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Potentialities of a Highway Alignment Optimization Method in an I-BIM Environment

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Abstract

The BIM (Building Information Modeling) approach potential in the civil engineering field opened novel scenarios in the design idea concept, from planning to executive and constructive phases. The related advantages are numerous and not only limited to a real-time interaction among the involved subjects, that can actually operate in an optimized 3D shared environment. Owing to the sharing information philosophy and to the features of various "smart objects" combined in the project, this innovation reduces potential errors and increases the effectiveness of the design solution in terms of both functionality and cost. Despite these advantages, the highway alignment design problem remains very complicated and not easy to solve without appropriate supporting tools. In recent years, several efforts have been spent in defining highway optimization procedures for helping designers in the selection of an optimal solution in compliance with numerous different constraints. Introducing these procedures in a BIM environment may represent a crucial step in the improvement of the highway design procedures, exploiting the full representation and modelling potential of the approach. In this paper, the authors present the advantages of a 3D highway alignment optimization algorithm, based on the Particle Swarm Optimization method, and its possible implementation in a BIM platform. A proper I-BIM environment can exploit the potential of the alignment optimization algorithms, simplifying the analysis of the different solutions, the final representation and the eventual manual modifications.

Keywords

I-BIM, alignment optimization, artificial intelligence, smart design, highway project

1 Introduction

The road alignment design problem is traditionally a very complicated task in infrastructure engineering, due to the several and heterogeneous skills required to the engineers for the analysis. Moreover, a significant amount of time is required for finding an acceptable and proper solution. The complications are generally due to the different aspects and issues involved in the design which define very important constraints (economical, environmental, geometrical, social, etc.) and strictly condition the road alignment.

Since traditional approaches are too slow and error-prone, in recent years many efforts have been made for developing novel tools and algorithms that can actually support the designers in these delicate tasks. These algorithms – nowadays generally based on Artificial Intelligence (AI) techniques – may analyze and compare thousands and thousands of different solutions, to optimize the alignment and select the best road corridor. These algorithms are also able to define the most appropriate highway geometric characteristics that can minimize costs (not only for construction, but also management and external costs) and reduce eventual critical situations [1]. Among the various solutions, the most interesting algorithms relied on the Genetic Algorithms (GA) approaches [1–8] or the Swarm Intelligence (SI) methods [9–12] and provided significant and effective results. In general, all the alignment optimization approaches aim to simplify the design phase by helping the engineers in the road-planning task for reducing errors and inaccuracies, minimizing costs and execution times.

Similar aims regard another excellent innovation that has been interesting the civil engineering field in the last years, causing the so-called BIM (Building Information Modeling) revolution. The BIM is a novel and useful way of

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thinking, handling, representing, and analyzing the design of any construction object in civil engineering [13]. It represents a shared 3D environment, in which all the subjects involved in the project can operate in parallel, offering their contributions in real-time and simplifying the knowledge sharing [14]. This approach can significantly reduce errors and inaccuracies in the project and increase the efficiency of the work-group, since the members can immediately update and share all the information. Furthermore, the entire project is based on a 3D realistic representation of the construction, by means of several specific "smart objects" representing the core element of the BIM environment [15]. These provide not only an easy-to-understand 3D reproduction of the single elements and their interaction, but also all the relevant related information that can influence and condition the different project phases (from planning to construction), stored in a complete and large relational database. By analyzing and processing this large amount of data, the most advanced BIM tools can offer support and forecasts in all these phases, simplifying the cost and time estimates and also the working operation organization and scheduling [16, 17]. Then, it is easy to understand that, considering the particular needs of a complex highway design, this kind of solution is strategical and very productive.

In truth, despite the great progress reached in the structural field, the I-BIM (Infrastructure-BIM) tools and environments are nor adequate and developed enough for an exhaustive and significant contribution in the project design and management phases [18]. However, the attention on the topic is high and the progress is continuous and quick.

In this paper, the authors analyze the advantages that can be determined by the implementation of the most modern and efficient alignment optimization procedures in a complete and detailed I-BIM environment. As deeply discussed in the following sections, this integration can exploit the full potential of both the innovations, since the BIM relational database can directly provide all the needed information for the alignment examination. Moreover, the final suggested solutions can be easily represented in 3D in a realistic frame, in which the designers can also easily compare and eventually modify them. In the following sections, first useful notices regarding the BIM and I-BIM approaches are provided. Then, the authors present a brief literature review on the main highway alignment optimization algorithms and provide general guidelines for the problem modelling. Finally, the advantages of practically implementing these algorithms in I-BIM environments are analyzed and critically discussed.

