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Automatic routing of water supply pipelines

Traçado automático de adutoras de abastecimento de água

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ABSTRACT

This paper presents an algorithm capable of calculating the optimal route for pipelines that traverse terrain with or without additional displacement constraints to the difference in ground elevations and head losses to be overcome by pumping. The criterion used to determine the pipeline diameter and calculate feasible routes was minimizing the annual cost, which results from the sum of (i) annualized costs related to the acquisition of the pipeline and (ii) costs of payment for electric power to operate the system throughout its useful life. The geometry of the shortest routes in the multidimensional search space is calculated by the proposed algorithm, called BAGDA (**B**usca pelo **A**juste **G**eométrico da **D**espesa **A**nual, in Portuguese, or Search for the Annual Cost of Geometric Tuning, in English), thus obtaining the optimal combination of length and manometric head of the pipeline. The performed applications show the efficiency of the algorithm in providing subjectivity-free routes sensitive to the most important variables considered in the design of piping systems.

Keywords: Pipelines; Route optimization; Search algorithms.

RESUMO

É apresentado um algoritmo capaz de calcular a rota ótima para adutoras que atravessam terrenos com ou sem restrições de deslocamento adicionais às diferenças de cota e às perdas de carga a serem vencidas por bombeamento. O critério empregado, tanto na definição do diâmetro da adutora, como no cálculo das rotas viáveis é o da minimização da despesa anual, resultante da soma dos (i) custos anualizados referentes à aquisição da tubulação com os (ii) custos de pagamento pela energia elétrica para funcionamento do sistema ao longo de sua vida útil. A geometria das rotas mais curtas no espaço multidimensional de busca é calculada pelo algoritmo proposto, denominado BAGDA (**B**usca pelo **A**juste **G**eométrico da **D**espesa **A**nual), obtendo-se assim a combinação ótima entre comprimento e altura manométrica da adutora. As aplicações realizadas evidenciam a eficiência do algoritmo em fornecer traçados isentos de subjetividades e sensíveis às variáveis mais importantes consideradas no projeto de sistemas adutores.

Palavras-chave: Adutoras; Otimização de rotas; Algoritmos de busca.

INTRODUCTION

Implementing pipelines is the most frequent infrastructural solution adopted for water supply in cities. The designer should look for a route to transport water from the catchment points to the delivery points that, in light of the criteria considered most appropriate for measuring the quality of the available solution, costs as little as possible.

In recent years, research aimed at solving problems of this nature has leaned towards the use of geographic information systems (GIS), considering not only water pipelines as application objects but also other long engineering works, such as highways, gas pipelines, and hydraulic canals. The works published by Jankowski & Richard (1994), Luettinger and Clark (2005), Nonis et al. (2007), Hardin et al. (2008), Salah & Atwood (2011), Balogun et al. (2012), Marcoulaki et al. (2012), Huseynli (2015), Roy et al. (2017) and Simon et al. (2021), exemplify well this form of approach that typifies the state of the art.

Jankowski & Richard (1994) present an approach to integrating a GIS-based land suitability analysis and multicriteria evaluation in a spatial decision support system for water pipeline route selection. Luettinger & Clark (2005) used GIS as a rational basis for narrowing hundreds of potential alternative routes of a water supply pipeline, obtaining a final alignment corridor, from which the ideal route was obtained, according to construction costs and other issues not involving costs. When addressing the route of a gas pipeline in India, Nonis et al. (2007) point out the lack of a structured methodology to derive the relative preferences of the different factors that affect the route as the main drawback of using GIS.

With the objective of minimizing the weight of subjective opinion in determining the ideal route for a water supply pipeline built in an urban area, Hardin et al. (2008) discuss a methodology to identify applicable evaluation criteria, establish a quantitative rating system, and develop an unbiased rating of the importance of each route criterion. Salah & Atwood (2011) consider the definition of the viable zone for solving the problem as dependent on variables directly related to construction and material acquisition costs, as well as other constraints, such as construction time, potential conflicts, impact on residents and business, etc., whose considerations in the context of the use of the GIS Spatial Analyst tool are not unaffected by subjectivity.

Balogun et al. (2012) consider human, environmental and financial factors in determining the optimal route of a pipeline located in Malaysia. Also studying the lowest cost layout for pipelines, Huseynli (2015) uses GIS with weighted layers (land slope, geology, land use and population) representing environmental and risk factors. Marcoulaki et al. (2012) propose a systematic search for optimal and near-optimal solutions based on stochastic optimization for the problem, using simulation tools and information that determines alternative routes. Roy et al. (2017) uses thematic spatial data (topography, geomorphology and land use - and landcover) to carry out a pre-feasibility studies of proposed pipeline networks in rural India. Following the same methodological approach typical of the use of GIS, Simon et al. (2021) (i) maps the existing public water distribution infrastructure in an urban area, (ii) produces a slope map of the study area, and (iii) uses a version of the network analysis tool available in GIS environments to determine the route shorter distance between origin and destination for the water supply of an adjacent community.

Called BAGDA (acronym in Portuguese for “Search for the Annual Cost of Geometric Tuning”), the new algorithm proposed in this article incorporates in its design a modification of the algorithm known as A* (read as “A star”), widely used in electronic games in its original form. In the dynamic operation of the BAGDA algorithm for determining the optimal route for any pipeline, the modified A* algorithm plays the role of generating the shortest routes, not simply in metric terms, as its original version does, but also operating in a specifically built search space, formed by dimensional axes representing the two characteristic variables of the searched solution: the length of the pipeline and the corresponding manometric head. Each route’s sinuosity is determined by a parameter, the *sinuosity coefficient* (CS), introduced in a specific equation, which penalizes displacement in the search space. Details of the original conceiving of the A* algorithm are found in Sarmento (2014). Further on, the modification introduced in the A* algorithm is presented.

On a recurring basis, throughout its execution, the BAGDA algorithm searches for the shortest path between two points in the built search space. The choice of the A* algorithm to perform this task was due to the advantage of being a guided search method, whose basic equation divides the decision score for the direction of displacement into parts that can be penalized depending on the type of problem to be solved, which inspired the modification proposed here.

The geometric abstraction on which the conception of the BAGDA algorithm was based can be mentally visualized as the systematic deformation of routes generated by the modified A* algorithm. For each new sinuosity imposed by this deformation, the total annual cost was calculated, obtained by adding the annualized costs related to the purchase of pipes and the expenses with electricity to run the pumping system.

The deformation of the generated routes is produced by the systematic adoption of different contour lines, called *exclusion contour lines* (ECL), whose contours are taken as *exclusion zones* delimiters, that is, zones made inaccessible in the search space of the modified A* algorithm.

The optimal route will be the one that presents the lowest total annual cost, that is, the one whose geometry is shaped by the optimal combination between ECL and CS, determinants of the length and manometric head that led to the lowest sum between the annualized costs and the acquisition of pipes and expense with electricity.

MATERIALS AND METHODS

Annual cost method for economic sizing

To determine the economic diameter of a water pipeline, it is necessary to use a criterion that jointly considers the most significant costs in each of the phases of project implementation. These costs, taken as annual costs (D_{anual}), are then composed of the cost of purchasing the pipes (C_{tubo}) and the cost of electricity ($C_{energia}$). This criterion is the core of the Annual Cost Method, fully described in Sarmento (2012), from which we transcribed the equation that translates the total annual cost as:

$$D_{anual} = C_{tubo} + C_{energia} \tag{1}$$

To obtain the value of the economic diameter, D_e, Equation 1 should be written as a function of the pipe diameter variable (D), derived in relation to D and the derivative should be equal to zero to get the minimum point of the function D_{anual}, resulting in:

$$D^{5.87}\left(A_1 + 2A_2 D\right) = \frac{k_p}{k_t} \tag{2}$$

Where A_1 and A_2 are two of the adjustment coefficients of a parabola representing the relationship between the commercial diameter D (in meters) and the unit weight (in kg/m) for the pipe manufacturing material employed; k_t is the cost of the pipe converted into annual installments; and k_p is the constant associated with electricity costs. The ratio $\frac{k_p}{k_t}$ represents the proportion between the pumping costs and the pipe purchasing costs on an annual basis. This formula is essential to determine the optimal route for the pipeline, as will be seen later.

The data needed to calculate the variables in Equation 2, according to Sarmento (2012), are: pumping flow rate, useful life, annual interest rate, number of annual operating hours of the system, overall efficiency of the motor-pump set(s), electricity rate per unit ($R\$/kWh$) and price table of pipes per length and weight units as a function of diameters for the material used in the pipeline.

