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Optimization of new roads path using a program based on A* algorithm

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Abstract: In highways engineering, finding the optimal path for a new road to join two-end points is a major challenge. This is due to presence of many complex and interrelated factors that should be taken in consideration beside a good balance between cost and geometric criteria. Many researches used models to optimize that problem and different algorithms to help designers to find the most economic and efficient path. Most of these models focus on either horizontal or vertical alignments resulting in a sub-optimal solution to the problem. In this paper, optimization of a new road path joining two end- points using heuristic techniques was studied. A* Algorithm which is considered one of optimization heuristic techniques, was used to write a programmed python script to find the target optimal path joining two end- points taking into consideration both design criteria and cost. The practical manual designed road of Toshka – El Oweinat was used as a case study to verify using of A* Algorithm in optimization of new roads path joining two end- points. By applying the model on the practical constructed road, It was found that the A* algorithm gives results with total cost less than the manual solution by about 2%.

Keywords: Highway design; Horizontal alignment; Vertical alignment; Heuristic algorithm; A* Algorithm.

1. INTRODUCTION

Technology has helped us in all engineering fields including methods of design, problems optimization, and even maps. When you request a road from one point (starting point) to another (destination point), the result is usually the "shortest path" from starting point to destination point, [1]. One of the main challenges facing planners and designers prior to road construction is developing a model for optimizing a new road's path. These models must be applied, which calls for the formulation of all necessary road construction costs, the modification of appropriate, usable algorithms, and the efficient use of geographic data. The manual solution by planning process is too slow, laborious, time-consuming, and expensive for relatively large-scale areas to solve this kind of problems. These solutions to these issues don't promise to be the best ones. Furthermore, it is nearly impossible to compare and analyze several potential plans created using manual techniques in an efficient manner, [2].

This complexity of choosing a path for a new road alignment connecting two given endpoints comes from the variety of complex and interrelated factors that the process depending on. Soil conditions, topography, environment and socioeconomic factors are important. The planner needs to meet all these factors in addition to satisfying a set of operational and design constraints. Traditional highway design necessitates experienced engineers to repeatedly evaluate various alternatives in order to identify the most promising one due to the complexity of the problem. Since there are countless options for connecting two highway end points, a manual design may produce a merely adequate result rather than a close to ideal one. The number of mathematical models for improving road alignments is excessive. The goal of the shortest path problem is to identify the shortest path or distance between vertices in a graph, in this case, a road network. An object in mathematics called a graph is made up of sets of vertices and edges, [3]. Finding the quickest route from one place to another is what is known as the shortest path problem. This problem is defined as finding the shortest (lowest-cost) route between two nodes [4] and [5]. In a graph with vertices connected by edges and each edge having a value or cost, the problem is to find the lowest cost path between two vertices, [6]. On the other hand, according to distribution process which is one of the marketing activities that helps producers send goods to customers. A producer serves a group of customers in an area during the distribution process. To meet each customer demand, a group of crews operates a group of vehicles located in a producer location known as a depot. In order to lower their overall operational transportation costs of distribution, the depot, as a producer, must identify an appropriate road network for the vehicles, [7]. Given an environment representation, there are various methods for computing paths. The most widely used methods are deterministic, heuristic-based algorithms [8] and [9] as well as randomized algorithms [10], [11], [12], and [13].

Because they offer limits on the quality of the solution path returned, deterministic algorithms are typically preferred when the dimension of the planning problem is low, for instance when the agent has few degrees of freedom [14]. [15] provided a description of a family of recently created heuristic - based path planning algorithms. The Dijkstra algorithm is a classic in the field of optimal path selection algorithms and calculates and selects the optimal path between nodes. The Dijkstra algorithm implemented and verified by experiments and practical applications, [16].

A literature review of mobile robot navigation and alternative path planning techniques was uncovered by [17]. As a result, several methodologies for solving the mobile robot path planning problem were presented and implemented. There are two types of optimization strategies for mobile robots: non - deterministic or classical approaches and deterministic or heuristic approaches. Classical methods include the Dijkstra algorithm, artificial potential fields, probabilistic roadmaps, and cell decomposition. Heuristic methods include fuzzy logic, neutral networks, particle swarm optimization, cuckoo search optimization, genetic algorithms, and artificial bee colonies. Figure 1 illustrates how optimization techniques used by many researchers are generally organized.

