Article

Highway alignment optimization: An integrated BIM and GIS approach

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Abstract: Highway alignment is an essential part of the highway planning and design phase. The isolation of highway alignment from the surroundings delays the planning process. This study therefore proposes a model that integrates building information modelling (BIM) and geographic information science (GIS) capabilities to manage the highway alignment in the context of a larger landscape. To support the integration, semantic web technologies are used to integrate data on a semantic level. The method facilitates highway alignment optimization by incorporating visualization, simulation, and analysis into the planning and design phase. 3D visualization of the proposed project can help reduce design errors and miscommunication, which, in turn, reduces project risk. Moreover, providing geological analysis helps to identify geohazards. In addition, based on the genetic algorithms, the optimal alignment can be produced. The proposed method provides future opportunities for users to have organized, reliable and dynamic ways to manage the project during construction.

Keywords: BIM; GIS; Highway alignment; optimization

1. Introduction

Highways are a fundamental component of human civilization, and highway networks are the backbone of modern society [1]. The alignment of highways plays an important role in any highway design project [2]. Once the highway alignment has been settled, other critical aspects and related costs, such as construction costs and user costs, are largely determined. In reality, highway alignments are subject to many code and external restrictions, and efforts should be made to discover optimal design alternatives.

Unlike building structures, on which the surrounding geometrical context has little effect, civil infrastructure projects are vulnerable to every little change in the terrain. Civil infrastructure projects are connected complex networks that span vast geographic areas. The proposed project is motivated by the existing project and the surrounding context. The optimum design should consider these interdependent networks. The design of a highway requires a large amount of data and information about the surrounding environment and geological conditions. The isolation of the geotechnical analysis from the infrastructural design also delays the planning process.

The current planning design process concerns only the highway itself. Additional related aspects and geotechnical conditions are not considered, and the process is time-consuming, inefficient and costly. To solve this problem, this study proposes an integrated BIM and geographic information science (GIS) model for enhancing the performance and automation of the civil infrastructural planning and design by allowing data exchange and incorporating geotechnical analysis into the planning and design process. Different data formats, such as industry foundation class (IFC) and GML, can integrate with both as the adoption of semantic web technologies.

The application of this model facilitates highway design by providing a cross-discipline approach to close the gap between the infrastructural and geotechnical planning processes. Moreover, the visualization of appropriate geological data allows users to detect potential hazards

and call for corrective methods. In addition, the proposed model generates a more accurate calculation of work quantity compared with traditional methods. The optimization algorithm (genetic algorithm [GA]) is also adopted to provide a scientific basis for an optimal option.

This paper is divided into six sections. Following the introduction, Section 2 provides a literature review. Section 3 illustrates the proposed model. Section 4 uses a case example to validate the feasibility of the proposed approach. Section 5 provides a brief result discussion. Section 6 concludes the paper.

2. Literature Review

2.1. Building information modelling (BIM) and civil information modelling (CIM)

BIM is a set of interacting processes, technologies and rules generating a method to manage and control critical project data in digital format throughout a building's lifecycle [3]. CIM commonly refers to the application of BIM to civil infrastructure facilities, such as bridges, tunnels and roads, in the architecture, engineering and construction (AEC) industry (Cheng et al., 2016). As BIM has shown great success in the building market, the application of BIM for civil infrastructure (CIM) has increased.

There are three major differences, however, between BIM and CIM. First, the components of building structures are different from those of civil infrastructure facilities. For example, the windows in the buildings do not exist on highways. Second, different terms are used in buildings and civil infrastructure facilities. For example, the foundation in a building is called a 'pile', while that in a highway is called a 'subbase'. Finally, BIM model buildings rise vertically floor by floor while CIM model bridges and highways extend horizontally relative to the axis. Apart from these noted differences, the data exchange and management of BIM and CIM are similar.

2.2. BIM-GIS integration

BIM can provide detailed project information and has been widely accepted in the AEC industry. GIS is a powerful tool to perform complex spatial analysis and generate the optimum path [4]. However, sometimes GIS has been only used as a database to store and manage data. BIM-GIS integration usually uses BIM to capture detailed information of the project and GIS to carry out the surrounding environment analysis of the project [5].

