the haul road centerline, which connects the work sites at the bottom of Pit 1 and Pit 2 to the entrances of the waste dump and the stockpile, respectively. The haul road interconnects the lower work site of the mine and the upper earth surface in a spiral shape. The two haul roads departing from the lower work site of Pit 1 and Pit 2, respectively, are combined at one point near the earth surface and share the same path. A zigzag-shaped path was analyzed due to the limitation of the raster-based LCPA method.

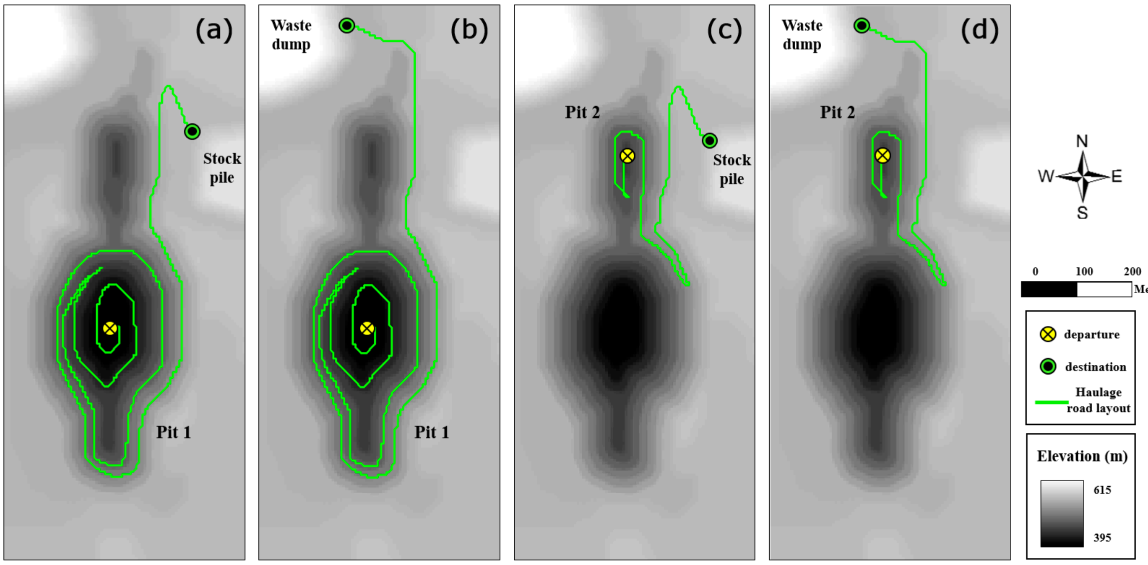

Figure 13. Haul road layout in the Pit 1 and Pit 2 areas analyzed by LCPA. The paths connect the loading point in Pit 1 with (**a**) the stockpile and (**b**) the waste dump and the loading point in Pit 2 with (**c**) the stockpile and (**d**) the waste dump.

Figure 14 shows the simplification of a zigzag-shaped haul road layout using the Douglas-Peucker algorithm. The tolerance used in the simplification work was set as 5 m, which is identical to the resolution of the DEM.

The radius of curvature was calculated using Equation (4). The maximum speed when the truck runs on a downward slope without a load was set at 40 km/h, as in Table 3. Furthermore, the super-elevation was assumed to be 4% (approximately 2°), and the friction coefficient was set at 0.3, assuming a sandy road surface. The substitution of the parameter values in the equation enabled us to calculate the radius of curvature as 37.6 m. Figure 15 shows the haul road layout modified by considering the radius of curvature.