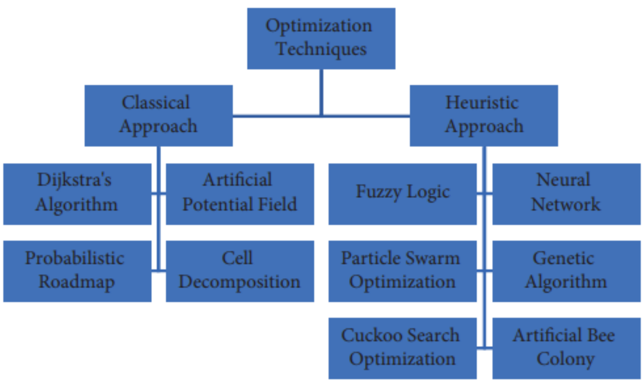

Fig 1: Selected optimization techniques used.

As a limited number of researchers used A* Algorithm, which is a heuristic algorithm in the field of artificial intelligence, in planning of roads. The use of the A* algorithm to optimize a new road path between two definite ends were introduced through this paper and verified with a practical case study.

2.A* Algorithm in path optimization

In this paper, one of the most effective path optimizing algorithms for solving a new road path problem was used. The A* algorithm is a heuristic algorithm in the field of artificial intelligence algorithms. The consistent road network information and the information of the known target ends are first introduced as part of the A* algorithm's optimization. When the explored ends are chosen, the end information is immediately called. In order to choose the end that will follow the next path, the function is then used to calculate the separation distance between the chosen end points. The benefit of the A* algorithm is that it avoids traversing all ends by moving along the desired road (the target end that needs to be encountered) in accordance with the chosen heuristic function.

A* algorithm works by a function that depends on the lowest cost path starting from a defined start point, going through other neighbor points to reach a final defined target point. What makes A* algorithm good at searching for optimum path solutions is that A* algorithm uses a function f(n) that calculate the total cost of total path estimation using that node. Then A* algorithm updates the total path cost while going throughout the points Therefore, A* algorithm uses a heuristic technique, which is a different technique than other path optimization algorithms. This technique makes A* algorithm gives better realistic solutions for path optimization problems and the basic formula of A* algorithm is expressed as:

$$f(n) = g(n) + h(n) \tag{1}$$

Where:

$f(n)$: is the total path cost for the node n.

$g(n)$: is the cost from the previous point to point n.

$h(n)$: roughly cost from point n to the final target point.(A heuristic part, so it is like a guess).

The only distinction between the A* algorithm and Dijkstra's algorithm is that the former uses a heuristic function to try to find a better path while the latter priorities nodes that are thought to be superior to others and the steps of A* algorithm are as follows:

.1- Set the starting point distance to be 0, and all other point distances to be infinity.

2- For each point, including the starting point, make a non-visited node.
3- The current node "C" should be the unvisited node with the shortest current distance.
4- Add the current distance of "C" with the weight of the edge connecting "C" - "N" and the weight to the destination point (heuristic) for each neighbour "N" of your current node. Make it the new current distance of "N" if it is less than the current distance of "N."
5- Indicate that node "C" is currently visited.
6- Up until one of the neighbours "N" is the final destination, repeat the previous steps from step 3 as necessary..

3.New Roads Construction Costs

It is necessary to thoroughly formulate all related construction cost factors in order to obtain the best highway route based on cost minimization. However these cost factors shouldn't have the same weight in the formula. The type of formulated factors and its weight in the formula plays a great role in alignment path selection. Different types of costs shall lead to different alignment configurations. For example, cost factors related to alignment length, vehicle operating characteristic and fuel consuming makes the alignment favor to be straighter with minimum total path length whereas cost factors related to geographical data makes the alignment tend to be more indirect.

Costs of new roads construction could be classified into three categories *i.e.* location costs, length costs and earthwork costs.

