An electromagnetism-like algorithm for solving a three-dimensional highway alignment problem

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Abstract. Road alignment design is an important determinant of the development cost of road networks. On the one side, it affects road construction and maintenance costs, constituting a significant part of country-wide infrastructure development, management, and operation budget each year. On the other side, it affects road user-related costs of travel time and vehicle use, comprising a significant portion of the total transportation cost. This study adapts the existing electromagnetism-like meta-heuristic algorithm to solve a three-dimensional highway alignment problem, which explores and finds a good route between two given points on a terrain. It detects the potentials of the given initial routes, which are enhanced and shaped to find better positions by means of local and global searches. The final good solution is, then, fine-tuned for a better alignment. Several example problems are designed to show the behavior of the algorithm. The results show that the algorithm satisfactorily maneuvers to by-pass obstacles and build highway structures where necessary. The set of the example problems in this paper may also serve to establish a basis for evaluating the performance of alternative algorithms.

1. Introduction

Roads have crucial effects on development; hence, road construction is an important endeavor in all, particularly in the developing, countries. One important aspect of road construction is the specification of its alignment within a real environment. The alignment is then given to the highway designers to fine-tune the horizontal and vertical curves, bridges, tunnels, and other fixtures. When we connect two points in a three-dimensional space together by a highway, the benefit of this investment is basically accrued and known, and it remains to make this connection to minimize the total cost (of construction, maintenance, and operation).

The costs related to a highway may constitute road users' costs (travel time, vehicle operating cost, and accident cost), operator's costs (road construction, maintenance, and operation), and environmental costs (natural land development and adverse environmental effects including the non-users' costs). It may be expected that these costs affect the demand for road use and, thus, the road benefit.

There are many constraints in the roadway alignment and construction, which may be classified as follows:

(a) Technical constraints (maximum slopes, curve radii, safe distances, etc.);

(b) Resource constraints (budget, equipment, and materials);

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(c) Environmental constraints (ecological, green-land, wet-land, sensitive areas, etc.);

(d) Archaeological constraints;

(e) Technological constraints (in building bridges, tunnels, etc.);

(f) Standards on adverse effects of road use impacts (noise pollution, visual intrusions, ground vibration, etc.) on human beings and activities;

(g) Adverse effects on neighborhood and land-use integrity.

This paper deals with the following problem. Herein, there is a terrain with known topography and geographical as well as man-made features (lakes, wet-lands, forests, historical buildings, archaeological remains, monuments, preserved areas, etc.). There are two points in the region that are intended to be connected by a new road. The problem is to find the alignment of this road in the study region, such that it is feasible with respect to the constraints and the objective(s) of road construction is optimized. The alignment may only use the allowable areas of the terrain. In practice, the solution to this problem may not be found by classical optimization methods [1]. The current study has chosen to adapt a new meta-heuristic algorithm, the electromagnetic-like algorithm, to solve this problem.

The purpose of this paper is to adapt an electromagnetism-like algorithm as an effective alternative approach to solve the three-dimensional road alignment problem. The following are excerpts of the contributions of this paper:

- Defining a simple 3D road alignment problem at the strategic level;

- Adapting a new electromagnetism-type algorithm to solve the problem;

- Defining a flexible breaking point concept to produce smoother alignments;

- Designing a highway alignment algorithm that works over continuous 3D surfaces;

- Designing a procedure that possesses the ability to maneuver in backward directions to find the optimal alignment;

- Designing test problems to evaluate the maneuvering capabilities of such algorithms, which may form a platform for comparing future algorithmic developments.

This paper first reviews the literature in Section 2. An overview of the solution procedure is discussed in Section 3, followed by the detailed algorithm in Section 4. The algorithm is calibrated in Section 5 and, then, applied to seven example problems in Section 6.

Section 7 concludes the paper and proposes future research directions.

2. A review of the literature

2.1. General statements

The road alignment or highway routing problem, usually formulated as an optimization problem, started with a two-dimensional (2D, horizontal or vertical) alignment problem. Eventually, it evolved into a three-dimensional (3D) alignment, or routing, problem. It includes both 2D versions of the problem and aspects of the road interaction with its users.

A 2D horizontal alignment problem is involved more than a 2D vertical alignment problem is. This is because the former problem involves political, economic, social and environmental issues more than the latter, and the latter basically involves technical problems. Thus, in general, optimization procedures are more effective in finding a better horizontal alignment than a vertical (alignment) one might be. Nevertheless, there are many algorithms for vertical alignment design, most of which deal with particular road construction cost, such as cuts and fills. Moreover, in vertical alignment design, there is no fear of self-intersecting routes. Kim et al. [1] and Kang et al. [2] presented some previous works in these two areas, which are complemented and summarized in Table 1. In this table, these works are categorized based on the type of the solution procedure employed to solve the problem.

The real-world road alignment problem is, however, three-dimensional. This means that the designer of the alignment has to address:

(a) The planar aspects of the road (that is, the geographical positioning of the road with respect to privately-owned land as well as reserved and preserved historical and environmental sites) and the land acquisition costs;

(b) The profile-related matters of the road (that is, construction aspects of the road such as grades, cut/fill, bridges, and tunnels) and of course the respective construction costs.

Moreover, since a 3D road map is to be implemented in the real world, it has to consider:

(c) The aspects of the problem when it undergoes the actual load of traffic (that is, the road maintenance costs as well as the user travel costs).

The general formulations of 3D and 2D alignment problems are very much similar to each other, except for the solution procedures employed to solve them. The 3D alignment road problem is usually formulated as an optimization one in which its objective comprises

Table 1. Previous endeavors on highway alignment design.*

Alignment optimization	Optimization procedure	References
Horizontal	Calculus of variations	[5-9]
	Network optimization	[10-14]
	Dynamic programming	[15,16]
	Neighborhood search heuristic with mixed integer programming	[17]
	Genetic algorithm	[18-20]
Vertical	Enumeration	[21]
	Dynamic programming	[22-25]
	Linear programming	[26,27]
	Mixed-integer linear programming	[28]
	Quasi-network flow model	[29]
	Numerical search	[30,31]
	Genetic Algorithm	[3,19,32]
Three-dimensional	Numerical search	[33]
	Distance Transform	[34,35]
	Genetic algorithm	[1-4,19,36-49]
	Gradient Method	[50]
	Particle Swarm	[51,52]
	Hybrid meta-heuristic algorithm	[53,54]

*: This is a more up-to-date form of similar tables presented by Kim et al. [1] and Kang et al. [2].

a set of costs related to the users and operator of the road, as well as the environment. Table 1 also summarizes previous works in the 3D road alignment section.

The race in 3D road alignment algorithms appears to be concerned, basically, with computational speed on the one hand, and the definition of a comprehensive objective function and constraint set, on the other hand. The objective functions related to the users and operator of the road may usually be expressed in monetary terms, and the objectives related to the environment may be expressed by rather complex constraints in the problem. Hence, this optimization problem may be better approached by heuristic than conventional routines, as was correctly mentioned by Kim et al. [1]. One good work in the area of 3D road alignment problem belongs to Jong and Schonfeld [3]. Similar to most other researchers, they employed a genetic algorithm to tackle the problem (see also [4]).

2.2. The problem's objective
The cost of roadway alignment includes the following:

(a) Location-related costs (C_N);

(b) Length-related costs (C_L);

(c) Earthwork-related costs (C_E);

(d) Bridge and tunnel construction costs (C_{Brg} and C_{Tnl});

(e) Road maintenance costs (C_M);

(f) User-related costs (C_U).

The total cost for the alignment (C_T) may be considered the sum of these costs:

$$C_T = C_N + C_L + C_E + C_{Tnl} + C_{Brg} + C_M + C_U. \qquad (1)$$

Note that different cost components tend to influence the road alignment differently. While the costs of cut and fill encourage indirect road alignment options, the costs of pavement, users' travel times, and vehicle fuel tend to encourage shorter and more direct routes. Some cost components are yearly, some depend on a user's demand rate (per year), and some are once in the road life-time which may be converted to yearly costs by suitable conversion factors, using an appropriate minimum attractive rate of return (e.g. [55]).

Despite the fact that many components of the objectives of highway alignment design may be measured by monetary units, some of the works in this area view the problem as multi-objective. Yang et

al. [49] presented one such procedure in which they separated sensitive area impacts from the costs of the agency building the road.

2.3. The problem's constraints

There are considerable constraints on road alignments, which include the minimum radii of horizontal curves, maximum grades, minimum sight distance, and maximum positive grade length. Some constraints may define the allowable maneuvering area for the alignment.

Table 2 presents the model of this study in terms of its objective function and constraints. This table, also, shows details of the computational expressions employed to solve the problem. Table 3 defines the notations used in this model. The road alignment problem in this study is a constrained, shortest path problem in a 3D environment, with the following peculiarities:

(a) In the road alignment problem, the nodes and links are free in (x, y, z)-space, while they are fixed and given in the shortest path problem;

(b) The link (or node) costs are given in the latter problem, while we need to decide link types and compute link costs in the former problem;

(c) Road alignment problem has constraints in traversing links, while there is no constraint (like maximum grade) in an ordinary, shortest path problem.

It is worth nothing here that some researchers have also considered geometrical design constraints (such as vertical/horizontal curve design) into the road alignment problems (e.g. [55]). The authors of this paper believe that such minor considerations are not warranted to be included in the road alignment search and should be considered as a next-step activity for the final/chosen alignment. There are several reasons for this assertion:

(a) Road alignment search is a strategic decision compared to the detailed geometric design features of the problem. As an analogy in the jargon of the network design problem, it is as if major highway decisions are mixed (to build/not to build them) with operational projects (one-way/two-way decisions of streets). The objectives, constraints, decision flexibility, sources of funds, etc. of strategic and tactical decisions are substantially different and do not mix well/at all. This is why the subject is referred to as highway *alignment* or *routing* (that is, finding the general direction), and not highway *design* (that involves details such as tangent-spiral-circular combination design, super-elevation, horizontal and vertical sight distances, etc.);

(b) Inclusion of such operational/tactical details would unnecessarily add to the computational complexities of the problem; particularly, the available information and data at strategic levels do not support such actions as highlighted next;

(c) The precision of the information and data at strategic and detailed designs is different. At a road alignment level that deals with roads of several hundred kilometers, we require information accuracy, say, at the 30 m level in planar (x, y) coordinates and the 1 m level in (contour line) elevation, z, while such degrees of precision should be, say, in 1.0 m and 0.1 m, respectively, for detailed designs such as horizontal/vertical curve or maximum grade length;

(d) Finally, there is no point in designing a vast population of such routes within meta-heuristic procedures in detail and, then, throwing them away. After all, compared to more rigorous and computationally involved gradient-based methods, one of the merits of meta-heuristic procedures, as an example, is that the former procedures abandon higher computation for finding a "good" solution per iteration with the higher number of solutions, which are found and evaluated swiftly in an iteration.

2.4. The solution procedures

The procedures employed in the literature for the solution of the road alignment problem include numerical methods and meta-heuristic algorithms. The latter form the majority of the procedures employed in the solution of the problem, basically in the form of genetic algorithm, as Table 1 shows. It may be noted in the development of these procedures that researchers are still in search of methods to fulfill the following objectives:

(a) Defining it in an appropriate manner, e.g., a single level single objective problem (the most prevalent form of the problem formulation), a single level multi-objective problem (as mentioned below), or a bi-level programming problem [46];

(b) Solving it effectively (higher alignment quality in lower computation time);

(c) Equiping the solution procedure (path finder) with necessary tools and apparatuses to help designers and construction companies to be responsive to the ever-mounting demand on the design and environmental sides of the problem, particularly in this era of high resource and environmental consciousness.

Examples of the above-mentioned tools for solution procedure enhancement include the following:

Table 2. Definition of the 3D highway alignment model and its components in this study.