While there have been some attempts to integrate BIM and GIS systems, there are fundamental differences between these two technologies. One of the main differences is data structure, as BIM has a highly standardized structure while GIS has a user-defined structure [6]. Data exchange in BIM is usually file-based, while GIS is mostly server-based. Even with these differences, there are still more efforts to integrate, which are mainly concerned with four areas: BIM-based, GIS-based, proprietary and semantic web methods. The significant challenges are the different data schema IFC and GML, and the conversion of lines or curves instead of objects. Creating a new data schema requires great time and numerous efforts. IFC development takes almost 15 years to complete. Another attempt has been made in semantic web technology. In [7], the integration of BIM and GIS was examined by extracting building and geographical characters in the Resource Description Framework file format.

The existing methods for data exchange between BIM and GIS mainly focused on developing a standard format. Many AEC consortiums attempted to develop a standard that allows seamless data exchange between BIM and GIS. The commonly used standard formats in the AEC industry are IFC, information delivery manual and buildingSMART [8].

In [9], the finding that IFC could be incorporated into the GIS model was explored, and GML was extended to support IFC semantics and geometries. Similarly, the possibility of a conversion between BIM and GIS was investigated in [10]. In [11], an approach was used to extend BIM's scope to the area that was supposed to use GIS analysis. In [12], in order to facilitate information exchange between IFC and GML, semantic reasoning and ontology technologies were adopted. In [13], a model was developed to incorporate information from IFC and GML data as well as contextual data.

2.3. Previous works about highway design

Some studies have been done in the field of three-dimensional (3D) modelling of proposed highway projects to facilitate planning, design and construction phases. In [14], a model was developed for the highway to display properties of alternative solutions. The findings of study [15] also demonstrated that 3D modelling with corresponding analysis can improve significantly the performance of highway improvement. According to the results of study [16], the 3D visualization of the proposed project can increase users' understanding and help them obtain detailed information about the project and its context. Based on the conclusion of study [17], a 3D model can provide a complete image of the proposed project prior to completion. In addition, 3D modelling technology was used to emphasize aesthetic concepts during highway design in the study [18].

3. The proposed approach

There are many factors that influence the alignment selection. The main geological features should be considered emphatically. Moreover, the alignment selection is impacted by the space constraints and disturbance of the existing projects. The proposed model that integrates the BIM and GIS systems carries out spatial data analysis to facilitate the highway alignment at the planning stage. It can minimize the time and efforts needed to assess different highway alignment alternatives and automatically generate several alignment options and the cut-fill quantities and costs related to each alternative. The proposed approach is summarized in Figure 1.