3.1 Location Costs:

Location costs include all costs related to geographical data, earth shape and then the quantities of cut and fill resulted from the formation of the road path levels. The less the earthworks is, the more economical the road is. There might be other location constrains that must be avoided such as archaeological areas, cemeteries and military areas. The road shouldn't go through these areas. Hydrological studies location recommendations also should be taken in consideration while determining a new road path.

3.2 Length Costs:

Length costs include all costs that depend on the total length of the alignment road. Some of these costs are directly related to road length such as road construction materials like base course, asphalt layers, curb installation and rain water drainage system. Other costs are indirectly related to road length such as environmental costs like air and noise pollution, oil extraction, fuel consumption and other Vehicle-operating. Therefore the shorter road length, the more economical it is. The shortest route is what we're looking for in order to satisfy the other requirements.

3.3. Earthwork Costs

By calculating the volume of rock and common material that must be moved in order to construct the road, the cost of the earthwork is determined. The earthwork production rate is calculated by dividing the required cubic metres per km by the maximum cubic meters per hour that can be dug and placed.

Road construction superintendents can frequently determine the number of meters per hour that their equipment can build a road after looking at the topography and using their local expertise. For calculating the amount of earthwork as a function of side slope, road width, and cut and fill slope ratios, the engineer employs formulas or tables. Bulldozers and hydraulic excavators have available production rates.

3.4 Roads Geometric Design Constrains:

When selecting a new road path, it must be imperative to meet the design criteria for horizontal and vertical road alignment. The most effective criteria in vertical design are minimum and maximum limits of grades. The maximum grade limits depend on the type of the road and its importance, the topography of the natural ground, road design speed, design vehicle type and its operating characteristics. On the other hand, the minimum grade limits should also be achieved in regions of flat terrain for rain water drainage purposes. According to AASHTO (1994), the sight distance and the algebraic difference between the road grades play a large role in determining the minimum vertical curve length.

The most important and critical variable in our model would be the proposed road slope between each two successive points in the points grid that represents the geographical survey of the study region. The slope limits and the maximum length on grade are as given in AASHTO.

4.Application of A* on Road Path Optimization Problem

By formulating all the factors that were previously stated, the used A* function in this study has three cases:

Case 1: If the natural ground slope is greater than the maximum upgrade slope in AASHTO ($S_n > S_d$), Figure 2, therefore it is a cut segment. In this case cost function between any two successive points in the grid P_n (X_n ,Y_n ,Z_n) and P_{n+1} (X_{n+1} , Y_{n+1} , Z_{n+1}) to reach a final target point P_f (X_f , Y_f , Z_f) would be formulated as follows:

$$f(n) = g(n) * \frac{Grid\ distance}{d} + f(n) * \frac{Grid\ distance}{\sqrt{(x_f - x_{n+1})^2 + (y_f - y_{n+1})^2}} \quad (2)$$

$$g(n) = \frac{1}{2} * d * (Z_{n+1} - Z_n - S_d * d) * w * C_{cut} + \sqrt{(x_{n+1} - x_n)^2 + (y_{n+1} - y_n)^2 + (S_d * d)^2} * w * C_{surface} \quad (3)$$

$$h(n) = \sqrt{(x_f - x_{n+1})^2 + (y_f - y_{n+1})^2 + (z_f - z_{n+1})^2} * C_{surface} \quad (4)$$