Model

Original problem:

$$\min_{K} \quad C_T(R_K^{AB}) = \sum_{a \in R_K^{AB}} C_{Ta} = \sum_{a \in R_K^{AB}} \left(\sum_{t \in S} C_{ta} \right)$$

$$= \sum_{a \in R_K^{AB}} (C_{Na} + C_{La} + C_{Ea}$$

$$+ C_{Tnl,a} + C_{Brg,a} + C_{Ma} + C_{Ua})$$

s.t.: $\quad |\text{grade}(a)| = |(z_j - z_i)/HL_a| \le G_{\max}, \qquad \forall \, a \in R_K^{AB}$

$\Longrightarrow$

Transformed problem:

$$\min_{K} \quad C_T \left(R_K^{AB} \right) + M\delta_k,$$

$$\delta_k = \begin{cases} 1 & \text{if } \exists a \in R_K^{AB} \\ & \text{such that } |\text{grade}(a)| > G_{\max} \\ 0 & o/w \end{cases}$$

Cost type	Cost expressions	Remarks and definitions
C_{Na}	$0.5(K_{R,i} + K_{R,j}).w_r.Len_a$	$Len_a = HL_a$ or L_a; however, the unit cost of right-of-way is defined.
C_{La}	$K_L.L_a$	$HL_a = \sqrt{(x_j - x_i)^2 + (y_j - y_i)^2}$; $L_a = \sqrt{(x_j - x_i)^2 + (y_j - y_i)^2 + (z_j - z_i)^2}$

$C_{Ea} + C_{Tnl,a} + C_{Brg,a}$

$\eta_a.K_c.E_{ca} + (1 - \eta_a).K_{Tnl}.HL_{ca}$
$+\xi_a.K_f.E_{fa} + (1 - \xi_a).K_{Brg}.HL_{fa}$

If i and j are cut sections:
$$HL_{ca} = HL_a \text{ and } HL_{fa} = 0$$
If i and j are fill sections:
$$HL_{fa} = HL_a \text{ and } HL_{ca} = 0$$
If i is cut section and j is fill section:
$$\begin{cases} HL_{ca} = (Z_{gi} - Z_{ri})/(Z_{gi} - Z_{ri} - Z_{gj} + Z_{rj}).HL_a \\ HL_{fa} = (Z_{rj} - Z_{gj})/(Z_{gi} - Z_{ri} - Z_{gj} + Z_{rj}).HL_a \end{cases}$$
If i is fill section and j is cut section:
$$\begin{cases} HL_{ca} = (Z_{gj} - Z_{rj})/(Z_{ri} - Z_{gi} + Z_{gj} - Z_{rj}).HL_a \\ HL_{fa} = (Z_{ri} - Z_{gi})/(Z_{ri} - Z_{gi} + Z_{gj} - Z_{rj}).HL_a \end{cases}$$

If i is cut section:
$$A_i = [w_r + (Z_{gi} - Z_{ri}).\cot\theta_c].(Z_{gi} - Z_{ri})$$
If i is fill section:
$$A_i = [w_r + (Z_{ri} - Z_{gi}).\cot\theta_f].(Z_{ri} - Z_{gi})$$

$$\eta_a = \begin{cases} 0 & \text{if } K_{Tnl}.HL_{ca} < K_c.E_{ca} \\ 1 & o/w \end{cases}$$

$$\xi_a = \begin{cases} 0 & \text{if } K_{Brg}.HL_{fa} < K_f.E_{fa} \\ 1 & o/w \end{cases}$$

If i and j are cut sections:
$$E_{ca} = 0.5(A_i + A_j).HL_{ca} \text{ and } E_{fa} = 0$$
If i and j are fill sections:
$$E_{fa} = 0.5(A_i + A_j).HL_{fa} \text{ and } E_{ca} = 0$$
If i is cut section and j is fill section:
$$E_{ca} = 0.5A_i.HL_{ca} \text{ and } E_{fa} = 0.5A_j.HL_{fa}$$
If i is fill section and j is cut section:
$$E_{fa} = 0.5A_i.HL_{fa} \text{ and } E_{ca} = 0.5.A_j.LH_{ca}$$

| C_{Ma} | $(C_{Na} + C_{La} + C_{Ea} + C_{Brg,a}$ $+C_{Tnl,a}).\omega.prs\_value.$ | $prs\_value = [\exp((r_t - \rho).n_y) - 1]/(r_t - \rho)$ Ref.: Jha et al. [55] |

C_{Ua}

$$\left(\sum_{d \in \{1,2\}} \text{Fuel}_{\text{Cost,a}}^{d} + TT_{\text{Cost,a}} \right).prs\_value$$

$$\text{Fuel}_{\text{Cost},a}^{d} = \frac{HL_a}{5280 \times 1000} \sum_{m \in [pp, pn, o]} \left[Q_m.H_m.\bar{V}_m. \sum_{n \in [Mc, 2A, 3S]} F_n.U_n.T_n \right]$$
Ref.: Jha et al. [55]

$$TT_{\text{Cost},a} = \sum_{m \in [pp, pn, o]} \left[Q_m.H_m.\frac{HL_a}{\bar{V}_m}. \sum_{n \in [Mc, 2A, 3S]} \nu_n.T_n \right]$$
Ref.: Jha et al. [55]

Table 3. Definitions of the parameters and the variables used in the model of this study.

Parameter	Definition
F_n	Fuel consumption for vehicle n ($n = Mc, 2A, 3S$, see below) (gallons/1000 miles)
$G_{\max}$	Maximum allowable grade
K_{Brg}	Unit cost of bridge construction (\$/ft)
K_c	Unit cost of cut plus transportation to a landfill (\$/ft^3)
K_f	Unit cost of fill plus transportation from a borrow pit (\$/ft^3)
K_L	Unit cost of pavement (\$/ft)
$K_{R,i}$	Unit right-of-way cost at point i (\$/ft^2)
K_{Tnl}	Unit cost of tunnel construction (\$/ft)
M	A large number (for example, set it equal to "length of point A (origin) to B (destination) $\times K_{Tnl}$")
n_y	Planning period (year)
r_t	The annual growth rate of AADT
T_n	Percent of vehicle n in traffic n ($n = Mc, 2A, 3S$, see below)
U_n	Unit fuel prices for vehicle n ($n = Mc, 2A, 3S$, see below) (\$/gallons)
w_r	Road width (ft)
θ_c	Cut slopes
θ_f	Fill slopes
v_n	Unit values of travel time for vehicle n ($n = Mc, 2A, 3S$, see below) (\$/hr)
ρ	Minimum attractive rate of return on investments
ω	Portion of total construction cost which is defined as yearly maintenance cost

Variable	Definition
A_i	Highway cross-section area at point i (ft^2)
$C_{Brg,a}$	Bridge construction costs of link a (\$)
C_{Ea}	Earthwork-related costs of link a (\$)
C_{La}	Length-related costs of link a (\$)
C_{Ma}	Road maintenance costs of link a (\$)
C_{Na}	Location-related costs of link a (\$)
C_T	Total cost (\$)
C_{Ta}	Total cost of link a (\$)
C_{ta}	Component t of the total cost of link a (\$)
$C_{Tnl,a}$	Tunnel construction costs of link a (\$)
C_{Ua}	User-related costs of link a (\$)
E_{ca}	Volume of cut of link a (ft^3)
E_{fa}	Volume of fill of link a (ft^3)
$\text{Fuel}_{\text{Cost},a}^d$	Traffic fuel consumption cost in direction d in the base year in link a (\$/year)
H_m	Total numbers of hours the road is under traffic condition m ($m = pp, pn, o$, see below) per year
HL_a	Horizontal length of link a (ft)
HL_{ca}	Horizontal length of earth excavation of link a (ft)
HL_{fa}	Horizontal length of earth embankment of link a (ft)
L_a	Length of link a (ft)
prs_value	Present worth factor (converting annual costs to present value)
Q_m	Hourly volume under traffic condition m ($m = pp, pn, o$, see below)
R_K^{AB}	Alignment (route) K from origin A to destination B
$TT_{\text{Cost},a}$	Traffic total travel time costs in the base year in link a (\$/year)
$\bar{V}_m$	Average running speeds under traffic condition m ($m = pp, pn, o$, see below)
(x_i, y_i, z_i)	The coordinates of point i (ft)
Z_{gi}	Ground elevation at point i (ft)
Z_{ri}	Road elevation at point i (ft)

Others	Definition
$2A$	2-axle single unit truck
$3S$	3-S2 diesel truck
Mc	Medium car
o	Off-peak period
pn	Peak period in non-prevalent direction
pp	Peak period in prevalent direction
S	Set of cost types

(i) Using complementary concepts, such as Pareto optimality, in multi-objective analysis of the problem [47,49] or sustainable development [47];

(ii) Employing additional techniques to improve computational speed or alignment quality in genetic algorithms [1,48] and devising new hybrid search techniques [53,54], or new mixed integer programming procedures, to upgrade computational precision in earthworks [28,29];

(iii) Embedding complementary information systems, such as GIS, in the solution procedure [4,20, 36,38,51];

(iv) Incorporating important decisions for the choice of intersections, bridges, and tunnels into the alignment design [37,41].

Recent advances in this area add the vehicular fuel consumption and safety aspects to the alignment design [56].

One important drawback of the existing path-finding algorithms is the rigidity of the procedures in adapting road alignments to the terrain at fixed points along the line joining the two ends of the road (for example [55]). The proposed procedure in this paper is flexible in this sense. It is able to maneuver around obstacles, land features, etc. by adding as many breaking points as required to pass smoothly through them. The designed test problems evaluate the maneuvering capabilities of the proposed algorithm.

One research direction in the field of highway alignment design is to devise/discover methods to arrive at quality solutions effectively. This aspect of the solution methods will gain high importance soon in the light of the additional inertia that will be imposed on the methods by the features mentioned above. Proof of ingenuity of the procedures in arriving at quality solutions needs some test problems which are able to assert it. Such a set of test problems could serve as a basis for alternative method comparisons, in which corresponding researches are found to be very limited in the literature, particularly on a common basis (see, for example, Shaw and Howard [6], and Cheng and Jiang [57], in this respect.). The suggested test problems may form a platform for comparing future algorithmic developments and providing bench marks for different algorithmic performances.

3. The proposed solution procedure

The procedure employed to solve the road alignment problem has a meta-heuristic nature. To comply with the nature of such a procedure, it is run only over feasible solutions (routes). In doing so, constraints (such as maximum grade) are investigated for each candidate (newly found) alignment, and a large cost (M) is added to the objective function of infeasible routes. Table 2 shows the transformed problem in this respect. Note that, in practice, we need not to bear the cost of objective function computations for infeasible alignments, as it is set equal to a large number, M.

The procedure used in this study to solve the 3D road alignment problem is an electromagnetism-like meta-heuristic algorithm (EA). This algorithm, introduced by Birbil and Fang [58], is notably different from other meta-heuristic algorithms as follows: they are not only local and global elites that influence others (like particle swarm algorithm [59]), but so do all the particles. Moreover, particles not only exert attraction forces upon other particles, they repel other particles, too. While good solutions' elements are strengthened by pheromone addition and the other elements are weakened by pheromone evaporation (a size n operations) in algorithms such as ant system, in EA, we have a size $n \times n$ operation of getting closer to all good elements and getting away from the inferior ones, proportional to the attraction/repulsion forces exerted upon them. In the former algorithm, all effective (ineffective) alternatives are treated alike, while alternatives are given merits (demerits) in EA proportional to their attraction (repulsive) forces. The EA is more suitable for continuous variable unconstrained optimization, and our 3D alignment problem may be defined in such an environment. The following review of EA provides us with the justification to use and prefer an adaptation of this algorithm to the other meta-heuristics.

The application of the electromagnetism-like algorithm has found its way into many areas of science and engineering. Examples include medical data classification and prediction of diabetes mellitus [60], sensor distribution strategy to increase the coverage area of wireless sensor network after random distribution of sensors [61], machine-cell formation and layout problem in cellular manufacturing system in which parts with different characteristics and needs are assigned to the cells of distinctively divided machines [62], optimization of tool path planning in 5-axis CNC machining to reduce the geometrical deviations of the ruled surfaces [63], scheduling of the flow shop problem [64], and computation of numerical solutions to the inverse kinematic problem of robotic manipulator [65].

Moreover, EA has found applications in operations research problems, too. Recent examples include traveling salesman problem with time windows [66], vehicle routing problem with delivery time cost [67], capacitated vehicle routing problem [68], and uncapacitated multiple p-hub median problem [69]. Recent applications in transportation problems also include location and transportation planning in the supply chain problem [70].

It is also interesting to note that the electromagnetism-

like algorithm has been found effective in solving system design problems in hybrid forms with other heuristic algorithms [62,64], meta-heuristic algorithms such as Particle Swarm Optimization (PSO) [71], Simulated Annealing (SA) [64,67], as well as with conventional optimization methods [65] and in improved formats of EA algorithm [60,68].