Modified Algorithm A* to operate in the Annual Cost Domain (ACD)

The main limitation of applying the A* algorithm to the blueprint design of long engineering works is the fact that the physical world does not consist of a flat board, idealized for the purpose of demonstrating the power of this algorithm to find exit routes in mazes consisting of accessible pipe screens (free passage), impassable screens (closed passage, infinite passage cost), and screens with penalized passages. A description of the A* algorithm differentiating its operation in situations with and without the cost of passing through the various types of pipe screens is found in Sarmento (2014).

When processing the A* algorithm in its basic form, it is necessary to associate each pipe screen, cell, or node with a score (P), based on which the best path to the target will be selected. The score for each cell results from the sum of two values: (i) the cost of the path from the beginning until the cell in question, referred to as G and computed as being the number of moves to reach the mentioned point, and; (ii) the so-called *heuristic* (H), commonly represented by the Euclidean distance (or the Manhattan distance), that is, the distance between the cell bordering the cell where the direction of the displacement and the arrival point will be decided. This distance is calculated without considering the existence of any barred cells to the passage.

The proposed modification of the A* algorithm to insert it into the BAGDA algorithm preserves the original formulation given by:

$$P = G + H \tag{3}$$

In addition to the score P, a pointer is needed to indicate the direction from which the displacement preceding the arrival at the analyzed cell came, that is, the direction of the so-called "mother cell".

The annual costs for purchasing pipes and paying for electricity are incorporated as a suggested modification to the A* algorithm by using two equations from the Annual Cost Method, reorganized and added to the motion cost calculation G. The first of these equations translates the *annual unit cost* (R\$/m) for purchasing pipes (DAU_t), that is (Sarmento, 2012):

$$DAU_t = k_t\left(A_0 + A_1 D + A_2 D^2\right) \tag{4}$$

Where the expression in parentheses represents a parabola describing the relationship between commercial diameters and price per meter of pipe. The annualized coefficient k_t is the equivalent of the proportionality coefficient C_1 between the weight and the unit price of pipes (R\$/kg). It is calculated with an interest rate of j over T years of dilution of the investment for purchasing this material, as (Sarmento, 2012):

$$k_t = C_1 \times j \times \frac{\left(1+j\right)^T}{\left(\left(1+j\right)^T - 1\right)} \tag{5}$$

Also taken from the Annual Cost Method formula, the second equation expresses the *annual cost per unit* of electricity (DAU_e) to raise a certain Q flow rate to a unitary manometric head). Based on Hazen-Williams' pressure loss equation (C is the Hazen-Williams friction coefficient), we will have (Sarmento, 2012):

$$DAU_e = 104.272 \times C_2 \times \frac{Q^{2.85}}{\eta C^{1.85} D^{4.87}} \tag{6}$$

Where $C_2 = n \times E_{consumo}$, that is, the product of the energy cost per unit (R\$/kWh) by the number of hours n the system operates annually. Then the total annual unit cost will be the sum of the unit annual costs related to pipes and electricity:

$$DAU_{total} = DAU_t + DAU_e \tag{7}$$

With this, the total penalty P_T to be applied to the motion G calculation in the modified A* algorithm can be expressed as a weighted sum involving the parts of the annual expenditure influenced by (i) the length of the path (first two parts of Equation 8 and (ii) by the weighted contribution of topographic differences to the formation of the annual unitary expense related to electric energy, that is:

$$P_T = L \times DAU_t + L \times J_u \times DAU_e + \left[DAU_e \times \left(z_m - z_f\right)\right] \times CS \tag{8}$$

Where:

L = Is the distance traveled when a cell moves towards the one adjacent to it in the discretization grid of the search space. Its

value will be multiplied by $1.4\ (\approx \sqrt{2})$ when the movement happens along the cell's diagonal;
J_u = Unit pressure loss calculated with the Hazen-Williams formula (mca/m);
z_m and z_f = are the topographical elevations of the current mother cell and child cell, respectively.
CS = It is the so-called *sinuosity coefficient*, through which the *virtual weight* of the annual energy cost is established, exclusively related to the topographical unevenness between the mother and child cells.

It is important to emphasize that Equation 8 derives from formulas in which the considered variables express values that are compatible with the physical and cost reality, so it is possible to add any additional penalties as long as they are expressed in monetary units per year.

For example, in order to consider special zones that generate different costs for crossing, e.g. a swampy or flooded zone, the costs of concrete enveloping or aerial crossing of the pipe must be duly evaluated to be added as displacement costs. In areas where natural terrain slopes are above the normative limit or the limit recommended by the pipe manufacturer, it is possible to simply make them *exclusion zones*, which should encompass all pairs of contiguous grids that exceed the allowed limit.

The sinuosity coefficient (CS)

To better understand the meaning of the parameter CS, as well as present further explanation and applications, we will take as an example a topographic section of an area in the state of Pernambuco (Brazil), in which the upper left corner is located in latitude 8.70° and longitude 38.38°, covering the implementation area of catchment and part of the adduction through the East Axis of the São Francisco River Integration Project (Figure 1). This topographic section (SRTM – Shuttle Radar Topography Mission/ TOPODATA) has altimetry ranging from $313.52m$ to $426.31m$.

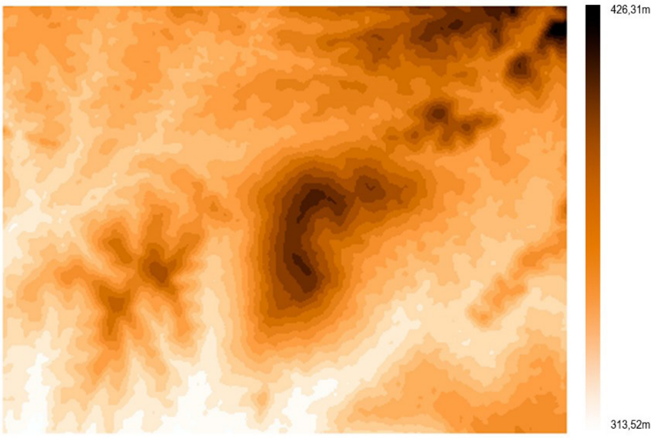


Figure 1. Topographic section used (SRTM – Shuttle Radar Topography Mission/TOPODATA).

In Figure 2, the water catchment (green circle) and delivery (red circle) points have the following coordinates and elevation: latitude 8.767618°, longitude 38.34113°, elevation = 322.295 m and latitude 8.723493° S, longitude 38.30437°, elevation = 370.211 m, respectively. ECL has elevation 380 m and limits the gray hatched area. The route that goes around the left side of the topographic elevation (with elevation above $380m$) was obtained with $CS = +3$, while the route that goes around it on the right side was calculated with $CS = -3$. Each pixel in the image is equivalent to a pipe screen of $30m \times 30m$. The topographic section chosen is $11.4km$ wide by $8.55km$ high.

The topographic profiles (line in green) and piezometric lines (in blue) of both routes appear to the left and right of the topographic section (center) and come from the routes with $CS = +3$ and $CS = -3$, respectively. Both routes were calculated considering a pumping flow rate of $351L/s$, over a useful life of 50 years, an annual interest rate of 6%, with the system working 20 hours/day (thus avoiding peak hours of electricity consumption), an overall efficiency of $\eta = 85\%$, and an energy cost of $0.31R\$/kWh$—an average amount of the energy cost per unit charged to CAERN (the Water and Sewage Company of Rio Grande do Norte (Rio Grande do Norte, 2018) —, and the unit costs of pipes per length and weight as a function of diameters.

Before calculating the routes, these same values were used to determine the economic diameter of the line, resulting in $D_e = 600mm$ (material: cast iron, 857.60 R$/m, price of pipes made by CAERN via a bidding process held in 2018, as stated in Rio Grande do Norte, 2018).

The ideal value of parameter CS needs to be determined with ECL to identify the optimal combination between the length of the pipeline and the manometric head to be overcome. How these two parameters are determined together is the core of the BAGDA algorithm.

Penalty isolines

Negative values of CS generate a map of $P = G + H$ on the total annual cost plan in which the highest values—therefore the

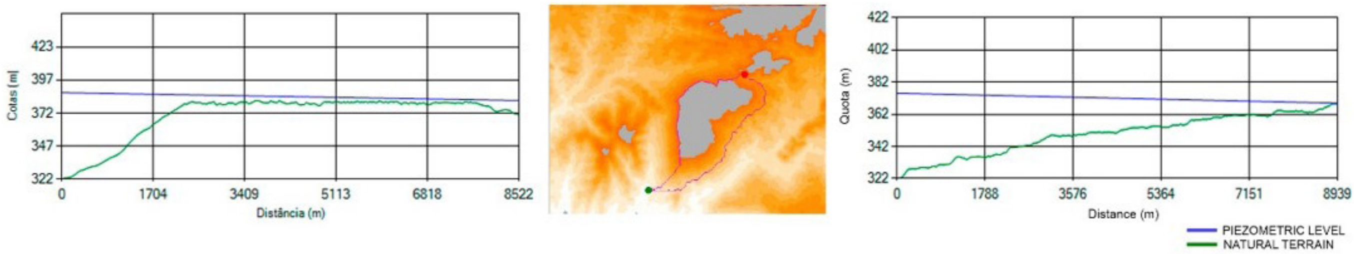


Figure 2. Topographic section with $\boldsymbol{ECL = 380\ m}$ and two routes differentiated by $\boldsymbol{CS}$.

least attractive for solving the issue—will be where the highest topographical elevations are, as can be seen in Figure 3 (left). Figure 3 also shows that the isolines of P to the right of the topographical elevation are farther apart from each other, which allows the algorithm to advance through smoother gradients, therefore preferential to the left path of the elevation.