The analysis process of the proposed model is described in four phases as follows. In the first phase, an accurate topographic and geographic investigation of the site is required, and alignment of the proposed highway project is necessary to be designed in BIM, specifying the grades. In the second phase, the design information of the highway is exported into the GIS model and forms a new model. In the third phase, the new 3D model is used to analyse the geotechnical structure to provide several alignment options. In the last phase, the selection process of the alignments is performed according to GAs. If modification is required, the changes to the highway are transferred back to the BIM model.
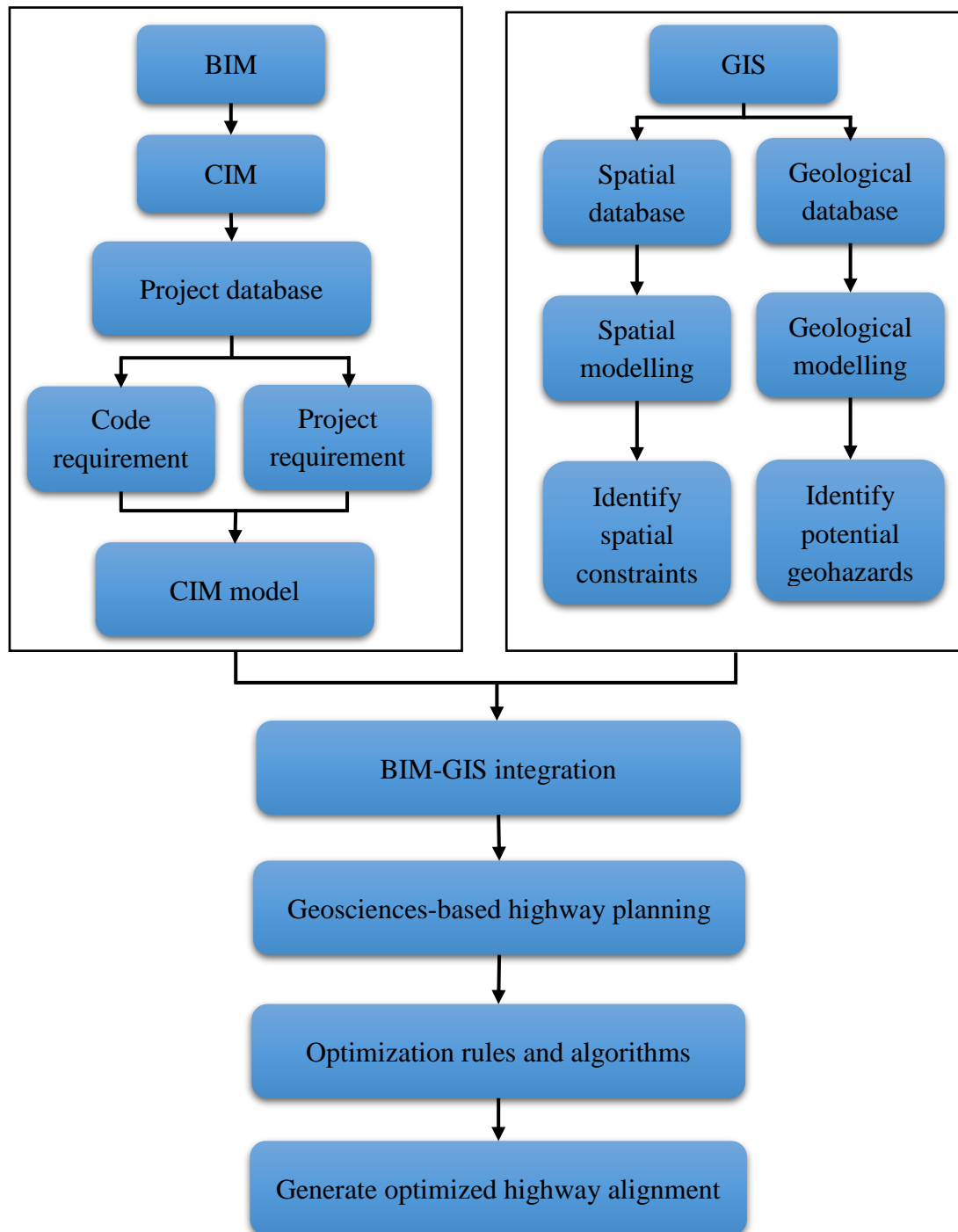
Figure 1. The proposed approach overview

3.1. Ontology and semantic modelling

Without the application of BIM, highway planning used to experience significant difficulty. Cut and fill calculations are time-consuming and tend to be very costly. Accurate earthwork calculations can help reduce overall costs for the highway project. By utilizing BIM, the cut and fill calculations can be conducted automatically.

Recently, GIS has emerged as a powerful computer-based tool that includes data management, spatial analysis and geographical visualization. For geotechnical purposes, GIS has been developed and applied to predict and plan for natural hazards, such as earthquakes and landslides. Topographic and geologic data and information were obtained from the geological database. The gathering data were manipulated in GIS to obtain geological analysis reports and various highway subsections.

BIM and GIS systems have a different level of information and data structures. Seamlessly integrating these two systems is not easy. The ontology technology as part of semantic web technology is introduced to facilitate the integration. Ontology is defined as explicit specifications of a conceptualization that can be used to describe information such as concepts, relationships, data properties and restrictions within a domain in a machine-readable manner, and it is usually instantiated for a target system [19].

