TOOLS FOR HIGH-SPEED RAIL PLANNING OPTIMIZATION: PRELIMINARY DEVELOPMENTS OF A CASE STUDY

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ABSTRACT

This paper discusses the main issues in the development of a decision aid tool for High-Speed Rail in Portugal. A model is proposed to address normal operating conditions. The model is applied to a synthetic case study and solved using the Simulated Annealing Algorithm. Preliminary results are presented. Future developments should incorporate the geotechnical and seismic risks that affect the infrastructure in the Portuguese context.

Keywords: High-Speed Rail, Planning, Optimization

INTRODUCTION

Following the goal of developing a European high-speed rail (HSR) network, Portuguese authorities decided to link Portuguese major cities and establish a high-speed connection to Europe, through Spain's network.

Due to the large costs involved and since different feasible and valid alternatives exist, the planning stage plays a major role in the project's viability, as it can narrow down the options available and enhance the cost-benefit ratio. Accounting for all the variables and uncertainties in decision-making requires systematic and solid tools to support the process. Risk Assessment and Management for High Speed Rail Systems (RISK) is an international research project of the MIT|Portugal Program addressing these issues. The RISK project involves collaboration between several Portuguese Universities and Research Centers and MIT, aiming at combining and integrating different risk dimensions in decision aid tools.

This paper presents an overview of the problem, establishes the model used to represent it and depicts the optimization procedures implemented as part of the research. Finally, a preliminary assessment of the functioning of the decision aid tool proposed herein can be carried out by means of a synthetic case study.

PROBLEM DESCRIPTION

A HSR network in Portugal intends to link a set of geographic locations. The connection of some locations is required, while connecting other locations can be desirable but optional, considering the implications on costs and benefits of the infrastructure. Solutions must be identified for each set of locations to link.

The definition of the HSR line must comply with functional and technical specifications (EC 2008). The track layout is defined by straight lines, circular curves and transition curves, both in the plan view and the longitudinal profile. The curvature radius in the plan view restricts the maximum allowed speed. HSR layout should favor straight lines and the maximum radii possible. The gradient of the straight lines in the longitudinal profile also affects the traffic characteristics of the HSR line. Hence, maximum values of the gradient are set. In addition, the track layout depends on the local ground conditions. Overcoming topography obstacles may lead to smaller curvature radii and higher gradient, than the desired values, but within feasibility limits. Tolerances exist and the policies on the values to adopt for specific cases can vary (EC 2008). The track layout is also influenced by environmental aspects. In the preliminary stage of the track layout, the environmental restrictions need to be identified (Profillidis 2006). Also, expropriation costs, which can be prohibitive in some urban areas, can have significant impact on the track layout.

Along with the track layout, the cross-sections to adopt have to be defined. Embankments, cuts, viaducts, bridges and tunnels are defined to overcome the obstacles and the differences between the ground profile and the longitudinal profile of the HSR. The technical specifications in each case depend on the local ground conditions and the project's parameters. Project parameters reflect the design loads and the conditions under which performance must be assured. These have important degrees of uncertainty and can be related for instance to the occurrence of heavy rain, floodings or earthquakes.

In the Portuguese context, geological and geotechnical conditions are diverse and relate to several geotechnical risks. These risks can be triggered or accentuated by the occurrence of extreme climate events. Also, the ground behavior and the significant seismicity of the country result in significant seismic risks. As planning for worst case scenario is economically infeasible and the infrastructure's performance is highly demanding, the methodology proposes an approach of a scenario-based design considering uncertainty. The purpose is to achieve, for the planning stage, a robust solution that complies with the HSR restrictions and that performs well for all conditions of performance in the infrastructure's lifetime. Within this framework, a very important step is to find the optimal or near optimal solution for a scenario under normal operating conditions. This considers no occurrence of extreme events. However it is the scenario under which the infrastructure should perform during most of its lifetime.

This paper discusses the main issues when developing a decision aid tool for HSR. It presents the modeling of a specific solution under normal operating conditions. Results obtained are discussed in the context of a synthetic case study.

SPECIFIC MODEL

Representation of location dependent properties

The location dependent properties are of great importance to the HSR corridor optimization process. The model needs to represent spatially distributed properties. This is achieved by layered maps. Each layer relates to a different location dependent property and each color within a particular layer represents a different value for that property in space. These are also referred to as the search space properties. The items considered are (Figure 1):

1. Elevation
2. Geological and geotechnical conditions
3. Expropriation Value
4. Land-Use

Figure 1 illustrates how the representation of the properties through layered maps allows one to identify, at any point along the alignment's length, the value of a given property. This is achieved by overlaying the planned configuration and the respective layer.

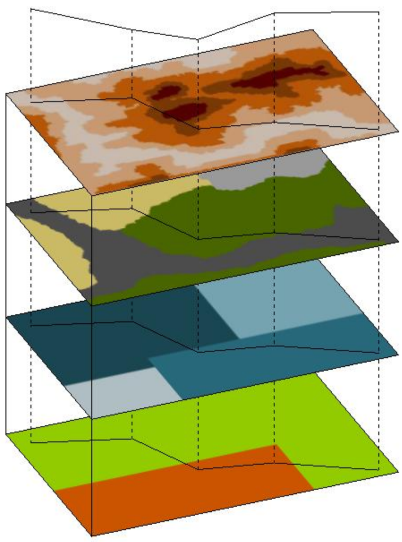

Figure 1 – Location dependent properties that affect a solution's definition and performance (from top to bottom): elevation, geological/ geotechnical conditions, expropriation value and land use.

Definition of a Configuration

The three-dimensional (3D) alignment of railways, including high-speed railways, is defined by a set of tangents and curves, both in horizontal and vertical planes. The proposed model considers a simplified version. The configuration is defined by linear sections that connect a set of sequential nodes (Figure 2), representing 3D points in space. This allows one to also establish the type of structure (embankments, cut, viaduct/bridge or tunnel) and associated cross-section along the planned alignment, provided that a model of the terrain exists. General cross-sections for embankments and cuts are illustrated in Figure 3 and Figure 4.

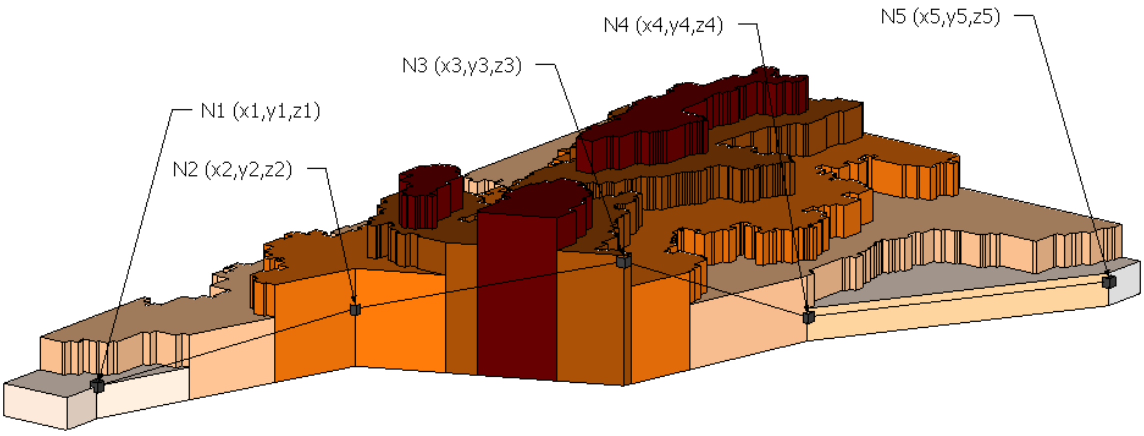

Figure 2 – Three-dimensional representation of a solution.

