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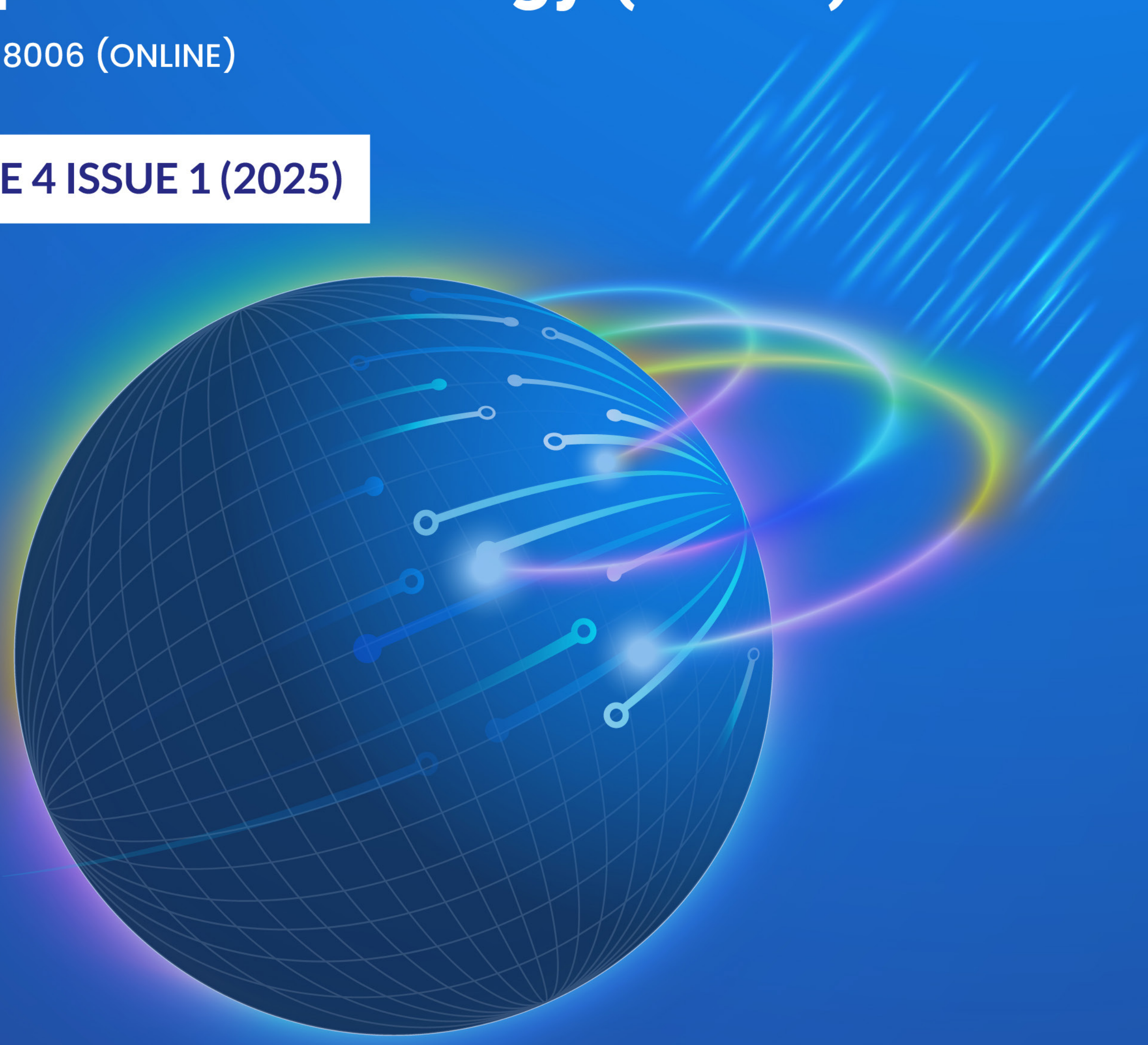

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Optimization of Road Construction Planning Using GIS and Remote Sensing Technologies

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ABSTRACT

Roads play a vital role in providing adequate transportation and developing sustainable infrastructure. The planning stage, including the decision on route and site locations, has considerable effects on the cost, time, and environmental friendliness of the project. Conventional planning schemes are generally based on a time-consuming and resource-intensive manual consideration of many factors. This paper presents an integrated method for optimizing road construction planning, utilizing the facilities of Geographic Information Systems (GIS) and Remote Sensing (RS). Utilizing spatial and satellite data, parameters of consideration such as topography, land use, soil type, hydrology, and environmentally sensitive areas are built into the model. Multi-criteria decision-making methods and optimization algorithms are used to evaluate alternative routes and select the final feasible alignment. The developed model improves the interoperability between geospatial data and assists automated decision support for road planning. Additionally, remote sensing data provide timely and large-scale information for detecting geohazards, slope instability, and ecological risks. The approach is tested and illustrated in an actual road construction project to show better efficiency in planning, less environmental impact, and fewer project risks. With the integration of GIS and RS technology, this model provides an example of a practical, cross-disciplinary-based planning model for sustainable and economic road construction.