The aim of semantic web technology is to enable data to be shared easily by wider communities and to be processed automatically. Semantic web technology can integrate data from different sources because it can provide machine-readable schemas-ontologies [20]. Moreover, semantic web technologies also allow bidirectional transformation between BIM and GIS. Ontology defines the terms and transforms them into semantic annotations. In practice, ontologies typically support applications by contextualizing data, capturing meaning, facilitating rule application, standardizing terminology and producing new knowledge. The semantic information is specifically defined in both domains, but data integration is still possible on a semantic level. In addition, the defined ontologies still available for future use. The data exchanges are realized by the adoption of semantic web technologies. The interface of the integrated BIM and GIS model is shown in Figure 2.
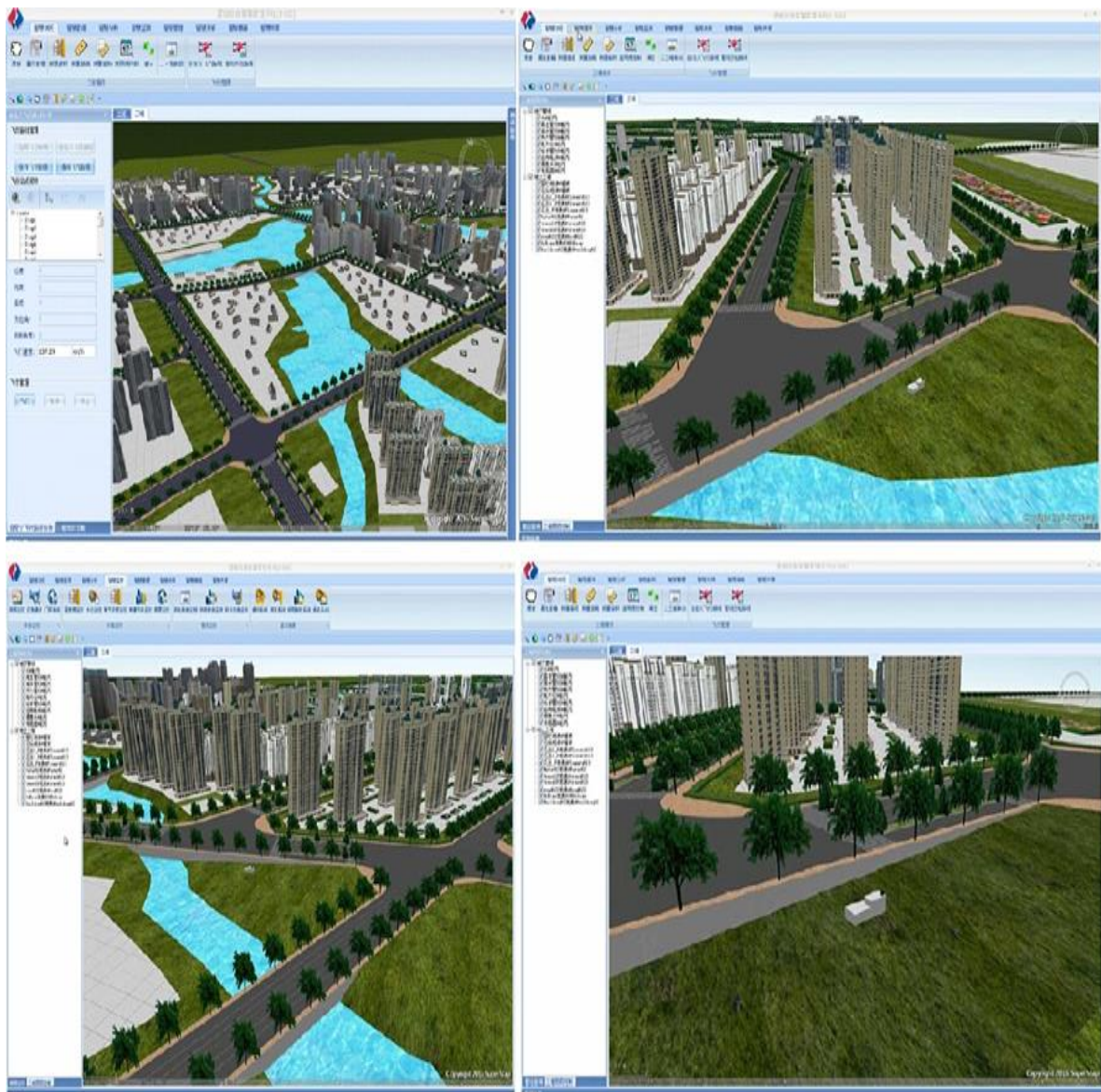