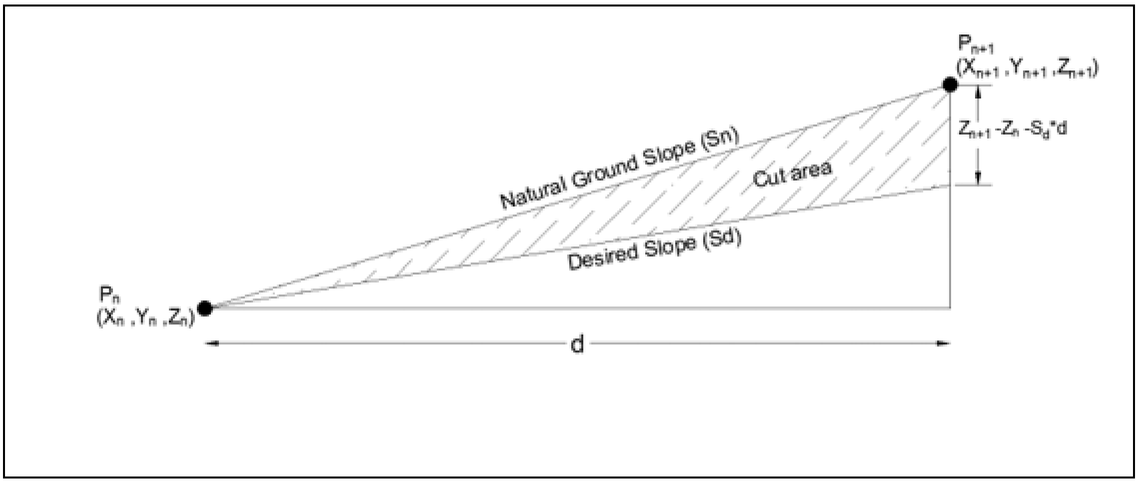

Fig 2 The natural ground slope is greater than the maximum upgrade slope

Where:

d : Horizontal distance between the two points, $d = \sqrt{(x_{n+1} - x_n)^2 + (y_{n+1} - y_n)^2}$.

S_n : Natural ground slope, $S_n = \frac{Z_{n+1} - Z_n}{d}$.

S_d : Desired design slope of road.

w : Road width.

C_{cut}: Unit cost of cut (£/m^3).

$C_{surface}$: Unit cost of pavement layers, base, MC, binder, RC and asphalt (£/m^2).

Case 2: If the natural ground slope is less than the maximum downgrade slope in AASHTO (S_n<S_d), Figure 3, therefore it is a fill segment. In this case cost function between any two successive points in the grid P_n (X_n ,Y_n ,Z_n) and P_{n+1} (X_{n+1} , Y_{n+1} , Z_{n+1}) to reach a final target point P_f (X_f , Y_f , Z_f) would be formulated as follows:

$$f(n) = g(n) * \frac{Grid\ distance}{d} + f(n) * \frac{Grid\ distance}{\sqrt{(x_f - x_{n+1})^2 + (y_f - y_{n+1})^2}} \quad (5)$$

$$g(n) = \frac{1}{2} * d * (Z_n - Z_{n+1} - S_d * d) * w * C_{fill} + \sqrt{(x_{n+1} - x_n)^2 + (y_{n+1} - y_n)^2 + (S_d * d)^2} * w * C_{surface} \quad (6)$$

$$h(n) = \sqrt{(x_f - x_{n+1})^2 + (y_f - y_{n+1})^2 + (z_f - z_{n+1})^2} * C_{surface} \quad (7)$$

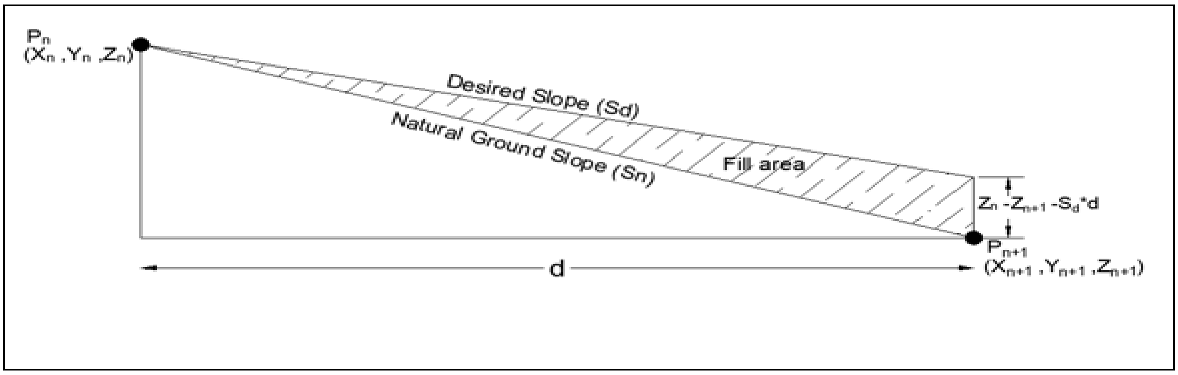

Fig 3 The natural ground slope is less than the maximum downgrade slope

Where: C_{fill}: Unit cost of fill (£/m^3).

