An Automated Optimization Framework for Hierarchical Access Road Design in Onshore Wind Farm Construction

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Abstract –

Onshore wind power plays a critical role in sustainable energy development. However, its deployment is often constrained by complex construction-stage logistics, particularly the planning and design of access roads. During the early-stage evaluation of onshore wind projects, construction road layout design and earthwork estimation remain labor-intensive due to terrain and engineering constraints.

This study proposes an automated optimization framework for the design of hierarchical access roads during onshore wind farm construction. The framework integrates high-resolution terrain data with parametric road modeling and constrained optimization to generate geometrically feasible road alignments. Key engineering constraints, including longitudinal gradient limits, deviation ratio from wind turbine locations, and cut-and-fill earthwork requirements, are explicitly incorporated into the optimization process. By formalizing road layout planning as a solvable computational problem, the proposed method transforms a process into an automated decision support workflow.

The applicability of the proposed framework is illustrated through an example, demonstrating its capability to generate feasible access road alignments while satisfying engineering constraints. The automated workflow supports rapid construction cost estimation during the planning stage.

Keywords –

Wind turbine access roads; Road alignment optimization; Earthwork optimization; Engineering constraints

1 Introduction

Wind energy has become a critical pillar of the global renewable energy portfolio, driven by the increasing demand for clean and sustainable power sources [1]. Despite challenges related to technology deployment, environmental constraints, economic feasibility, and social acceptance [2,3], onshore wind power continues to attract substantial investment and accounts for a significant share of the global energy market [4]. As global decarbonization targets accelerate, the efficient development of onshore wind farms remains essential for meeting future energy demands [5,6].

From a construction perspective, the deployment of onshore wind projects involves a multi-stage process. Typical workflows include candidate site selection based on wind resource assessment, for instance, by NEDO [7], wind turbine layout optimization considering terrain conditions, and construction planning and cost estimation. Among these stages, construction access road planning encompassing route selection, geometric design, and earthwork quantity estimation, represents a major bottleneck in practical project implementation. This stage is inherently complex and resource-intensive, as it must account for diverse land-use classifications, junction design between turbine platforms and access roads, the integration of disaster prevention facilities, and detailed construction cost calculations.[8] In practice, these tasks rely heavily on manual expertise and iterative trial-and-error processes, leading to high labor demands and prolonged project timelines. For example, even when multiple candidate plans satisfy the same preliminary conditions, a comparative evaluation is still required, as these plans may differ in design priorities. [8-10].

To address this challenge, this study proposes a computational approach that formalizes construction access road planning as an automated optimization problem. A geometric optimization framework is developed using high-resolution point cloud data to generate geometrically feasible road alignments and gradients under engineering constraints. By transforming a traditionally experience-driven task into an automated decision support workflow, the proposed method streamlines construction stage planning and facilitates more efficient and reliable construction cost estimation for onshore wind farm projects.

2 Problem Definition and Design Constraints

2.1 Road Design for Wind Turbine Access Roads

Road design is a critical aspect of civil engineering, particularly for access infrastructure in complex terrain. It involves alignment planning, longitudinal gradients, and earthwork operations, including excavation, embankment formation, grading, and compaction, to ensure adequate drainage, structural stability, and construction feasibility.

In the specific context of wind turbine access roads, road geometry and earthwork quantities are strongly coupled. Longitudinal gradients and alignment continuity govern the feasibility of transporting heavy construction vehicles and oversized turbine components. In addition, road design must account for heterogeneous land use conditions, such as agricultural land, forest areas, and developed zones. Consequently, earthwork requirements, road geometry, land use, and environmental considerations must be addressed in an integrated manner to ensure the overall feasibility and performance of wind turbine access road design.

2.2 Engineering Design Constraints

Engineering design must satisfy a set of interrelated constraints to ensure construction feasibility, operational safety, and regulatory compliance. In this study, the following key design constraints are incorporated into the optimization framework.

2.2.1 Wind Turbine Siting Constraints

Wind turbine locations are treated as predefined inputs in the access road planning process. Turbine siting is determined based on wind resource assessments, environmental regulations, and geotechnical feasibility, and is assumed to be fixed prior to construction road design. Each turbine location therefore acts as a mandatory destination that access roads must connect to, subject to geometric and constructability requirements.