What promotes the use of EA further in our problem is the encouragement that is inspired by the higher performance of EA compared to the other counterparts, as reported in the literature. In the recent studies of the following authors, the electromagnetism-like algorithm has been found to be (in their words) superior to the common state-of-the-art methods [60], preferable to Particle Swarm Optimization (PSO) and Artificial Bee Colony (ABC) [61], and significantly better than the Genetic Algorithm (GA) [62]. EA is reported, also, to outperform Simulated Annealing (SA) and many well-recognized constructive heuristics as well as to yield more effective solutions than PSO [64]. Moreover, the following statements have been reported in some other studies regarding the EA: feasible and near-optimal results are generated within shorter computational times as compared to the test algorithms, including beam-ACO (Ant Colony Optimization), Compressed Annealing (CA), specifically designed heuristics, and dynamic programming [66]. Furthermore, Yurtkuran and Emel [68] found EA to be giving promising results within acceptable computational times when compared to other novel meta-heuristics such as Tabu Search (TS), SA, GA, ACO, and PSO. In addition, according to Kratica [69], EA shows excellent performance (compared to GA) by reaching all the previously known optimal solutions on the instances studied in a reasonable time and has advantages over the compared meta-heuristics on large-scale instances.

In what follows, an overview of the electromagnetism-like algorithm is presented within the context of our problem. Highway alignment determination in a 3D space by the proposed algorithm is done in four macro-steps, as shown in Figure 1. In Step 0, the problem space is introduced to the procedure by defining the topography of the region, the two end points of the route, the objective function of the problem, and the constraints that should be observed when constructing the route. The forbidden area constraints have been introduced to the program by specifying extremely high land-acquisition cost for the right-of-way of the road in the forbidden region.

Step 1 of the macro-procedure is devoted to the generation of a set of random road alignments between the two end points, which together cover the region fairly well. In Step 2, an adaptation of the algorithm of Birbil and Fang [58] is applied to improve the current road alignments and to form a better set of alternative alignments. This algorithm is comprised

of two search routines: performing global and local searches. In the global search, by using Coulomb's law, the algorithm exerts the equivalent electrostatic forces on the particles (points along alignments) and changes the positions of the breaking points of the alignments, thus making new road alignments. In the local search, the algorithm changes the breaking points of the alignments randomly, with the hope of finding alignments with better values of the objective function.

Our initial experiments with this algorithm have shown that increasing the global search iterations beyond a certain number does not change the better alignment found, and it is only the local search which reduces the objective function further. On the other hand, a great deal of computation time is spent to generate alignments with the higher number of breaking points and to compute the total cost of the new alignments. Thus, to increase the speed of the algorithm in concluding the final result and avoid excessive ineffective searches, Step 3 of the algorithm only conducts local searches around the better alignment found in Step 2, without any global search. In the proposed algorithm, the initial alignments are built only with two breaking points. Steps 2 and 3 may increase these breaking points to form better alignments. The algorithm may also save computation time by holding the breaking points constant and move between consecutive steps.

4. The proposed algorithm

In this section, an electromagnetism-like meta-heuristic algorithm is proposed to find and apply the solution of the 3D highway alignment design problem. Further descriptions of the original algorithm may be found in [58]. A pseudo-code of the algorithm, first, is presented to bring the whole picture into the sight and, then, present a detailed version of the algorithm.

4.1. Pseudo-code of the proposed algorithm
A pseudo-code of the proposed electromagnetism-like meta-heuristic algorithm for the solution of the 3D alignment problem, based on Figure 1, is as follows:

0. *Preparation.* Specify the inputs of the problem;

1. *Initial alignments.* Produce a pre-specified number of two-breaking-points alignments;

2. *Road alignment design:*
   2.1. Do while breaking points declared adequate;
   2.2. Do while maximum iteration no. reached:
      2.2.1. *Local search.* Search in the vicinity of the breaking points for improvements;
      2.2.2. *Global search.* Produce better routes by the electromagnetic law;
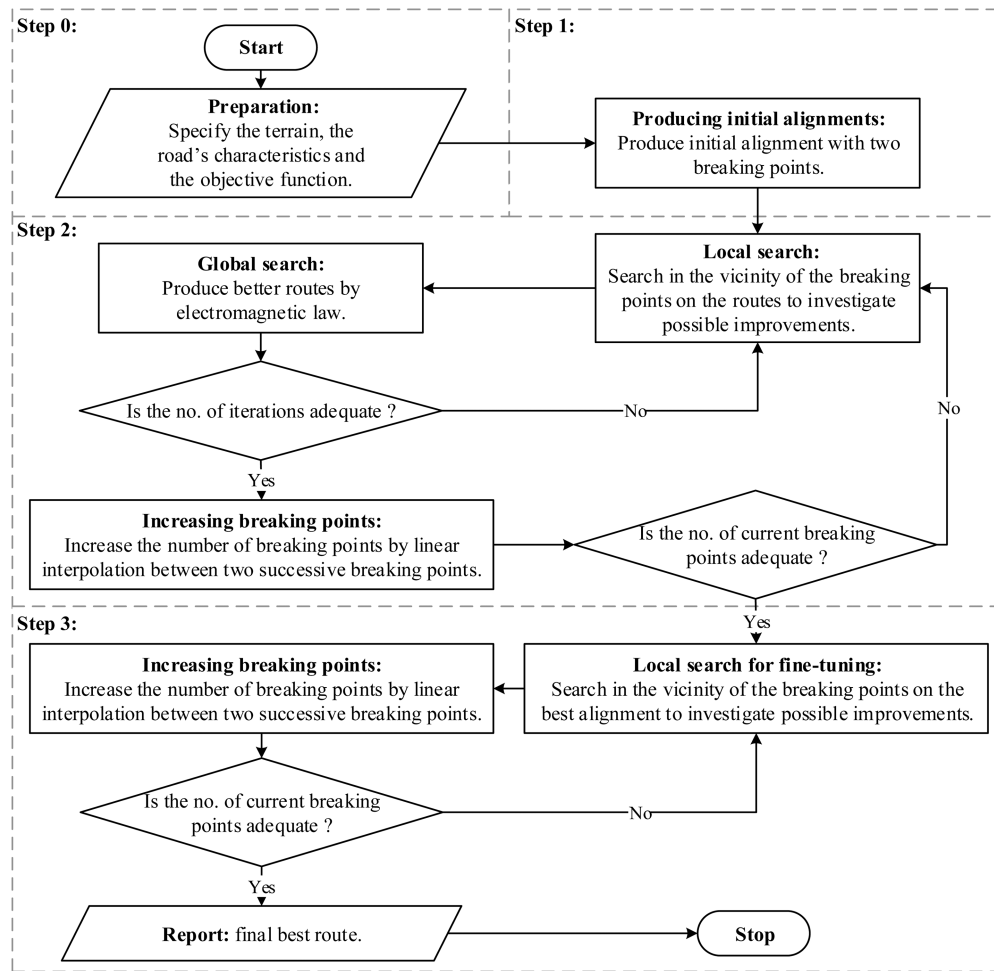   *Endo 2.2.*

Figure 1. Basic structure of the electromagnetism-like model.

2.3. *Raise the no. of breaking points.* Increase the no. of breaking points by a linear interpolation between two successive breaking points;

Endo 2.1.

3. *Alignment fine tuning.* Do while breaking points declared adequate:

3.1. *Local search.* Search in the vicinity of the breaking points for improvements;

3.2. *Raise the no. of breaking points.* Increase the no. of breaking points by linear interpolation between two successive breaking points;

Endo 3.

Report the best alignment design specifications.

4.2. Detailed description of the proposed algorithm

The algorithm is described below:

Step 0. *Determination of specifications of the problem.*

(a) *Terrain.* Specify the (x, y, z) coordinates of the points that define the topology of the ground surface of the study area. Software, like Matlab, R2011b, may model the terrain by having the important points and may estimate the elevation of any other point by linear interpolation between those points.

(b) *Road.* Specify the following alignment and design specifications: the coordinates of the end points $A : (x_A, y_A, z_A)$ and $B : (x_B, y_B, z_B)$, the maximum allowable grade $(G_{\max})$, the road width (w_r), and the cut and fill slopes $(\theta_c$ and $\theta_f)$;

(c) *Objective function.* Determine the unit costs of the components of the objective function given in Eq. (1).

Step 1. *Specification of the initial highway alignments.* Each specific alignment i of the road, R^i, is represented by a matrix with three rows showing the (x, y, z) coordinates and the number of columns equal to that of the breaking points of the road plus two end points A and B. Thus, each column of this matrix represents the coordinates of a turning point on the
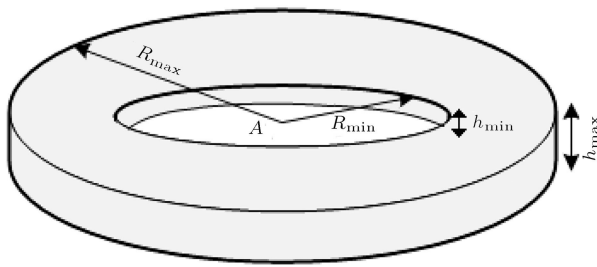
Figure 2. Selection of the space of the first and second breaking points for the initial set of highway alignments.

alignment under considerations. Generate m random alignments between A and B as follows. All initial alignments have two breaking points between A and B. For any such alignment, specify the breaking point next to A within a hollow cylinder around it, with internal radius $R_{\min}$, external radius $R_{\max}$, internal height $h_{\min}$, and external height $h_{\max}$, as shown in Figure 2.

The above-mentioned four parameters are determined as follows:

$$d = \left[(x_B - x_A)^2 + (y_B - y_A)^2 + (z_B - z_A)^2 \right]^{1/2}, \quad (2)$$

$$R_{\min} = \frac{d}{3}, \qquad R_{\max} = 1.5 R_{\min},$$

$$h_{\min} = R_{\min} \times G_{\max}, \quad h_{\max} = R_{\max} \times G_{max}. \quad (3)$$

Step 2. *Global and local searches by the electro-magnetism-like algorithm.*

(a) *Model parameters.* Specify the following model parameters:

δz_{global} The range of global search in the vertical direction;

δz_{local} The range of local search in the vertical direction;

δx and δy The ranges of allowable search in the horizontal directions;

α The coefficient of local search in the horizontal directions;

ϑ The exponent of the denominator of the Coulomb's Law;

$BP_{\max}$ The maximum number of breaking points on the alignment;

$GSIter$ The maximum number of Global Search Iterations;

$LSIter$ The maximum number of Local Search Iterations.

Start local search. Local search is planned to investigate possible improvements of the alignments in the vicinity of these routes. Such improvements may be identified by performing

the following operations. For each alignment, R^i, a new alignment, R^i_{new}, is built.

(b) Replace the intermediate (breaking) points of the route ($t = 2, 3, \cdots$, and $t \neq$ first and last columns) with the following respective points:

$$R^i_{1t \ \text{new}} := R^i_{1t} + (Rand - 0.5).\alpha.\delta x,$$

$$R^i_{2t \ \text{new}} := R^i_{2t} + (Rand - 0.5).\alpha.\delta y,$$

$$R^i_{3t \ \text{new}} := R^i_{3t} + (Rand - 0.5).\delta z_{\text{local}}, \quad (4)$$

where R^i_{st} is the (s, t) entry of matrix R^i ($t =$ breaking point; $s =$ coordinate axis); in addition, we will have a new alignment matrix as follows:

$$R^i_{\text{new}} = \begin{bmatrix} x_A & x^i_{1\text{new}} & x^i_{2\text{new}} & x_B \\ y_A & y^i_{1\text{new}} & y^i_{2\text{new}} & y_B \\ z_A & z^i_{1\text{new}} & z^i_{2\text{new}} & z_B \end{bmatrix},$$

where $Rand$ is a uniformly distributed random number in [0,1].

Cost computation. Compute the cost of the newly found alignment R^i_{new}. If the cost of R^i_{new} is less than R^i, save alignment R^i_{new}. If the number of iterations is less than $LSIter$, go to Step 2(b); else, go to Step 2(c).

(c) Replace the incumbent alignment, R^i, by the better solution of R^i_{new} (end of local search).

(d) **Start the global search.** Now, using the electromagnetic law, push alignment R^i away from the worse alignments and bring it closer to the better ones. Sort all alignments R^i in the order of increasing cost and identify the better one by R^{best}.