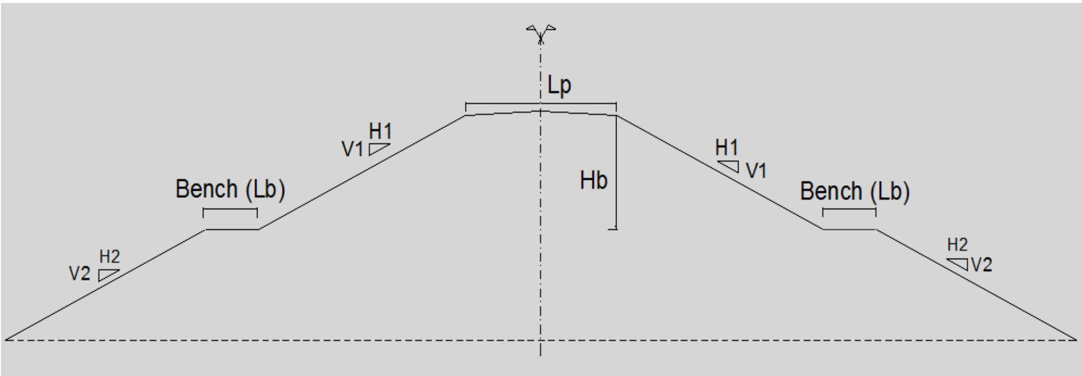

Figure 3 – General cross-section for embankments

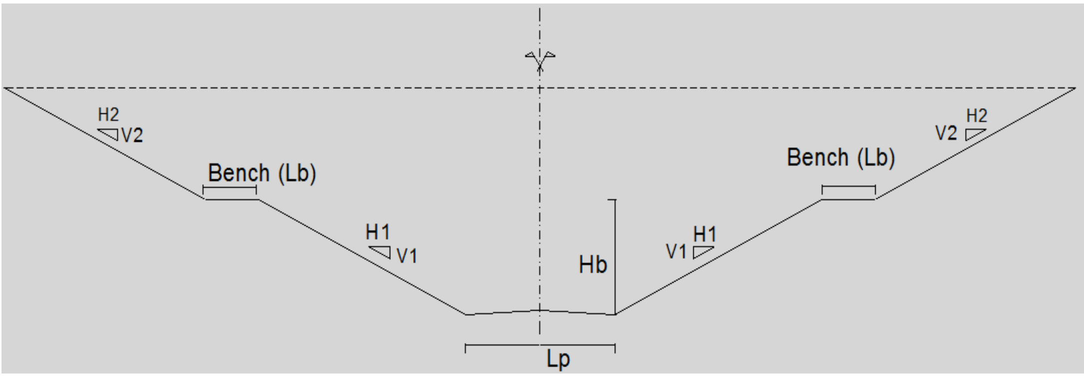

Figure 4 – General cross-section for cuts

The choice as to which structure and cross-section to adopt (embankment, cut, viaduct/bridge or tunnel) is unequivocally defined by the height difference between the planned alignment elevation and the terrain. At this stage, local ground behavior defines only some specifics, such as the slopes of the embankments and cuts. Figure 5 identifies the ground behavior units along a particular alignment section, by overlaying the layout and the ground behavior's layer.

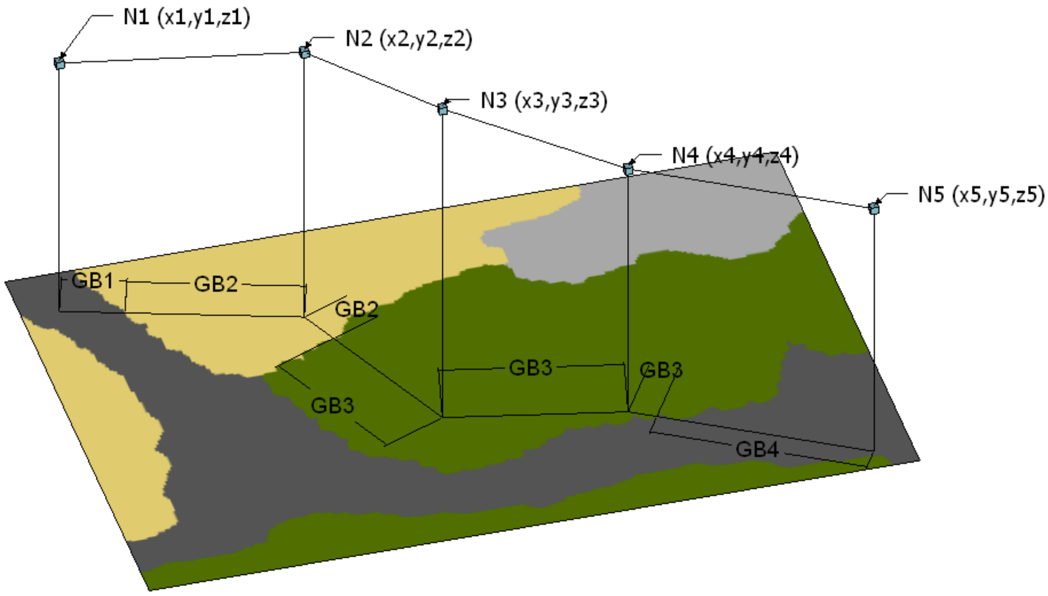

Figure 5 – Identification of ground behaviour along a solution's length.

Optimization Model Formulation

For a scenario of normal operating conditions, the optimization model can be expressed as follows:

$$Min\ (C_{const.}(\mathbf{N}) + C_{Pen.}(\mathbf{N})) \quad \text{(eq.1)}$$

s.t.

$$G_i(X) \leq G_{Lim}, \forall i = 1,..(n-1) \quad \text{(eq.2)}$$

$$H_i(X) \geq H_{Lim}, \forall i = 2, ... (n-1) \quad \text{(eq.3)}$$

$$X \supset (x_M, y_M, z_M)_i, \forall (x_M, y_M, z_M)_i \epsilon N_M \quad \text{(eq.4)}$$

$$X \not\supset (x_{LF}, y_{LF}, z_{LF})_i, \forall (x_{LF}, y_{LF}, z_{LF})_i \epsilon A_{LF} \quad \text{(eq.5)}$$

where,

$\mathbf{N} = \{(x_1,y_1,z_1), \ldots(x_i,y_i,z_i) \ldots,(x_n,y_n,z_n)\},\ \forall_{i=1,\ldots,n}$ is the solution's set of all nodes in sequential order, defined by the spatial coordinates x_i, y_i, z_i for each node *i*;

n is the number of nodes in the solution;

$C_{const.}(\mathbf{N})$ is the construction related cost for a given solution set of nodes $\mathbf{N}$;

$C_{Pen.}(\mathbf{N})$ is the penalty cost for a given solution set of nodes $\mathbf{N}$;

$G_i(\mathbf{N})$ is the gradient of a linear section *i* linking two consecutive nodes of the solution set of nodes $\mathbf{N}$;

G_{Lim} is the maximum allowed gradient for any given linear section of solution set of $\mathbf{N}$;

$H_i(\mathbf{N})$ is the angle formed by linear sections at a intermediate node *i* of the solution $\mathbf{N}$;
H_{Lim} is the minimum allowed intermediate node angle for any given intermediate node of solution $\mathbf{N}$;
$(x_M, y_M, z_M)_i$ defines a mandatory node of the optimization problem;
N_M is a set of mandatory nodes that the solution $\mathbf{N}$ must cross;
$(x_{LF}, y_{LF}, z_{LF})_i$ defines a point of the optimization problem which is forbidden because of land-use restrictions;
A_{LF} defines the area of all forbidden land use points that the solution $\mathbf{N}$ must not cross.