Case 3: If the natural ground slope is within the allowable design slope in AASHTO therefore earthwork can be neglected in this sector of road. In this case cost function between any two successive points in the grid P_n (X_n ,Y_n ,Z_n) and P_{n+1} (X_{n+1} , Y_{n+1} , Z_{n+1}) to reach a final target point P_f (X_f , Y_f , Z_f) would be formulated as follows:

$$f(n) = g(n) * \frac{Grid\ distance}{d} + f(n) * \frac{Grid\ distance}{\sqrt{(x_f - x_{n+1})^2 + (y_f - y_{n+1})^2}} \quad (8)$$

$$g(n) = \sqrt{(x_{n+1} - x_n)^2 + (y_{n+1} - y_n)^2 + (S_d * d)^2} * w * C_{surface} \quad (9)$$

$$h(n) = \sqrt{(x_f - x_{n+1})^2 + (y_f - y_{n+1})^2 + (z_f - z_{n+1})^2} * C_{surface} \quad (10)$$

5.Results of A* algorithm with Practical Case Study of Toshka – El Ewinat Road.

Toshka El Ewinat road is a major road in Egypt that connects two ends. The first one is at Toshka Project (386878.39, 24370.1, 249.25), a large agricultural project located in the southern part of the country. The second end is at the El Ewinat area in the New Valley Governorate (501878.39, 24370.1, 207.88). The road is used by trucks and other heavy vehicles to transport goods, equipment and people to and from Toshka Project. The road is approximately 130 kilometers long, 26 meters width (23 m asphalt carriageway + two 1.5 m earthen shoulders) as shown in Figure 4. The road construction was from September 2020 to April 2022 as a part of Toshka Project.

A grid contains a cloud of points that represents the natural ground would be used as input for A* algorithm to work on as shown in Figures (5 to 7). The distance between the grid points is 2.5 Km x 2.5 Km which is based on the AASHTO charts of the maximum length on grade.