(e) *Electromagnetism.* Compute virtual electromagnetism q^i of alignment R^i as follows:

$$q^i = \exp \left(-m \frac{f(R^i) - f(R^{\text{best}})}{\sum_{k=1}^{m} (f(R^k) - f(R^{\text{best}}))} \right). \quad (5)$$

(f) *Electromagnetic force.* Compute the electromagnetic force exerted on alignment R^i by alignment R^j as follows:

$$F^{ji} = \begin{cases} (R^j - R^i) \frac{q^i q^j}{\|R^j - R^i\|^{\vartheta}}, & \text{if } f(R^j) < f(R^i) \\ (R^i - R^j) \frac{q^i q^j}{\|R^j - R^i\|^{\vartheta}}, & \text{if } f(R^j) \geq f(R^i) \end{cases} \quad (6)$$

and, thus, the resulting force is as follows:

$$F^i = \sum_{\substack{j \neq i}}^{m} F^{ji} \qquad i = 1, 2, \cdots, m. \quad (7)$$

F^{ji} and F^i are both 3-row matrices with columns equal to the respective breaking points.

(g) *Alignment reformation.* Move each breaking point of alignment R^i in the direction of the force exerted on it by a step size λ, which is a uniformly distributed random variable at the interval of [0,1], as follows:

$$
R^i_{st} := \begin{cases} R^i_{st} + \lambda \frac{F^i_{st}}{\|F^i\|} \left(\max_s \left(R^i_{st} \right) - R^i_{st} \right), \\ \quad \text{if } 0 \leq F^i_{st} \\[2mm] R^i_{st} + \lambda \frac{F^i_{st}}{\|F^i\|} \left(R^i_{st} - \min_s (R^i_{st}) \right), \\ \quad \text{if } F^i_{st} < 0 \end{cases}
$$

$$
s = 1, 2, 3, \qquad i = 1, \cdots, m, \quad i \neq \text{best}. \quad (8)
$$

Herein, $\max_s(\ )$ and $\min_s(\ )$ define the boundaries of the coordinate axes. In this process, the best alignment, R^{best}, does not move from its place and will be transferred to the next iteration of the algorithm in its original form.

(h) *Cost computation.* Compute the cost of the new alignments.

(i) *Maximum iteration check.* If the number of iterations equals *GSIter*, go to Step 2(j) to smooth out alignments; else, go to Step 2(b) for local search.

(j) *Start increasing breaking points.* To increase the precision of the alignments and to decrease their costs, if the number of breaking points along the alignments is less than $BP_{\max}$, increase the number of breaking points along the alignments by linear interpolation between two successive original breaking points along these routes. Add these new breaking points to the alignments and go to Step 2(b) for local search, after reducing coefficient α of horizontal local search by half, i.e., setting $\alpha := \alpha/2$ in order to reduce the chance of the alignment intermingling in Step 2(b). Else if the number of the breaking points is greater than or equal to $BP_{\max}$, go to Step 3 for local fine-tuning of the best alignment found.

Step 3. *Local search for fine-tuning the best alignment.*

(a) *Set model parameters.* Specify the following model's parameters for this step:

$\widehat{BP}_{\max}$ The maximum number of breaking points on the alignment;

$\widehat{LSIter}$ The maximum number of local search iterations;

SubIter The maximum number of iterations for the local search sub-iteration.

Set local search iteration to $q := 1$ and the local search Sub-iteration to $r := 1$.

(b) *Start local search.* For alignment R^{best}, build a new alignment $R^{\text{best}}_{\text{new}}$ by replacing the intermediate (breaking) points of the route with the respective points as computed in Eq. (4). Thus i is replaced by "*best*".

Cost computation. Compute the cost of the newly found alignment $R^{\text{best}}_{\text{new}}$. If the cost of $R^{\text{best}}_{\text{new}}$ is less than R^{best}, save alignment $R^{\text{best}}_{\text{new}}$. If $r < SubIter$, set $r := r + 1$ and go to Step 3(b); else (if $r \geq SubIter$) go to Step 3(c).

(c) Replace the incumbent alignment R^{best} by the better solution of R^{best}_{new} (end of local search).

(d) *Redo local search:* If $q < \widehat{LSIter}$, set $q := q + 1$, and go to Step 3(b); else (if $q \geq \widehat{LSIter}$) go to Step 3(e).

(e) *Start increasing R^{best} breaking points.* If the number of the breaking points along the alignment is less than $\widehat{BP}_{\max}$, increase the number of breaking points along R^{best} alignment by linear interpolation between the two successive original breaking points along this route. Add these new breaking points to the alignment and go to Step 3(b) for local search, after setting $q := 1$, $r := 1$, and $\alpha := \alpha/2$, else if the number of the breaking points is $\geq \widehat{BP}_{\max}$, introduce R^{best} as the best route and stop. □

5. Calibration of the proposed algorithm

To calibrate the algorithm for an efficient and effective use, the model's parameters are classified into three groups:

(a) Various iteration limits;

(b) Parameters that follow certain rules;

(c) Irregular parameters.

The first group includes *GSIter* and *LSIter* in Step 2 as well as $\widehat{LSIter}$ and *SubIter* in Step 3. The number of the initial alignments, m, in Step 1 is also of this nature. It affects the computational complexity in Step 2. By running the algorithm, and finding that the best-found alignment (according to our objective function in Eq. (1)) remains the same, after several iterations, that iteration may be considered as *GSIter*. The increase in the iteration limits of the parameters in Group (a) would increase the precision of the results on the one hand, while increasing the computation time on the other hand.

Group (b) parameters follow certain available binding information. These parameters comprise the following: δx, δy, $BP_{\max}$, and $\widehat{BP}_{\max}$. The first two parameters, which show the allowable variations in the

two horizontal directions, may be defined as follows:

$$\delta x = \max(x) - \min(x),$$

$$\delta y = \max(y) - \min(y). \tag{9}$$

In other words, δx and δy show the dimensions of the terrain under study. The other two parameters, however, limit the maximum number of the breaking points along the alignment. Let P be the current number of the intermediate breaking points in an alignment. Then, this number turns to:

$$P := 2 \times P + 1, \tag{10}$$

after finishing the next smoothing-out operation along the road alignment. An appropriate value for P is a function of the extent of barriers and obstructions encountered when joining the two endpoints of the road alignment by a straight line. Such obstructions include (boundaries of) mountains, valleys, forests, wet areas, etc. The turning points provide opportunities to bypass such obstructions. Figure 3 helps to describe this point better. It also shows how the number of the turning points increases in later iterations. $BP_{\max}$ is specified based on the number of the turning points that allows bypassing obstruction smoothly in connecting the two end points of the route. $\widehat{BP}_{\max}$ is determined based on the design criteria for the minimum distance between the two consecutive stations required to settle the alignment on the ground. Thus, the upper bound $\widehat{BP}_{\max}$ may be found by dividing the route length by the minimum station distance. This value should be lower than that obtained by Eq. (10).

Finally, Group (c) contains irregular parameters that hardly follow certain rules and may differ from one problem/case to another. In our procedure, ϑ, α,

δz_{global}, and δz_{local} fall into this group. Determining appropriate values for these parameters may be done by sensitivity analyses.

To calibrate our model, the case studied by Jha et al. [55] is employed for data availability reasons. The case comprises a terrain of 2100×1400 ft^2. This terrain is shown in Figure 4, both in 3D form and in contour lines. Table 4 presents the unit costs for this purpose and the specifications of the alignment.

To use the model, it should be calibrated first for better performance. Since there is insufficient experience and data, if any, in this regard, we will resort to a heuristic procedure as follows, with the hope that the proposed model performs better than the un-calibrated model by choosing the better performing values for the parameters. It is notable that, at worst, we will work with an "inefficient" algorithm. Then, the value of the most important parameter will be specified, and the value of that parameter of the model will vary within a reasonable range. To reduce the effect of non-calibrated parameters on the calibration of another parameter, the value of the parameter of concern within its range will vary, while the other parameters will be kept at their average (mid-range) value, or the best value found. It should be noted that the use of the average (mid-range) value of a variable with n possible equally likely values (because there is no information about their probability distribution at hand) would minimize the error of the choice. Computation of the value of the objective function in this one-dimensional search determines the value of that parameter, corresponding to the better value(s) of this function. To avoid the effect of the iteration number of the algorithm on the results, the number of iterations is held constant (herein, 20 for the sensitivity analysis on ϑ and 10 for such analyses on α, δz_{local},
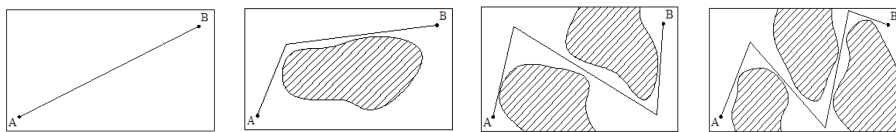

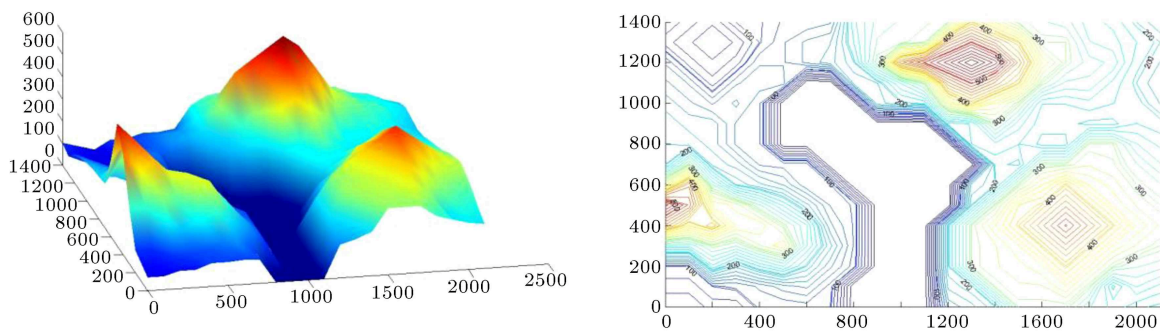**Figure 3.** Increase of breaking points with the increase of barriers.

Figure 4. 3D view and contour line of the case study for sensitivity analysis.

Table 4. Unit costs and design parameters used in this study for the reference problem obtained from Jha et al. [55].

Unit cost of		Unit cost	Design parameter	Design value
Pavement		0.15 (\$/ft)	Start point coordinate*	(100, 100, 200)
Cut plus transportation to a landfill		37 (\$/yd^3)	End point coordinate*	(1800, 1300, 250)
Fill plus transportation from a borrow pit		53 (\$/yd^3)		
Fuel	Gasoline	1.25 (\$/gallon)	Maximum grade	5%
	Diesel	0.85 (\$/gallon)	Cut/fill slope	45 degree
Travel time	Medium car	8.5 (\$/hr)	Analysis period	30 (years)
	2A single-unit truck	20 (\$/hr)	Alignment width	35 (ft)
	3-S2 diesel truck	23 (\$/hr)		

*: The end points of the alignment are specific to our study, but are very close to those in Jha et al. [55].

(a) Without local search   (b) With local search
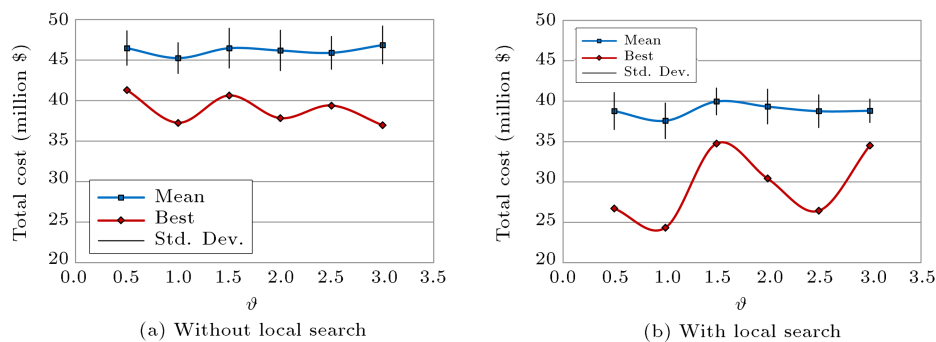
Figure 5. Changes in the mean and the best cost obtained from 20 consecutive runs for different ϑ with and without local search effect

and δz_{global}). To reduce the effect of the initial set of alignments on the results, the algorithm is run many times (herein, 20), and the collective results are considered. The size of the initial set of alignments is chosen to be 20. The parameters are calibrated in the order and ranges of $\vartheta \in [0.5, 3.0]$ in Eq. (6), $\alpha \in [0.05, 0.5]$ in Eq. (4), $\delta z_{\text{global}} \in [0.25, 1.75] \times \Delta Z$, and $\delta z_{\text{local}} \in [0.01, 0.25] \times \Delta Z$ in Eq. (4), where ΔZ is $\max.\{\delta h, |z_B - z_A|\}$, where δh represents a certain appropriate positive value. This order is a perceived order of importance, and the ranges are deemed reasonable based on the information found in the literature or perception. The calibration procedure pursued in this study is as follows:

Step 1. *Specification of ϑ:* Parameter ϑ relates to the global search and, hence, its value will be sought in two cases. First, Step 3 is omitted (of the local search), and *LSIter* (the maximum number of the local search iterations) is set equal to 1 (this would reduce the effect of the local search on the results to a minimum). Next, Step 3 is added to examine the joint effect of the local and global searches on the results. In all runs, the initial alignments are kept the same. Figure 5 shows that $\vartheta = 1.0$ is the better value

in both cases; however, the case with the local search step further reduces the minimum objective function;

Step 2. *Specification of δz_{global}, δz_{local}, and α:* To calibrate the model for these three parameters, the initial alignments and the generated random numbers may become effective. Hence, these two dimensions are considered by constructing five sets of initial alignments; for each set, the program is run for 20 times. Then, the average (and, to some degree, the best) value of the objective function will indicate the most suitable parameter values as described below.