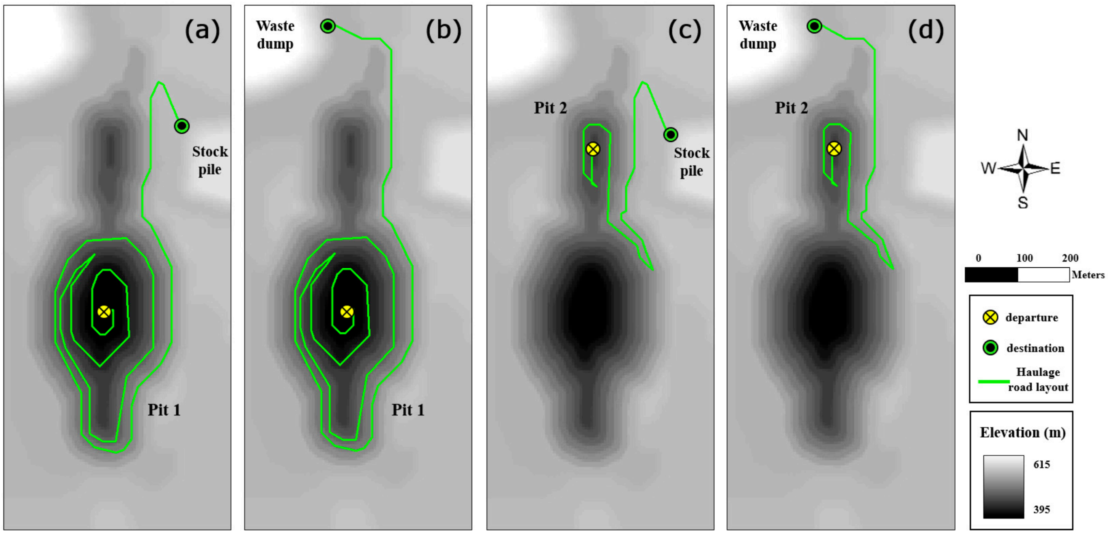

Figure 14. Simplification of haul road layout of Pit 1 and Pit 2. The paths connect the loading point in Pit 1 with (**a**) the stockpile and (**b**) the waste dump and the loading point in Pit 2 with (**c**) the stockpile and (**d**) the waste dump.

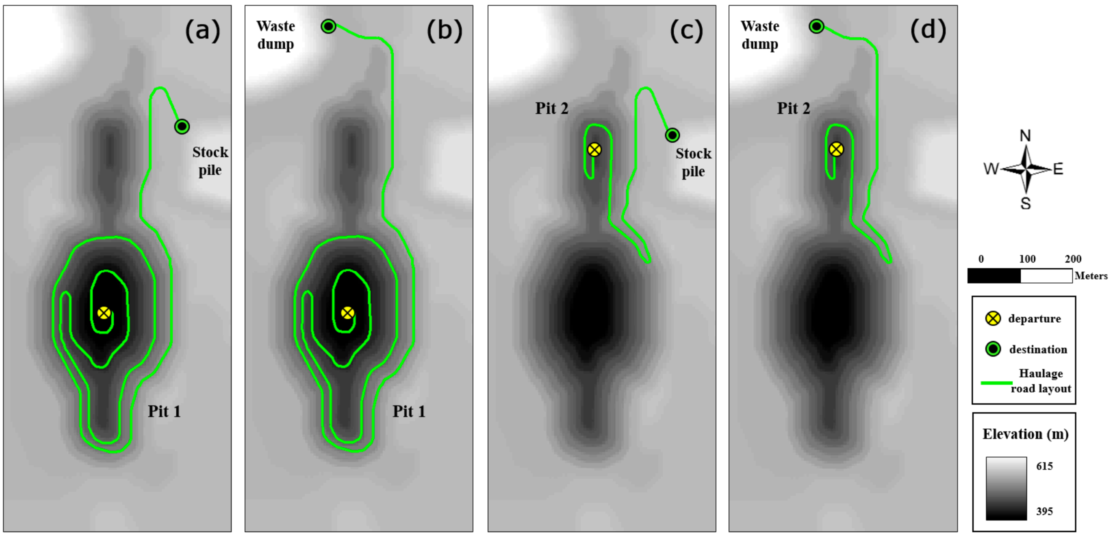

Figure 15. Results of modifying the road layout in Pit 1 and Pit 2 by considering the radius of curvature. The paths connect the loading point in Pit 1 with (**a**) the stockpile and (**b**) the waste dump and the loading point in Pit 2 with (**c**) the stockpile and (**d**) the waste dump.