INTRODUCTION

Road is a key national developmental index, which promotes secure economic activities and the citizenry's social well-being through the safe, reliable, and reasonable movement of people and goods (Ali *et al.*, 2021). Transport systems not only link rural areas with cities, but also facilitate trade, access to social services, and social integration. And so it is that the road planning has a crucial function to perform (Chen *et al.*, 2025). The predominant one in the planning process is the choice of the most appropriate position of the planned road (Zhang *et al.*, 2025). Nonetheless, this is a very complicated process that involves many trade-offs between construction cost, environmental impact, ground conditions, and long-term viability. Once a road alignment is determined, significant project outputs (construction costs, maintenance costs, user benefits) are finalized. Thus, forethought in the design phase is crucial to prevent costly mistakes and inefficiencies down the road. In contrast to buildings, road construction projects typically face specific challenges such as different elevation levels of land, shifting geology, and changing environmental conditions (Li & Xiao, 2025). These dynamic elements render infrastructure projects more susceptible to unanticipated interference. The construction of roads needs extensive data on topography, soil characteristics, hydrology, vegetation, and human habitations (Niyogakiza & Liu, 2025). It is not uncommon that planning and design have in the past been conducted in isolation, one from geological and environmental analysis, and in a manner that results in excessive cost and delay. Existing methods of road alignment planning are usually road-oriented, with very little attention paid to the wider context of environment, geotechnical, and socio-economic influences. Therefore, the planning process is time-consuming, discontinuous, and inadequate. To minimize the challenges, the GIS and remote sensing approach offer an integrated framework to plan the road construction effectively (Pelden *et al.*, 2025). A geographic information system (GIS) allows the gathering, storing, managing, and analyzing of spatial information, while remote sensing facilitates the timely and accurate monitoring of the Earth's surface through satellite images and aerial photographs. By integrating these technologies, planners can analyze multiple data sets, including land use, slope, elevation, vegetation, water, and socio-economic characteristics, in a single analytical framework (Başkent & Başkent, 2025). This integrated method allows easier decision-making processes and more accurate identification of feasible road alignments. One of the major problems in road planning is data interoperability and integration. The road project is a multifaceted social and technical object that relies on the inputs of engineering, geotechnics, environment, and socio-economics (Spanidis *et al.*, 2025). Remote sensing offers dependable and broad information, including DEMs, soil moisture estimations, and land cover maps. When incorporated into GIS, these data sets support various spatial analyses. Slope maps generated from DEMs, for instance, assist in locating sites susceptible to landslides or soil erosion, and land use land cover data indicates environmentally sensitive zones that must be left untouched (Hossen *et al.*, 2025). The combined analysis

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guarantees that road layout is now based not only on cost and distance, but also on the maintenance of a safe, environmentally friendly system (Al Hawarneh & Shahria Alam, 2025). Another important aspect of road design is the analysis of different alignments. Several alternative paths are typical for any prospective road (Buuveibaatar *et al.*, 2025). These alternatives need to be compared by decision-makers according to several criteria. The straightest path isn't necessarily the best, especially on those marginal numbers and where alternatives ultimately may be cheapest, safest, better for the environment or man, or more harmonious with the communities through which these routes play out. One-variable decisions, such as basing decisions on price, are not always the best choice. As such, multi-criteria decision-making techniques that utilize GIS and remote sensing are required for the simultaneous evaluation of alternative options. Recently, simulation optimization methods based on, genetic algorithms (GAs) have become more popular for alignment planning (Liu *et al.*, 2025). These approaches enable planners to specify the objective combination of tangible (minimum construction cost, travel distance, etc.) and intangible (environmental disturbance) criteria, and then optimize for what alignment best meets the criteria above. Integrated with the GIS and remote sensing data, optimization models can perform well with a data-driven approach with less manual intervention and subjectivity (Dritsas & Trigka, 2025). This improves the economy and precision of road construction planning. The application of GIS and remote sensing-derived models has the following advantages over conventional methods. It allows such a cross-disciplinary approach as integrating engineering, environmental, and socio-economic perspectives in a single framework. This integrated perspective improves the relationship between the technical design and the actual geospatial context. Secondly, using remote sensing data increases the capability to identify potential hazards (such as flood risk areas, unstable slopes, or deforestation zones), which in turn can lead to more proactive planning and turnaround decisions before the construction. The third benefit is that combining spatial data with project data enhances the accuracy of project-related analysis, such as earthwork volume calculation, material estimation, and cost prediction (Li *et al.*, 2025). In conventional practice, such calculations can be time-consuming and subject to error, such that the overall cost of the project tends to rise. In this regard, GIS and remote sensing provide more accuracy, fewer delays, and more reliable cost estimation. And the visualization function of GIS can facilitate easier understanding of complicated data for planning, engineering, and decision-making. Maps, 3D models, and so on can be produced to show how various alignment choices would interact with the topography and environs. This enhances technical analysis and simplifies communication with interested parties, including government officials, environmental agencies, and community members (Tumpa & Naeni, 2025). Early involvement of stakeholders facilitates the identification of possible conflicts and the integration of social issues with the planning. In general, the incorporation of GIS and remote sensing technologies has become a paradigm shift in road development planning. Through facilitating powerful and extensive data analysis, multi-criteria optimization, precise visualization, reducing the waste of resources, cost reduction, and sustainability of infrastructure are addressed. When contrasted to the standard approaches, it makes planning more automatic, efficient, and environmentally and socially friendly.