In contrast, positive values of CS result in a map of inverted P with respect to the topographical map, that is, the cells with values of P that are most attractive to make up the shortest route in the annual cost plan will correspond to those where the highest topographical elevations are found, as seen in our example in Figure 3 (right).

For a given ECL, if it is impossible to access the terrain portions where the lowest values of the variable P occur, the shortest route found by the modified A* algorithm to work in the ACD (Figure 3, right) takes the shape of the ECL itself, bypassing it to the point where it is driven to reach the final water transportation destination. This movement in search of more attractive values of P (but inaccessible, since they belong to the exclusion zone) substantially reduces the space checked by the algorithm when searching for the shortest route in the ACD because the lowest values of P are concentrated in the highest portion of the relief, which starts to act as an attractor for the searches.

Adopting value zero for parameter CS implies a reduction in the total penalty P_T, which is reflected in the geometric plan, in the form of straighter routes for the pipeline. That is, for $CS = 0$, the layout is less flexible, with virtually no sinuosity. Therefore, it is a route made up of straight-line segments that respect all exclusion zones eventually intercepted on the path.

BAGDA Algorithm (Search for the Annual Cost of Geometric Tuning)

The BAGDA algorithm determines the optimal route in a search space formed by two dimensions, namely, (i) the axis corresponding to the annual cost related to purchasing pipes and (ii) the axis representing the annual cost due to the system operation, expressed as the electricity cost to run the motors.

This search space allows us to represent in the same two-dimensional plane the annual costs resulting from the equation that includes all the variables involved in the problem: water flow rate, final pipeline length, the unit cost of piping for the calculated economic diameter, manometric head, power required by the motors, electricity cost per unit, number of hours of annual system operation, the interest rate of financing the purchase of pipes, and the useful life of the enterprise. Therefore, in superposition to the topographic domain, there is another search space already called the *ACD*.

Once the water catchment and delivery points are defined in the topographical plan, the BAGDA algorithm operates as follows to provide the computational solution to the problem:

Search without exclusion zones

The algorithm chooses a contour line whose elevation is above the highest point of the existing terrain between the water catchment and delivery points. That is, in this first round of searching for the optimal route, in the range most likely to harbor it, there are no exclusion zones. Thus, the search for the optimal CS will take place for all values in the range limited by the minimum and maximum limits chosen for this parameter, incremented as desired (e.g. $-1 \le CS \le +1$ with an increment of $0{,}1$). The routes corresponding to each value assumed by CS are free of any influence of ECL that could change the geometry of the shortest route found in the ACD. This type of search applied to the example is illustrated in Figure 4.

Search with exclusion zones

The ECL elevation is then lowered by a certain Δh, implying different delimitations of exclusion zones. For every new ECL, the shortest route calculation procedure is repeated not only for the values of CS whose resulting routes pass through grids with elevations greater than or equal to that of the ECL in question, but for the entire range of CS. This is due to the fact that the generated routes can be influenced not only by interception but also by mere proximity to the ECL, since such proximity can interfere with the algorithm's search space and generate other routes, different from the one that would be obtained if there were neither interception nor too much proximity. In the end, we have the total annual cost for all feasible combinations of ECLs and

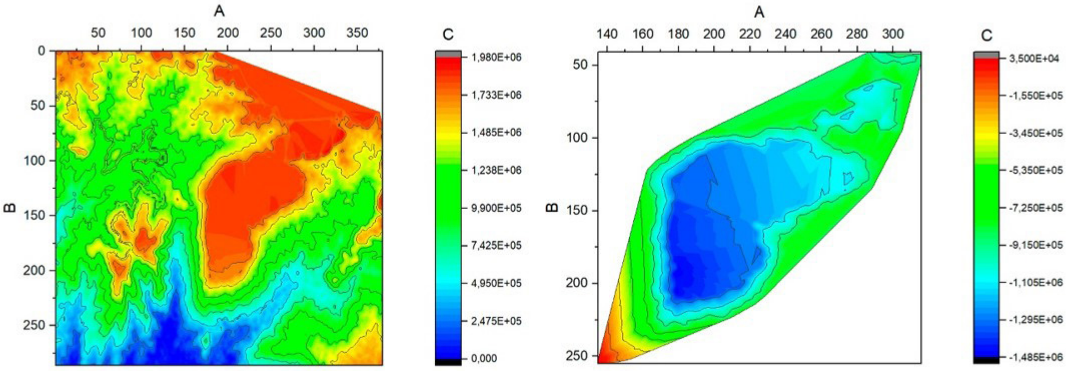


Figure 3. Mapping of isolines of $\boldsymbol{P}$ in the total annual cost plan Generated with $\boldsymbol{CS} = -3$ (left) and $\boldsymbol{CS} = +3$ (right).

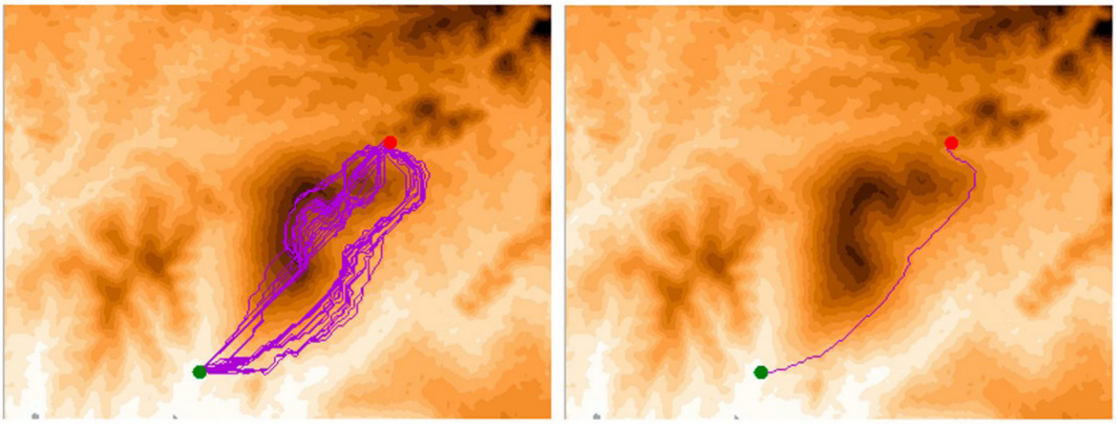


Figure 4. Search without exclusion zones Left: minimum cost routes with sinuosity coefficient $-3 \le \boldsymbol{CS} \le +3$ incremented by 0.1. Right: Optimal route found for $\boldsymbol{CS} = -1.4$.

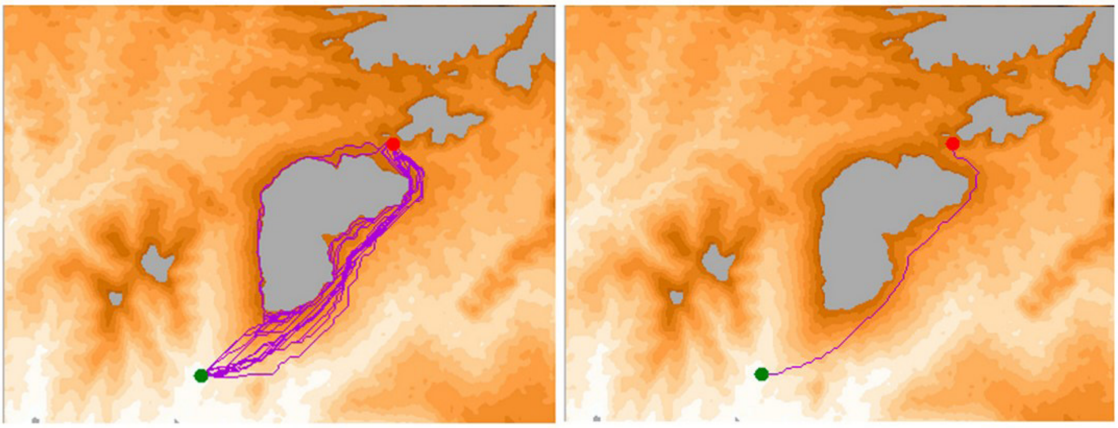


Figure 5. Search with exclusion zones at elevation 380 m Left: minimum cost routes with sinuosity coefficient of $-3 \le \boldsymbol{CS} \le +3$ incremented by 0.1. Right: Optimal route found for $\boldsymbol{CS} = -1.2$.

values of *CS*, having chosen the combination that corresponds to the lowest value of annual cost. Figure 5 shows the results for this type of search according to the example above.