4.4. Three-Dimensional Modeling and Visualization of Road Design Result

In this study, a 3D haul road was designed using the AutoCAD Civil 3D software of Autodesk. The 3D haul road was designed by using the 3D mine terrain formed in Section 4.1 and the 2D haul road layout analyzed in Section 4.2 as the input for the software. Figure 16 shows the terrain profile (solid line), showing the altitude of the haul road and the vertical alignment design result (dashed line) of the haul road. The vertical alignment of the haul road was designed in such a manner that the surrounding terrain would not be cut artificially. In other words, it was designed to fill in a new terrain for the difference in altitude between the haul road and the surrounding terrain. Considering that this is a small mine, one lane was assumed and the width of the small haulage equipment was assumed as 4 m. The width of the haul road was calculated as 8 m using Equation (4). The fill slope was designed to be identical to the bench surface slope.

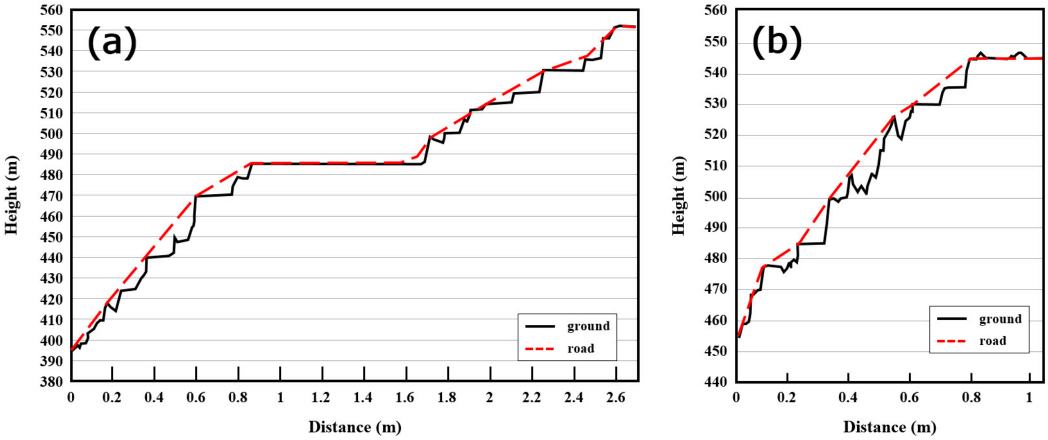

Figure 16. Results of analyzing the terrain profile (solid line) and designing the vertical layout (dashed line) of the haul road in (**a**) Pit 1 and (**b**) Pit 2.

Figure 17 shows the design result of the haul road of the open-pit mine and its 3D visualization that was obtained by combining the mine terrain model designed with benches and the result of the 3D haul road layout design. The interconnection between the lower and upper benches enables the smooth operation of haulage equipment. The lower terrain of the haul road was filled for the difference in altitude with the surrounding terrain to form a new terrain.