To specify α, we set $\vartheta = 1.0$ (its best value), $\delta z_{\text{global}} = 1.0$, and $\delta z_{\text{local}} = 0.13$ (their respective range average values). Figure 6(a) shows the best and average values of the objective function for the five sets of alignments and for each given value of $\alpha \in [0.05, 0.5]$ in increments of 0.05. Considering the average value of the objective function over the 5 alignment sets and over the 20 iterations for each alignment set, a minimum value at $\alpha = 0.25$, where the minimum value of the objective function has also a good stance. Hence, $\alpha = 0.25$ is set.

To specify δz_{global}, $\vartheta = 1.0$, $\alpha = 0.25$ (their best values), and $\delta z_{\text{local}} = 0.13$ (its range average value) are
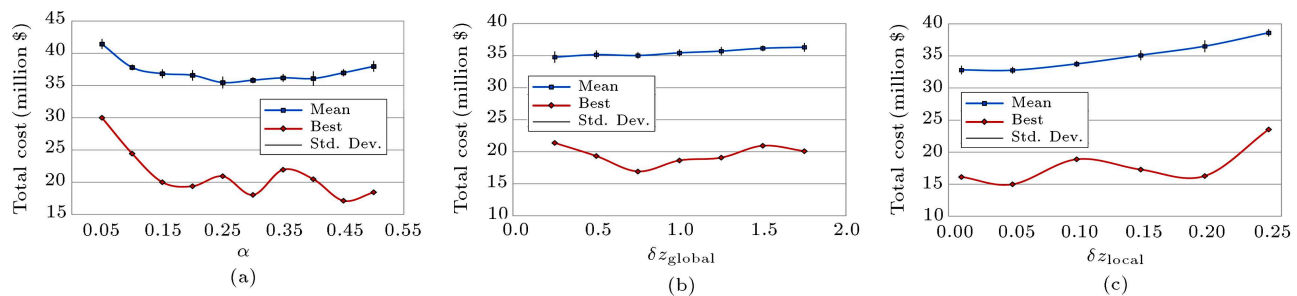
Figure 6. Changes in the mean and the best cost obtained from five sets of initial alignments for three model parameters α, δz_{global}, and δz_{local}.

Table 5. The pursued calibration procedure of the electromagnetism-like algorithm in this study.

Order of calibration	Parameter for calibration	Range of parameter	Other parameters' values assumed in the calibration				Calibrated parameter value
			ϑ	α	δz_{global}	δz_{local}	
1	ϑ	$[0.5, 3.0]$		0.25	1.0	0.13	1.0
2	α	$[0.05, 0.5]$	1.0		1.0	0.13	0.25
3	δz_{global}	$[0.25, 1.75] \times \Delta Z$	1.0	0.25		0.13	0.25
4	δz_{local}	$[0.01, 0.25] \times \Delta Z$	1.0	0.25	0.25		0.05

set. Figure 6(b) shows the best and average values of the objective function for the five sets of alignments and for each given value of $\delta z_{\text{global}} \in [0.25, 1.75]$ in 0.25 increments. It is evident in this figure that the average value of the objective function decreases and, then, stabilizes with the decrease of δz_{global}. Hence, $\delta z_{\text{global}} = 0.25$ is chosen.

For δz_{local}, $\vartheta = 1.0$, $\alpha = 0.25$, and $\delta z_{\text{global}} = 0.25$ (at their best values) are set, and $\delta z_{\text{local}} \in [0.01, 0.25]$ in 0.05 increments varies (except for the first 0.04 increment). The variations of the average and best values of the objective function, due to the variation of δz_{local} in its range, are shown in Figure 6(c). It seems in the figure that $\delta z_{\text{local}} = 0.05$ is a more suitable value.

Table 5 summarizes the calibration procedure for the algorithm and presents the results.

6. The performance of the algorithm

In what follows, the proposed algorithm is applied in the solution of several specifically designed problems to show its performance. The English System of measurements (instead of the Metric System) is chosen because of the data at hand. Most unit costs have been borrowed from Jha et al. [55]. The program is coded in Matlab R2011b and run on a laptop computer with Intel Core 2 Duo 2.80 GHz CPU and 4.00 GB RAM.

6.1. Example 1. The shortest arrival distance

Herein, we aim to find the shortest path between the two points with the coordinates $(800, 800, 200)$ and $(2000, 2000, 300)$. The objective function is the
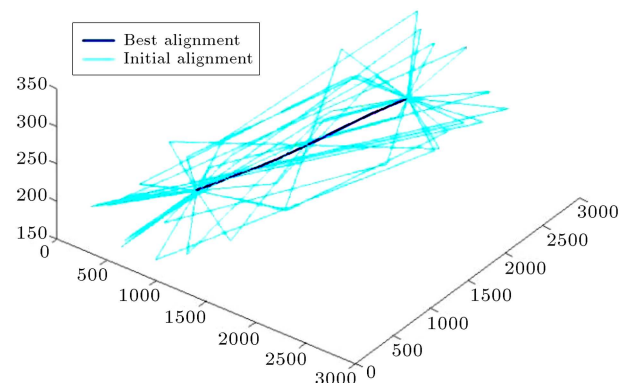

Figure 7. The shortest arrival distance (Example 1).

distance between these two points, and there is no constraint on the shortest path alignment.

Figure 7 shows 20 initial alignments and the shortest path (finally discovered). The shortest path between these two points has a length of 1700.0 ft, and it is also evident from this figure that none of the initial alignments is close to the shortest alignment. The results of 10 runs to solve the problem presented the shortest alignment lengths and the respective CPU times for finding them, as given in Table 6. The figures in this table indicate good precision and solution speed for this problem.

6.2. Example 2. The forbidden area problem

The forbidden areas are places where passage of the road alignments through them is not allowed. They include forests, ponds, wet areas, and other reserved areas that have environmental, archaeological, or simi-

Table 6. Alignment distance and run times for Example 1.

Run	Distance (ft)	Run time (sec)
1	1700.47	1.919
2	1700.14	1.888
3	1701.83	1.872
4	1700.55	1.904
5	1700.64	1.904
6	1700.28	1.888
7	1700.89	1.903
8	1700.39	1.935
9	1700.01	1.919
10	1700.5	1.857
Min	1700.01	1.857
Mean	1700.57	1.8989
Max	1701.83	1.935
Std. Dev.	0.51	0.02

Table 7. Total costs of the best-found alignments and the respective run times for Example 2.

Run	Total cost (million $)	Run time (sec.)
1	7.70	199
2	6.94	205
3	7.40	204
4	6.87	209
5	7.07	202
6	6.91	199
7	7.74	186
8	7.27	204
9	7.32	198
10	6.70	205
Min	6.70	186
Mean	7.19	201
Max	7.74	209
Std. Dev.	0.35	6.40

lar importance. In this example, an example terrain of 2100×1400 ft^2 is constructed which includes a body of water, as shown in Figure 8(a). In Examples 2 through 6, the unit costs of Table 4 and road maintenance cost of about 10% of the road construction cost are used.

The road end points have coordinates (600, 1300) and (2000, 300) on the horizontal plane. Table 7 presents the results of 10 different runs to solve this problem, and the best alignment is shown in Figure 8(b). It shows how the algorithm finds the best alignments to bypass the forbidden area between the two end points of the road.

6.3. Example 3. Flat area with several obstructions

The terrain in this example is more difficult to handle than that in Example 2, and the route has to wind through the area (Figure 9(a)). The two end points of the road have horizontal plane coordinates of (200,

1350) and (1900, 50). We do not allow building tunnels in constructing this route; therefore, it has to wind around the obstructions. The terrain in this example is of the same size as in Example 2 with different features in the topography. The results of 10 runs are presented in Table 8, and the best alignment is shown in Figure 9(b). This figure shows the capability of the algorithm to bypass the mountains. Moreover, based on Figure 9(b), the algorithm is able to move backward to find a better alignment.

6.4. Example 4. Bridge construction

Bridges and tunnels may trade-off capital cost with road length-related costs: Higher construction costs with shorter roads. In Examples 4 through 6, the terrains are built ruggedly to promote the construction of roads with such facilities. Figure 10(a) and (b) show a terrain with a deep valley, and either of the two end points is located on either side of the valley

(a) 3D view from SW

(b) Best alignment found
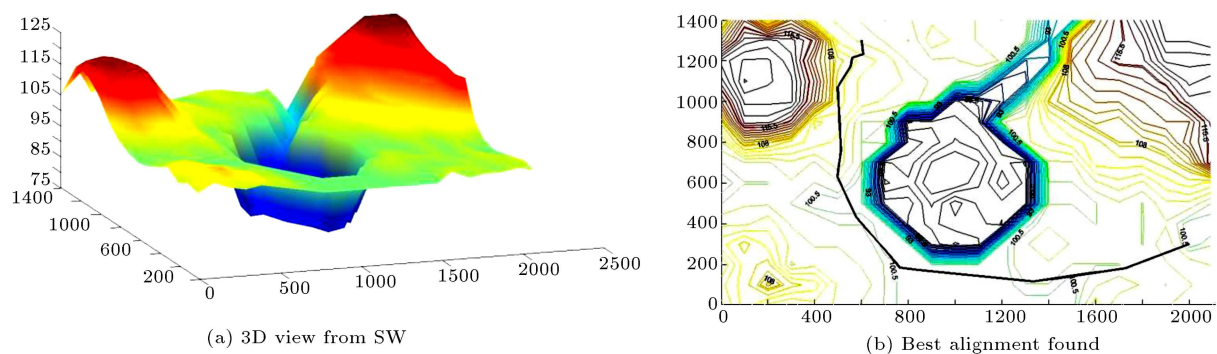
Figure 8. The forbidden area problem (Example 2).

(a) 3D view from SW

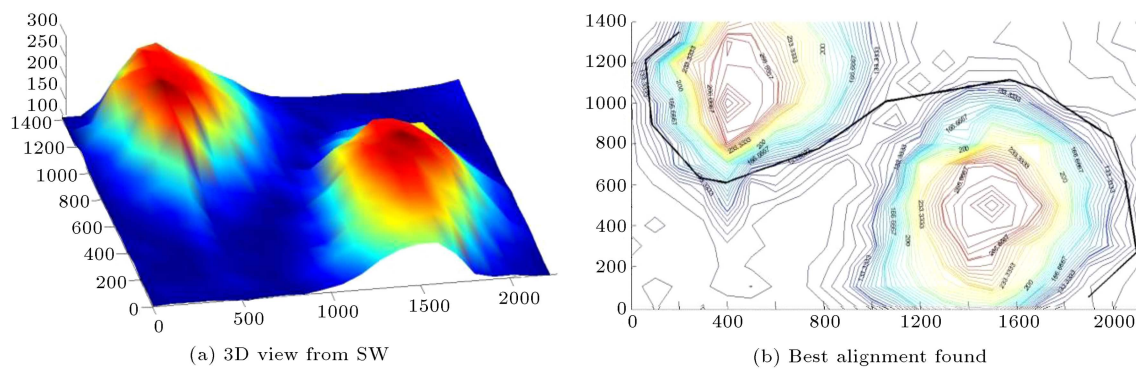

(b) Best alignment found

Figure 9. Flat area with several obstructions (Example 3).

Table 8. Total costs of the best-found alignments and the respective run times for Example 3.