The lower the elevations ECL assumes, the more extensive will be the areas through which the pipeline cannot cross and, consequently, the longer the perimeter of this contour. This expansion of the exclusion zone boundary will both divert and increase the routing associated with values of *CS* near zero and may also force the elasticity of routes associated with higher (positive and negative) values of this parameter. This phenomenon decreases energy costs to overcome geometric differences and increases costs for purchasing pipes.

This algorithmic dynamics established with the sequential decrease in ECL elevation—combined with obtaining shorter routes (in the ACD) calculated with each value of *CS* — generates, for each of these geometric combinations, corresponding pairs of annual costs with piping (proportional to the total pipeline length) and annual costs referring to electricity fees. If the search range Δh of the ECLs elevation and the range of parameter *CS* variation are properly chosen, it can be expected that, for one of these combinations, the total annual cost will pass through a minimum point. In this way, we determine an optimal, well-balanced combination between the pipeline length and the implied manometric head in the corresponding route.

In summary, with the application of the BAGDA algorithm, the optimal solution to the pipeline routing problem emerges from the systematic exploration of the search space idealized in the ACD limited (i) above by a horizontal surface defined by the ECL, whose elevation decreases Δh with every iteration of the search process, and (ii) below by the most sinuous analyzed route, defined by the extreme negative value of parameter *CS*, which, incremented along the process until reaching its positive extreme value, will produce routes increasingly closer to the current exclusion zone.

This top-down (ECL with decreasing elevation) and bottom-up (CS increasing from a negative value to its positive opposite) search movement constitutes the essence of the BAGDA algorithm. In this context, the algorithm guarantees the shortest pipeline path in each geometric scenario distinguished by its ECL and its coefficient *CS*.

RESULTS AND DISCUSSION

The simplicity of the BAGDA algorithm for defining the optimized route between water catchment and delivery points allowed its coding in Visual Basic language, resulting in an application that receives the input data and presents, with a mere click on a button on the interface screen, the optimized route between the water catchment and delivery points. Figure 6 shows the three tabs that are part of the developed application interface screen.

A comparison in qualitative terms leads to the conclusion that the superiority of the BAGDA algorithm is asserted over the various methods based on GIS technology because it offers solutions that are not relativized by the degrees of importance (weights) attributed to the modeling criteria of the problem. The proposed algorithm synthesizes the two classic forms of decision making, as it mathematically solves the problem as an optimization model formulated as a multi-criteria model, insofar as it translates in terms of a single parameter – a specific annual expense, specific to each criterion (e.g. R$/m) – the financial impacts of the route constraints not only on the construction phase, but also on the system operation phase. After all, for each sinuosity, the shortest path in the search space is composed of unit displacements (e.g., 30 m or 1-pixel segments), whose direction is decided as a function of the proportion between implementation and operating costs, which endows the route as a whole with the optimism present in the parts (each segment).

Additional advantages of the BAGDA algorithm in relation to the methodologies currently dominant in the available literature are: (i) to integrate the pipe sizing phase with the pipeline routing phase, since it makes use of the same variables in both design phases (for each viable diameter, the algorithm can determine the most economical combination between the diameter value and the respective pipeline drawing); (ii) quickly verify the robustness of the solution found by means of a sensitivity analysis involving variables such as: unit cost of electricity, capital recovery interest rate, motor efficiency, etc.

To demonstrate the versatility and efficiency of the proposed algorithm, four applications involving different positioning of the water catchment and delivery points in the chosen topographic area will be presented below, starting with the example used when presenting the method. In all applications, the same input data regarding pipe and energy costs, interest rate, and other already mentioned data were used.

Application 1

The water catchment and delivery points in this first application are the same as those used to present the method and are shown in Figures 2, 4, and 5. Table 1 shows the values of the most important variables for some of the calculated routes, including, in the last row, the optimal route. As can be seen in Table 1, the best combination of length and manometric head for the water pipeline in question occurs with the ECL elevation of 371 m and a CS of $CS = -0.4$, which results in an optimal total pipeline length of $L = 7,652.72\,m$ and $H_m = 52.83\,mca$, with a total annual cost of R$ 883,782.60.

Figure 7 shows six screenshots of the BAGDA algorithm dynamics in terms of the geometries involving the various exclusion zones and the range of CSs ($-3 \le CS \le +3$, incremented in the algorithm at every 0.1), considering the ECLs in Table 1. In the left column of Figure 7, we can see the growth of the exclusion areas and their effects on the routes obtained for different values of CS. The right column shows the optimal route obtained for each ECL.

When the ECL assumes the values 450 m (no exclusion zones) and 400 m (with exclusion zones), the optimal route does not change, which is expected, since the minimum annual cost found corresponds to $CS = -1.2$, that is, a route to the right of the hill not affected by these ECLs. For ECL = 390 m, the exclusion zone widens and the shortest route in the ACD plan occurs at $CS = -1.4$.

From the 380 m ECL on, several routes corresponding to the different values of CS are affected by these exclusion zones, whose contours impose deviations on the paths, making them longer. For the ECL of 372 m, there are no longer routes bypassing the topographic elevation on the left side, since the passage to reach the water delivery point using this alternative route became part of the exclusion zone.

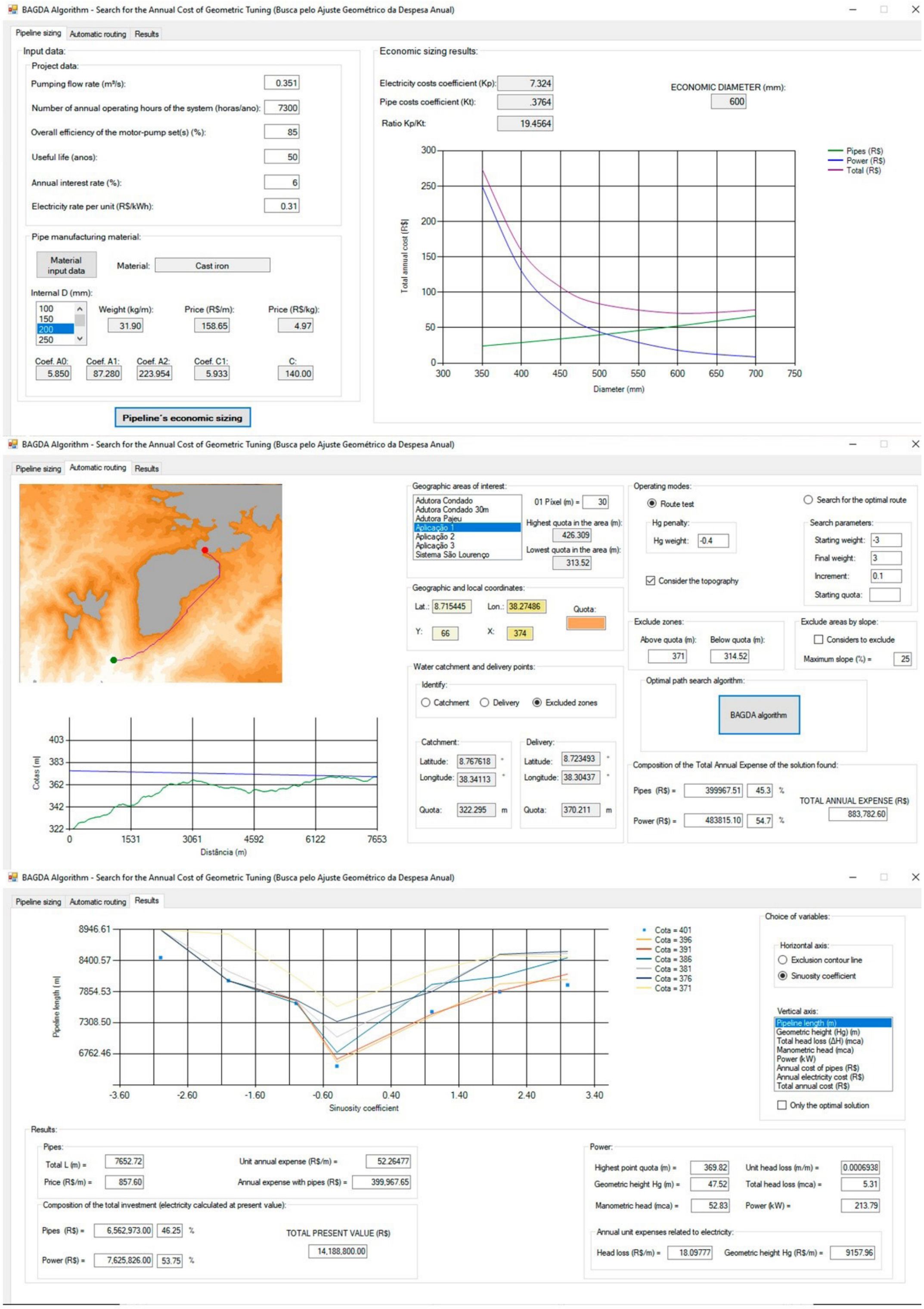
Figure 8 highlights the final solution found, where the ECL is equal to 371 m, conjugated to a $CS = -0.4$. The left side of Figure 8 shows that several of the 61 routes resulting from the variation $-3 \le CS \le +3$ (incremented at every 0.1) almost adhere to the ECL. The center of Figure 8 shows the final portion of the pipeline and, to the right, its topographic profile and corresponding piezometric line.