LITERATURE REVIEW

Geographic Information Systems (GIS) have emerged as the most powerful technology for spatial data handling, analysis, and visualization. They are used in various fields like transportation, urban planning, park path management, disaster mitigation, logistics, etc. As in the case of road planning, GIS helps in dealing with large-scale geospatial data, such as topography, hydrology, land use, and soil data (Yan *et al.*, 2025). This capability to overlay spatial layers and analyze relationships is what makes GIS indispensable for infrastructure. Through GIS applications, professionals can incorporate the project environment into the planning process, which is essential for infrastructure projects due to their complexity (Pelden *et al.*, 2025). For example, slope maps, DEMs, and land cover data can all be scrutinized at once to reveal countertops, flood-prone areas, or data inconsistencies. It supports the advanced planning of site layouts through life-like simulations of material transport, accessibility, and prevention of space conflicts (Şimşek *et al.*, 2025). Additionally, GIS is useful in project management issues, like schedule management, cost forecasting, and safety plan preparation using detailed spatial queries and simulations. are executing as there is a lack of filter operators. The rising need for sustainable and data-driven infrastructure planning has made GIS go from being a leading force to a driving force in the global infrastructure industry. Remote sensing is a good source of spatial data at a large scale and in real-time for GIS analysis (Babbar & Rani, 2025). Remote sensing through satellite imaging, aerial photography, and LiDAR (light detection and ranging) is increasingly playing an important role in road planning, where it provides detailed data on land cover, vegetation type, as well as soil moisture and terrain morphology. Remote sensing-derived DEMs are widely used for slope stability analysis, cut-and-fill data generation, and erosion risk prediction. Remote sensing is also useful in monitoring land use and environmental changes (Yono *et al.*, 2025). For instance, land cover classification aids planners by avoiding development in ecologically fragile zones, and a vegetation index is used to point out deforestation or wetland regions that should not be disturbed. The timely and extensive acquisition of data and resources in hundreds of thousands to millions of km^2 inaccessible areas has eliminated the need to conduct large field surveys and saved time and cost. Furthermore, high-resolution satellite imagery can be used to identify specific coordinates of settlements, rivers, and key infrastructure, which is required when considering alternative road options. Integration of GIS and RS has improved the process of road planning through multi-criteria considerations. Remote sensing gives raw spatial information, while GIS is the tool used to organize and analyze thus, the fusion of both technologies is instrumental in the best planning and implementation of road infrastructure. GIS and RS are interdependent technologies that, combined, provide a robust platform for road construction planning (Chenchu *et al.*, 2025). Remote sensing contributes with continuous spatial data coverage, and GIS with handling, analyzing, and visualizing the data in decision-making. Integration of the software is a capability that allows planners to perform spatial analysis with greater complexity, such as relief modelling, slope stability analysis, watershed delineation, and land use suitability analysis (Melsse *et al.*, 2025). For infrastructure projects, the integration of GIS and remote sensing has been adopted to locate the best routes by avoiding environmentally sensitive areas, decreasing the costs of earth movements, and lessening impacts on local populations. The combination of these tools allows a more holistic perspective that takes into consideration engineering and environmental aspects as well. Planners may use the integration of several spatial datasets to construct a 3D terrain model, to design different alignments, and to assess impacts on the economy and the environment. Planning of road alignment is, by nature, a multi-criteria problem, as distance, cost, safety, environmental, and social issues need to be viewed in concert. Integration of GIS and remote sensing systems for planning enables planners to weigh various criteria and simultaneously explore several alignment alternatives (Xiaoyu *et al.*, 2025). Prioritization of alternatives is commonly carried out using Multi-Criteria Decision-Making (MCDM) techniques like Analytical Hierarchy Process (AHP) and Weighted Linear Combination (WLC). In addition, optimization methods such as genetic algorithm (GA), linear programming (LP), and dynamic programming have been used to optimize road planning (Ramyar *et al.*, 2025). Especially the GAs can find close-to-optimal solutions by constantly looking for better alignments that minimize the costs and environmental impact and guarantee the safety. When supplemented with GIS and remote sensing information, these optimization approaches are even more robust and practical with fewer requirements for manual corrections. Apart from alignment planning, GIS and RS can also be used at all stages of road construction (Akindele *et al.*, 2025). During construction, material flows can be monitored, site layouts can be optimized, and safety zones can be monitored using GIS. Real-time monitoring of land changes with remote sensing can also provide early warnings for erosion, landslide, and flooding risks. Post-construction, they help with maintenance and monitoring as well, looking for surface damage and vegetation intrusion, and noting drainage issues. GIS, with its ability to visualize, becomes a means to communicate among various participants (Hannum *et al.*, 2025). With maps, 3D models, and interactive tools, planners can display options to decision makers, citizens, and environmental regulators. This process of engagement enhances transparency, helps minimize conflict, and helps to ensure that actions support wider development objectives (Tumpa & Naeni, 2025). The task to be most concerned about in road construction planning is the optimal arrangement of alignment. The purpose of the challenge is to find a route from some start point to some end point while minimizing total cost and environmental "damage". However, the conventional approaches to selection of alignments are labor-intensive, and the process is subjective. Contemporary methodologies use GIS and remote sensing information for the stricter thematic mapping of terrain, land use, and geology (Jabeen *et al.*, 2025). A variety of optimization models have been used in this domain, such as linear programming, dynamic programming, network optimization, and heuristics. In this, genetic algorithms have proved to be the most encouraging owing to the fact that they could produce real alignments and have co-optimized vertical and horizontal paths, resulting in tremendous gains in both time and cost. Aided by remote sensing data and GIS analysis, these algorithms can offer a reliable and automatic solution that improves the traditional planning approaches.