Run	Total cost (million $)	Run time (sec.)
1	13.74	301
2	12.51	264
3	13.71	260
4	13.45	258
5	15.39	299
6	16.87	254
7	13.28	266
8	13.35	268
9	13.28	244
10	13.81	280
Min	12.51	244
Mean	13.94	270
Max	16.87	301
Std. Dev.	1.26	18.68

Table 9. Total costs of the best-found alignments and the respective run times for Example 4.

Run	Without bridge		With bridge	
	Total cost (million $)	Run time (sec.)	Total cost (million $)	Run time (sec.)
1	10.89	251	7.22	112
2	11.12	246	7.25	119
3	11.92	255	7.28	117
4	11.37	258	7.33	113
5	10.96	251	7.38	119
6	12.16	252	7.39	116
7	11.77	252	7.50	111
8	10.84	251	7.44	118
9	11.09	252	7.16	113
10	11.33	248	7.27	115
Min	10.84	246	7.16	111
Mean	11.35	252	7.32	115
Max	12.16	258	7.50	119
Std. Dev.	0.46	3.39	0.11	2.83

with coordinates on the horizontal plane as (100, 400) and (1350, 300), so that the alignment between them needs to cross the valley axis line. This study assumes a bridge unit construction cost of 5000 $/ft (within certain specifications regarding bridge length, valley depth, etc.). Table 9 presents the results of 10 runs of the algorithm for either case of when bridge construction is/is not possible. According to this table, in the case where bridge construction is possible, not only the total construction cost reduces, but also does the CPU computation time. The latter happens due to the relation between the computation efforts and the length of the alignment that reduces because of the bridge construction. Figure 10(c) and (d) show the best alignment of each of the two cases under considerations. It is interesting to compare the components of the total costs in the two cases, as shown in Table 10. The extra cost of the bridge construction is more than off-set by the reduction of all other cost components.

6.5. Example 5. Tunnel construction

Constructions of roads in mountainous terrains often require construction of tunnels. Figure 11(a) and (b) show a terrain designed for the purpose of this example, in which a high mountain obstructs the straight line alignment between the two end points of the route. The coordinates of these two points on the horizontal plane are assumed to be (200, 700) and (1800, 800). A tunnel unit construction cost of 3000 $/ft is assumed. Table 11 shows the results of 10 runs of the algorithm for two cases with/without tunnel construction. Once again, this table shows that the case with tunnel construction, as compared with the case of its alternative under considerations, reduces both the total construction cost, as well as the CPU computation times, for the same reasons mentioned before for bridge
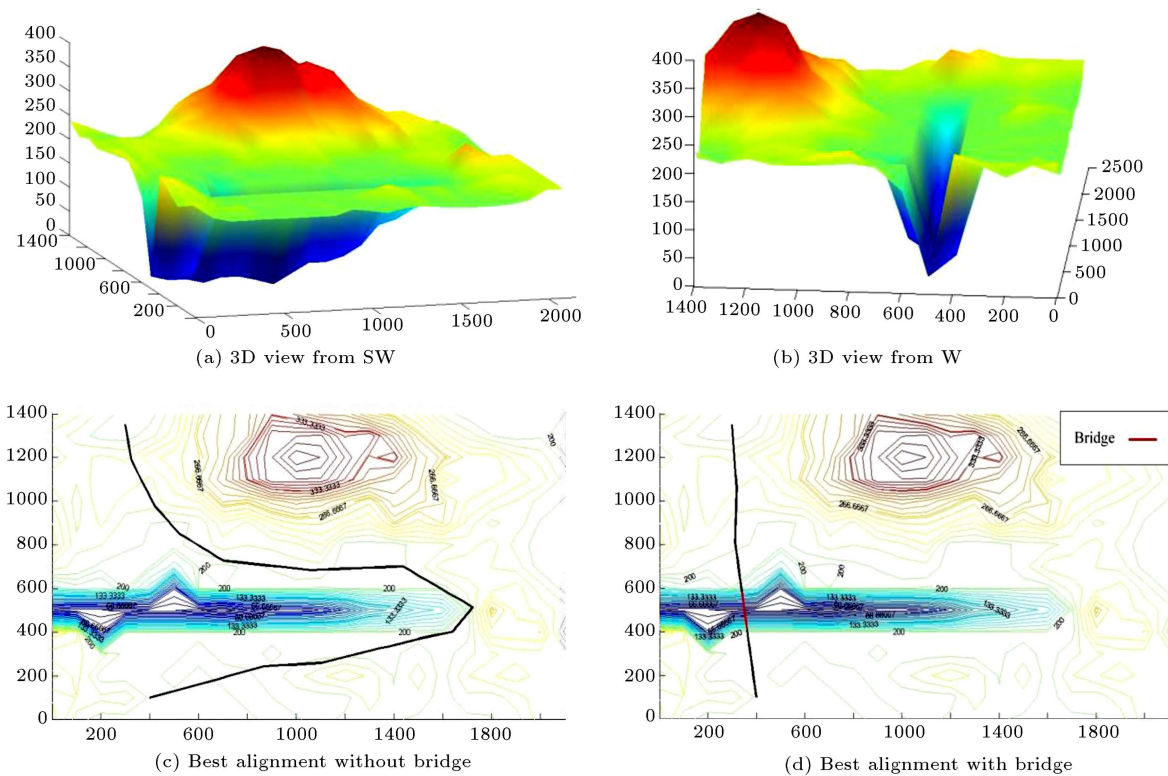
(a) 3D view from SW

(b) 3D view from W

(c) Best alignment without bridge

(d) Best alignment with bridge

Figure 10. Bridge construction (Example 4).

Table 10. The total cost break-downs for the best alignment with/without bridge.

Cost components	Best alignment cost (thousand $)	
	Without bridge	With bridge
Pavement	0.492	0.189
Earthworks	957	578
Fuel	607	233
Travel time	3212	1231
Bridge construction	0	1192
Right-of-way	1943	581
Maintenance	4123	3343

Table 11. Total costs of the best-found alignments and the respective run times for Example 5.

	Without tunnel		With tunnel	
Run	Total cost (million $)	Run time (sec.)	Total cost (million $)	Run time (sec.)
1	9.77	205	7.60	131
2	9.87	216	7.44	133
3	10.64	212	7.65	130
4	10.29	216	7.38	126
5	10.08	216	7.60	123
6	13.37	187	7.81	121
7	10.94	213	7.74	129
8	10.42	195	7.64	129
9	10.66	213	7.70	127
10	9.91	222	7.76	125
Min	9.77	187	7.38	121
Mean	10.60	210	7.63	127
Max	13.37	222	7.81	133
Std. Dev.	1.05	10.96	0.13	3.72

construction in Example 4. Figure 11(c) and (d) show the best alignment of each case under consideration. A component-wise comparison of the total costs of the two alignments in Table 12 indicates that the extra cost of tunnel construction is more than off-set by the reduction of all other cost components.

6.6. Example 6. A more general terrain
In this example, a more general terrain is made to show the performance of the proposed algorithm when more than one feature is present on the straight line alignment between its two end points. The end points are assumed to be at the coordinates (200, 2700) and

(4200, 2500) on the horizontal plane. The terrain consists of a dam (a body of water that may not be crossed) and a rugged area (Figure 12(a) and (b)), so that the alignment is better served by bridges and tunnels. In this example, the bridge and tunnel unit construction costs are assumed to be 5000 $/ft and
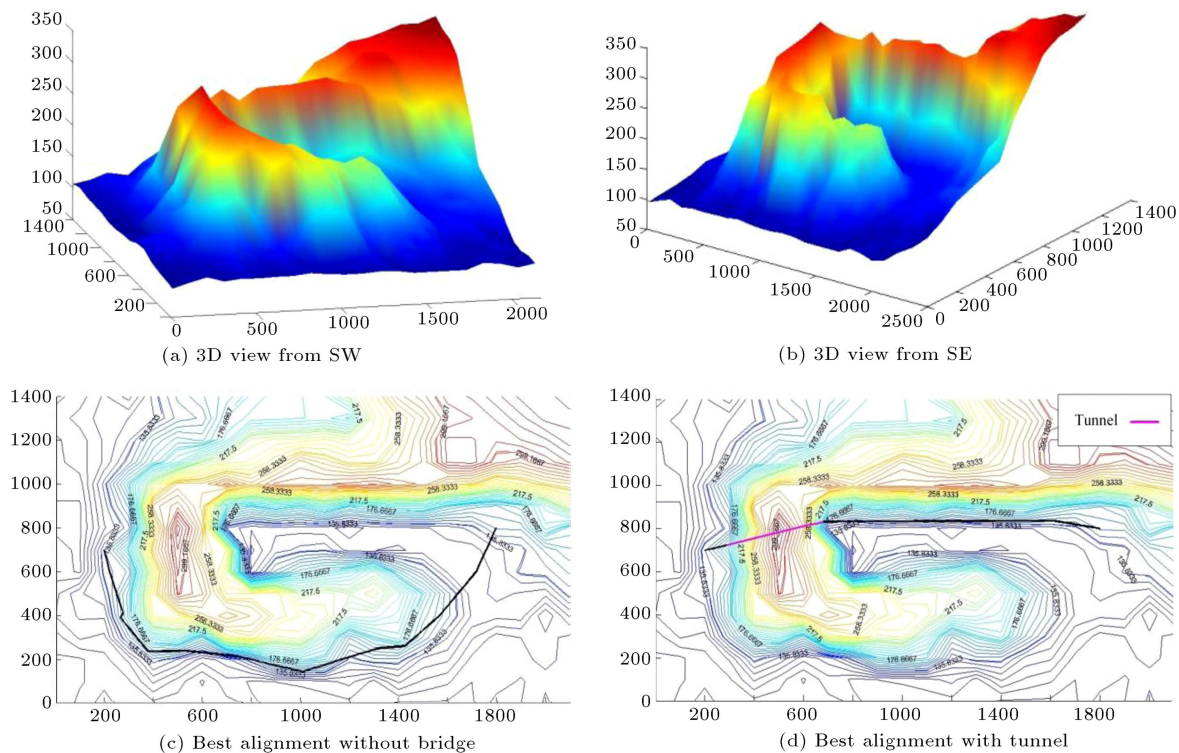
(a) 3D view from SW

(b) 3D view from SE

(c) Best alignment without bridge

(d) Best alignment with tunnel

Figure 11. Tunnel construction (Example 5).

Table 12. The total cost break-downs for the best alignment with/without tunnel.

Cost components	Best alignment cost (thousand $)	
	Without tunnel	With tunnel
Pavement	0.338	0.243
Earthworks	1600	340
Fuel	417	300
Travel time	2208	1588
Tunnel construction	0	1195
Right-of-way	1353	734
Maintenance	4197	3225

Table 13. Total costs of the best-found alignments and the respective run times for Example 6.

Run	Total cost (million $)	Run time (sec.)
1	33.01	444
2	34.50	467
3	34.48	506
4	33.72	512
5	37.02	518
6	35.29	408
7	33.33	434
8	34.50	544
9	38.03	475
10	37.87	505
Min	33.01	408
Mean	35.18	481
Max	38.03	544
Std. Dev.	1.84	42.94

8000 \$/ft, respectively. Table 13 shows the results of 10 runs of the algorithm for the solution of this problem. Figure 12(c) shows the best alignment among the 10 runs. It shows the use of the bridge on the deep valley and two tunnels to overcome the two high mountains on the sides.