Figure 2. The example of the integrated BIM and GIS model

3.2. Geological analysis

The proposed model incorporates the geotechnical planning into the infrastructural design and thus increases the collaboration and avoids misunderstanding between the two parties. During the analysis process, the potential geohazards can be identified and mitigated or avoid; the geological information of the site is presented vividly. This would help the engineers in further analysis and design of the proposed highway project and related structural works. The geotechnical analysis may lead to several required changes in the highway design. These changes then are transferred back to the BIM model. This analysis provides efficient and effective screening to concerned area studies and enables a reasonable view of overall area risks. The section of geological analysis is displayed in Figure 3.
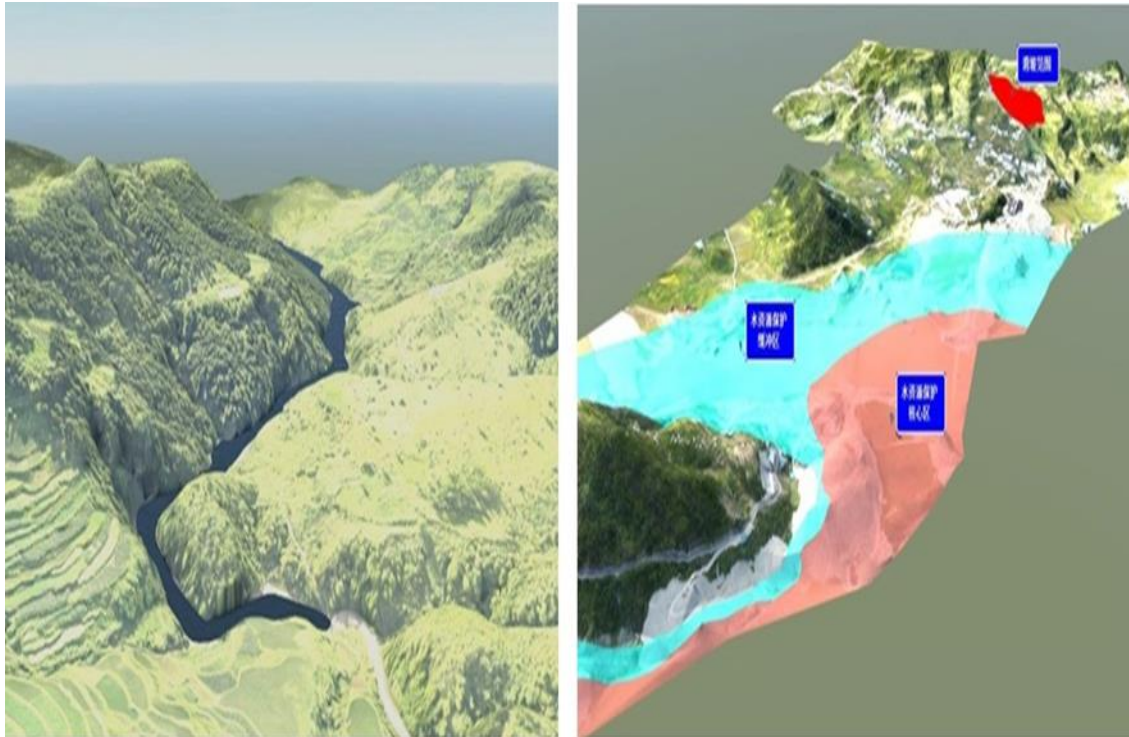
Figure 3. The example of geological analysis

3.2.1. Landslide

Prior to construction, a detailed geotechnical analysis of the site is required to identify the landslide risks because they are one of the most common and serious geological hazards. GIS can be used to predict landslide risk by incorporating information about landscape, geologic origin and weather conditions. Further analysis that takes into account the information, such as maximum rainfall, average annual rainfall and historic landslide, can predict the potential degree of landslide for the area.