Figure 9(a) shows the relationship between the ECL elevation and the pipeline length determined by the CS values in the range $-3 \le CS \le +3$. For any value of CS, the tendency is a clear reduction in the pipeline length as the elevation of the ECL increases. This behavior is expected because this elevation implies a smaller exclusion zone and, consequently, more space for tracing the routes. The same data are depicted in Figure 9(b), now having CS on the horizontal axis. The minimum point of the pipeline length occurs for $CS = -0.2$ (the ECL elevation equals 401 m), that is, for the route with sinuosity close to zero, formed by more rectilinear segments, which tend to correspond to the shortest distance between two points.

Table 1. Solutions found by the BAGDA algorithm dynamics.

ECL (m)	*CS*	TAC (R$)	% Pipes	% Energy	L (m)	Hm (mca)
450 - 400	-1.2	930,845.80	43.1	56.9	7,680.59	57.81
390	-1.4	911,924.40	44.9	55.1	7,828.45	54.90
380	-0.8	929,430.40	42.6	57.4	7,578.16	58.24
375	-1.2	916,197.70	44.5	55.5	7,796.32	55.55
372	-0.1	884,101.90	44.4	55.6	7,515.14	53.65
371	-0.4	883,782.60	45.3	54.7	7,652.72	52.83

ECL: exclusion contour line. CS: sinuosity coefficient. TAC: total annual costs. L: pipeline length. Hm: manometric head.



BAGDA Algorithm - Search for the Annual Cost of Geometric Tuning (Busca pelo Ajuste Geométrico da Despesa Anual)

Pipeline sizing | Automatic routing | Results

Input data:

Project data:

Pumping flow rate (m³/s): 0.351

Number of annual operating hours of the system (horas/ano): 7300

Overall efficiency of the motor-pump set(s) (%): 85

Useful life (anos): 50

Annual interest rate (%): 6

Electricity rate per unit (R$/kWh): 0.31

Pipe manufacturing material:

Material: Cast iron

Internal D (mm): 100, 150, 200, 250 (200 selected)

Weight (kg/m): 31.90

Price (R$/m): 158.65

Price (R$/kg): 4.97

Coef. A0: 5.850

Coef. A1: 87.280

Coef. A2: 223.954

Coef. C1: 5.933

C: 140.00

Economic sizing results:

Electricity costs coefficient (Kp): 7.324

Pipe costs coefficient (Kt): .3764

Ratio Kp/Kt: 19.4564

ECONOMIC DIAMETER (mm): 600

BAGDA Algorithm - Search for the Annual Cost of Geometric Tuning (Busca pelo Ajuste Geométrico da Despesa Anual)

Pipeline sizing | Automatic routing | Results

Geographic areas of interest: Adutora Condado, Adutora Condado 30m, Adutora Pajeu, Aplicação 1 (selected), Aplicação 2, Aplicação 3, Sistema São Lourenço

01 Pixel (m) = 30

Highest quota in the area (m): 426.309

Lowest quota in the area (m): 313.52

Geographic and local coordinates:

Lat.: 8.715445 Lon.: 38.27486

Y: 66 X: 374

Quota:

Water catchment and delivery points:

Identify: ○ Catchment ○ Delivery ● Excluded zones

Catchment: Latitude: 8.767618 ° Longitude: 38.34113 ° Quota: 322.295 m

Delivery: Latitude: 8.723493 ° Longitude: 38.30437 ° Quota: 370.211 m

Operating modes: ● Route test ○ Search for the optimal route

Hg penalty: Hg weight: -0.4

☑ Consider the topography

Search parameters: Starting weight: -3 Final weight: 3 Increment: 0.1 Starting quota:

Exclude zones: Above quota (m): 371 Below quota (m): 314.52

Exclude areas by slope: ☐ Considers to exclude Maximum slope (%) = 25

Optimal path search algorithm:

Composition of the Total Annual Expense of the solution found:

Pipes (R$) = 399967.51 45.3 %

Power (R$) = 483815.10 54.7 %

TOTAL ANNUAL EXPENSE (R$) 883,782.60

BAGDA Algorithm - Search for the Annual Cost of Geometric Tuning (Busca pelo Ajuste Geométrico da Despesa Anual)

Pipeline sizing | Automatic routing | Results

Choice of variables:

Horizontal axis: ○ Exclusion contour line ● Sinuosity coefficient

Vertical axis: Pipeline length (m) (selected), Geometric height (Hg) (m), Total head loss (ΔH) (mca), Manometric head (mca), Power (kW), Annual cost of pipes (R$), Annual electricity cost (R$), Total annual cost (R$)

☐ Only the optimal solution

Results:

Pipes:

Total L (m) = 7652.72

Price (R$/m) = 857.60

Unit annual expense (R$/m) = 52.26477

Annual expense with pipes (R$) = 399,967.65

Composition of the total investment (electricity calculated at present value):

Pipes (R$) = 6,562,973.00 46.25 %

Power (R$) = 7,625,826.00 53.75 %

TOTAL PRESENT VALUE (R$) 14,188,800.00

Power:

Highest point quota (m) = 369.82

Geometric height Hg (m) = 47.52

Manometric head (mca) = 52.83

Unit head loss (m/m) = 0.0006938

Total head loss (mca) = 5.31

Power (kW) = 213.79

Annual unit expenses related to electricity:

Head loss (R$/m) = 18.09777

Geometric height Hg (R$/m) = 9157.96

Figure 6. The three tabs of the BAGDA application interface screen.

Although the optimal ECL elevation for the variable *L* (pipeline length) is the highest surveyed, the lowest total annual cost, as seen before, has the optimal elevation of 371 m, that is, the bottom-most elevation in Figure 9(b) (represented by small squares). Therefore, the elevation that results in the longest pipeline lengths—as it delineates the largest generated exclusion zones— reduces the search spaces for optimal routes.

The next variables to be plotted against CS are the annual expenses for the purchase of pipes (annual investment) and the payment for the electric power to run the pumping system. The two graphs in Figures 10(a) and 10(b), respectively, show that, for the minimum point of annual pipe cost, the ECL elevation is the highest (elevation 401 m); in contrast, for the minimum point of annual energy cost, the ECL elevation variation is on the opposite side, that is, at 371 m.