MATERIALS AND METHODS

As such, the developed methodology aims at combining GIS and remote sensing for road planning in a holistic method. In the pre-design phase of a highway route, a reliable analysis and accurate spatial information are needed to assist with decision-making. For doing so, it includes an integrated GIS remote sensing model, an analysis layer, and an optimization process. The coupled model utilizes key geospatial and environmental data from remote sensing and GIS databases to facilitate advanced analysis and optimization. GIS offers high-resolution spatial and topographic data, and remote sensing can provide real-time geodata information on terrain, vegetation, land use, and environmental situation. Then these data sets are used by the analysis layer: geological evaluation, network and accessibility analysis, cost evaluation, and environmental impact assessment. These analyses are then used in the optimization to produce alignment alternatives for road construction. The first step of the workflow is the creation of precise topographic information (DTM and DSM) and geographic information, along with satellite imagery and remote sensing-derived data. The datasets are used to create a digital terrain model (DTM) by GIS, so that they can be analyzed on a spatial and geological level. Incorporation of remote sensing improves the identification of geohazards, constraints, and land cover changes that affect route alignments. As preliminary alignments are formulated, several options will be developed and screened utilizing optimization algorithms, taking the cost, safety, environmental, and engineering feasibility into account. Models that require alteration feed back into the model, therefore being iterative and adaptive planning. It uses GIS and remote sensing data integration, automation of processes, minimizing risk of human error, as well as storing data in a structured way for analytical functions that are often developed specifically for the task at hand. While GIS can accommodate a variety of analysis functions, remote sensing transmits timely and accurate information required for large-scale estimations. Together, the technologies provide optimal road alignment (considering engineering efficiency, economic feasibility, and environmental sustainability). This integrated solution enables much better planning in the design of road construction projects using data-driven insights at the disposal of decision-makers. The geospatial ontology offers the semantic basis of integrating GIS and remote sensing with road construction planning. An ontology is the conceptual model of a domain, which allows us to define the concepts and to specify how they are related, in order to enable advanced analysis. In this regard, the GIS and Remote Sensing tools in the transportation infrastructures are considered with a semantic framework concept responsible for data harmonization, analysis, and decision making. In this conceptualization, primitive concepts are key classes of spatial and environmental information (e.g., terrain models, land use categories, and vegetation indices), and defined concepts describe the finer-grained subclasses derived from these primitive classes. For instance, a terrain model from digital elevation data is primitive, and slope classification or elevation zones from that model are defined. This structured conceptualization facilitates the linking of numerous datasets needed for well-founded planning of the road alignment. The use of semantic structuring makes it possible to effectively include information pertaining to space and environment from remote sensing images in GIS-based studies. Remote sensing produces extensive geospatial data, such as topographic, land cover, vegetation health, and hydrologic patterns, whereas GIS stores this data in relational constructs that are conducive to analysis and visualization. A GIS spatial database may have tables correlated with spatial features, including their attributes. Once integrated with semantic modelling, these attributes can be converted into understandable properties, helping to solve complex geospatial queries and time-critical optimization processes. This abstraction allows a simple and transparent mapping from remote sensing acquisition to data structures usable in any GIS context. For example, imagery from satellites may be turned into raster that depict land cover, which raster in turn may be classified and stored as attributes in layers in GISs. Such values can then be incorporated into optimization algorithms, determining valid roads that have the minimal impact on the environment and society. And by the semantic concepts structuring of relationships among the GIS features and remote sensing derived data manipulation, decision makers can perform precise multi-criteria analysis for decision-making, and solve questions. Diagrams representing such a process may be used to visualize how spatial databases are translated into semantic representations and how remote sensing data and GIS layers are integrated to compute a complete decision-support environment for road construction planning.

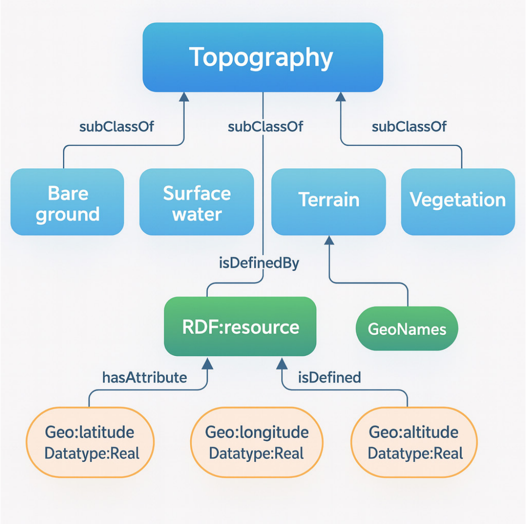
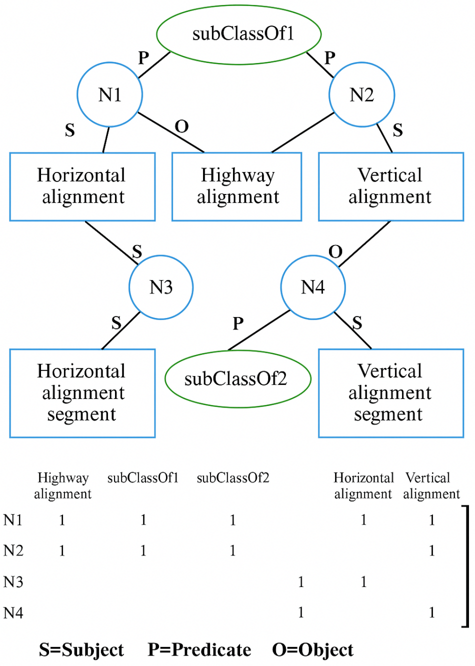


Figure 1: A geographic information science (GIS) entity representation as an RDF.