2.2.2 Longitudinal Gradient Constraints

Longitudinal gradients of access roads are constrained to ensure the safe transportation of heavy construction vehicles and oversized turbine components. Maximum allowable gradients are specified according to engineering standards and vehicle performance limitations, typically less than 12% [11], also depending on site conditions. In the proposed framework, gradient constraints are enforced along the entire road alignment and directly interact with earthwork requirements.

2.2.3 Connectivity to Existing Roads and Forest Trails

Access road layouts must ensure appropriate connectivity to existing public roads and forest trails to support construction logistics and long-term site accessibility. Feasible connection locations are constrained by traffic safety requirements, visibility conditions, environmental regulations, and land-use limitations. In the optimization framework, access road alignments are restricted to connect through predefined candidate access points while satisfying geometric and constructability requirements.

2.2.4 Cut-and-Fill Earthwork Constraints

Cut-and-fill earthwork constraints are introduced to control excavation and embankment volumes along access road alignments. Excessive imbalance between cut and fill increases construction costs, material transportation demands, and environmental impacts, and may compromise slope stability. Accordingly, earthwork constraints are formulated to promote balanced material utilization. In practice, cut and fill volumes are not exchanged on a 1:1 basis due to soil bulking and compaction effects. In this study, however, the influence of bulking and shrinkage factors on the relative comparison among candidate routes is expected to be limited. Thus, earthwork quantities are used for comparative evaluation of alternative routes, and these effects are therefore not explicitly considered.

2.2.5 Horizontal Curvature Constraints

Horizontal curvature constraints are imposed to accommodate the maneuverability of construction and maintenance vehicles, particularly those transporting large wind turbine components. In practice, these constraints are expressed as minimum allowable turning radii to ensure safe vehicle operation and compliance with design standards. In the present study, however, horizontal curvature is treated as a general alignment consideration rather than an explicit minimum turning-radius constraint.

2.3 Optimization Problem Overview

Based on the engineering considerations described above, access road planning is addressed as a multi-objective optimization problem within an optimization framework. The objective aims to identify road configurations that achieve a favorable balance between construction-related effort, such as earthwork quantities, and road accessibility, while satisfying the prescribed engineering requirements. Meanwhile, soft performance is also taken into account through penalty terms. The detailed representation and solution strategy are described in the subsequent chapter.

3 System Framework and Modeling Approach

3.1 Overall System Architecture

To address the challenge of construction access road optimization under complex terrain conditions, this study proposes an automated framework composed of three primary components: (1) ridge detection for terrain feature extraction, (2) primary access road selection, and (3) secondary access road selection. These components are supported by two core computational modules, namely parametric road model creation and cut-and-fill earthwork volume calculation. Within the framework, terrain data are first processed to identify ridge features and generate initial road profiles, which are subsequently refined through road modeling and earthwork evaluation. By integrating these elements, the proposed framework enables the systematic selection of main and branch access road alignments that balance construction cost, earthwork demand, and accessibility requirements. An overview of the proposed framework is illustrated in Figure 1.

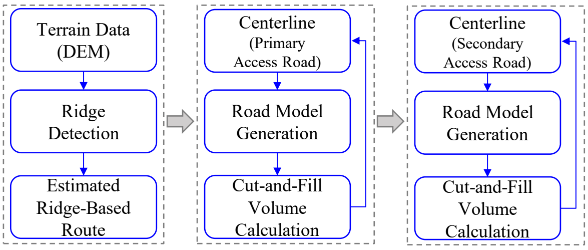


Figure 1. Framework overview

3.2 Ridge Detection and Terrain Feature Extraction

Ridge detection is employed to support access road planning for wind turbine construction, as routing roads along ridge lines generally minimizes earthwork demand and reduces construction costs. In this study, mountain ridges are identified using a watershed-based terrain analysis approach, where ridges are defined as topographical boundaries separating adjacent drainage catchments. The target terrain is first represented as a Digital Elevation Model (DEM), which is then processed using a watershed algorithm to extract ridge features. In this procedure, the DEM is treated as a surface subjected to a simulated flooding process initiated from local minima. As water levels rise uniformly within individual catchment basins, watershed boundaries are formed at the interfaces where adjacent basins meet. These boundaries constitute a network of watershed lines that correspond to mountain ridges. The extracted ridge features provide terrain-aware guidance for generating initial access road profiles, forming the basis for subsequent road modeling and optimization. The overall concept of ridge detection using the watershed approach is illustrated in Figure 2.