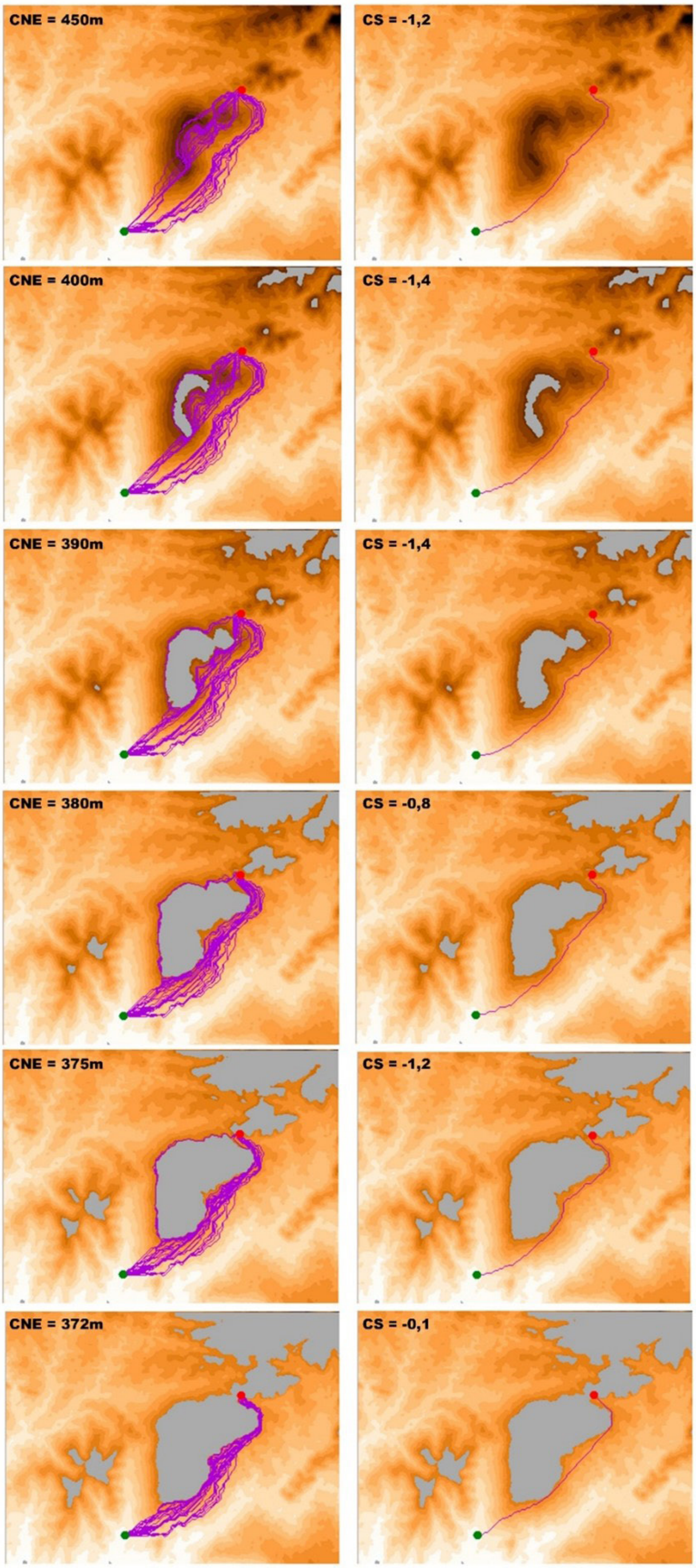


Figure 7. Evolution of the exclusion zone with the decay of ECL; on the left, the shortest routes to $-3 \leq \boldsymbol{CS} \leq +3$, incremented at every 0.1; on the right, the lowest annual cost route for every ECL, with its respective optimal value for $\boldsymbol{CS}$.

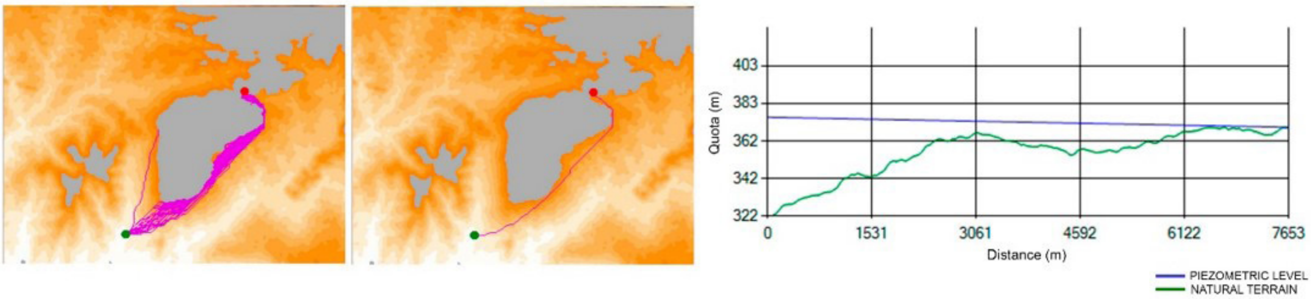


Figure 8. Left: Routes for a 371-m ECL and the shortest routes to $-3 \le \boldsymbol{CS} \le +3$ (incremented at every 0.1); Right: optimal pipeline routing solution with $\boldsymbol{CS} = -0.4$.

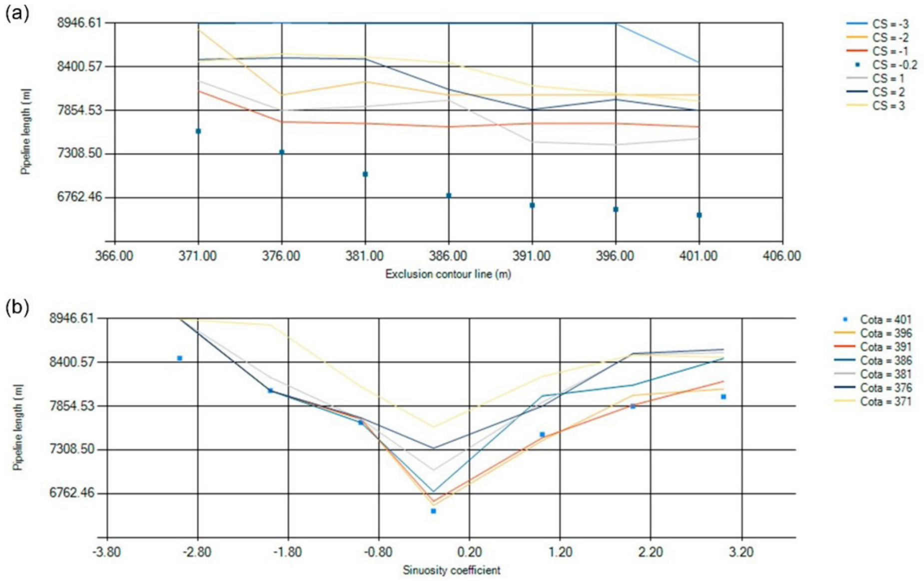


Figure 9. BAGDA algorithm: Relationship between the pipeline length and (a) the ECL elevation determined for each value of $\boldsymbol{CS}$; and (b) the sinuosity coefficient of $\boldsymbol{CS}$ for each ECL.

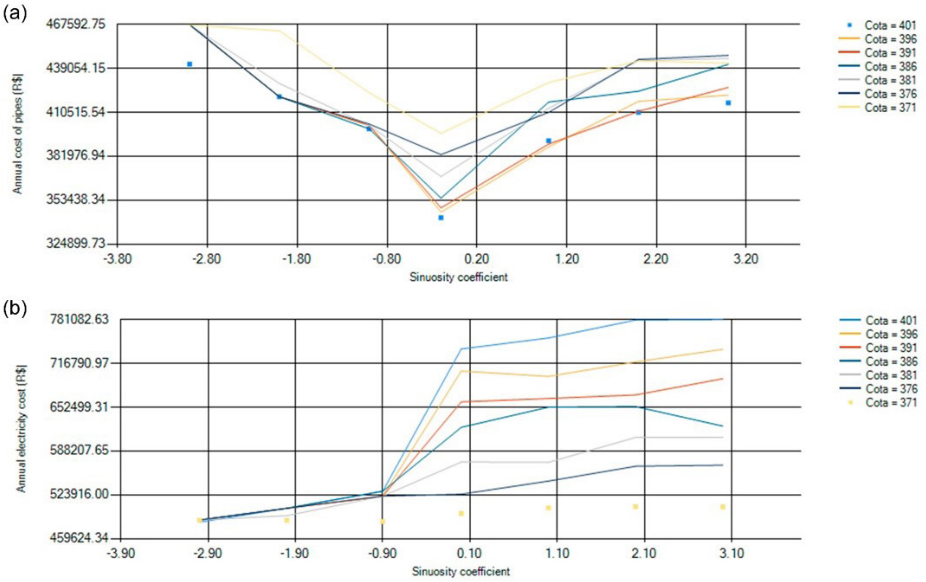


Figure 10. BAGDA algorithm: Relationship between the sinuosity coefficient of $\boldsymbol{CS}$ and the annual cost for (a) purchasing pipes (annual investment) and (b) electricity cost.

The values of CS for these two minimum points are $CS = -0.1$ and $CS = -0.9$, respectively, which indicate greater sinuosity of the route corresponding to the second value in relation to the route calculated using the first value. It is consistent with the idea that less sinuous routes imply lower costs in pipes and higher costs in energy, while the opposite occurs with more sinuous routes.