The following subchapters discuss each of these components and the cost formulation considered.

Cost Formulation

The goal of the optimization problem is to find the solution that yields the minimum total cost, which is given by the sum of two distinct components (eq.1): Construction Related Costs (C_{Const}) and Penalty Costs (C_{Pen}).

The Construction Related Costs are based on the studies for the high-speed rail connection Porto-Vigo on Portuguese territory (RAVE 2006e). The Penalty Cost component cannot be obtained from the budget estimates of RAVE (2006e). It is a model cost component that translates undesirable effects or properties of the solution into a cost value. This means that a value is computed in order to penalize the solution if it lacks compliance with a problem constraint. The use of penalties is one mechanism in optimization problems that disencourages configurations that conflict with the desirable values.

The specifics of construction related costs and penalty costs are discussed below

Construction Related Cost

Construction related cost is one of the main components to be considered in the model for normal operating conditions. It is obtained through the sum of costs for the items expropriations and construction costs of earthworks, viaducts and bridges and tunnels.

Expropriation Cost

The expropriation value is computed by overlaying, in the plan view, the solution with a map of spatial unit cost distribution, as shown in Figure 6, where each color represents a different expropriation unit cost. The unit measure is the square meter (m^2) and the area to consider for expropriation is established through an offset beyond the footprint of the infrastructure. An example for an embankment or cut is shown in Figure 6 in the zoomed box. The area to expropriate is obtained by an offset to the earthworks' footprint limit. This methodology complies with the established parameters for the Portuguese high-speed rail (RAVE 2006d). The document also establishes offset values.

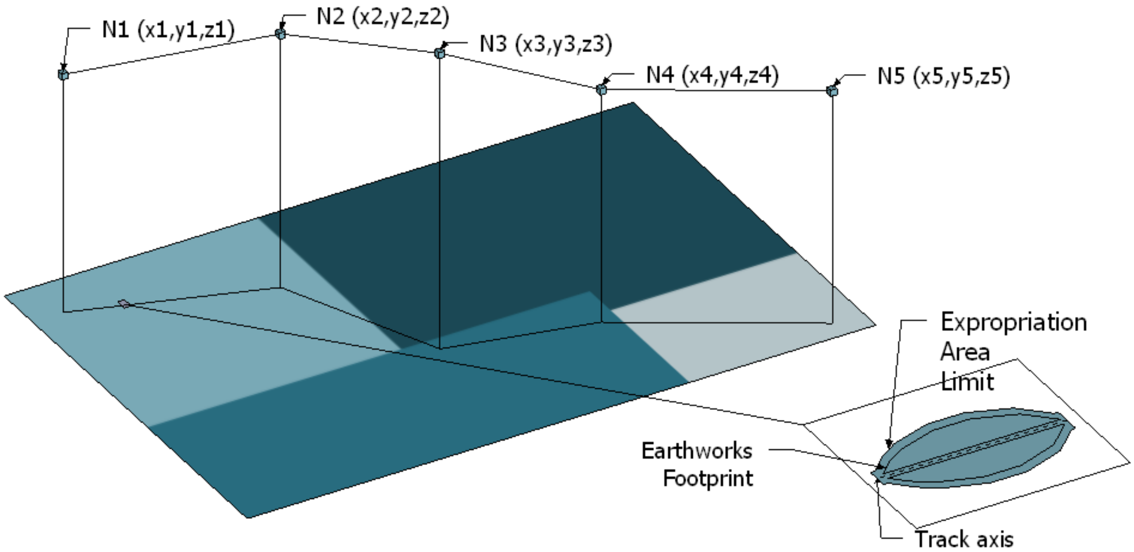

Figure 6 – Expropriation Costs: solution and expropriation cost map.

Earthworks

The cross-section to adopt for cuts and embankments depends on the difference of ground and alignment altitude, as well as on the local ground conditions. As both can vary greatly along the longitudinal profile (see example in Figure 1), the cost computation is performed by summing the unit cost of each individual component, along the entire length of the solution. Figure 7 illustrates the procedure for a given length of a cut. The units and unit cost values of each item (Table I) considered for cost computation are in accordance with RAVE (2006e).

Table I – Model's earthworks cost items and units

Item	Units
Ground improvement by removal and replacement	€/m^3
Cut with mechanical means	€/m^3
Cut with explosives	€/m^3
Embankment	€/m^3
Capping	€/m^3
Sub-ballast	€/m^3

The slopes and sub-ballast, capping and ground improvement thicknesses depend on the ground behavior along the planned alignment. Also, cut methods depend on the local ground conditions. To address these issues, the model considers units of ground behavior mapped for the entire region, as shown in Figure 5. In the example, 3 of 4 ground behavior are crossed. Each ground behavior unit defines a specific combination of properties (Table II).

Table II – Model's ground behaviour properties

Property	Units
Slopes (embankments and cuts)	(m/m)
Cut method (% of excavated volume with mechanical	Volume %
Ground improvement thickness	m
Capping thickness	m
Sub-ballast thickness	m

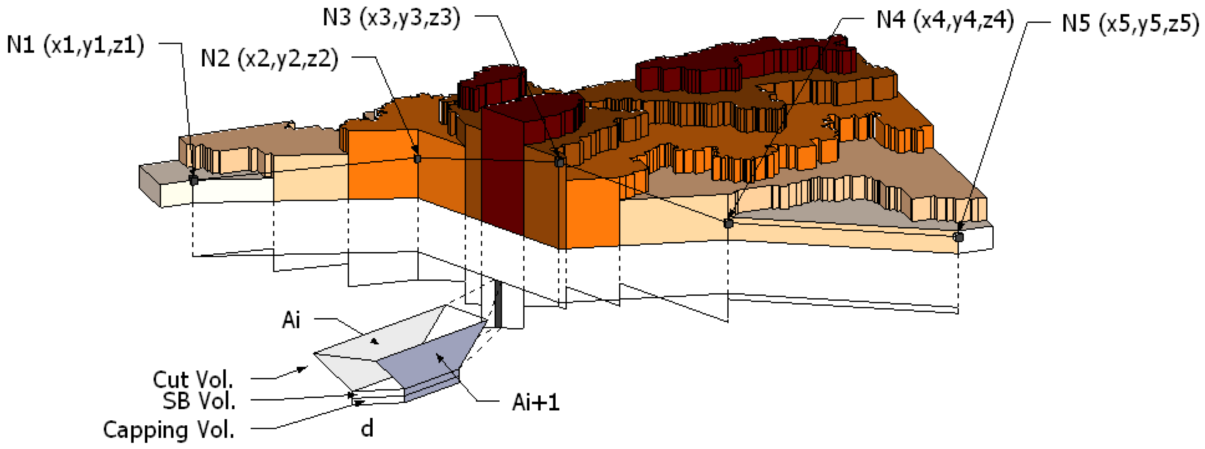

Figure 7 – Diagram of relative ground and solution elevation and volume computation for a cut.