Figure 2. Watershed-based detection concept [12]

3.3 Parametric Road Modeling

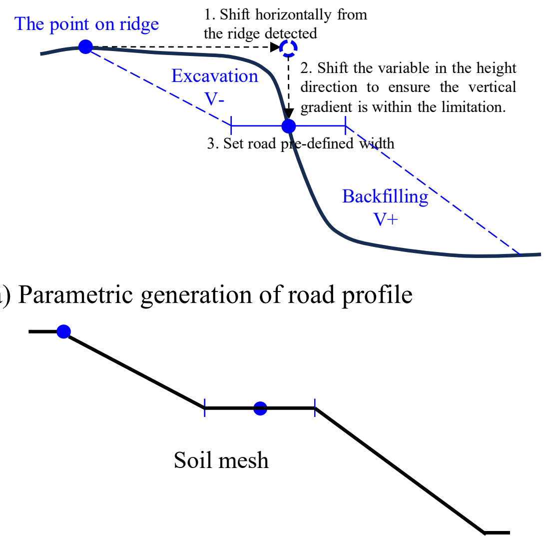
The road model creation module generates an integrated mesh representation of access roads, including the road surface and associated cut-and-fill slopes. The module requires three primary inputs: road width, side batter width, and the prescribed cut-and-fill slope angle. As illustrated in Figure 3(a), the process begins with a parametric calculation that determines the initial road profile location. At this location, a horizontal road surface with a predefined width is generated. The outer edges of the road surface are then extended at the specified slope angle to form cut-and-fill side slopes. For each edge, the model automatically determines whether a cut or a fill operation is required by comparing the edge elevation with the existing terrain surface. If the edge lies below the terrain, a cut slope is generated upward until it intersects the ground surface; if the edge lies above the terrain, a fill slope is generated downward until ground intersection is achieved. The resulting road-and-slope mesh as shown in Figure 3(b) provides a geometrically consistent representation of the road cross-section and is subsequently passed to the earthwork calculation module for cut-and-fill volume estimation.

3.4 Cut-and-Fill Earthwork Calculation

The final earthwork volumes are computed by spatially comparing the modified terrain mesh incorporating the road model with the original terrain mesh. The volumetric difference between these two surfaces represents the total cut-and-fill earthwork required for access road construction. In the proposed framework, earthwork volumes are calculated by evaluating the vertical differences between the two meshes over their shared horizontal projection. Regions where the modified road mesh lies above the original terrain are classified as fill volumes (V+), corresponding to material that must be placed, whereas regions where the modified mesh lies below the original terrain are classified as cut volumes (V-), corresponding to material that must be excavated. These cut and fill volumes are computed independently and aggregated over the entire road alignment, providing quantitative inputs for construction planning, earthwork balancing, and cost estimation within the automated workflow.

3.5 Optimization Formulation and Solution Strategy

A hierarchical optimization approach is adopted to balance construction cost and road accessibility in access road planning. Although numerous researchers have proposed a wide range of multi-objective optimization algorithms [13-15], evaluating candidate road networks in this study requires computationally expensive geometric modeling and earthwork calculations, which makes conventional population-based methods inefficient for large-scale exploration. Considering the large-scale nature of the problem and the objective of preliminary estimation rather than detailed design, a surrogate-assisted multi-objective optimization strategy based on Radial Basis Functions (RBFMOpt) is employed. Different objective functions are formulated at different stages, and RBF-based surrogate models are used to approximate these objectives, reducing the number of expensive evaluations while enabling efficient exploration. This solution strategy enables efficient optimization within the proposed automated framework and is well suited for construction-stage decision support under complex terrain conditions.



(a) Parametric generation of road profile

(b) Road earthwork mesh

Figure 3. Parametric road and earthwork modeling

4 Route Optimization Methodology

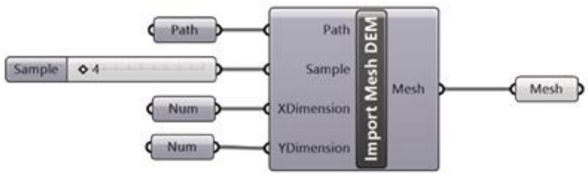
4.1 Computational Environment and Modeling Tools

The proposed optimization framework is implemented within the Rhino–Grasshopper computational environment. Rhino [16] is used for precise three-dimensional geometric modeling, while Grasshopper [17] provides a visual programming interface that enables flow-based logic control of geometric operations without conventional text-based coding. This environment allows direct integration of geometric road modeling, terrain processing, and optimization workflows, making it well suited for construction-stage access road planning. In addition, Grasshopper's extensive ecosystem of community-developed plugins provides tools for terrain analysis, parametric modeling, and multi-objective optimization, enabling seamless integration of the geometric modeling modules and optimization solvers required by the proposed automated framework.