2 BIM and I-BIM

The BIM technologies have been introduced at the end of last century in the civil engineering field. BIM cannot only represent a software solution or a specific technical procedure. On the contrary, it defines a change in the way of thinking, a novel approach to design, modelling, and management of every civil engineering construction [13]. The BIM technologies - made possible by the recent software progress and the modern microprocessor performance [19] – rely on some essential and simple principles, shown in Fig. 1. All these aspects improve the project accuracy and reliability and increase project team efficiency and construction quality, providing advantages for all the involved subjects.

BIM adoption in the building design has been relatively quick and effective. Even if the approach is in continuous evolution and the available solutions are not completely exhaustive, designers and technicians have generally moved from CAD-based design approaches to the BIM methodologies. This is essentially due to the great advantages produced by the BIM adoption, as it can not only actually reduce and, maybe, avoid design inadequacies or mistakes and, thus, the number of legal disputes, but also the time spent for every modification or correction. The BIM produces an overall optimization of the project, since it does not offer advantages to the planning and design phases only, but it can incorporate all design information for organizing and optimizing all the stage of the building lifecycle [20]. Consequently, it is common, nowadays,

Fig. 1 BIM principles

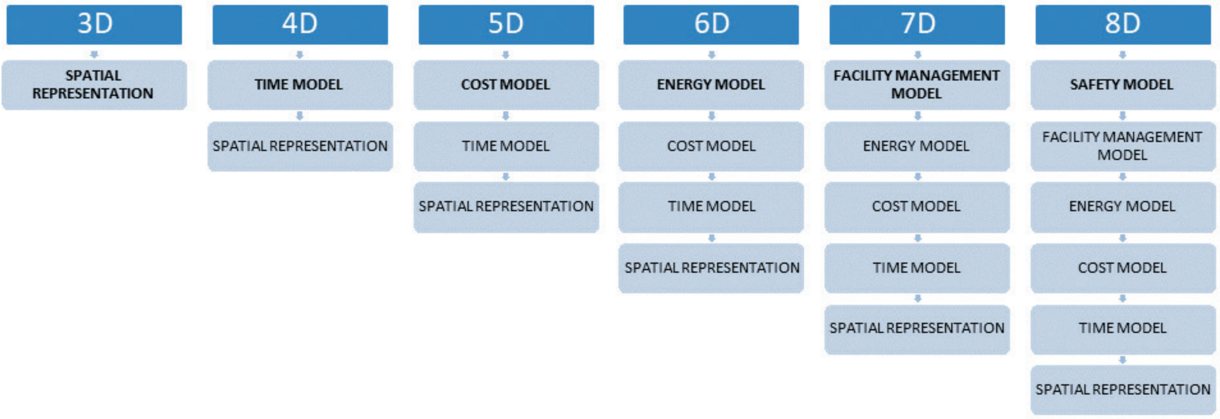


Fig. 2 BIM dimensions

to increase the number of construction representative dimensions from the traditional 3D (for a spatial representation) up to n dimensions [21]. For simplicity, we can list the first 8Ds (Fig. 2), considering:

- a time model (4th dimension, for construction activity visualization and analysis);
- a cost model (5th dimension, for budget analysis and control);
- an energy model (6th dimension, for evaluation of energy consumptions);
- a facility management model (7th dimension, for management and maintenance organization for the entire life-cycle);
- a safety model (8th dimension, for checking operators' risks and preventing critical hazardous scenarios).

This evolution, relied on the "smart-object" information included in the BIM relational database, simplifies a complete management of the building, from design, to construction, to the future actual management. Then, it produces significant economical savings and reduces inaccuracies and critical situations [22]. In detail, for each object, the database contains information regarding all the main internal and external aspects, such as width, height, material, weight, interaction with other objects, etc. This information is collected and stored in specific file formats, of which the IFC (Industry Foundation Classes, developed by buildingSMART; [23]) represents the current reference standard for general BIM objects.