Volumes for the items in Table I are computed by the "average-end area method". The volume between two cross sections spanning a given length (Figure 7) is obtained by multiplying the average of the areas from both cross-sections by the length between them (eq.4).

$$V = \frac{A_i + A_{i+1}}{2} d \qquad \text{(eq.4)}$$

where,

V is the volume, A_i is the area measured at cross-section i, A_{i+1} is the area measured at cross-section $i+1$ and d is the distance between the two cross sections.

Bridges and Viaducts

RAVE (2006a) defines bridges and viaducts as the necessary structures to overcome natural obstacles. The term bridge is employed when the obstacle to cross is a body of water and the end locations of the structure are affected by the water line shape. The construction cost of a bridge or viaduct varies with length, pier span, pier height and foundations and the construction method.

The model considers cost computation of bridges and viaducts varying with length. A unit cost is set per linear meter (m).

Tunnels

The tunnel cost definition in the model is similar to the viaducts and bridges. Although in the real world it is also affected by local ground conditions, the model formulation defines unit costs per length in accordance with studies related both with the high-speed rail projects in Portugal and Spain (RAVE 2006b & Cardoso 2009).

Constraint and Penalty Cost Definition

Some constraints need to be set, in order to simulate real-world restrictions. As discussed in the problem description chapter, parameters in a planned configuration have desirable values. However, allowances can be made up to a mandatory limit value. The model considers constraints associated with the geometry items, nodes and land use. Simplifications are made as described.

The definition of constraints in the model results in the definition of two values: limit/mandatory and normal/desirable values. In order to accommodate these preferences in the model, penalties are established in the form of cost when the normal/desirable values are not satisfied. The formulation of the problem also requires that each solution computed is feasible, meaning that it must comply with the mandatory restrictions.

Geometry Constraints: Gradient in the Longitudinal Profile and Intermediate Node Angle in the Plan View

These constraints relate to geometry. According to studies for the Portuguese high-speed rail network (RAVE 2006c), the design should favor low grades, and comply with a maximum limit value (Figure 8), while in the plan view it should favor straight lines or large radius curves, and comply with a minimum admissible value. These constraints lead to the establishment of two design values for each item. They are named normal and limit values.

The gradient constraint is defined along the longitudinal profile. The actual gradient of each alignment is compared with the normal and limit values, as shown in Figure 8 for a section *i*.

The rising and falling gradient limit values (equal in absolute value for rising and falling gradient limit values) define the interval of feasible gradient values for each linear section. The rising and falling normal gradient values (also equal in absolute value for rising and falling gradient limit values) define, for each linear section, the most favorable design gradients.

In order for a problem solution to be feasible, all linear sections must be feasible. This implies that gradients, either rising or falling, must be smaller than the limit gradient.

As previously discussed, the solution is defined by linear alignment sections. This means that the alignment is formed from linear segments and leads to the consideration of normal and limit values for angles between alignments, in intermediate nodes, instead of radii of curvature. This is illustrated in Figure 9 for an intermediate node i.

In the plan view, for each intermediate node, the angle between the linear sections that ends at that node and the linear segment that start at that node is the angle to compare with the normal and limit angle values.

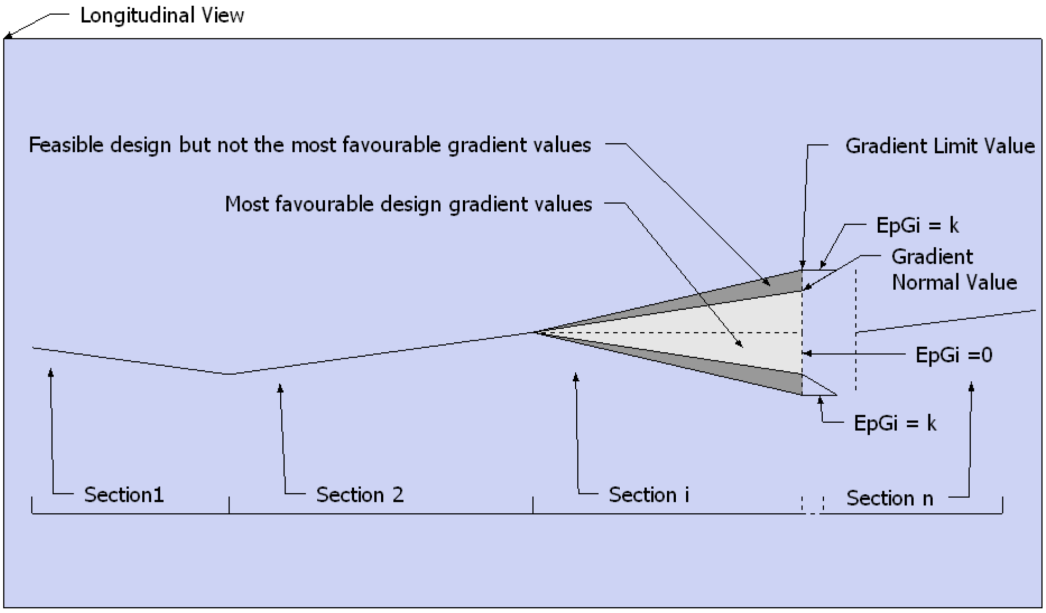

Figure 8 – Schematic longitudinal profile: limit and normal grading values and penalty definition

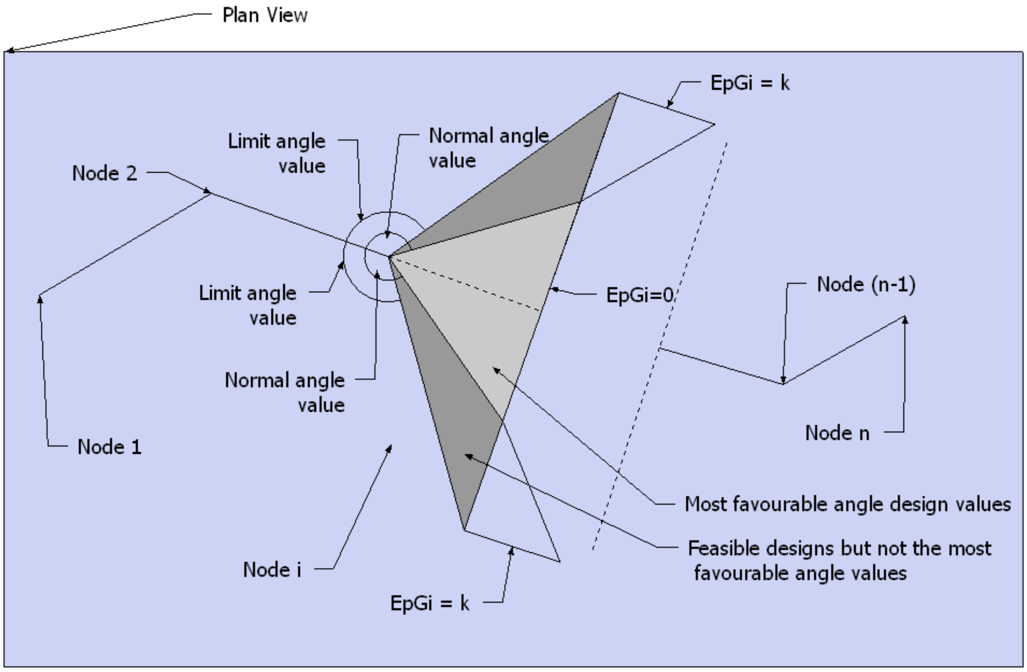

Figure 9 – Schematic Plan view: limit and normal angle values for intermediate nodes and penalty definition