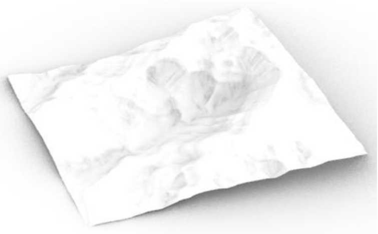
4.2 Terrain Data Preparation

The terrain data used in this study are based on 5-meter-high-resolution open-source Digital Elevation Model (DEM) data provided by Geoscience Australia [18]. The DEM serves as the topographic foundation for watershed-based ridge detection and subsequent access road planning. In the proposed workflow, the DEM is imported into the Grasshopper environment as a mesh using a module from the Bison package [19], with input parameters defining the file path, sampling factor, and spatial resolution in the horizontal directions, as shown in Figure 4(a). A square site with plan dimensions of 495 m × 495 m was selected as the illustrative case study area, with elevations ranging from 376.82 m to 596.02 m, as illustrated in Figure 4(b).

The terrain geometry and turbine layout are visualized in both top and perspective views within the Rhino–Grasshopper environment, as shown in Figure 5. The terrain is represented as a continuous mesh surface derived from the DEM, while the wind turbine locations are overlaid as discrete points distributed across the site. As the same time, ten wind turbine locations were randomly generated within the study area and treated as fixed constraints in the subsequent access road alignment optimization, also as shown in Figure 5.

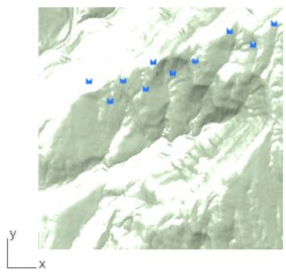


(a) DEM import workflow

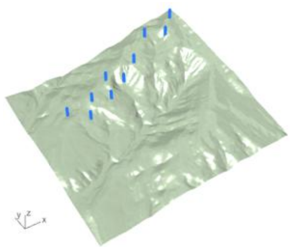


(b) Generated terrain mesh.

Figure 4. Terrain data preparation.



(a) Top view



(b) Perspective view

Figure 5. Terrain mesh and wind turbine locations

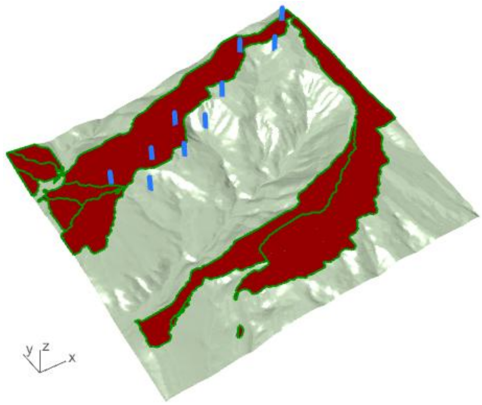
4.3 Optimization of Primary Access Roads

4.3.1 Ridge-Based Initial Route Estimation

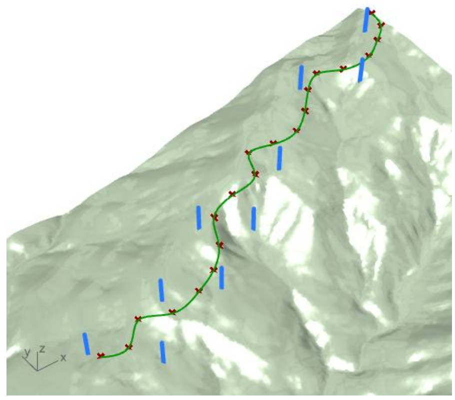
Initial candidate routes for the primary access road are generated based on the Digital Elevation Model, as illustrated in Figure 6(a). Ridge lines identified through watershed-based analysis provide elevated paths that generally minimize earthwork demand. To improve geometric continuity and constructability, the rough alignment is subsequently smoothed through interpolation. In this study, as shown in Figure 6(b), the initial alignment was discretized into approximately 20 segments, and an interpolated curve was generated to form a continuous and refined initial route that serves as the starting point for further optimization.