Road construction planning Ontology matching is introduced in the integration of the heterogeneous datasets in GIS and remote sensing forth road construction planning. Since these technologies usually represent spatial and environmental details in various structures and forms, the ontology matching offers a systematic procedure for resolving them as a single framework. This process aims to semantically align various types of knowledge including topography, land use, vegetation indices, and hydrology to enable better data-driven decision support. It is the structural similarity that is essential to this integrated process. Graph-based ontology matching methods are employed to discover and quantify the relations between GIS-based spatial entities and the remote sensing-based environmental characteristics. In this method, we also generalize both of GIS data (e.g., vector layers like roads, rivers, and land parcels) and remote sensing data (e.g., raster layers like elevation, slope, and vegetation cover) into a bipartite graph. Structural relationships between these graphs are then tested to recognize significant correspondences. There are several phases in the process of ontology matching. First, GIS and remote sensing data are converted into spatial graph representations, so their structure can be expressed in a consistent manner. Second, we use coordination rules of vector-based and raster-based data to align heterogeneous data types which are from different resolution or attribute presentation. Third, matrix representations of both the datasets are made, initial values of similarity are specified and convergence is threshold is set. Last, an iterative matching process is implemented until the stable 1:1 mapping from the GIS and remote sensing data set features to the classes is established. Results of ontology matching establish a one-to-one relation between geographical entities and environmental causes that leads to the merge of topographical, climatic and land-use data into a unified DSS. By doing so, it becomes possible for road planners to perform multi-criteria analysis, improve alignment routes, and reduce environmental and social impacts during road construction.



	Highway alignment	subClassOf1	subClassOf2		Horizontal alignment	Vertical alignment
N1	1	1	1		1	1
N2	1	1	1			1
N3				1	1	
N4				1		1

S=Subject P=Predicate O=Object

Figure 2: RDF bipartite graph and matrix representation of the GIS ontology example

In road construction planning, data from GIS and remote sensing are typically generated in diverse formats, such as shapefiles, raster images, and tabular datasets. However, these formats are not directly accessible for semantic web queries, as traditional GIS and remote sensing tools do not support them. To address this challenge, heterogeneous datasets are transformed into the Resource Description Framework (RDF), which provides a standard semantic representation. Once GIS and remote sensing datasets are formalized into RDF graphs, querying becomes possible using SPARQL, the standard query language for RDF. SPARQL enables planners to retrieve, filter, and analyze data across integrated spatial and environmental layers. For example, queries can be executed to identify road alignments that minimize slope constraints, avoid ecologically sensitive zones, or optimize land acquisition costs. The results of these queries can be exported in semantic web–compatible formats such as Turtle, N-TRIPLE, JSON-LD, and RDF/XML, ensuring accessibility across various applications. This provides a unified knowledge base where spatial features and remote sensing attributes are integrated into a single semantic schema. By applying SPARQL, an integrated RDF graph of GIS and remote sensing data is established. This graph consolidates geometries (e.g., road networks, terrain elevation) and complementary properties (e.g., soil stability, vegetation indices), offering a comprehensive decision-support environment. This integration allows road construction planning to move from fragmented datasets toward a semantically enriched model that supports multi-criteria optimization and sustainable infrastructure development.

RESULTS AND DISCUSSIONS

The planned scheme will use several layers of analytical tools in GIS and remote sensing technologies to provide optimized solutions for alignment selection. Central analyses consist of geological and geospatial analysis, network analysis, and cost estimation. Geomorphological and geospatial investigation support in locating potential hazards in the project vicinity, such as instability of slopes, susceptibility of areas to flooding or erosion (Rawat *et al.*, 2025). High-resolution remote sensing images for terrain and environment understanding. The remote sensing images are the scale images of the terrain and environment, while the GIS can build out cover, elevation, and hydrological conditions. This integration lets planners decide which areas will be affected and design a plan to mitigate impacts or to bypass low-safety areas (Van den Hurk *et al.*, 2014). Network analysis allows efficient determination of routes that link points with prescribed orientations in space, taking into account constraints revealed by geological and geospatial analysis. By using vector GIS data and remote sensing-based terrain models, this analysis can calculate several alignment options in terms of travel distances, accessibility, and positioning in the road network. The cost estimates are combined between construction and maintenance aspects, using geospatial and remote sensing information to estimate earthwork volumes, material needs, and possible environmental remediation costs (Schnebele *et al.*, 2015). By integrating GIS and remote sensing technology, geotechnical and environmental data can be visualized in detail and can be used to promote closer cooperation among planners, engineers, and environmentalists. Dangerous areas and key ground features can be easily distinguished, adding to the decision-making process and assisting in altering proposed alignments. These analyses provide the basis of optimization for selected road alignments that are safe, cost-effective, and will not cause significant environmental impacts. Featuring direct visibility to the possible risks and resource demand, this analysis module effectively reduces planning effort and helps to work out the right road construction strategies.