However, despite these encouraging innovations, there has not been a parallel and complete development for these solutions in the infrastructure field. Concerning BIM for infrastructures, the related standardization process and the available solutions are not fully adequate for reliable practical applications [24, 25]. For instance, due to the intrinsic differences in the models, IFC format is not directly adaptable for I-BIM projects, but attempts have been already made for improving this standard or producing new formats strictly related to road modelling [26–29].

However, I-BIM solutions can be generally used for realizing the conceptual BIM model of a road infrastructure in a realistic 3D territorial context. In a “user-friendly” environment, the operator can design the entire alignment by defining and combining simple smart objects, representing all a complete road section. Each object is actually represented in the 3D model, considering in real-time its interaction with the existing territorial conditions and with the other road elements. At the same time, the operator can adjust and design the vertical alignment of the road by means of simple selections on the object reference points. Model dynamism and flexibility offer many advantages in a complex project management, as any modification in the horizontal alignment, the vertical profile, or the road cross section immediately affect the other representations. Further, I-BIM solutions are strategical for optimizing collaborations among various groups of specialized operators that can in parallel operate on different aspects of the infrastructure (alignment, walls, bridges, hydraulic systems, etc.) in the existing 3D shared model.

Finally, as previously said, each object is not a simple representation of the realistic element in the 3D scenario, but it consists in a list of features that guarantee an exhaustive understanding of the object characteristics, role, interactions, and influence on the external context. This information, stored in a relational database, can be used for performing any kind of further analysis on the project, in order to evidence inaccuracies or optimize the design of specific parts of the construction. Moreover, similarly deep analyses can be performed for forecasting organization and scheduling of the working activities, cost trends, and any kind of further simulations. Naturally, the simulation outcomes can be used for evaluating the efficiency of the project from different point of view and optimizing the activity scheduling [30, 31]. As another example, geometrical and topography data can be combined with pluviometry estimates for evaluating the road hydraulic vulnerability. Further, traffic-simulator tools can also process the road geometry, for checking the influence of the designed road in the infrastructure network. Naturally, implementing these models in the I-BIM tools can improve the method efficiency and reduce the operational times and effort, simplifying and optimizing the final solutions.

3 Highway alignment optimization problem

Since 1970, many researchers focused on how to simplify and support engineers in the highway alignment definition. After many preliminary attempts by means of several traditional analytical techniques [32–34], the main results have been obtained using AI techniques (in particular, using GA and one SI approach, i.e. the PSO method – Particle Swarm Optimization method). Both GA and PSO represent iterative evolutionary approaches and start from some random initial solutions that, after each cycle, are improved and corrected to minimize specific cost functions and observe several constraints. Their main differences concern the analytical methods adopted for modifying and optimizing the various solutions. Since GAs consider an evolutionary theory - derived from Darwin's theory on genetic evolution - in which only the best ones survive and reproduce after each cycle, the solutions of each cycle are rearrangements and combinations of the previous ones. The PSO, on the contrary, moves in the search space the different solutions, as it derives from the observation of flocks of birds moving in the space and searching for food.

In detail, the SI was introduced by Kennedy and Eberhart [35] and is based on the social interaction typical of particular simple groups of animals that, without a leader and through simple and coordinated behaviors, can perform very complex global tasks. Even if the individuals do not have a real collective awareness, the group is able to achieve exceptional goals.

The hypothesis of the PSO is that each bird (particle) does not know the real food position, but only its distance from it; then, it modifies its speed, step by step, and thus its position, in order to minimize this distance. Similarly, each particle symbolizes a possible solution, moving in the space of the solutions, searching for global optimum. Each particle changes its position according to its own experience and by imitating other particle movements and experience. The position is evaluated through a specific fitness (or cost) function to be maximized (or minimized). The equations to calculate the position and the speed of each particle after each iteration depends on some stochastic parameters and the best positions achieved both by the swarm and the generic particle. The methodology can be very efficient also in terms of computational costs, especially compared to GA. However, since GA and PSO show different advantages, various papers [10, 36–38] proposed hybrid methods for assuring a more extensive exploration of the searching space (typical of GA) and guaranteeing higher calculation speed and model convergence (PSO).