6.7. Example 7. Solution to an existing problem

In this example, the performance of the proposed algorithm in this study will be shown on a test problem given by Jha et al. [55]. The terrain of the problem is shown in Figure 4. The unit costs and alignment specifications, used in this comparison, are given in Table 4, respectively. To have the results closer to the respective ones, given by Jha et al. [55], this study ignores maintenance cost in the cost computation, but considers the accident costs equivalent to 10% of the total cost of the alignment (according to the information given by Jha et al. [55]). Table 14 shows the results of three (×10) runs of the proposed
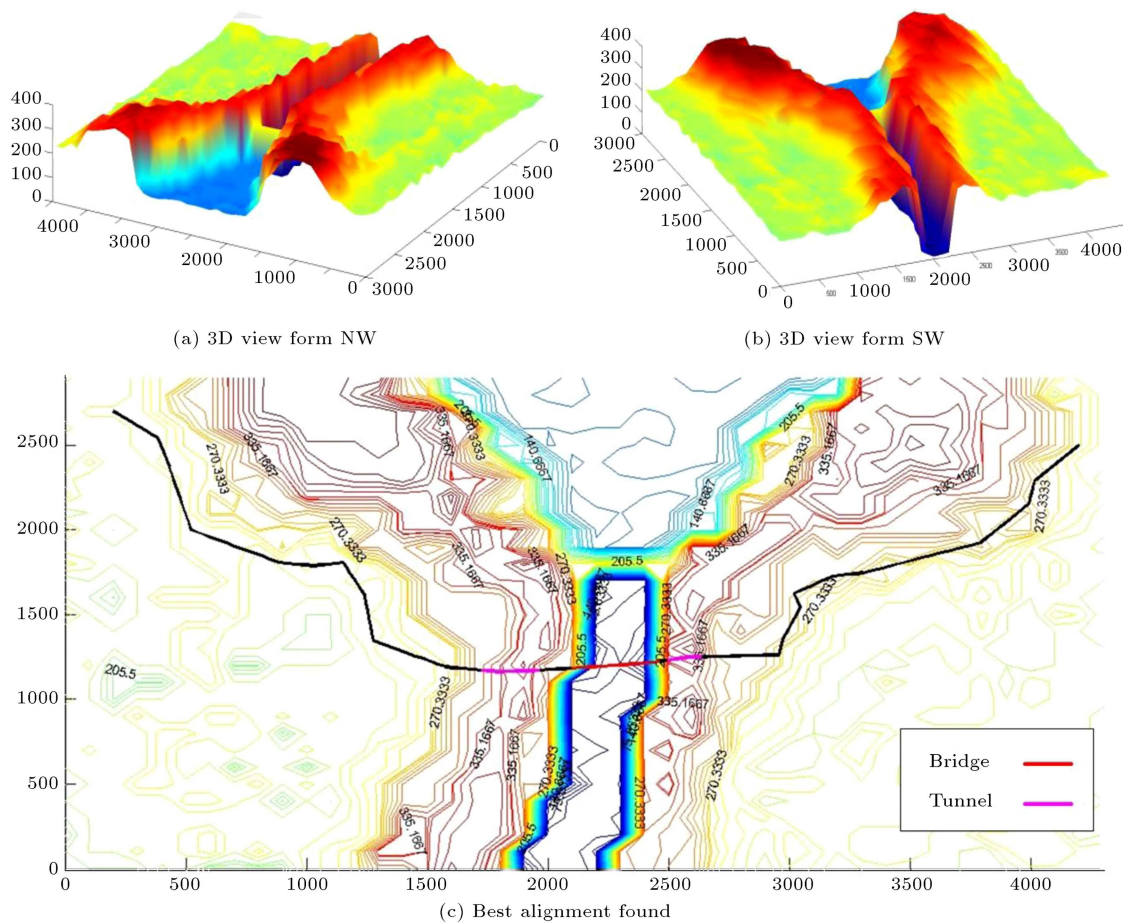
(a) 3D view form NW

(b) 3D view form SW

(c) Best alignment found

Figure 12. A more general terrain (Example 6).

Table 14. The results of three separate trials of the algorithm in this study and those of Jha et al. [55] on the same problem (million $).

Run	Trial 1	Trial 2	Trial 3	Jha et al. [55]
1	16.06	14.22	15.28	27.202
2	19.13	17.58	19.31	24.412
3	14.21	14.97	21.88	27.323
4	15.63	19.35	17.05	25.370
5	14.60	16.83	14.95	21.086
6	14.21	20.25	15.24	23.154
7	20.14	17.07	14.73	23.709
8	13.97	16.54	15.47	25.223
9	17.024	19.54	14.78	24.845
10	14.28	14.29	15.33	25.942
Min	13.97	14.22	14.73	21.086
Mean	15.93	17.06	16.40	24.827
Max	20.14	20.25	21.88	27.323
Std. Dev.	2.20	2.17	2.38	1.879

electromagnetism-like algorithm. This table shows that, in all of the three separate experiments, the proposed electromagnetism-like algorithm finds alignments whose mean construction costs (for the 10 runs)

are very similar to each other. The best alignment among the three alignments is shown in Figure 13. It also shows how an increase in the number of the breaking points in our alignment design would affect the capability of the proposed algorithm in providing a more flexible alignment to fit the topography of the terrain. Table 14 also includes the values of the objective function for the 10 runs of the algorithm presented in Jha et al. [55]. It is to be noted that, although the objective functions of the two studies are basically the same, their alignment specifications (constraints) differ in some respects (for example, in building the horizontal and vertical curves). This is why we lose ground for the comparisons of the two algorithms. In the passing process, based on Table 14, it is worth noting that our three trials result in higher standard deviations for the objective function values of the 10 solutions found in the different runs, as compared to the study result of Jha et al. [55]. This is because the algorithm of this study, unlike that of Jha et al. [55], does not constrain itself in the 3D space when searching for better alignments.

Figure 14 presents the break-down of the total cost of the final route alignment in this example (Note that the pavement cost is low, not zero in this figure.).
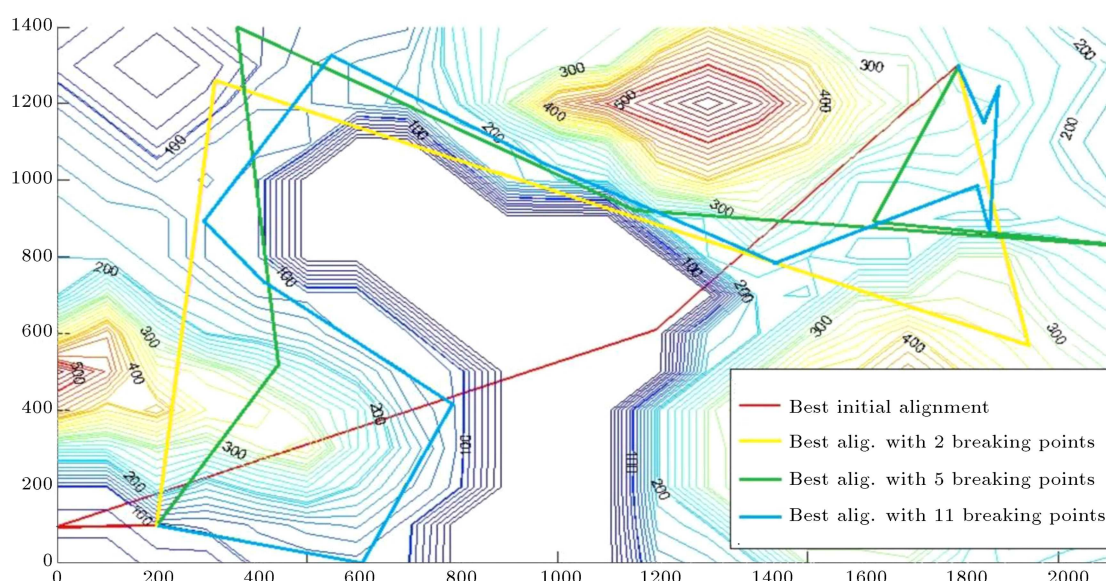
Figure 13. The best alignment between end points A and B found by the algorithm for different breaking points in Example 7.
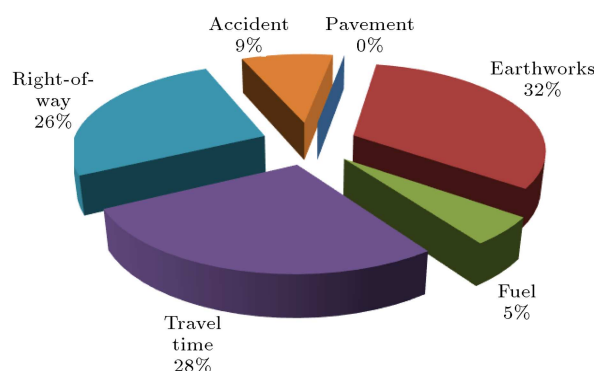

Figure 14. The shares of the major cost components for the best alignment in Example 7.

This figure shows that, based on the input data, three cost components of earth works (32%), users' travel time (28%), and right-of-way (26%) sum up to 86% of the alignment total cost.

7. Summary and conclusions

This paper presented an adaptation of the electromagnetism-like algorithm to solve the three-dimensional route alignment design between two points. The review of the literature in this area revealed that after a break-through progress from the two-dimensional alignment design algorithms to the three-dimensional ones, there was a potential for enhancing the quality of the 3D alignment design and embedding capabilities for deciding different trade-offs between various cost components. More specifically, such trade-offs exist between road structural elements, like bridges and tunnels, and all other road length-related costs, like earthworks (cuts and fills) and the user's travel times.

For this purpose, an electromagnetism-like algorithm [58] was adapted to solve the 3D alignment design problem. Seven examples were devised to test the performance of the algorithm in terms of the algorithmic capabilities, design, and speed of solving the problem. The application of the algorithm in these examples showed satisfactory results.

The contributions of this study to the field are as follows:

1. Introduction and adaptation of an efficient algorithm to solve the 3D alignment problem, which can:
   (i) Consider the real-world cost components;
   (ii) Make a trade-off between cost components by comparing more conventional wavy or zigzag routes with more modern structures to build more straight alignments;
   (iii) Observe the constraints in the alignment design, such as the maximum slopes and reserved/forbidden areas.

2. Implementation of the concept of breaking point mechanism within the algorithm, which grants the algorithm the necessary flexibility to bypass obstructions more smoothly.

It is not possible to compare our algorithm with the existing algorithms due to the differences in the objective functions as well as the constraints of the problems under study. Table 15 presents the specification of this study with those of a prominent algorithm in the 3D highway alignment problem. As is evident in this table, we think that maintenance cost is an important cost component to consider, and maximal allowable horizontal and vertical curvatures

Table 15. A comparison of the objective functions and constraints in this study and those of Jha et al. [55].

	Items	Problem cost components in the objective function								Problem constraints		
		Location-related	Length-related	Earthwork-related	Accident costs	Bridge and tunnel construction	Road maintenance	Traffic fuel consumption	Traffic total travel time	Maximal allowable gradient	Maximal allowable curvature for horizontal alignment	Maximal allowable curvature for vertica alignment
Overall	This study	✓	✓	✓	—	✓	✓	✓	✓	✓	—	—
	Jha et al. [55]	✓	✓	✓	✓	✓	—	✓	✓	✓	✓	✓
Example 7	This study	✓	✓	✓	✓	—	—	✓	✓	✓	—	—
	Jha et al. [55]	✓	✓	✓	✓	—	—	✓	✓	✓	✓	✓

are detailed design-level, and not highway alignment-design-level, considerations. Such differences prevent easy comparison of the performances of different algorithms. We hope that with the information provided in this study about the 7 test examples, there will be a common platform for such comparisons in the future. This will obviate the awkward and unnecessary task of the iterative computer coding of other involved procedures for comparison purposes in order to convince independent observers of the merits of the new algorithms.

Further study in this area may pay more attention to linking such algorithms with geographical information systems and its application to cases where sufficient efforts have been made to arrive at final alignments, which may serve for validation purposes.

References

1. Kim, E., Jha, M.K., and Son, B. "Improving the computational efficiency of highway alignment optimization models through a stepwise genetic algorithms approach", *Transportation Research Part B: Methodological*, **39**(4), pp. 339-360 (2005).

2. Kang, M.-W., Jha, M.K., and Schonfeld, P. "Applicability of highway alignment optimization models", *Transportation Research Part C: Emerging Technologies*, **21**(1), pp. 257-286 (2012).

3. Jong, J.-C. and Schonfeld, P. "An evolutionary model for simultaneously optimizing three-dimensional highway alignments", *Transportation Research Part B: Methodological*, **37**(2), pp. 107-128 (2003).

4. Jha, M.K. and Schonfeld, P. "A highway alignment optimization model using geographic information systems", *Transportation Research Part A: Policy and Practice*, **38**(6), pp. 455-481 (2004).

5. Howard, B., Bramnick, Z., and Shaw, J., *Optimum Curvature Principle in Highway Routing*, Road Research Laboratory/UK (1969).

6. Shaw, J.F. and Howard, B.E. "Comparison of two integration methods in transportation routing", *Transportation Research Record*, **806**, pp. 8-13 (1981).

7. Shaw, J.F. and Howard, B.E. "Expressway route optimization by OCP", *Transportation Engineering Journal*, **108**(3), pp. 227-243 (1982).

8. Thomson, N. and Sykes, J. "Route selection through a dynamic ice field using the maximum principle", *Transportation Research Part B: Methodological*, **22**(5), pp. 339-356 (1988).