3.2.2. Seismic hazards

A significant effort is needed to develop refined seismic design procedures for highways due to the damage resulting from recent large earthquakes [21]. The possibility of soil liquefaction after quakes should also be considered. In addition, the bearing capacity of the underlying soil may be exceeded after an earthquake, which leads to embankments sliding and crack openings on the highway surface.

Based on geographical and geological information of the region, a potential area of earthquake and active faults were identified and selected. From the earthquake historical records, higher

magnitudes were chosen for further seismic analysis. After the seismic analysis, the liquefaction results of the selected points were achieved. This can give users a more comprehensive knowledge of the site situations and help them develop a solution to avoid or alleviate any seismic hazards.

3.3. Cut and fill calculations

Cut and fill cost accounts for almost 25% of the total project cost [22]. Owing to the complexity in cut and fill calculations, it is essential to adopt GIS technology in the calculation with the limitation in the BIM model [23]. The proposed model that integrates BIM and GIS is used to carry out cut and fill calculations.

The highway geometry information in BIM includes road shape, cross-section, centrelines, elevation, curb and embankment. While the information such as triangle co-ordinates and group, geographical and geological reference, soil type and terrain data can be accessed in the GIS model. The data in BIM and GIS are stored in IFC and GML format, respectively. Semantic web technology allows the integration to combine in the same platform. The quantity calculations of cut and fills are based on the existing topography elevation in the GIS model. The earthwork simulation aims to minimize the earthwork by balancing the cut and fill operation.

In the highway project, vertical alignment is based on the centreline of the road, so the centreline is regarded as the reference line. The centreline elevation occasionally represents the topography of the entire cross-section in terms of earthwork balancing. The term optimal centreline elevation is a centreline elevation where cut and fill are balanced within the cross-section. The main idea of this method is to make the earthwork optimization possible in terms of cut-fill balancing and earthwork minimization. A mathematical representation of the method is shown in Equation (1).

$$\sum_{i=1}^{n} V_C(i) = \sum_{j=1}^{m} V_F(j), \tag{1}$$

Where $V_C(i)$ is the volume for cut areas in cross-section; $V_F(j)$ is the volume for fill areas in cross-section; n is the number of cut areas in cross-section; and m is the number of fill areas in cross-section.

3.4 Optimization algorithms

In the highway alignment planning phase, the general practice is to identify several alignment options and decide the optimal option based on the multiple rules. Economic considerations are one of most essential factors influencing highway projects [24]. In some cases, mitigating risks against individual hazard may increase vulnerability to another hazard. An economic highway alignment may more vulnerable to geohazards. The highway design should aim at optimizing overall risks and costs and carry out this efficiently and effectively.

Genetic algorithms (GAs) were previously used for highway alignment optimization [25]. GAs are suitable for optimization problems with several local optima and fits to parallel processing. In these specified GAs, the problem (highway alignment optimization) is considered the environment, and a set of possible solutions to the proposed problem is regarded as the population. Each alignment in the population is referred to as a chromosome and encoded into a string representation. At every generation, the alignment alternatives (individuals) compete with each other for reproducing offspring based on their fitness (minimum cost) to the environment (the problem) by using genetic operators (like mutation or crossover). Through several successive generations, the most fit alignments would survive and impact future generations, whereas poorly adapted alternatives would become extinct. The alignments (population) finally converge to a near-optimal solution.