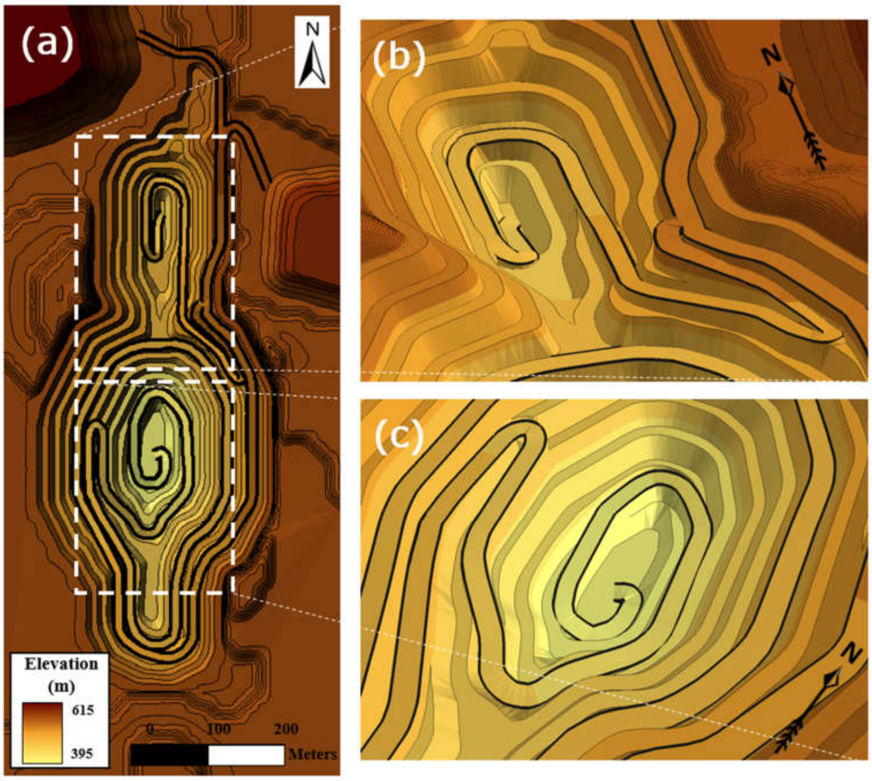

Figure 17. (**a**) Open-pit mine with bench and haul road. 3D views: (**b**) Pit 2 area, (**c**) Pit 1 area.

In this study, the haul road layout was re-analyzed by using LCPA to obtain a topographic model of an open-pit mine designed with a haul road. For the analysis, the 3D mine terrain designed with a haul road was converted to a DEM consisting of 5 m $\times$ 5 m grids. The departure point of the truck was set as the work site at the bottom of Pit 1, and the destinations of the truck were set as the respective entrances to the stockpile and the waste dump. Furthermore, the terrain slope of every cell comprising the DEM was calculated, and the cost map was created by assigning the travel time per unit distance of the truck to each cell according to the terrain slope. The vertical and horizontal factor models are shown in Figure 12.

Figure 18 shows the haul road layout analyzed through LCPA based on the 3D mine terrain model in Figure 17. The layout of this haul road has an almost identical path to the haul road layout in Figure 15. The approximate one-way travel time, travel distance, and speed of the truck could be estimated additionally by analyzing the haul road layout (Table 4). The travel time and distance calculated for the truck were higher and the travel speed of the truck was lower on the upward slope compared to the downward slope. The approximate haulage operation time in an actual mine can be estimated by using the one-way operation time data of the truck. Furthermore, our method enables a haulage operation plan in an open-pit mine to be established because the type, number, and combination of haulage equipment required in haulage operations can be determined.