Figure 9 shows that for angle values smaller than the limit angle value the angle is infeasible. If the angle is greater than the limit but smaller than the normal value, the angle is feasible but has not the most favorable value. If the angle value is greater than the normal value the angle is feasible and is within the most favorable design interval.

Similarly to gradient constraints in the longitudinal profile, in order to have a problem solution that is feasible, the angles at all intermediate nodes must be greater than the limit value.

For similar circumstances, in highway alignment optimization, Jha & Schonfeld (2004) developed a cost formulation for constraints. The authors set penalty costs to avoid design violations of geometric constraints such as gradients and vertical curve length (general formulation for both as in eq.6 and eq.7).

$$C_{Pgi}= \begin{Bmatrix} \alpha_0 + \alpha_2(g_i - G_{lim})^{\alpha_3}, & if\ g_i is\ outside\ limit\ bound\ G_{lim} \\ 0, & if\ otherwise \end{Bmatrix}, \qquad \text{(eq.6)}$$

$$C_{Pg} = \sum_{i=0}^{n} C_{Pgi}, \qquad \text{(eq.7)}$$

where,

C_{Pg} is the total geometric cost penalty for each restriction, given by the sum of the individual element cost C_{Pgi}, with α_0, α_2 and α_3 ($\alpha_3>1$) being user specified coefficients, G_{lim} the limit value for each geometric restriction and g_i is the actual geometry value at each individual element.

The authors propose the cost penalty associated with a measure of the actual values and the constraint limit values. However, the coefficients that represent that relation mathematically, as a cost penalty function, are not further detailed.

Since the definition of penalty costs through coefficients requires a careful study for each coefficient, the present methodology proposes a simpler first approach: the application of a penalty cost proportional to each solution's overall construction cost and the relative distance to the desirable constraint value. With this formulation, as the difference of the constraints desirable and actual values, as well as the construction costs described in the previous section, are known, the only parameter that needs to be set for each constraint is proportionality coefficient. Also, defining the penalty unit costs proportionally to the construction cost of each solution allows for some degree of normalization.

Hence, the penalties for both the gradient and horizontal angles for intermediate nodes, are computed as in eq.8 and eq.9:

$$C_{PGi}= \begin{Bmatrix} \frac{|G_{normal}-G_i|}{|G_{normal}-G_{limit}|}\gamma C_C, & if\ G_i\ is\ between\ G_{limit}\ \&\ G_{normal} \\ 0, & if\ otherwise \end{Bmatrix}, \qquad \text{(eq.8)}$$

$$C_{PG} = \sum_{i=0}^{n} C_{PGi}, \qquad \text{(eq.9)}$$

where

G_{normal} and G_{limit} are, respectively, the normal and limit values set for each constraint; G_i is the value for gradient at alignment *i* or horizontal angle at intermediate node *i*; C_C is the construction cost of the solution being computed, γ is user specified coefficient and n is the number of alignments or nodes.

Costs are individually assessed each alignment or each intermediate node (C_{PGi}). The total cost of gradient and horizontal angle (C_{PGi}) is obtained by summing the individual components.

Nodes

The definition of start and end points has much to do with the scope definition of the project. Although there is room for variation of the exact location, their broad location is well established. Varying from project to project, the same can be said for some nodes in-between. However, there are intermediate locations that could favor aspects of the solution performance but with a loss for other factors. The reasons to consider them may relate to social factors, future necessities or other aspects translated into indirect costs.

In order to address this issue, the formulation proposes three different types of nodes: mandatory, technical and geometric nodes. All are spatially defined by 3D coordinates (x,y,z). For a node to be of type mandatory, technical or geometric, two additional parameters are set:

1. a binary parameter m (m=1 if the node is mandatory and m=0 otherwise)

2. a binary parameter t (t=1 if it is a technical node and t=0 otherwise)

Both parameters m and t are null for the geometric nodes. Accordingly, the type of the node can be perfectly defined, as follows for the generic nodes i, j and k:

1. Mandatory Node i: $[(x_i,y_i,z_i); m_i=1 ; t_i=0]$

2. Technical Node j: $[(x_j,y_j,z_j); m_j=0; t_j=1]$

3. Geometric Node k: $[(x_k,y_k,z_k); m_k=0; t_k=0]$

The mandatory nodes reflect the locations that the solution must cross in order to be considered feasible like start and end nodes as well as some imposed middle locations. In Figure 10 three mandatory nodes (in red) are given. One of the represented solutions does not include a mandatory node and therefore is infeasible.

Technical nodes are represented in Figure 10 in yellow. These nodes reflect the locations that are optional, but have some specific characteristics that can enhance the social or economic impact of the solution. The binary parameter t=1 defined above indicates that this type of node has an associated penalty cost to encourage solutions to cross as many technical nodes as possible. However, the cost formulation and the penalties are not discussed in this paper.

Geometric nodes have no additional bearing to the solution's performance, except for the geometric definition. The null values for both parameters m and t reveal that this type of nodes is neither mandatory nor has it a penalty associated with them. A geometric node is represented (in grey) in Figure 10.

The node penalty definition is shown in Figure 11. It is similar to the geometry penalty definition. An individual penalty cost (C_{PNi}) is assessed for each of the technical nodes. The cost of each technical node is null if crossed by the configuration layout or proportional to the construction related costs if otherwise (eq.10). The total cost for the nodes' penalty (C_{PN}) is obtained by summing the individual costs of each technical node.

$$C_{PNi} = \begin{Bmatrix} \gamma C_C, & if\ node\ i\ \notin solution \\ 0, & if\ node\ i\ \in solution \end{Bmatrix}, \qquad \text{(eq.10)}$$

$$C_{PN} = \sum_{i=0}^{n} C_{PNi}, \qquad \text{(eq.11)}$$

where

C_C is the construction cost of the solution being computed, γ is user specified coefficient and n is the number of technical nodes.

Land Use

The existence of protected areas, where construction is controlled or prohibited, can cause clear restrictions to the high-speed rail line planning. Several reasons may lead to the identification of areas where crossing is inadmissible or possible but undesirable. Various issues with consequences related to land use are well identified in the Environmental Impact Assessment report for the Portuguese high-speed rail project (RAVE 2008). For illustration, and not as an exhaustive list, the following factors may be mentioned: agricultural, ecological, induced noise and/or vibration.