Considering the alignment optimization problem, it concerns the choice of an optimum backtracking 3D highway alignment linking two known points in the 3D space in compliance with the various considered constraints. In this context, the optimum solution is the one minimizing the total costs, defined through a proper cost function. The position of the vertices defining the alignment may represent the independent variable; then, in a 3D space, each solution is represented by 3 *np* independent variables, where *np* is the number of the internal vertices of the alignment preliminarily fixed.

A well-defined and accurate Digital Terrain Model (DTM) can reproduce the region topography (Fig. 3). In the study region, it is possible to evidence some areas characterized by various constraints (economic, historical, environ-

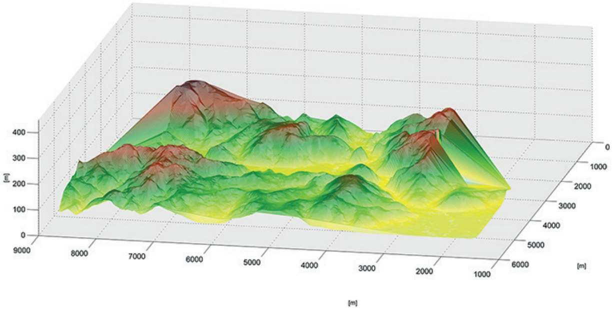


Fig. 3 Example of a DTM representation [12]

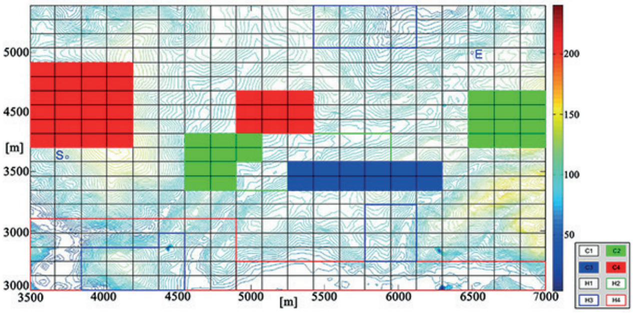


Fig. 4 Example of grid for zone condition and cost assignment [12]

mental, etc.). In traditional approaches, this characterization may be handled by means of rectangular grids (Fig. 4) easily adaptable to all conditions or through GIS (Geographic Information Systems) regions. Area information should include different kind of details related to the actual economical (natural or historical) value of the area, to the soil conditions, and to the environmental hazard (such as seismic, hydraulic, and geo-morphological hazard).

For clarity, the optimization algorithm is divided into various steps, as shown in the flowchart represented in Fig. 5. The initial solutions are very essential to solve the problem properly and, in general, there are various alternatives for choosing them. Even if the easier method is a random definition of the several initial solutions for favoring a whole exploration of the study area, other methods can avoid loops and critical solutions and, thus, increase the method efficiency [3, 11]. Regarding the vertical alignment, the algorithm chooses the *z* coordinate of each vertex. Since an appropriate DTM query provides the ground elevation for each vertex, the algorithm slightly modifies these values, in order not only to maintain as close as possible the road and the ground elevations, but also to define a smooth and correct vertical profile, in compliance with the adopted road standards. Generally, the vertices of the horizontal path can be selected as vertices of the vertical profile also, but the designers can define different criteria according to the project characteristics.

Concerning the radius design for vertical and horizontal alignments, determining random radius values within a given range is a feasible approach, but the values must be checked to assure alignment continuity and avoid intersections between following curves. It is also preferable to maintain also a certain minimum straight segment (according to the specific national road standards). The algorithm obviously can include in the design traditional transition curves (such as clothoids), but innovative solutions can be also adopted for increasing users' comfort [12]. Special penalty functions will charge additional costs to improper solutions, in which the difference between following radii is too high or the radius values exceed the Road Standard boundaries.

In general, the cost function to be minimized is the key element of the optimization procedure (Eq. 1). In this case, the total cost of each solution, C_T, is the sum of the real cost, C, and various penalties, P, useful to discard incorrect alignments by increasing the related cost in proportion to the related violation.

$$C_T = C_{len} + C_{loc} + C_E + P_{Rmin} + P_R + P_{ret} + P_G + P_{Rv} + P_{dz} + P_E \quad (1)$$

where C_{len} is the length-dependent costs, C_{loc} the location-dependent costs, C_E the earthwork costs, P_{Rmin} the minimum radius of circular curves penalty, P_R the ratio of following circular curves radii penalty, P_{ret} the minimum and maximum tangent segment length penalty, P_G the maximum grade penalty, P_{Rv} the minimum radius of parabolic curves penalty, P_{dz} the maximum height (depth) of fill (cut) sections penalty, and P_E the environmental penalty.