Several optimization algorithms are available, such as GAs, network optimization, enumeration, calculus of variations, dynamic programming, numerical research and linear programming. Among them, the six approaches other than GAs have some essential disadvantages for highway alignment optimization, in which cost function are implicitly noisy. GAs have critical distinctions over other algorithms as they: (1) search from a population rather than a single point; (2) work with the encoding of parameter sets rather than parameters themselves; (3) adopt decisive information (objective

function) rather than auxiliary or derivatives knowledge; and (4) use probabilistic rules rather than deterministic rules [26]. Despite the above benefits, it should be noticed that GAs are not always suitable to all problems, but they can be regarded as an effective approach for finding near-optimal solutions fast. The objective function used in this study can be written in Equation (2).

$$\min_{f_1, f_2, \dots, f_n} C = C_P + C_E + C_R + C_U, \tag{2}$$

Where C is total cost; C_P is pavement cost; C_E is earthwork cost; C_R is right-of-way cost; C_U is user cost; and $f_1, f_2, \dots, f_n$ are decision variable factors.

4. Case Study

The DuAn highway construction project that is an important part of highway networks in Guizhou Province locates in the southwest part of China. It includes earthwork, pavement, slope protection and water drainage. The total length of the project is 282.9 km and the total project cost is 44.63 billion Yuan. The project is complicate due to several reasons: 1) the natural conditions is harsh; 2) the route layout is heavily impacted by existing structures such as railways, bridges and pipelines; 3) the selection of design planning is difficult. Moreover, the project area is a seismically active region, where a large-intensity earthquake has the potential to cause damage to the highway. Seismic shaking can also lead to soil liquefaction and damage to the highway surface. A seismic hazard analysis was undertaken for the project site to decide the seismic loads. According to loads and code requirements, the design of the highway could be generated. The 3D visualization model of the highway is presented in Figure 4.

Figure 4. The 3D model of the Highway with its surroundings

Construction activities consisted of excavation, subbase, base, subgrade, embankment, surface, drainage and slope protection. The major tasks in the work package were earthwork excavation and backfill, highway subbase and surface, slope protection and water drainage. For this project, three alignment options were available to determine the optimal alignment alternative. All three alignments used the same structural components and had the same start and end-point. Each of the three alignments had separate geological analysis, cut and fill calculations, and cost analysis. The cost and schedule durations could be estimated from a case-based reasoning method. Based on all the above analysis, the optimal alignment was selected. The optimized highway alignment is displayed in Figure 5.
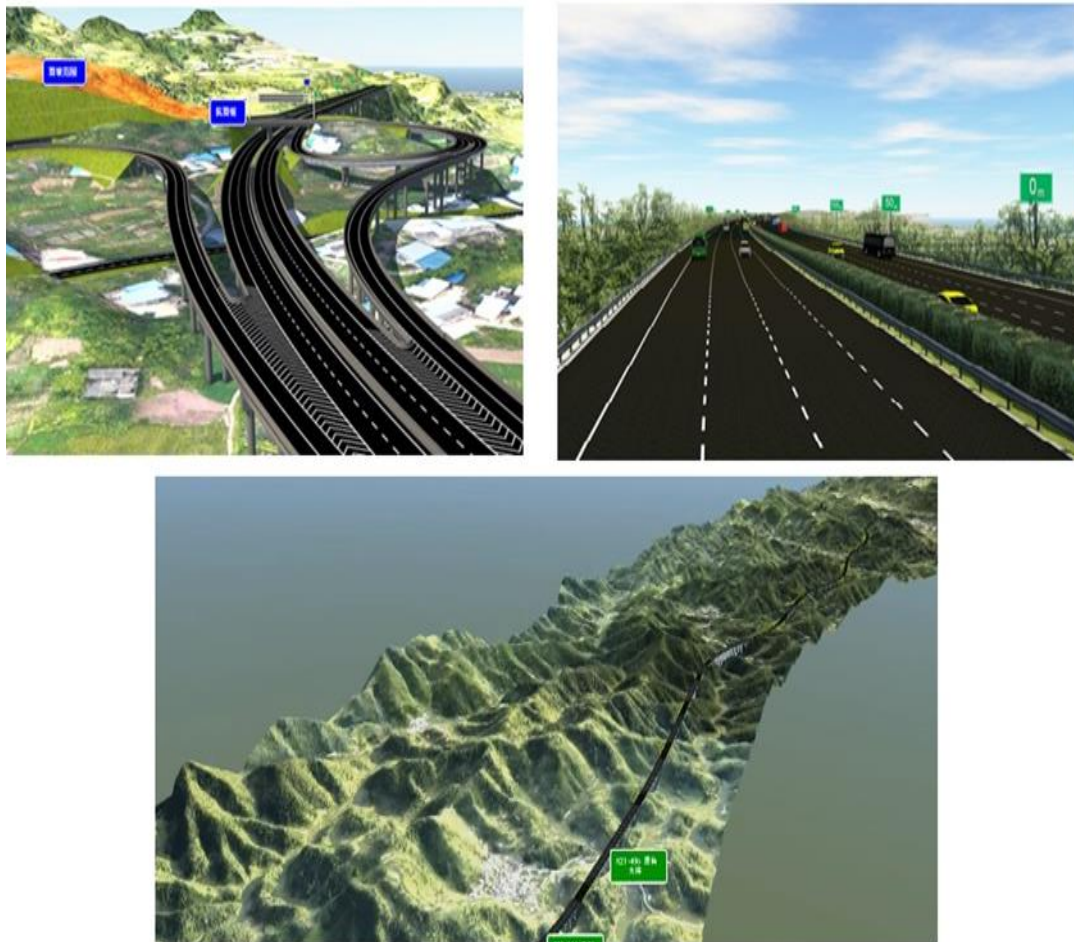