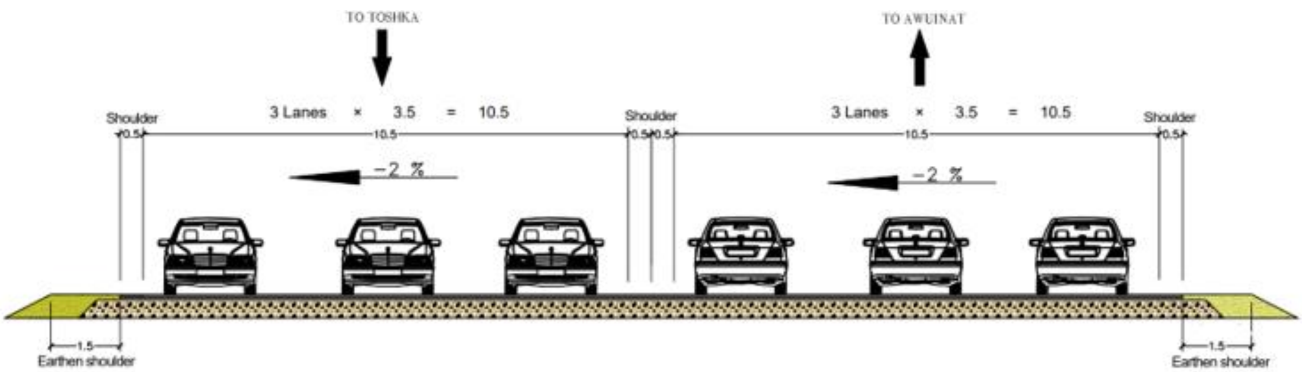

Fig 4 Typical cross section of Toshka – El Owainat Road

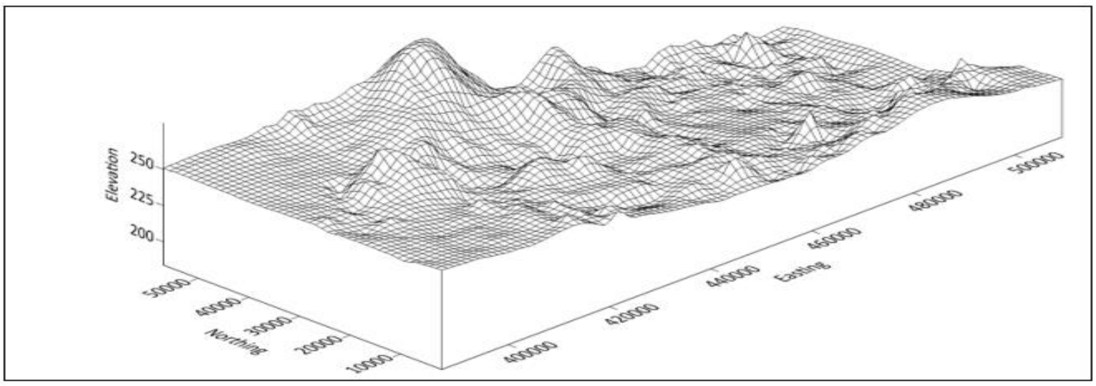

Fig 5: Grid shape of the used practical area

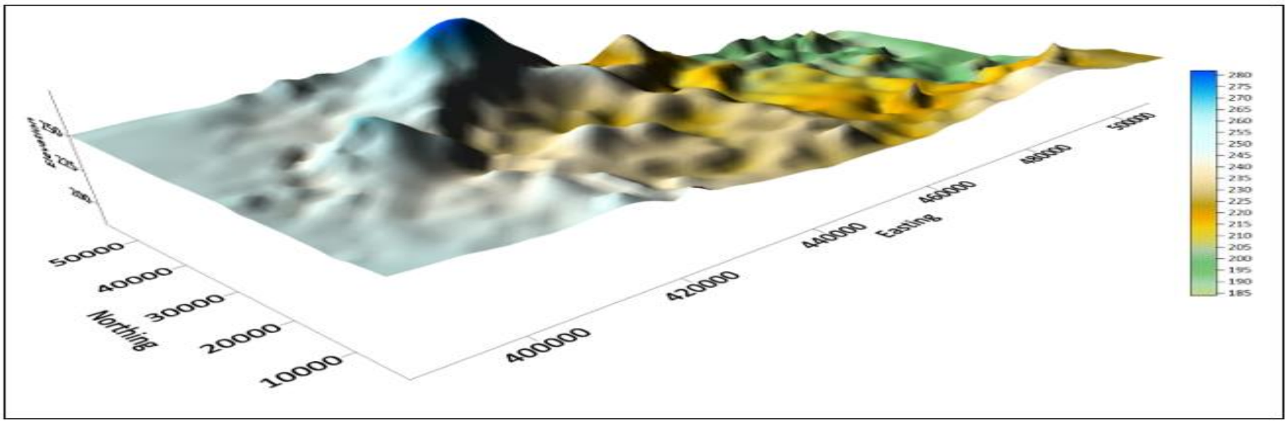

Fig 6: Topographic shape of the used practical area

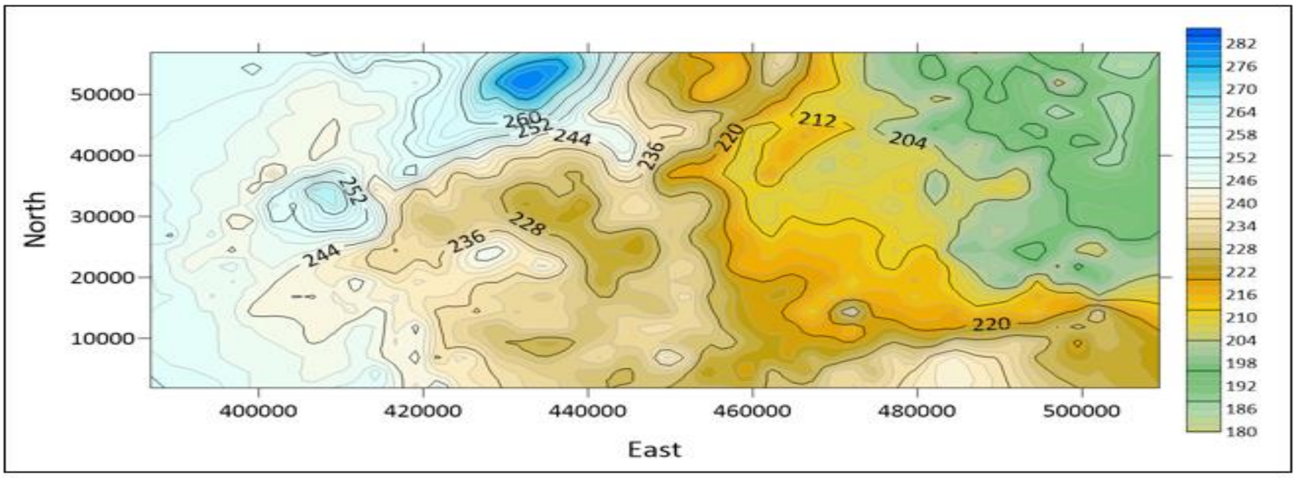

Fig 7: Contour map of the used practical area

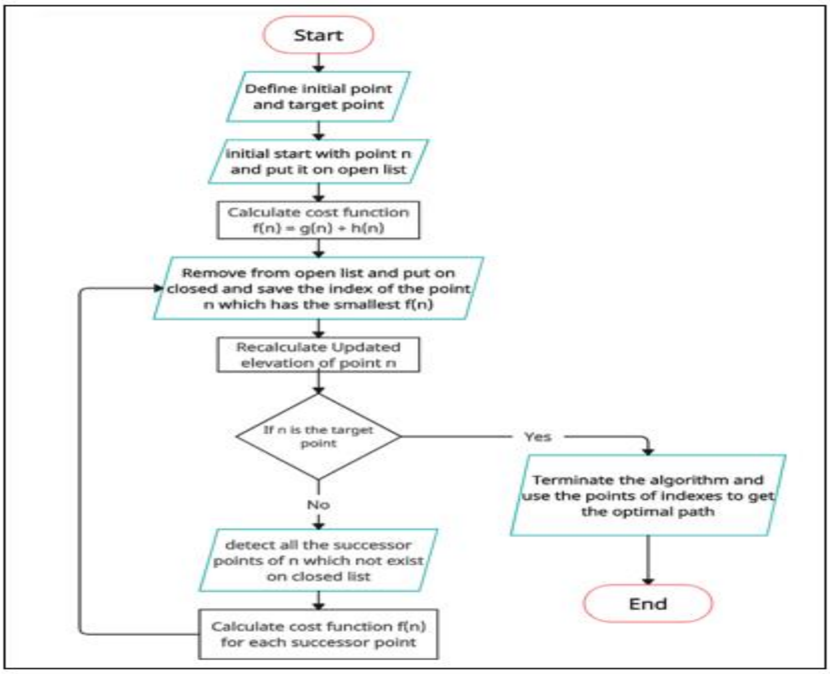

Fig 8: Flowchart of the prepared code.

Table 1: Verifying A* algorithm and the practical case results

	A* optimized path results		Practical road manual results		Percent of variance (%)
	Quantity	Cost (EGP)	Quantity	Cost (EGP)	
Span (Km)	132.15		130		1.65
Cut volume (m^3)	1,770,643	35,412,853	3,355,034	67,100,680	- 47.22
Fill volume (m^3)	1,130,681	94,977,204	1,303,066	109,457,544	- 13.22
Base course (m^3)	1,268,640	202,982,400	1,240,000	198,400,000	2.3
Asphalt (m^2)	3,039,450	922,473,075	2,990,000	907,465,000	1.65
Total cost (EGP)	1,255,845,532		1,282,423,000		- 2.07