Obviously, the cost function may be adapted to the specific project needs, adding different contributions. Finally, the introduction of particular operators (stochastic or corrective), derived from the GA theory and easily adaptable to the actual project issues, guarantees a rapid convergence and a larger exploration of the search space. The iterative approach reduces the total cost cycle-by-cycle, producing a final solution in compliance with the fixed constraints, by minimizing the cost function (Fig. 6).

4 Why implement alignment optimization tools in I-BIM environments?

As discussed, the adoption of reliable methodologies for optimizing highway alignments and supporting operators in the decisional planning phases are significant to improve the road design. On the other side, the I-BIM environment

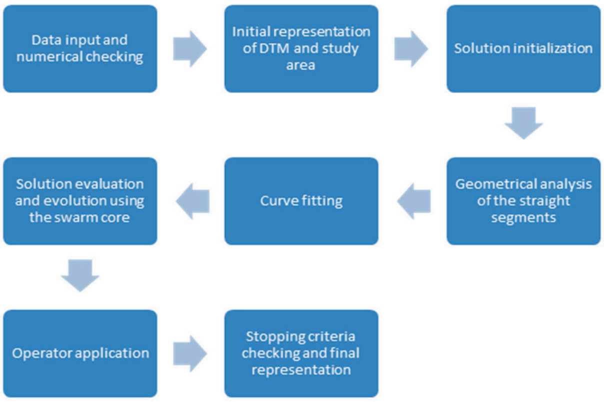


Fig. 5 Optimization algorithm

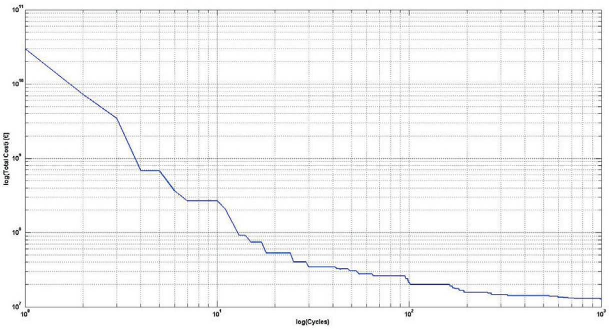


Fig. 6 Cost function minimization [11]

(despite its current minimalism and technical limits) may offer numerous advantages in terms of operational simplicity, interoperability, quick modification, and exhaustive knowledge of the entire construction ensemble (including the several objects of the construction, the external constraints, the territorial scenario, etc.). The consequent step of combining these solutions is crucial and, according to the authors, can improve the planning approaches exploiting potentialities of both the novel methodologies.

The BIM environment seems to be the most appropriate one for developing optimization tools as those described in section 3 (only for example, some representative scenarios are developed for test in a specific I-BIM environment, Autodesk® Infraworks®). First, the realistic and accurate terrain representation (Fig. 7) can improve the grid or GIS representation generally adopted in the highway optimization algorithms.

The I-BIM flexibility can simplify the analysis of parallel solutions and the realistic 3D representation (Fig. 8) can immediately evidence the differences between the best solutions proposed by the algorithm. The operator, by simple clicks on the relevant points of the alignment, is also able to improve and modify alignment vertices, changing the smart objects according to different design needs (Fig. 9).

Furthermore, the I-BIM relational database can represent a complete and exhaustive source of information for evaluating, in detail and with great accuracy, the different contributions of the cost function. Right-of-way costs and soil conditions can be assigned properly to each square meter of the study area, guaranteeing an accurate and reliable evaluation of the external costs. Moreover, the high-resolution representation of the territorial morphology can be processed, in combination with other relevant