This type of constraint is introduced by a mapped identification of three different permission classes of land use: prohibited, restricted and unconditional. Two parameters can be set for the clear distinction between the three classes in land use constraint:

1. a binary parameter p (p=1 if land use is prohibited and p=0 otherwise)
2. a binary parameter r (r=1 if land use is restricted and c=0 otherwise)

Accordingly, the land use class related with a given area is distinguished as follows:

1. Prohibited: p = 1 & r = 0
2. Restricted: p = 0 & r = 1
3. Unconditional: p = 0 & r = 0

The prohibited area refers to the spatial condition for which, in a plan view, an overlap of any segment of the solution makes the configuration infeasible. In Figure 10 the lower left corner in green illustrates a restricted area. The shown overlap by a segment of one of the solutions makes it infeasible.

A restricted land-use area is also illustrated in Figure 10 in yellow (lower left corner). It relates to a spatial condition in plan view where crossing is not forbidden but is undesirable. The binary parameter r=1 indicates that this area has an associated penalty cost. Similarly to the previous constraints, penalty costs intend to discourage solutions that cross the restricted areas. The formulation of these penalty costs is outside the scope of this paper.

By default, the remainder of the space in the plan view (Figure 10) has no crossing restrictions or penalties associated with it. It corresponds to the unconditional land use. The null values for both parameters p and r reveal that crossing this area is neither prohibited nor penalty associated.

Similarly to geometry constraints, Jha & Schonfeld (2004) developed a cost formulation for environmental constraints. The authors set penalty costs to avoid crossing floodplains and wetlands (general formulation for both as in eq.12 and eq.13).

$$C_{Pej}= \begin{Bmatrix} \beta_0 + \beta_2 \left(\frac{A_{xj}}{Aj}\right)^{\beta_3}, \ if\ g_i is\ outside\ G_{lim} \\ 0, \quad if\ otherwise \end{Bmatrix}, \qquad \text{(eq.12)}$$

$$C_{Pe} = \sum_{i=0}^{n} C_{Pei}, \qquad \text{(eq.13)}$$

where,

C_{Pe} is the total environmental cost penalty for each restriction, given by the sum of the individual element cost C_{Pei}, with β_0, β_2 and β_3 being user specified coefficients, A_j the area of the j-th floodplain or wetland intersection and A_{xj} the actual intersected area.

The present research considers, at the current stage, a land-use penalty proportional to the length of the section that crosses the area of restricted land-use which is proportional to the construction related costs. Individual costs for environmental penalties (C_{Pei}) are computed for each section (L_i) that crosses the restricted area (Figure 11). The total land-use penalty (C_{Pe}) is the sum of the individual components.

$$C_{Pei}= \begin{Bmatrix} \gamma L_i C_C, \ \ if\ land\ use\ is\ unrecommended \\ 0, \quad if\ otherwise \end{Bmatrix}, \qquad \text{(eq.14)}$$

$$C_{Pe} = \sum_{i=0}^{n} C_{Pei}, \qquad \text{(eq.15)}$$

where

C_C is the construction cost of the solution being computed, γ is user specified coefficient and n is the number of segments (L_i) crossing undesirable land-use.

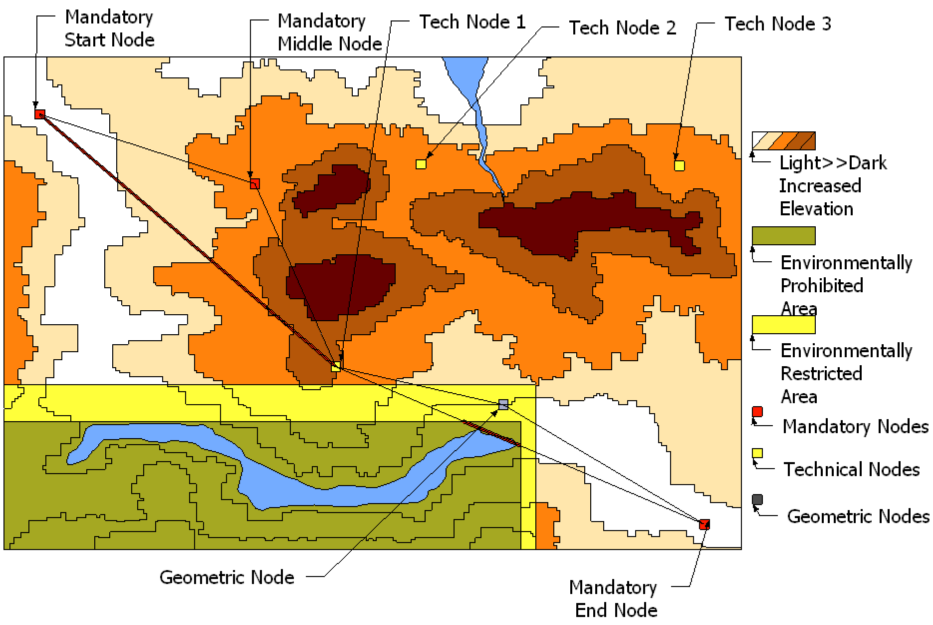

Figure 10 – Land use and node constraints

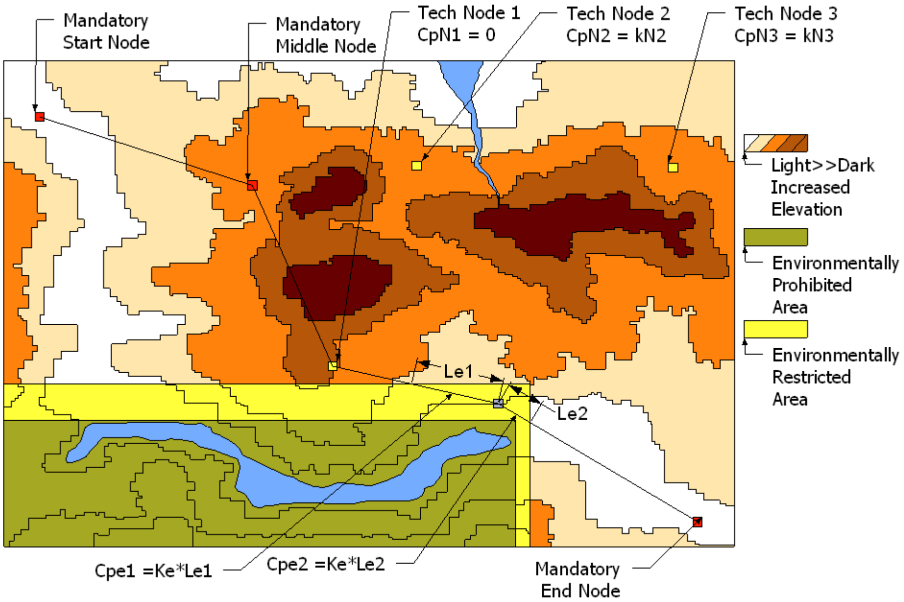

Figure 11 – Node and Environmental Penalty calculation scheme

OPTIMIZATION PROCEDURES

The previous chapter presents the model proposed to address the HSR planning problem. An optimization technique, the Simulated Annealing Algorithm, is implemented to obtain the optimal or near-optimal solution. An overview of this optimization technique is presented in the following sub-chapter.