9. Wan, F., *Introduction to the Calculus of Variations and its Applications*, Boca Raton, Florida, United States CRC Press (1995).

10. Turner, A.K. and Miles, R.D., *The GCARS System: A Computer-Assisted Method of Regional Route Location*, West Lafayette, Indiana, United States Lafayette, in Purdue University (1971).

11. Athanassoulis, G. and Calogero, V. "Optimal location of a new highway from A to B-A computer technique for route planning", *PTRC Seminar Proceedings on Cost Models & Optimization in Highway* (1973).

12. Parker, N.A. "Rural highway route corridor selection", *Transportation Planning and Technology*, **3**(4), pp. 247-256 (1977).

13. Trietsch, D. "A family of methods for preliminary highway alignment", *Transportation Science*, **21**(1), pp. 17-25 (1987).

14. Trietsch, D. "Comprehensive design of highway networks", *Transportation Science*, **21**(1), pp. 26-35 (1987).

15. Hogan, J. "Experience with OPTLOC optimum location of highways by computer", *PTRC Seminar Proceedings on Cost Models and Optimization in Highways (Session L10)*, London (1973).

16. Nicholson, A.J., Elms, D.G., and Williman, A. "A variational approach to optimal route location", *Highway Engineers*, **23**, pp. 22-25 (1976).

17. Lee, Y., Tsou, Y.-R., and Liu, H.-L. "Optimization method for highway horizontal alignment design", *Journal of Transportation Engineering*, **135**(4), pp. 217-224 (2009).

18. Liatsis, P. and Tawfik, H. "Two-dimensional road shape optimisation using genetic algorithms", *Mathematics and Computers in Simulation*, **51**(1), pp. 19-31 (1999).

19. Jong, J.-C., *Optimizing Highway Alignments with Genetic Algorithms*, Research Directed by Dept. of Civil Engineering, University of Maryland, College Park, Md. (1998).

20. Jong, J.C., Jha, M.K., and Schonfeld, P. "Preliminary highway design with genetic algorithms and geographic information systems", *Computer Aided Civil and Infrastructure Engineering*, **15**(4), pp. 261-271 (2000).

21. Easa, S.M. "Selection of roadway grades that minimize earthwork cost using linear programming", *Transportation Research Part A: General*, **22**(2), pp. 121-136 (1988).

22. Huarte, P. "OPYGAR: Optimization and automatic design of highway profiles", *Planning and Transport Research and Computation Seminar Proceedings on Cost Models and Optimization in Highways (Session L13)*, London (1973).

23. Murchland, J. "Methods of vertical profile optimization for an improvement to an existing road", *PTRC Seminar Proceedings on Cost Models and Optimisation in Highways (Session L12)*, London (1973).

24. Goh, C., Chew, E., and Fwa, T. "Discrete and continuous models for computation of optimal vertical highway alignment", *Transportation Research Part B: Methodological*, **22**(6), pp. 399-409 (1988).

25. Fwa, T. "Highway vertical alignment analysis by dynamic programming", *Transportation Research Record*, **1239** (1989).

26. Revelle, C.A. and Whitlach, E.E., *Civil and Environmental Systems Engineering*, Upper Saddle River, New Jersey, United States Prentice Hall PTR (1996).

27. Chapra, S.C. and Canale, R.P., *Numerical Methods for Engineers*, Boston, United States McGraw-Hill (2006).

28. Hare, W., Lucet, Y., and Rahman, F. "A mixed-integer linear programming model to optimize the vertical alignment considering blocks and side-slopes in road construction", *European Journal of Operational Research*, **241**(3), pp. 631-641 (2014).

29. Hare, W., Hossain, S., Lucet, Y., and Rahman, F. "Models and strategies for efficiently determining an optimal vertical alignment of roads", *Computers & Operations Research*, **44**, pp. 161-173 (2014).

30. Hayman, R.W. "Optimization of vertical alignment for highways through mathematical programming", *Highway Research Record*, **306** (1970).

31. Robinson, R. "Automatic design of the road vertical alignment", *PTRC Seminar Proceedings on Cost Models and Optimization in Highways (Session L19)*, London (1973).

32. Fwa, T., Chan, W., and Sim, Y. "Optimal vertical alignment analysis for highway design", *Journal of Transportation Engineering*, **128**(5), pp. 395-402 (2002).

33. Chew, E., Goh, C., and Fwa, T. "Simultaneous optimization of horizontal and vertical alignments for highways", *Transportation Research Part B: Methodological*, **23**(5), pp. 315-329 (1989).

34. Mandow, L. and Pérez-de-la-Cruz, J.-L. "Sindi: an intelligent assistant for highway design", *Expert Systems with Applications*, **27**(4), pp. 635-644 (2004).

35. De Smith, M.J. "Determination of gradient and curvature constrained optimal paths", *Computer Aided Civil and Infrastructure Engineering*, **21**(1), pp. 24-38 (2006).

36. Jha, M.K., *A Geographic Information Systems-Based Model for Highway Design Optimization*, Maryland, United States University of Maryland at College Park (2000).

37. Kim, E., *Modeling Intersections and Other Structures in Highway Alignment Optimization*, University of Maryland, College Park (2001).

38. Tat, C.W. and Tao, F. "Using GIS and genetic algorithm in highway alignment optimization", *Intelligent Transportation Systems. IEEE* (2003).

39. Kim, E., Jha, M.K., Lovell, D.J., and Schonfeld, P. "Intersection modeling for highway alignment optimization", *Computer Aided Civil and Infrastructure Engineering*, **19**(2), pp. 119-129 (2004).

40. Kim, E., Jha, M.K., and Schonfeld, P. "Intersection construction cost functions for alignment optimization", *Journal of Transportation Engineering*, **130**(2), pp. 194-203 (2004).

41. Kim, E., Jha, M.K., Schonfeld, P., and Kim, H.S. "Highway alignment optimization incorporating bridges and tunnels", *Journal of Transportation Engineering*, **133**(2), pp. 71-81 (2007).

42. Jia, P., Sun, Z., Kato, H., and Hayashi, Y. "Incorporating network impact analysis into road alignment optimization", *Journal of the Eastern Asia Society for Transportation Studies*, **7**, pp. 2074-2089 (2007).

43. Kang, M.W., Schonfeld, P., and Jong, J.C. "Highway alignment optimization through feasible gates", *Journal of Advanced Transportation*, **41**(2), pp. 115-144 (2007).

44. Kang, M.W., *An Alignment Optimization Model for a Simple Highway Network*, University of Maryland (2008).

45. Kang, M.W., Schonfeld, P., and Yang, N. "Prescreening and repairing in a genetic algorithm for highway alignment optimization", *Computer Aided Civil and Infrastructure Engineering*, **24**(2), pp. 109-119 (2009).

46. Kang, M.W., Yang, N., Schonfeld, P., and Jha, M. "Bilevel highway route optimization", *Transportation Research Record: Journal of the Transportation Research Board*, **2197**(1), pp. 107-117 (2010).

47. Maji, A. and Jha, M.K. "A multiobjective analysis of impacted area of environmentally preserved land and alignment cost for sustainable highway infrastructure design", *Procedia-Social and Behavioral Sciences*, **20**, pp. 966-972 (2011).

48. Jian-xin, C. and Qing, L. "Research on cost-oriented modeling and optimization for highway alignment", *Procedia Engineering*, **15**, pp. 3931-3935 (2011).

49. Yang, N., Kang, M.W., Schonfeld, P., and Jha, M.K. "Multi-objective highway alignment optimization incorporating preference information", *Transportation Research Part C: Emerging Technologies*, **40**, pp. 36-48 (2014).

50. Mohasel Afshar, A. "Design of optimum highway alignment using gradien based methods", MS Thesis, Dept. of Civil Engineering, Sharif University of Technology (In Farsi) (2004).

51. Shengwen, T., Xiucheng, G., and Shengwu, T. "Optimizing highway alignments based on improved particle swarm optimization and ArcGIS", *Transportation and Development Innovative Best Practices, ASCE* (2008).

52. Shafahi, Y. and Bagherian, M. "A customized particle swarm method to solve highway alignment optimization problem", *Computer-Aided Civil and Infrastructure Engineering*, **28**(1), pp. 52-67 (2013).

53. Pourzahedi, L. "A hybrid meta-heuristic algorithm for the solution of highway alignment problem", BS Project Report, Dept. of Civil Engineering, Sharif University of Technology (In Farsi) (2010).

54. Faghih, S. "A hybrid meta-heuristic algorithm to solve three dimensional highway alignment optimization problem", MS Thesis, Dept. of Civil Engineering, Sharif University of Technology (In Farsi) (2012).

55. Jha, M.K., ha, M.K., Schonfeld, P.M., and Jong, J.C., *Intelligent Road Design*, **19**, Southampton, Boston, United States, WIT Press (2006).

56. Kang, M.-W., Shariat, S., and Jha, M.K. "New highway geometric design methods for minimizing vehicular fuel consumption and improving safety", *Transportation Research Part C: Emerging Technologies*, **31**, pp. 99-111 (2013).

57. Cheng, J.-C. and Jiang, L.-J. "Accuracy comparison of roadway earthwork computation between 3D and 2D methods", *Procedia-Social and Behavioral Sciences*, **96**, pp. 1277-1285 (2013).

58. Birbil, Ş.İ. and Fang, S.-C. "An electromagnetism-like mechanism for global optimization", *Journal of Global Optimization*, **25**(3), pp. 263-282 (2003).

59. Kennedy, J. and Eberhart, R. "Particle swarm optimisation", *Proceedings IEEE International Conference on Neural Networks* (1995).

60. Wang, K.J., Adrian, A.M., Chen, K.H., and Wang, K.M. "An improved electromagnetism-like mechanism algorithm and its application to the prediction of diabetes mellitus", *Journal of Biomedical Informatics*, **54**, pp. 220-229 (2015).

61. Özdağ, R. and Karcı, A. "Probabilistic dynamic distribution of wireless sensor networks with improved distribution method based on electromagnetism-like algorithm", *Measurement*, **79**, pp. 66-76 (2016).

62. Jolai, F., Tavakkoli-Moghaddam, R., Golmohammadi, A., and Javadi, B. "An electromagnetism-like algorithm for cell formation and layout problem", *Expert Systems with Applications*, **39**(2), pp. 2172-2182 (2012).

63. Kuo, C.L., Chu, C.H., Li, Y., Li, X., and Gao, L. "Electromagnetism-like algorithms for optimized tool path planning in 5-axis flank machining", *Computers & Industrial Engineering*, **84**, pp. 70-78 (2015).

64. Naderi, B., Tavakkoli-Moghaddam, R. and Khalili, M. "Electromagnetism-like mechanism and simulated annealing algorithms for flowshop scheduling problems minimizing the total weighted tardiness and makespan", *Knowledge-Based Systems*, **23**(2), pp. 77-85 (2010).

65. Feng, Y., Yao-Nan, W., and Shu-Ning, W. "Inverse kinematic solution for robot manipulator based on electromagnetism-like and modified DFP algorithms", *Acta Automatica Sinica*, **37**(1), pp. 74-82 (2011).

66. Yurtkuran, A. and Emel, E. "Efficient constraint handling in electromagnetism-like algorithm for traveling salesman problem with time windows", *The Scientific World Journal*, **2014**, pp. 1-12 (2014).

67. Beheshti, A.K., Hejazi, S., and Mirmohammadi, S. "A hybrid metaheuristic algorithm for the vehicle routing problem with delivery time cost", *International Journal of Applied*, **4**(3), pp. 49-64 (2014).

68. Yurtkuran, A. and Emel, E. "A new hybrid electromagnetism-like algorithm for capacitated vehicle routing problems", *Expert Systems with Applications*, **37**(4), pp. 3427-3433 (2010).

69. Kratica, J. "An electromagnetism-like metaheuristic for the uncapacitated multiple allocation p-hub median problem", *Computers & Industrial Engineering*, **66**(4), pp. 1015-1024 (2013).

70. Fathian, M., Jouzdani, J., Heydari, M., and Makui, A. "Location and transportation planning in supply

chains under uncertainty and congestion by using an improved electromagnetism-like algorithm", *Journal of Intelligent Manufacturing*, **29**(7), pp. 1447-1464 (2018).

71. Lee, C.-H. and Lee, Y.-C. "Nonlinear systems design by a novel fuzzy neural system via hybridization of electromagnetism-like mechanism and particle swarm optimisation algorithms", *Information Sciences*, **186**(1), pp. 59-72 (2012).

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