Fig. 7 Terrain representation in a BIM environment

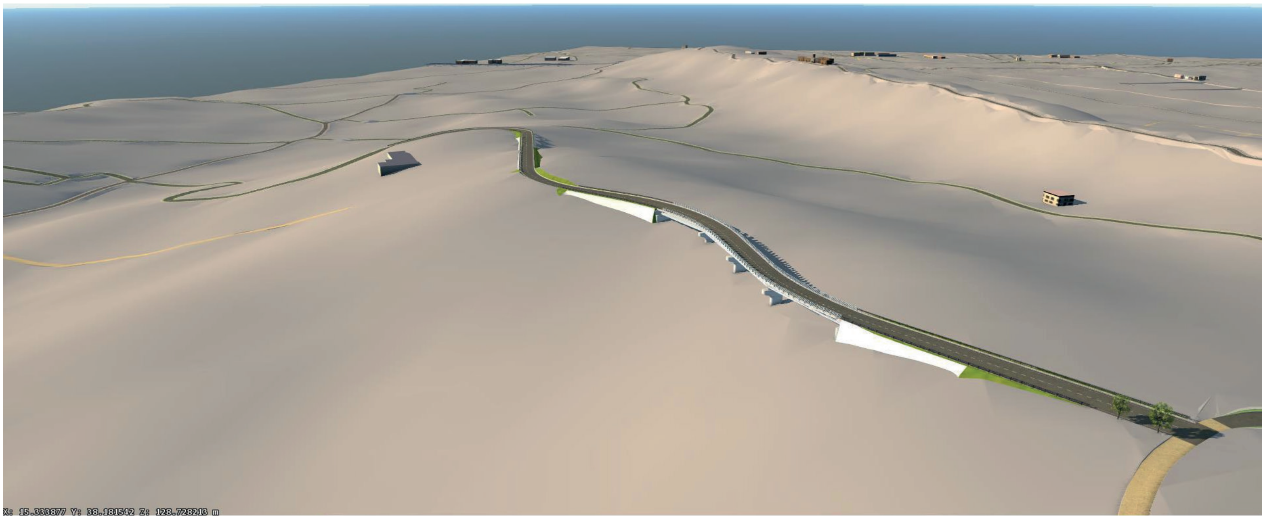
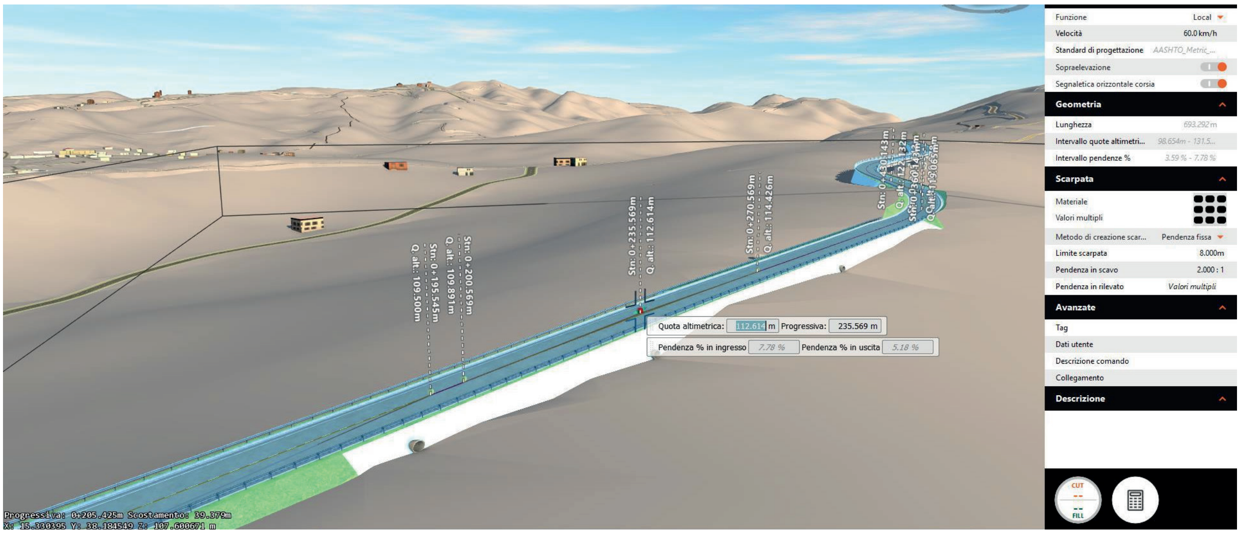