The Simulated Annealing Algorithm

The Simulated Annealing Algorithm is a heuristic method. As such, it is an experience based method. The use of heuristics mostly relates to complex combinatorial optimization problem solving (de Weck 2010). De Weck states that, although achieving the optimal global solution is not guaranteed, many good solutions are expected. Also, heuristics perform well in presence of local optima, incorporating mechanisms to avoid being stuck while searching for the global optimum.

The algorithm is credited to Kirkpatrick, Gelatt and Vecchi (1983) and traces its origins to statistical mechanics. In fact, the algorithm draws an analogy between the behavior of systems with many degrees of freedom to reach thermal equilibrium at a given temperature, such as the annealing process in solids, and the optimization of properties of very large and complex systems. The annealing process of solidifying metals aims at obtaining the configuration with the lowest energy state. Despite the fact that lower energy states relate to lower temperatures of the system, a low temperature by itself is not sufficient (de Weck 2004). Slow cooling is necessary in order to allow particles to rearrange into the lowest energy configuration. In this regard, the algorithm simulates the annealing process by searching for equilibrium conditions at successively decreasing temperatures. The analogy is drawn between obtaining the lowest energy configuration of a system and achieving the global optimum solution for the problem to be solved. Figure 12 presents a flow chart of the algorithm.

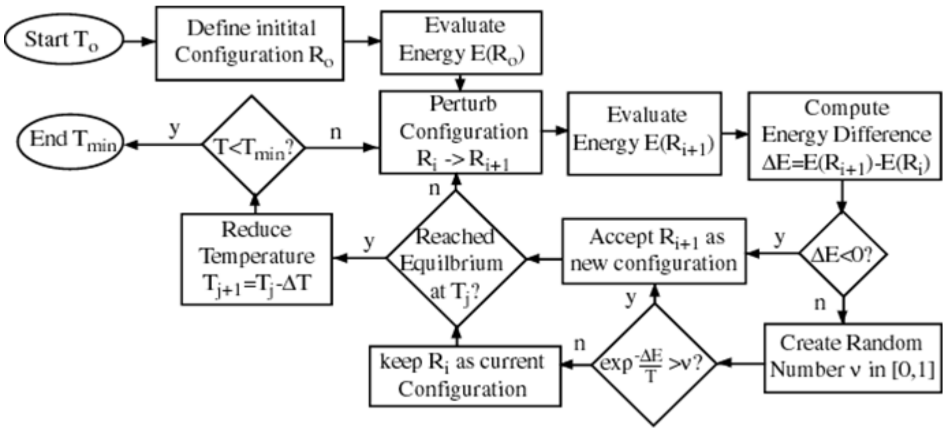

Figure 12 Simulated Annealing Algorithm flow chart (Adapted from de Weck 2004)

Several parameters need to be defined for the implementation of the algorithm. Besides establishing an initial configuration and the framework to evaluate every solution configuration along the optimization process, it is also necessary to define:

1. The initial system temperature
2. The cooling schedule
3. The equilibrium conditions
4. The termination criteria

De Weck (2004), Cunha (1999) and Cunha (2001) present implementations of simulated annealing to solve different problems, ranging from station placement for a radio telescope array to hydraulic infrastructure, and also present guidelines for setting the algorithm parameters.

Configurations are generated for each temperature until equilibrium conditions are reached. The temperature and the cooling schedule affect the probability of worsening solutions to be accepted and the decrease rate of that probability. The termination criteria define the end of the algorithm. The Simulated Annealing Algorithm is used to solve the proposed model, drawing the analogy between the energy evaluation and the cost computation of each HSR configuration.

SYNTHETIC CASE STUDY: PRELIMINARY DEVELOPMENTS

A synthetic case study is employed to demonstrate the general performance of the decision aid tool under development model and the implementation. The model has been solved with the Simulated Annealing Algorithm.

The problem proposed is to determine the optimum configuration for a High-Speed rail connecting two points located at the top left corner and bottom right corner of a rectangular area of 30*20 km^2, considering the local conditions and a set of specific requirements.

Location dependent properties are represented by several layers, as shown in Figure 13. The ground elevation ranges from 10 to 50 meters (darker colors correspond to higher elevation). Four ground behavior units are considered according to Table III. Four expropriation unit costs are considered. According to Figure 13, each color shading represents a different unit cost ordered, in decreasing value, as follows: lower right side shade, upper left side shade, upper right side shade and lower left side shade. The lower left color shade of the expropriation layer has a default null cost since it corresponds to a forbidden land-use restriction area (compare with land-use layer). Land use layer represents the forbidden area in brown, the restricted land-use in orange and the unrestricted land use in green.

The cut and embankment cross-sections consider a constant sub-ballast thickness of 0,30 meters and a platform width of 14 meters (L_p). For embankments (Figure 3) with height above 12 meters, a 3 meters bench (L_b) is placed at the 10 meter height (H_b). Maximum height for side benched embankments is 20 meters. Bridges and viaducts are implemented for heights above 20 meters. For cuts (Figure 4) deeper than 10 meters, a 3 meter bench (L_b) is placed at 8 meters (H_b). Maximum depth of benched cuts is 34 meters with benches every 8 meters. Tunnels are considered for depths greater than 34 meters.

Geometry restrictions consider a gradient limit value of 35 mm/m, a gradient normal value of 25 mm/m, a limit horizontal angle at intermediate nodes of 100º and a normal horizontal angle at intermediate nodes of 120º. Three mandatory nodes (represented in red in Figure 13) are placed at coordinates (0,0), (20,10) and (29,19) kilometers. A technical node (represented in yellow in Figure 13) is placed at coordinates (15, 2) kilometers. The origin of the coordinate system is located at the upper left corner of study area.

The case study area is discretized by a mesh of 600 square elements 1 kilometer wide, in the plan view. These elements establish the possible node locations when generating new neighbor candidate configurations to be assessed. The discretization also establishes that, for each plan view mesh element, possible vertical coordinates range from 0 to 60 meters. Runs were made for different Simulated Annealing Algorithm parameters: initial temperature, temperature decrease rate, minimum number of evaluated solutions at each temperature and consecutive temperature decreases with no improving solution found. The algorithm implementation was done according to Cunha (1999).