It is necessary to carry out accurate geotechnical survey work on the construction site before the road construction, as a road or pavement is subjected to severe stresses and pressures. Among the most frequent and costly problems in road construction are slope failures/landslides (Otoma & Ayothiraman, 2025). GIS in combination

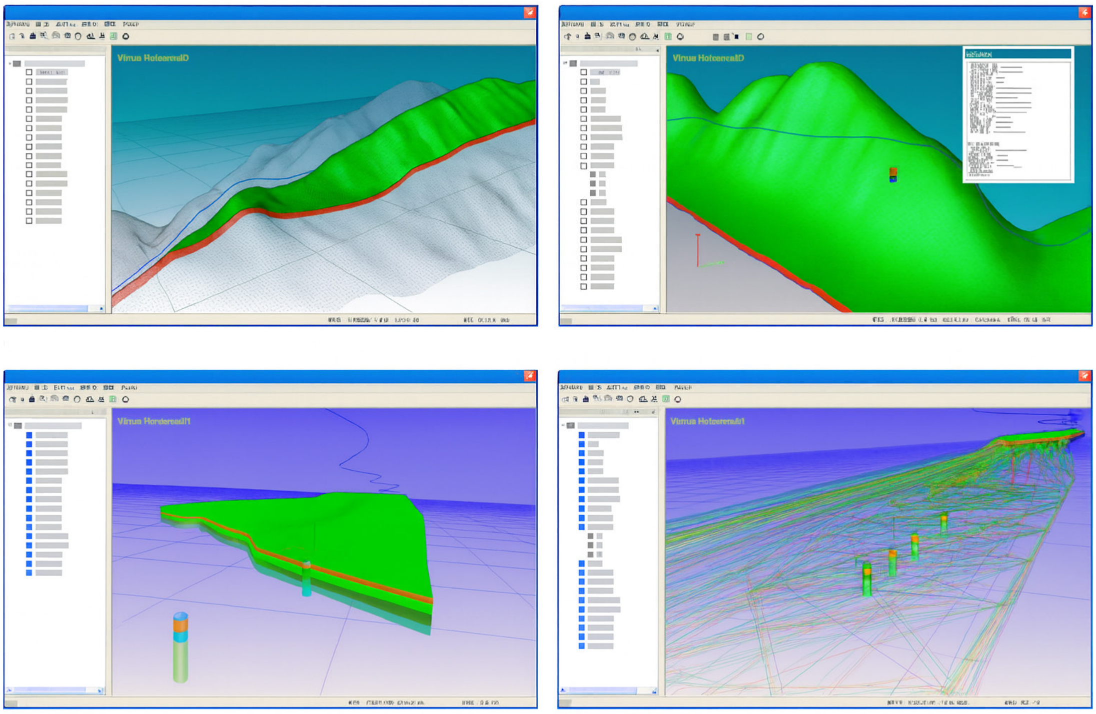


Figure 3: An example of geological analysis.

with remote sensing technologies can be used to forecast the susceptibility of landslides through the fusion of topological, geological, and climatic factors. Additional analysis, including maximum rainfall, historical average annual rainfall, and historic landslide history, is then used to predict the probability and magnitude of landslides in the area of the project (Klose *et al.*, 2016). Seismic risk also has an essential influence on decisions about road construction planning, particularly in seism genic areas. Soil liquefaction and decreased bearing capacity due to earthquakes can result in embankment failure or surface crack growth. Analysis of historical earthquake records and active fault mapping of GIS and remote sensing data can help in delineating potential seismic risk zones (Geiß & Taubenböck, 2013). Designers use this data to develop proposals to mitigate the impacts of earthquakes on the road system. Road building projects can have profound socio-economic and environmental implications for both the surrounding localities and cultural heritage, forests, wetlands, and even ecologically sensitive areas. Noise and air pollution can also rise during and after building. The GIS-based spatial analysis helps planners overlay road alignments on maps of socio-environmental data to avoid or minimize the impact on environmentally or socially sensitive areas. This holistic approach facilitates the decision for routes that are both technically feasible and environmentally/ socially acceptable.

Earthworks constitute a significant proportion of the total project cost & among the total cost, cut and fill take approximately 25%. Precise computation of cut and fill can play a crucial role in cost reduction and final adequacy of the material itself. When a BIM modeling system can be combined with terrain and soil data obtained from GIS and remote sensing, a complete model can be established to calculate the earthwork volume. The road's vertical profile, with reference to the center line, is used to determine cut and fill quantities that keep the cut and fill to a minimum, reducing costs and balancing the earthwork. This methodology ensures the central elevation is accomplished with the least amount of earthwork and that the alignment criteria are met. For the optimization of road alignment, several options are produced and assessed from the economic, environmental, and geotechnical points of view. The GIS and remote sensing data are used as essential inputs for the optimization algorithms, such as genetic algorithms. Each candidate alignment is encoded as a set of points on the centerline, the coordinates of which constitute a chromosome to be optimized by GA. The combined model computes costs such as earth work, pavement, right of way, user costs, and the cost of violations in environmental or design constraints. The GA constantly modifies alignment layouts to reduce the overall cost function while taking into account safety, according to standards for construction and environmental impact. The model developed considers a number of components in its cost function, including the cost of pavements, earthwork, right-of-way, the cost incurred by the user, and, for moves that violate environmental or design conditions, penalty costs. The cost of the pavement depends on the cost per unit, road length, and width, and the cost of the earthwork includes the cost of cut and fill and transport of materials. Right-of-way expenditure is charged based on the area of land altered by the road and the value of the land, while user cost is based on the length of the alignment in terms of travel distance