4.3.2 Local Optimization Under Gradient Constraints

Although the initial alignment was obtained, as shown in Figure 6(b), several segments did not satisfy the longitudinal gradient requirement for this illustrative case (20%), when the alignment was discretized into 20 segments. Consequently, these non-compliant segments were extracted for further processing.



(a) Extracted ridge features



(b) Smoothed ridge-based alignment

Figure 6. Ridge-based alignment extraction

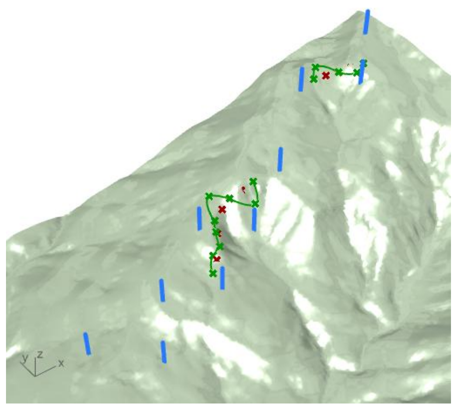


Figure 7. Local optimization under longitudinal gradient constraints

To address this issue, the maximum longitudinal gradient was treated as a strict engineering constraint rather than a conventional objective function. Specifically, the maximum longitudinal gradient was subject to an upper-bound constraint, and, even when this constraint was satisfied, it was still incorporated into the algorithm as a penalty term to encourage alignments with smaller gradient values. For each non-compliant segment, a midpoint was introduced to increase segment resolution, as indicated by the red crosses in Figure 7. The midpoints were then allowed to move in the *Y*-direction within the *XY* plane, while the corresponding longitudinal gradients were recalculated. Once all segments satisfied the prescribed gradient constraint, one of the optimized alignments was obtained, as illustrated by the green alignment in Figure 7.

4.3.3 Global Horizontal Alignment Optimization

Following the local optimization under vertical gradient constraints, an initially optimized main route alignment is obtained in the vertical plane. At this stage, the optimization only considers the maximum longitudinal gradient and does not account for additional geometric and planning factors. In the subsequent step, road length and deviation ratio *R* were treated as bi-objective functions, and RBFMOpt was used to generate Pareto-optimal candidate solutions. The final alignment was selected by minimizing road length among solutions satisfying an acceptable *R* threshold, without introducing weighting factors. As shown in Figure 8, the resulting alignment had a total road length of 1103.66 m and a maximum longitudinal gradient of 17.41%.

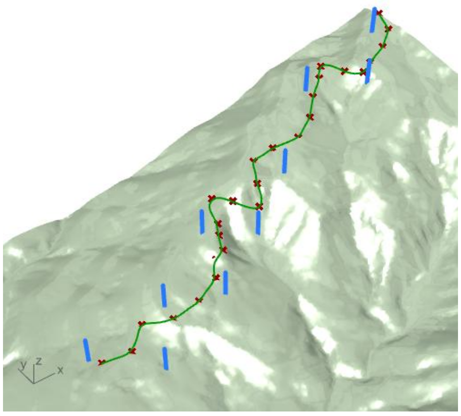


Figure 8. Local optimization under vertical gradient and total road length constraints

4.3.4 Global Vertical Alignment Optimization

Finally, global vertical alignment optimization is performed with earthwork volume introduced as an additional objective function. In this step, the first point of the main route is fixed, and subsequent points are iteratively adjusted in the negative vertical *Z*-direction to evaluate corresponding earthwork volumes. The earthwork volume consists of both cut and fill, which are calculated for each trial alignment. The resulting alignment under optimal conditions. In this case, as the Table 1 shown, the cut volume was 21,449.46 m^3, the fill volume was 83,846.15 m^3, and the total earthwork volume, defined as the sum of absolute cut and fill, was 105,295.61 m^3. The additional volume associated with cut-fill imbalance was 62,396.69 m^3. Through this procedure, the final main route alignment is determined hierarchically, with earthwork objectives optimized within the feasible space defined by prior gradient constraints.