The sum of the two sets of annual cost points produces the set of total annual costs depicted in Figures 11(a) and 11(b), relative to the ECL elevation and the value of CS, respectively. The graph in Figure 11(a) clearly shows the separation of the set of lines into two bundles. This regrouping occurs approximately starting at the 380-m ECL elevation. Most of the lines that follow the upward trend correspond to the positive values of CS, that is, lines that seek to approach the highest topographic portions, getting as close as possible to the exclusion zones. They are attracted because the lowest annual costs for the positive values of CS are in these zones (see Figure 3, right). The minority line bundle—practically horizontal—corresponds to the more sinuous routes ($CS < 0$), which tend to move away from the exclusion zones, seeking smoother gradients in the isolines of P, where we can find the zones of lower annual costs for negative values of CS (see Figure 3, left).

Figure 11(b) shows a change in the behavior of the evolution of the curves related to the CSs from $CS = -0.5$, in which the dispersion of the total annual cost starts to increase among the contours corresponding to each ECL considered. This behavior is no more than the same as that commented in Figure 11(a), since the routes calculated for higher ECLs constitute the most aggregated segment of the bundle in Figure 11(b) ($-3 \le CS \le -0.6$) and have the negative values closest to the surveyed endpoint. The value of CS corresponding to the minimum point of the total annual cost is $CS = -0.4$.

Application 2

In application 1, there was a geometric difference of $H_g = 47{,}916 m$ between the two endpoints to be connected by the pipeline. Running the modified A* algorithm to operate on the ACD without exclusion zones evidenced that none of the alternatives that pass through the higher areas of the existing hill are competitive in terms of total annual costs when compared to the routes that take the path to the right of the topographic elevation. This only underscores the fact that it does not make sense in that application to pump water to a higher elevation than that of the water delivery point. In situations like that, you can simply set the exclusion elevation to the closest possible value to the delivery elevation, varying only the CS.

However, there are other situations in pipeline design where it will be necessary to find the best match between pipeline length and manometric head, not necessarily when the ideal ECL elevation is close to the water delivery elevation. In such situations, it may be more feasible to pump to a higher elevation than the delivery elevation, provided that the corresponding route is sufficiently shorter compared to those that bypass exclusion zones to offset the additional energy cost with the pipe savings from the shorter route, which can be even greater if the diameter in the downstream section can be reduced to dissipate the excess potential energy.

The BAGDA algorithm was run with the water catchment and delivery points shown in Figure 12 (catchment at latitude 8.754297°, longitude 38.28989°, and altitude 349.354 m, and delivery latitude 8.712114°, longitude 38.34475°, and altitude 350.849 m) to generate 61 routes ($-3 \le CS \le +3$ for every 0.1) for each ECL, starting at elevation 381 m until 351 m, with a decrement of $\Delta h = 1m$, thus making up 31 ECLs. With these figures, the route with the lowest annual cost was determined by $61 \times 31 = 1{,}891$ different alternatives, individually optimized by the A* algorithm modified to operate on the ACD.

On the left, in Figure 12, there are several routes partially covered by the delimitation of the exclusion zone with an elevation equal to 351 m (the lowest verified by the algorithm, therefore the most comprehensive exclusion zone). The visible route through the exclusion zone is the optimal path determined by the BAGDA

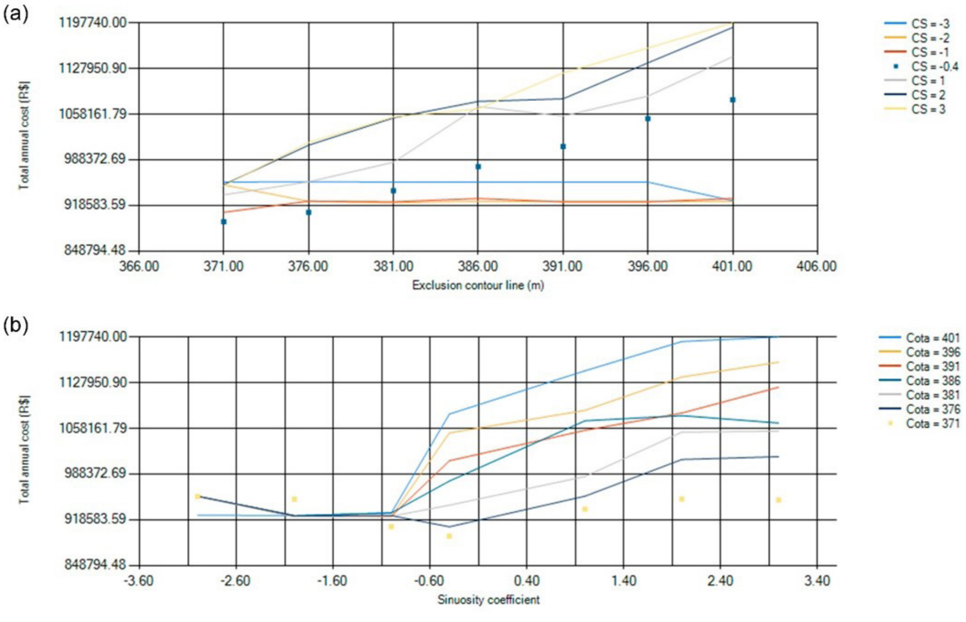


Figure 11. BAGDA algorithm: Relationship between total annual cost and (a) the ECL elevation and (b) the sinuosity coefficient CS.

algorithm and is reproduced isolated in the center of Figure 12, with its topographic profile and piezometric line shown on the right. Thus, the optimal pipeline route was identified at $CS = -0.1$ and the ECL elevation was equal to 361 m, therefore, $10.15\,m$ above the water delivery elevation ($350.849\,m$).

The optimal L-shaped route takes advantage of the opening that appears in the exclusion zone, when it assumes the 361 m elevation, reducing the path considerably and, at the same time, avoiding areas that are higher than this topographic gorge identified by the algorithm. The final length of the pipeline was 10,549.56 m, with a manometric height of 18.42 mca. A graphical summary of the results found by the BAGDA algorithm is shown in Figure 13. It clearly shows the dominant parabolic conformation assumed by the annual cost, in correspondence with the parameter CS for all the exclusion elevations analyzed. The lower concavity of the parabolic form occurs around a null value of CS, with the minimum occurring for $CS = -0.1$, when the ECL is 361 m (represented by small squares in Figure 13). Finally, there are two groupings of the annual cost versus the CS curves in Figure 13. The upper group is formed by the lower ECLs, which converted into an exclusion zone the topographical gorge through which the optimal route evolved, thus forcing the algorithm to go around the topographical elevation to the left, consequently increasing the costs with piping.

Application 3

Figure 14 shows the water catchment point at the location of the first pumping station (EBV-1) on the East Axis of the São

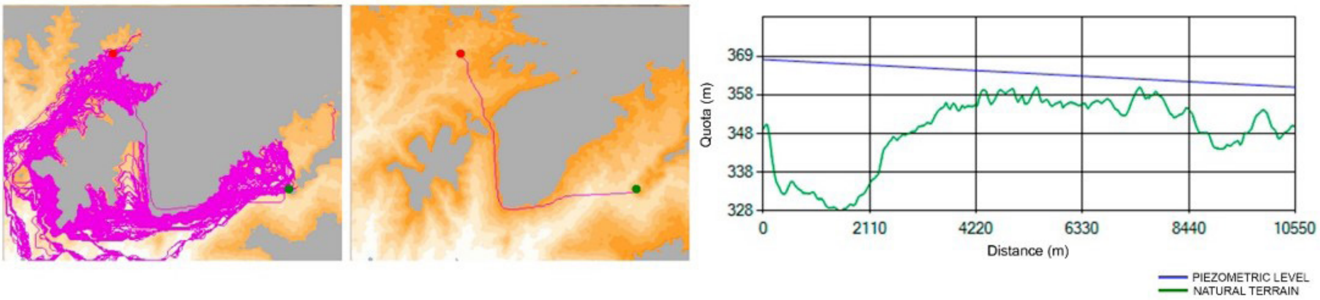


Figure 12. Left: Routes generated with the BAGDA algorithm; Center: Optimal route; Right: Topographic profile and piezometric line for the route with the lowest total annual cost.

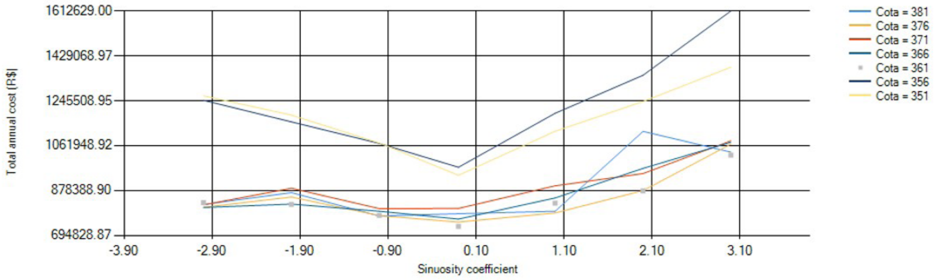


Figure 13. Curves relating annual cost to the sinuosity coefficient of CS for seven exclusion contour lines analyzed by the BAGDA algorithm.