(Geremew, G., 2024). Penalty costs are, of course, imposed when the alignment traverses ecologically sensitive lands or does not satisfy design criteria, thus making sure that the optimized solution adheres to biophysical and regulatory considerations. When GIS mapping, remote sensing, and optimization algorithms are integrated, the proposed method offers a tool for road construction planning. It facilitates planners in an efficient assessment of various alignment options, considering environmental and socio-economic conditions, geological hazards, and construction costs, so that the road infrastructure can be more sustainable, safe, and cost-effective.

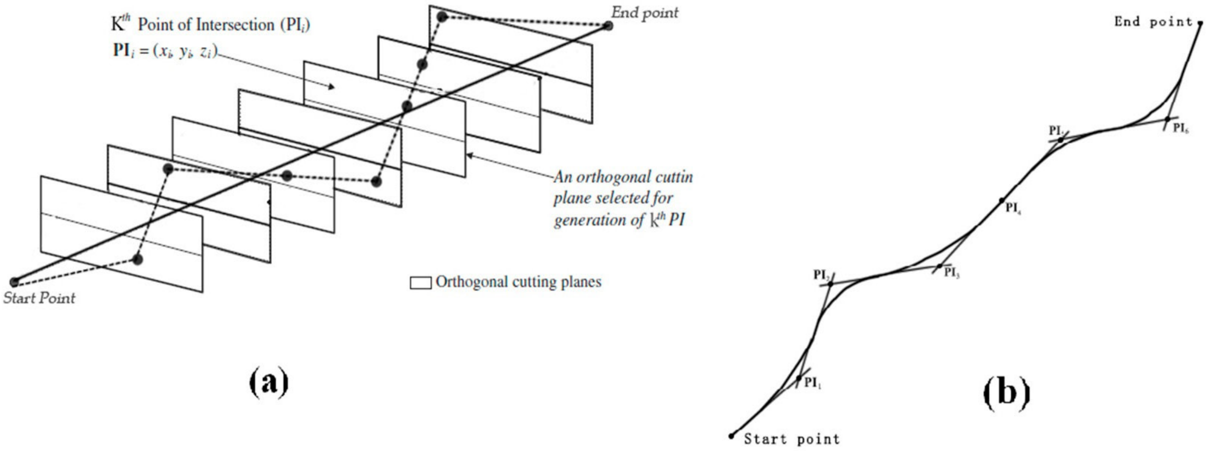


Figure 4: (a) A series of PIs; (b) geometric specification of typical horizontal alignment.

The project addressed in this paper is a significant road network in a region of high environmental and geological importance. The total length of the route is around 283 km and has an expected investment of 44.63 billion. The design speed for the road is 100km/h. Several factors make project planning and execution complex: the area is rugged and challenging to access, and the alignment has to avoid other infrastructure (railways, bridges, and pipelines); getting an optimal route requires careful attention to environmental and economic factors. Furthermore, the project area is located in an earthquake-prone region, and some severe earthquakes might have caused the failure of the road. Soil liquefaction may occur in response to seismic activity, resulting in embankment slide and surface cracking. A comprehensive seismic hazard analysis was carried out for use in design loads and mitigation planning (Sousa & Tsionis, 2025). Construction work mainly consists of mass excavation and backfill work, formation of subgrade and base, road surfacing, drainage setting up, and slope reinforcement. GIS and remote sensing data were used in the present case to strengthen the road alignment optimization. Satellite images (high resolution), the LiDAR-derived terrain model, and topographic data sets were transferred to GIS for spatial analysis. The GIS database contained data on terrain elevation, slope, soil type, hydrology, vegetation, and available infrastructure. The use of remote sensing data also improved the quality of hazard identification, such as landslide susceptibility and flood-prone areas. The BIM of the road was created to complement the geospatial analysis. Road components, pavement, embankment, bridge, tunnel, etc., with geometry and semantic information, were modeled by a software machine. The use of the BIM model enabled project information such as cross sections, plans, profiles, and material quantities. The BIM and GIS data were integrated based on advances in the semantic web to provide interoperability and to ultimately calculate the project cost, environmental influence, and construction possibility (Sarigul & Gunaydin, 2025). In the integrated model, the costs of highway construction, including pavement, earthworks, and user costs, were calculated by length, width, and material. This combination similarly facilitated not only planners to evaluate efficiently various alignment situations and to develop an optimal route based mainly on economic, environmental, and geotechnical effects.

Table 1: The summary of cost and environmental impacts of the alignment alternatives.