Fig. 8 Road alignment representation in a BIM environment



Quota altimetrica: 112.614 m Progressiva: 235.569 m
Pendenza % in ingresso 7.78 % Pendenza % in uscita 5.18 %

Progressiva: 0+205.425m Scostamento: 39.379m
X: 15.330395 Y: 38.184549 Z: 107.600671 m

Funzione	Local
Velocità	60.0 km/h
Standard di progettazione	AASHTO_Metric_...
Sopraelevazione	●
Segnaletica orizzontale corsia	●
Geometria	
Lunghezza	693.292 m
Intervallo quote altimetri...	98.654m - 131.5...
Intervallo pendenze %	3.59 % - 7.78 %
Scarpata	
Materiale Valori multipli	
Metodo di creazione scar...	Pendenza fissa
Limite scarpata	8.000m
Pendenza in scavo	2.000 : 1
Pendenza in rilevato	Valori multipli
Avanzate	
Tag	
Dati utente	
Descrizione comando	
Collegamento	
Descrizione	

Fig. 9 Road object information in a BIM environment

Fig. 10 Road visualization in a BIM environment

information on seismic and hydraulic exposure, to estimate with great accuracy the environmental risks for each particular alignment.

The I-BIM project dynamism allows the designers to evaluate impact of alignment modifications on all the other related aspects: for example, this can immediately show how shifting an horizontal vertex and the related curve, for avoiding a particular area, may modify the vertical alignment and the earth-work distribution in real-time.

Another key aspect to not forget is the possibility to define the project by means of different Levels of Development (LoD; also called Levels of Definition; [39–41]). They are used to classify the progression level of the informational model and affect the measure of the representation detail level for the 3D objects. In other words, their representation complexity decreases as the objects leave the point of view and, consequently, the closer the object, the higher the representation detail (not only in rendering terms, but also in a BIM-related semantic context). In this context, the optimization core may work using low LoD, reducing calculation complexity and increasing rendering efficiency for graphical and geometric aspects; then, the final optimum alignments can be improved and transformed in objects with higher LoD, for the final highway analyses.

Considering the other road-related civil works (bridges, walls, etc.) the advantages are very remarkable. First, by processing the differences between road and ground elevation, it is possible to include these elements in the cost functions, as a function of the involved heights and lengths. However, their representation and preliminary calculation in I-BIM environments is simplified and very realistic (Fig. 10), improving the following tasks of structural calculation and design optimization. The main bridges features (pile number, beam lengths, eventual deep geotechnical supporting structures) can be parametrized and, in parallel, both properly represented in the 3D frame and economically evaluate in the global project. Similarly, also the road pavement can be included accurately in the optimization procedure, considering specific smart objects for its single elements.

Finally, the other project dimensions defined in section 2 may offer another relevant contribution to the alignment optimization. The mole of information (regarding the various aspects previously discussed) stored in the relational database can be extended to the optimization procedure, adding novel terms to the cost function to define a more reliable solution from all the points of view. Then, the road alignment can be optimized through productive considerations regarding construction-area organization and management, workers' safety needs, resource availability and distribution, and construction activity scheduling. If properly tuned, all these aspects can significantly increase the project reliability, the final solution quality, and the economic margins for all the involved stake-holders.

5 Conclusions

In this paper, considering the highway alignment design complexity and the recent development of efficient BIM solutions, the authors have discussed the possible advantages produced by including the most advanced highway alignment optimization algorithms in an I-BIM environment. This combination is expected to increase the quality of the optimization process – and thus the solution – due to a more realistic representation of the ground and the related constraints. Moreover, it also simplifies the representation of several optimal solutions, easily comparable and manually modifiable by the designer by simple operations on the BIM smart objects. Moreover, the BIM philosophy and architecture can simplify the introduction of working-related problems, for defining objective functions that consider also construction and operational problems. Since the attention on I-BIM has been increasing recently, these tools will be developed and improved substantially in the next years; then, the authors believe it is essential to immediately implement these algorithms, for their efficient symbiotic development and practical utilization. Finally, the authors believe that the BIM philosophy should be extended also to the maintenance management process, by defining a novel way for representing road survey results and possible interventions as BIM smart objects, for a simpler and more immediate representation of the pavement condition and for increasing productivity and reliability of maintenance management.

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