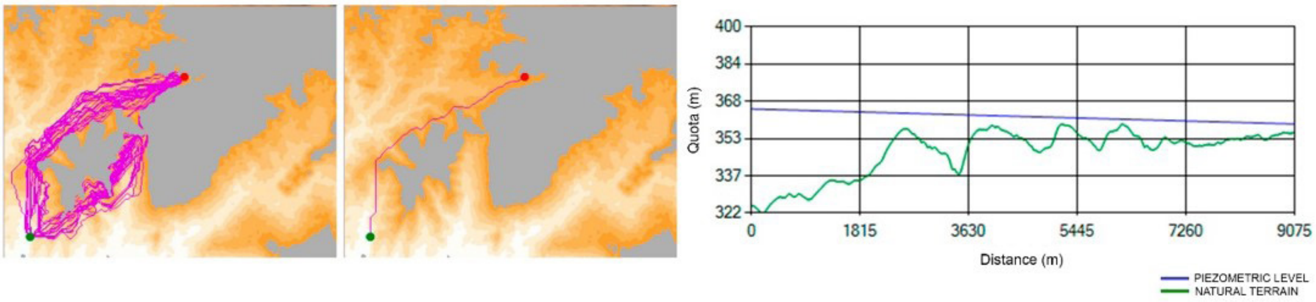


Figure 14. Left: Routes generated with the BAGDA algorithm; Center: Optimal route; Right: Topographic profile and piezometric line for the route with the lowest total annual cost.

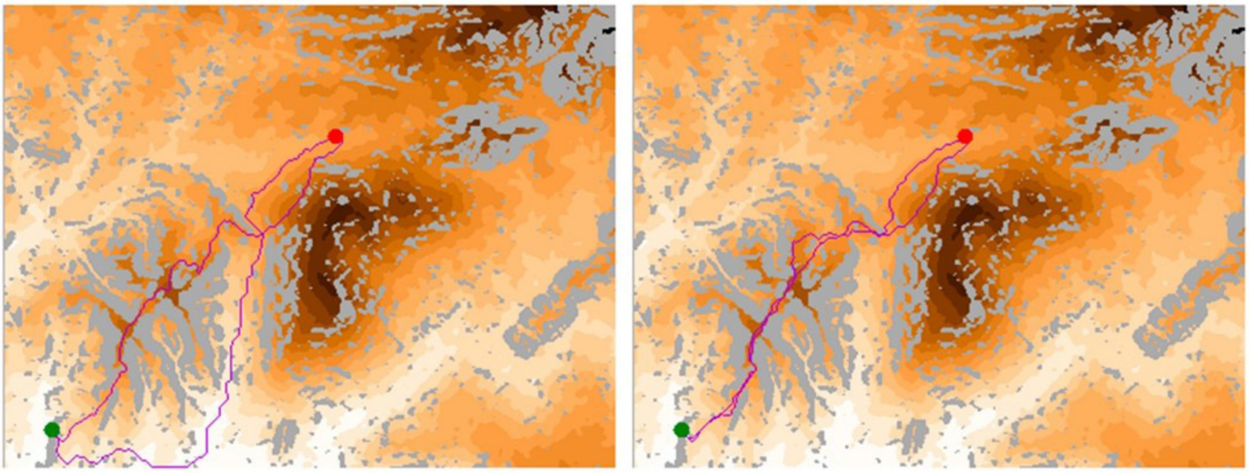


Figure 15. Search space restricted by ramp slope limitation Left: Left ($\boldsymbol{CS} = +3$) and right ($\boldsymbol{CS} = -3$) routes at $0.31\ \boldsymbol{R\$ / kWh}$. Right: Routes with $\boldsymbol{CS} = +3$ and $\boldsymbol{CS} = -3$ at $0.08\ \boldsymbol{R\$ / kWh}$.

Francisco River Integration Project (PISF) (latitude 8.770116°, longitude 38.37065°, and altitude 324.576 m) and the delivery point at the mouth of that channel at the Areias dam (latitude 8.719607°, longitude 38.32164°, and altitude of 357.042 m), a part of the transposition system. In Figure 14, partially obscured by the broader exclusion zone, there is a total of $6 \times 20 = 120$ routes obtained for six values of the ECL and 20 values of CS $(-1 \leq CS < +1)$.

The BADGA algorithm obtained as the optimal solution in terms of total annual cost the route shown in the center of Figure 14, along with the topographic profile and piezometric line (on the right). The ECL elevation corresponding to the depicted solution obtained for $CS = -0{,}3$ was 359.0 m.

If the ECL is raised by only one meter, that is, for $CNE = 360\,m$, maintaining $CS = -0.3$, the route found is similar to the previous one, to the point of not changing the annual cost calculated at R$ 847,386.40, with 55.0% of this value referring to the annual installments for purchasing pipes and 44.0% related to the annual electricity cost.

Application 4

The same catchment and delivery points from application 3 will now be used to demonstrate optimal routes relative to the chosen values of CS, this time considering terrain slope limitations. For the sake of example, all areas with slopes greater than 5%, marked in gray in Figure 15, were considered exclusion zones. Two optimized routes appear in that figure, namely, the one that goes uphill from the topographic elevation, obtained with $CS = +3$, and the one on the right, obtained with $CS = -3$. The route calculated with $CS = +3$ results in a total annual cost of R$1,220,432.00 (44.9% referring to pipes and 55.1% referring to electricity), while the route calculated with $CS = -3$ results in an annual cost of R$1,002,632.00 (60.3% referring to pipes and 39.7% referring to electricity).

In order to verify the sensitivity of the routes to a change in the cost of electricity, the algorithm was executed again with input data differing only in the energy cost per unit, now $0{,}08\,R\$ / kWh$ (a reduction of $\approx 74\%$). Figure 15 (right) shows that this reduction leads to almost a superposition of the routes obtained with the mentioned CSs, diverging only in their final sections. With this change, the pipe diameter also drops from $600mm$ to $500mm$. Both effects evidently derive from the change in the value of the electricity cost.

CONCLUSION

A new algorithm for determining optimal routes for water supply pipelines was presented, having in its basic formulation the variables total line length and manometric head, both defining the ideal solution.

Regarding the design and use of the BAGDA algorithm, the following should be noted:

a) The proposed methodology allows both the pipe sizing (Equation 2) and the definition of the optimal route for the water pipeline, in both cases, using the same economic criterion, that is, the minimization of the annual costs, formed by the costs of (i) acquisition of pipes and (ii) payment for electricity;

b) The modification in the A* algorithm through the introduction of Equation 8 has an important role in determining the optimal route, since it allows exploring the viable multidimensional space, generating routes with different sinuosities, representing different proportionality ratios between pipe costs and power costs;

c) There is no influence of human subjectivity in the calculation of the optimal route, since the algorithm obtains it as a mathematical function involving the two variables of greatest interest to the project: the total length of the pipeline and the corresponding manometric head;

d) This is a relevant advantage in relation to the most frequent approaches in the literature, since the subjective influences characteristic of GIS-based procedures end up inducing the choice of the determined optimal route, insofar as they privilege displacements that tend to approach or move away from infrastructural (roads) or natural (water bodies) elements that may exist between the starting and ending points of the route;

e) Interferences that restrict and/or condition the route, such as the presence of water bodies, rocky formations, excessively steep slopes, environmental preservation areas, flooded areas, as well as land use and occupation with its respective social, economic, and financial impacts, the need for expropriation, the existence of infrastructure works in the route, etc. can easily be considered by the BAGDA algorithm;

f) Areas with infinite passage costs can simply be converted into exclusion zones, as application 4 demonstrated, involving limiting the slope of the land. Areas with additional costs due to the difficulty of passing the pipeline require only that these costs be budgeted to have unit prices, that is, annualized monetary values to be paid per meter of pipeline installed;

g) In addition to the passage costs, the proposed equation incorporates parameters related to the implementation and operation phases of the system, which influence both the pipe sizing and the calculation of the optimal route. In application 4, this influence was analyzed for the parameter "unit cost of electricity". A future study may measure (i) the sensitivity of the final solution in different physical situations, given the variation of these influential parameters; (ii) to assess the rationality of the proportion between the implementation and operation costs of constructed water supply pipelines, which allows evaluating, in terms of annual operating expenses (to be paid over the entire useful life of the system), the consequences of the adoption of different design criteria;

h) The BAGDA algorithm is a simple and fast alternative for automating the search and determination of the optimal pipeline routing, as demonstrated by the applications performed.

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Authors contributions

Francisco Jácome Sarmento: Idealization of the methodology, computational development of the algorithm, conception of examples in the real world and writing of the work.

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