Alternatives	**Highway Alignment 1**	**Highway Alignment 2**	**Highway Alignment 3**
Length (km)	270.6	303.1	282.9
Total Cost (Billion BDT)	1874	2107	1856
Pavement Cost (Billion BDT)	380	430	400
User Cost (Billion BDT)	426	478	446
Right-of-Way Cost (Billion BDT)	199	223	208
Penalty Cost (Billion BDT)	197	136	133
Earthwork Cost (Billion BDT)	672	840	669
Geological Risk	Low	Low	Low
Impacted Historical Sites (m^2)	0	0	0
Impacted Farmland (ha)	1358	1204	909.53
Impacted Forest (ha)	508.5	487	444.9
Impacted Pasture (ha)	290.1	276.9	256.98

It forms part of an essential regional road network in Bangladesh. The overall length of the project is 283 km, and it passes through many districts with different geological, geographical, and environmental conditions. The design speed is 100 km/h and planning the project faces several challenges: (1) to work through a complex natural context (such as flood-prone region and depression land); (2) to deal with some bottlenecking obstacles including rivers, bridges, and local highways; and (3) to achieve the optimal alignment in terms of environmental conditions such as wetlands, and impacts on socio-economy. The project vicinity is also subject to possible seismic risks such as soil liquefaction during earthquakes. Construction activities include earthwork, subgrade, base, embankment, surface, drainage, and slope reinforcement. Topographic and surrounding site features were mapped using ArcMap and satellite imagery. They developed a CityGML schema to represent the objects, the relationships, and the attributes of the surroundings. A direct transformation from the CityGML to OWL was made. Similarities between the obtained OWL representations of the highway design (from BIM) and the surrounding environment (from GIS) were matched using Python scripts to integrate them using semantic web technologies. SPARQL queries were then employed to retrieve elements (e.g., horizontal and vertical alignment segments) defined in BIM but do not have direct representation in CityGML. The geometrical and geographical information is exported to the GIS module for 3D visualization of the artery and surroundings. Earthwork calculations and boundary costs were calculated in kilograms of ANP (ET) and value, respectively, considering the GIS model.

The analysis within the GIS was used to identify environmentally sensitive areas (ESA), which were in turn used to determine penalty costs to mitigate environmental damage. The employee teams made unanimous responses that the 3D integrated model helped them to understand the project better, communicate with the stakeholders effectively, and mitigate the risks. Alignment planning of highways of Bangladesh should consider environmentally sensitive and socially sensitive areas such as wetland, forest, agricultural land, residential, and necessary commercial regions. The trade-off values for each land-use type were included in the optimization. The Maximum Contributing Classes (MaxC) were imposed based on the priority of each land-use. As an example, historical sites and protected areas are assigned MaxC = 0 to exclude the highway from them; agricultural land and residential areas were minimized, but the model allows for some impact on them. The optimal highway alignment was found using a genetic algorithm (GA) based on minimum total project cost, considering the environmental and multiple design constraints (Al-Hadad *et al.*, 2024). The BIM module created the initial alignment route according to code and project requirements. These data were then imported to GIS, with the objective function including five cost elements: pavement cost, earthwork cost, right of way cost, user cost, and environmental impact cost. The GA mechanic successively improved alignment options over 100 generations. The overall cost calculations were established for each generation on the integrated BIM-GIS model. The best alignment should take into account minimizing economic cost, avoiding hazardous sites, and reducing environmental impact. Alignment 3, which was chosen as the best alternative, also had the shortest total length (283 km), influencing about 910 ha of farmland, 445 ha of forest, 257 ha of pasture, 59 ha of park, and 46 ha of residential land, but without influence on the historical heritage protection area. The optimized alignments were tested in terms of sensitivity to the cost components. We examined three objective function scenarios:

1. C = Pavement cost + User cost
   - Alignment passes through hazard-sensitive areas. Vertical alignment largely follows the terrain, but earthwork costs increase significantly in hilly regions.
2. C = Pavement cost + User cost + Right-of-way cost + Penalty cost
   - Alignment avoids environmentally sensitive areas but is longer and less optimal in terms of vertical profile.

3. C = Pavement cost + User cost + Right-of-way cost + Penalty cost + Earthwork cost

oAlignment minimizes overall cost, avoids hazards and environmentally sensitive areas, and closely follows the terrain profile.

The results indicate that considering all major cost components simultaneously is crucial for realistic highway optimization. The integrated BIM-GIS model enabled accurate estimation of individual cost items for each alignment alternative. Earthwork was the largest cost component, followed by user and pavement costs. Alignment 3 had the lowest total cost, demonstrating that the integrated approach effectively balances construction cost, environmental impact, and hazard mitigation. Table 1 summarizes the cost and environmental impacts for the three alternatives.

CONCLUSIONS

Road construction planning in Bangladesh is a complex and resource-intensive process, especially when evaluating multiple alignment alternatives across varied geographical and environmental conditions. This study proposes an integrated model that combines GIS, remote sensing, and BIM to streamline the planning process. Semantic web technologies and ontology-based approaches were employed to ensure seamless integration of diverse data sources.

The proposed model improves efficiency in geotechnical assessment and infrastructure planning, bridging the gap between highway design and site analysis while providing 3D visualization of the project. Optimization algorithms, specifically genetic algorithms, are used to select the most suitable alignment, minimizing construction costs and controlling geohazards simultaneously. The automated framework allows for the timely identification of optimal alignments, reducing manual effort and increasing precision compared to conventional methods. Application of the model to a highway project in Bangladesh demonstrates its practical relevance. As GIS, remote sensing, and BIM technologies continue to advance, this integrated approach can be widely adopted for efficient, informed, and cost-effective road construction planning. The model is also adaptable for other linear infrastructure projects and can be integrated with additional technologies for broader applications in construction and environmental management.

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