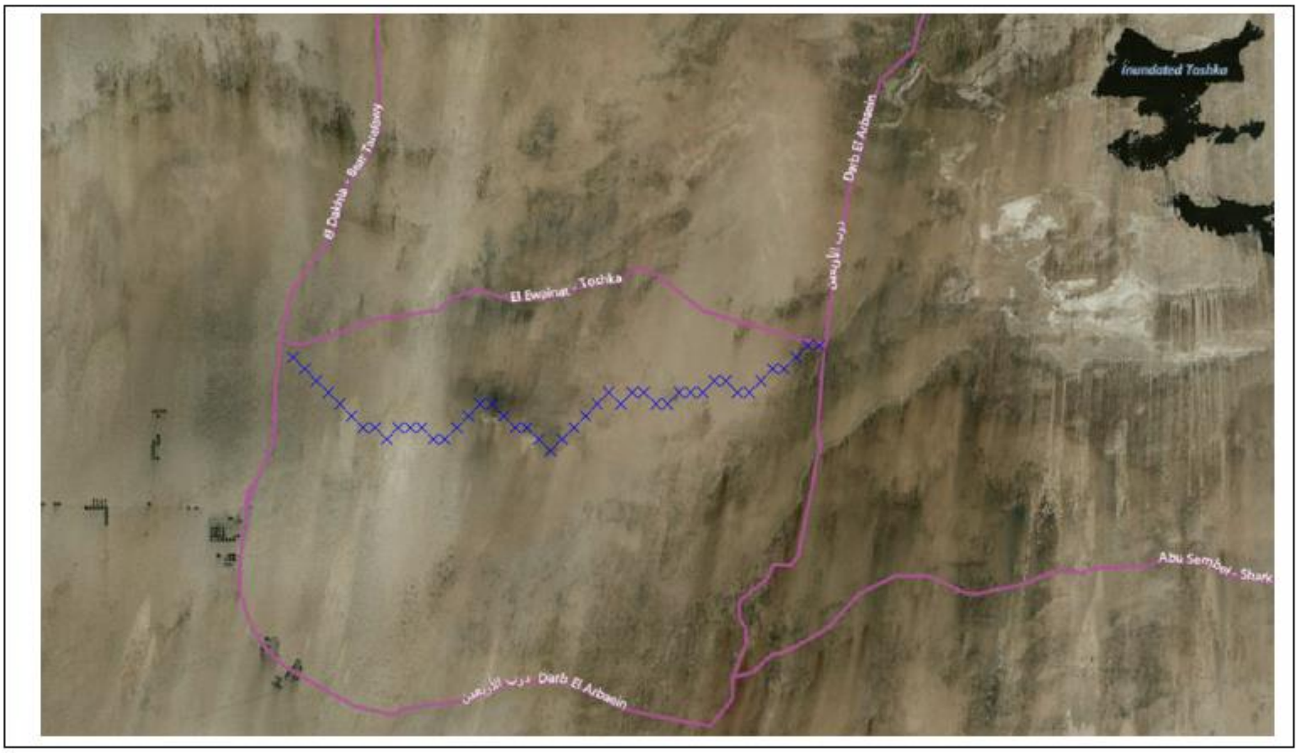

Fig 9: Verifying A* algorithm and the practical case results

By preparing a code in python to apply A* algorithm using the previous cost equations (1 to 10) on the points grid, the estimated output points would represent the optimal road path between the two ends. The following flowchart shows the steps of this process, Figure 8.

Through analyzing the obtained results of code using Autodesk Civil 3D program in the following steps:

1- Inserting the obtained points in the program.
2- Drawing horizontal alignment and vertical profile connecting these points.
3- Drawing an assembly that represent the cross section of the road.
4- Making a corridor for the road and calculating the road quantities.

By comparing the proposed road characteristics and quantities that represents the A* algorithm solution with the constructed practical road path, the following comparison was concluded as shown in Table 1 and Figure 9.

The used cost function in this model is based on the standard prices in Egypt in 2021. The unit price for cut (C_{cut}) is 20 £/m^3. The unit price for fill (C_{fill}) is 84 £/m^3. The unit price for base course is 160 £/m^2. The unit price for Asphalt layers is 303.5 £/m^2.

6.Conclusions

This paper optimizes the choice of various conditions and various requirements for new roads path optimization in the practical application based on the A* algorithm. The optimization algorithm combines various influence factors by creating a new weight function based on costs as a new requirement for path selection by A*, which increases search efficiency, minimize the total construction cost and meets the various geometric constrains of different roads. The study of the A* algorithm achieves the following goals:

(1) Choosing the optimal path for new roads in no time which help to save effort, money and labor in the preliminary design stage.

(2) The selected path satisfies the different design constrains in AASHTO.

(3) By applying the model on the practical constructed road, It was found that the A* algorithm gives results with total cost less than the manual solution by about 2%.

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