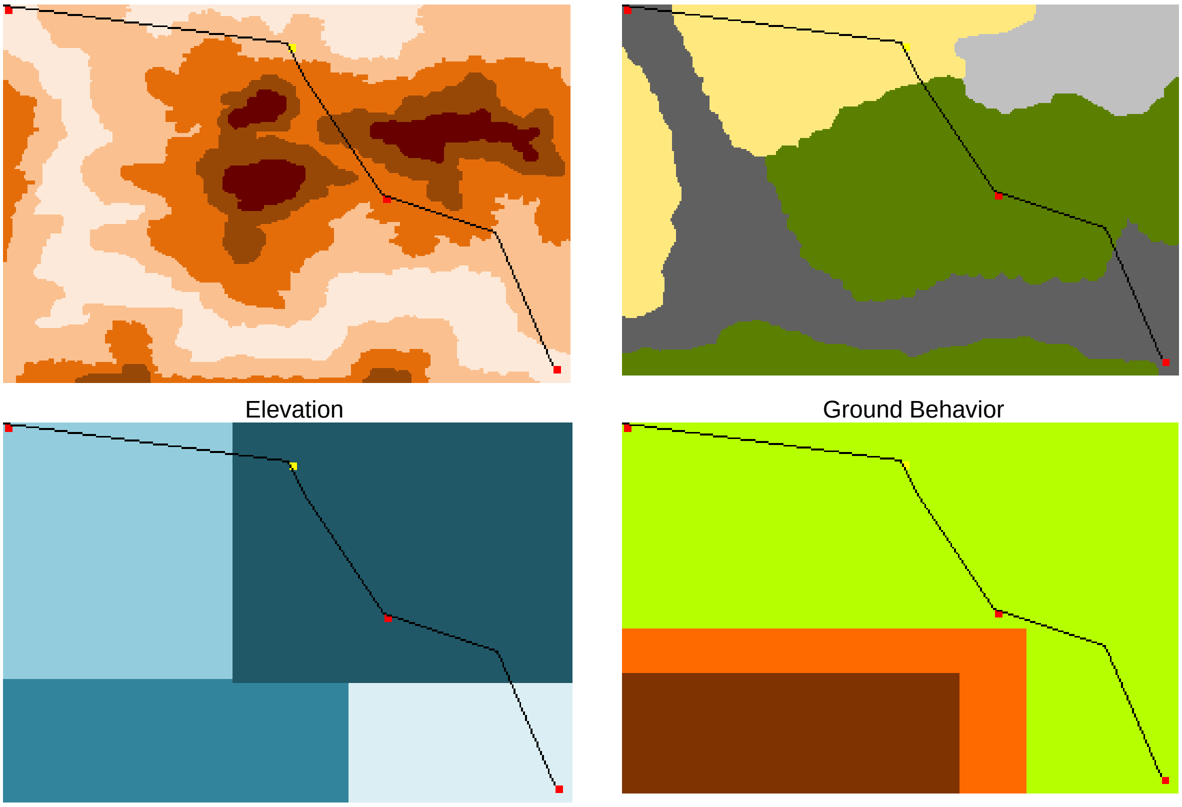

Figure 13 Case Study Layers with overlaid best found solution.

Table III – Ground Behavior Properties

Unit No.	Color		Slopes (V/H)		Excavation Method (Volume %)		Ground Improvement Depth (m)	Capping Thickness(m)
			Embankment	Cut	Mechanical Means	Explosives		
1	Light Grey		1 / 2	2 / 3	100	0	0	0,3
2	Yellow		1 / 2	2 / 3	100	0	1	0,6
3	Dark Grey		1 / 2	2 / 3	100	0	2	0,6
4	Green		1 / 2	1 / 1	50	50	0	0

The best configuration found is represented in Figure 13. It is clear that this configuration is mostly determined by some of the constraints imposed, namely the nodes, the topography and the land use. Figure 14 shows, for the respective simulated annealing run, the evolution of the best solution total cost with the iteration number. Table IV, Table V and Table VI present the cost summary, geometry layout and construction cost quantities for the best configuration found by the algorithm. This configuration is a feasible one, crossing all the mandatory nodes, complying with the limit values for gradient and intermediate node angle and not overlaying the forbidden land use. Also, all the desirable values are complied with, resulting in a null overall penalty cost. The layout crosses the technical node and also manages to avoid the restricted land use. All angles at intermediate nodes (plan view) are greater than the normal value of 120º and all linear sections have a lower gradient than the normal value of 25mm/m. No tunnels, viaducts or bridges are considered in the solution, reflecting the adjustment of the layout and ground elevation.

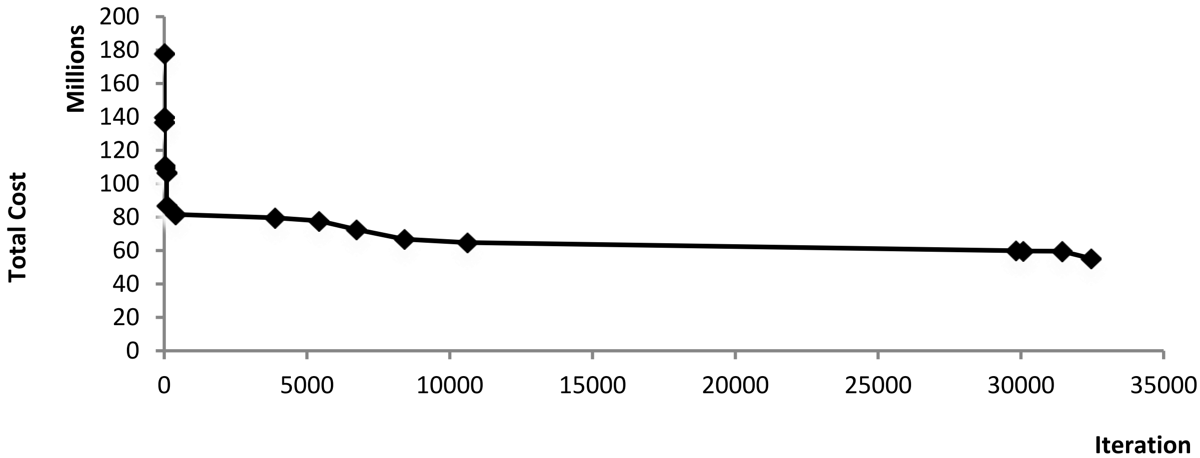

Figure 14 – Evolution of best found solution with iteration number o the simulated annealing run.

Table IV – Best configuration cost summary

Total Cost	Construction Cost	Penalty Cost
55300965	55300964	0

Table V – Best configuration geometry layout

	X (m)	Y (m)	Z (m)	Angle (º)	Gradient (mm/m)
Node 1	0	0	20		
Node 2	150	20	30	124	
Node 3	160	40	30	173	
Node 4	200	100	30	142	
Node 5	260	120	20	132	
Node 6	290	190	10		
Linear Alignment 1					0,665
Linear Alignment 2					0
Linear Alignment 3					0
Linear Alignment 4					-1,524
Linear Alignment 5					-1,313

Table VI – Best configuration construction cost quantities

	Quantity	**Units**
All Bridges	0	m
All Tunnels	0	m
Cut with Explosives	303958,4	m^3
Cut with Mechanical Means	477201,5	m^3
Embankment	1786793	m^3
Ground Improvement by Removal & Replacement	807231,7	m^3
Capping	218021,3	m^3
Sub Ballast	163832	m^3

CONCLUSIONS AND FURTHER DEVELOPMENTS

This paper discusses the main issues when developing a decision aid tool for High-Speed Rail (HSR) planning in Portugal. An overview of the problem is presented. A specific model is proposed to address the HSR problem under normal operating conditions. The model is applied to a synthetic case study and solved with the use of the Simulated Annealing Algorithm. Promising preliminary results are presented. The preliminary results presented in this paper, derived from a synthetic case study, are quite promising, considering that the decision aid tool yields a solution that complies with the constraints imposed at low cost.

Future developments of the model should consider all the operating conditions that affect the HSR lifetime. In addition to normal operating conditions, risk should be incorporated in the model with consideration of the geotechnical and seismic risks that affect HSR planning in Portugal. The model should be applied to case studies of increasing complexity and use real data.

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