Figure 5. Optimized alignment for DuAn highway

5. Results Discussion

The proposed model enables a more complete characterization of the DuAn highway. The three alignment alternatives in this study offer abundant data to decide an optimal alternative. Although alignment 1 may have the lowest cost, it is more subject to geohazards based on the geological analysis results. Moreover, constructing alignment 1 will exacerbate the clash problem with surroundings. Alignment 3 almost avoids all the potential geohazards, even those with the highest cost, but it has too many conflicts with existing structures on the basis of the 3D visualization model.

Considering all the important factors, alignment 2 therefore is the optimal option. The comparison results of the three alternatives are summarized in Table 1.

Table 1. Comparison of the three highway alignments

Alternatives	Cut & Fill quantities	Surrounding conflicts	Geological conditions	Construction cost
Highway 1	Low	High	Low	High
Highway 2	Medium	Low	Medium	Medium
Highway 3	High	Low	High	Low

The results indicate that the highway alignment determined by the proposed model can avoid the disastrous soil structure and geohazards, conform to the terrain changes and mitigate the disturbance of the existing projects. The earthwork calculation assisted by the proposed model also generates accurate results that save costs and time at the construction stage. In addition, the proposed model provides sufficient important information to facilitate the decision-making process.

6. Conclusion

Highway alignment planning is usually a complex and time-consuming process. The evaluation of different alignment alternatives is even more time-consuming and tends to be costly. The proposed model integrates BIM and GIS systems to facilitate the process. The integration of BIM and GIS systems is complex, however, and includes a large amount of data. Semantic web technologies and ontology were used to encourage the possibility of integration.

The proposed model improves the efficiency of the geotechnical and infrastructural planning and design process. It closes the gap in the information flow between the highway design and the geotechnical analysis, and it provides a 3D highway model. Moreover, the adoption of semantic web technologies allows for data exchanges between BIM and GIS systems and thus increases data interoperability. Furthermore, the optimization algorithms (GAs) also are used to select the optimal alignment. The proposed model is able to maximize control of geohazards and minimize project costs concurrently.

The automation process of the proposed model provides an opportunity to identify an optimal alignment in a timely way. The adoption of the proposed model on a real highway project has proved the potential of the application in the industry. As both BIM and GIS systems continue to develop in the civil infrastructure sector, the proposed model could become more shared and acceptable in the industry.

This study makes four contributions, First, the integration of BIM and GIS systems enables data exchange in two ways that significantly improve data interoperability. Then, GAs are applied to conduct multiple cuts and fill simulations. Second the proposed model can provide geological analysis to indicate highway alignment design to avoid or mitigate potential hazards. Third, the automation process of multiple alignment alternative analysis provides an opportunity to identify an optimal option in a timely way. Finally, the proposed model provides a virtual environment where decision changes can be made more easily and cost-effectively.

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