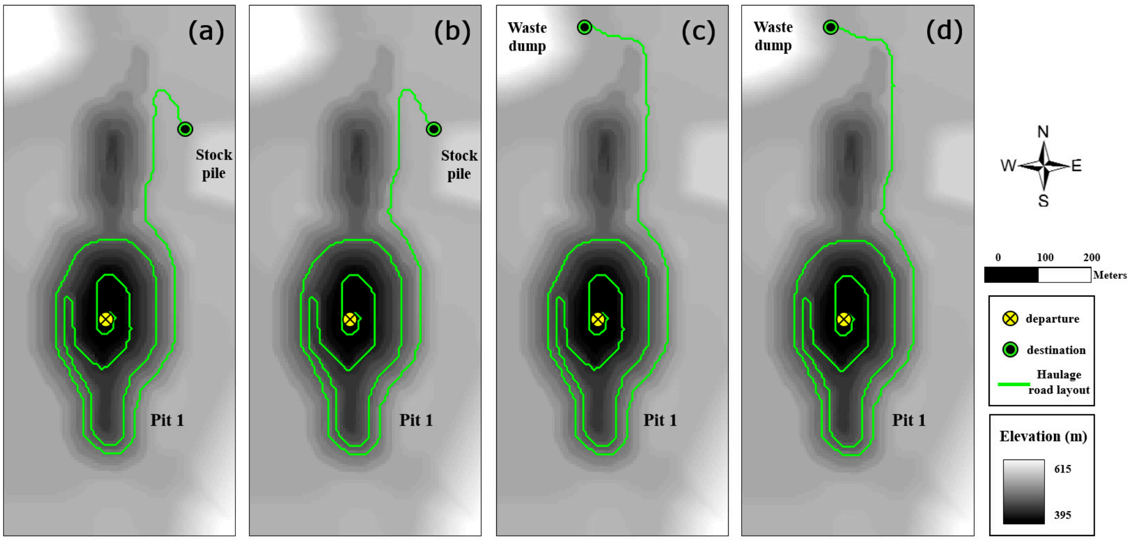

Figure 18. Result of analyzing the road layout based on the 3D terrain model shown in Figure 17, obtained using LCPA. The paths connect the loading point in Pit 1 with the stockpile when the truck moves (**a**) uphill and (**b**) downhill and also connect the loading point in Pit 1 with the waste dump when the truck moves (**c**) uphill and (**d**) downhill.

Table 4. Results of estimating the haulage time, haulage distance, and speed of the dump truck according to slope conditions.

Haulage Route From	To	Slope Condition	Haulage Time (min)	Haulage Distance (km)	Average Speed (km/h)
Pit 1	Stockpile	uphill	17.6	2.8	9.4
		downhill	11.7	2.8	14.1
	Waste dump	uphill	18.1	2.9	9.5
		downhill	12.4	2.9	13.8

5. Conclusions

A method for designing a haul road layout was proposed by considering the efficiency of truck haulage operations over the lifecycle of an open-pit mine. The haul road layout was analyzed by processing the terrain data with the final designs of the pit and bench obtained by the LCPA method. The zigzag haul road layout determined by the initial analysis was simplified by applying the Douglas-Peucker algorithm to obtain the actual road design, and the haul road layout was modified according to the radius of the curvature constraint presented in existing guides. Finally, the haul road of the open-pit mine was designed by using the terrain model of the mine together with the haul road layout as the input for AutoCAD Civil 3D and was visualized in three dimensions. The application of the proposed method to an area containing gold deposits made it possible to determine the slope limit of the haul road layout for the proposed open-pit mine as 10° (18%). Furthermore, it was possible to estimate the approximate work time, travel distance, and speed associated with haulage on the roads designed for the trucks.

The proposed method can resolve the problems (e.g., the zigzag path problem, the inability to consider the radius of curvature constraint) that occur when the haul road layout is determined with the conventional LCPA method only. As a result, our method enables us to not only analyze the optimum path for trucks moving along an existing road in open-pit mines at the production stage of their lifecycle, but also to design a haul road for an open-pit mine that is still in the planning and design stage and for which no road exists.

In open-pit mines, there are many obstructions such as trees, rocks, or other equipment, which reduce the drivers' visibility. The reduced visibility often incurs hazard situations for truck drivers. Therefore, in future work, it would be interesting to develop an extended method to consider the stopping and sight distances in designing the radius of curvature. The stopping distance of each vehicle is served by manufacturers, and methods for calculating sight distance can be found in the literature [1–5].

To construct haul roads in open-pit mines in the real world, it is crucial to select available construction materials for the pavement of a surface layer (i.e., the uppermost layer of the haul road). If the road pavement features are not suitable for driving, it may cause a decrease in the safety, efficiency, and productivity of haulage operations and an increase in the cost of maintaining the road. In other words, most of the benefits that are gained with the layout optimization will be lost. Several guides provide methods for selecting construction materials for the road pavement in open-pit mines [1–5,44–46].

The haul road layout determined by using our method can be used as the input data for road design by existing mining software. Furthermore, the estimation result for haulage operation time can be used to select the optimum type, number, and combination of haulage equipment, thus enabling the establishment of specific haulage operation plans for an open-pit mine in the production stage. Therefore, the proposed method can improve the road design and haulage operation planning functions for open-pit mines provided by existing mining software applications.

Furthermore, the proposed method can be used as a tool for the haul road layout design of civil engineering and construction sites in the planning and design stage, i.e., where no road exists, as well as for mining sites.

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