Table 1. Mass balance of primary road earthworks

Earthwork	Cut (-) [m^3]	Fill (+) [m^3]	Mass balance [m^3]
Volume	21,449.46	83,846.15	62,396.69

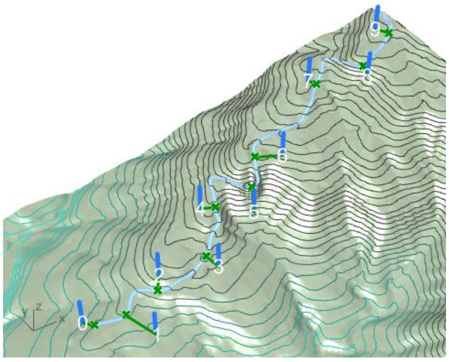
4.4 Optimization of Secondary Access Roads

4.4.1 Network-Level route selection

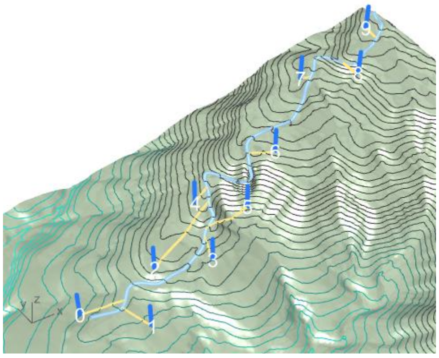
The network-level selection of secondary access roads connecting wind turbines to the primary route follows a systematic procedure. For each wind turbine, the closest point on the primary route alignment is first identified, and an initial straight-line connection between the turbine location and this point is generated, as shown in Figure 9(a), where contour lines with a 5 m interval are overlaid for visualization purposes. The straight-line branch is then divided into three equal sub-segments, and the vertical gradient of each sub-segment is evaluated. If all sub-segments satisfy the allowable gradient threshold, the straight line is retained as a candidate branch road. If any sub-segment violates the gradient constraint, the corresponding branch is selected for further refinement.

In this refinement step, the branch remains represented as a straight line, while the connection point on the primary route is iteratively adjusted to minimize branch length, subject to satisfying the prescribed gradient constraint for all sub-segments. By combining the resulting branch roads with the primary route, an initial configuration of the access road network is obtained.

Among the generated branches as shown in Figure 9(b), those serving turbines 0, 2, 3, 4, 5 and 8 were identified for subsequent secondary optimization, as no feasible connection point along the primary route can satisfy the gradient constraint through network-level adjustment alone. The remaining branches correspond to routes accepted at the initial network-level selection stage.

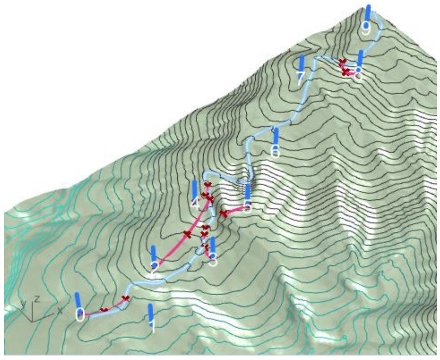


(a) Initial straight-line connection roads

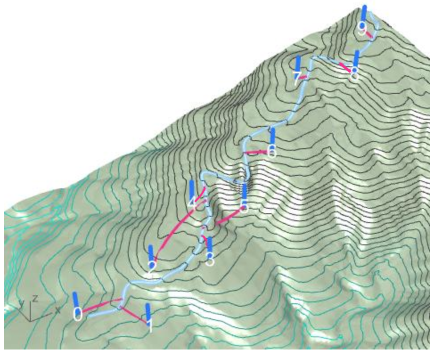


(b) Network-level selected branch roads

Figure 9. Network-level branch road selection



(a) Optimization of non-compliant branch roads



(b) Final optimized branch roads

Figure 10. Local optimization of secondary access roads

4.4.2 Local Optimization Under Gradient Constraints

Local optimization under vertical gradient constraints was subsequently performed for the branch roads serving turbines 0, 2, 3, 4, 5 and 8. For each branch, a midpoint is inserted into the initial straight-line segment while the two endpoints remain fixed. This midpoint is allowed to move within the *XY* plane to reduce excessive vertical gradients along the branch. A smooth curve is then fitted using the two endpoints and the midpoint to generate the optimized branch alignment, as illustrated by the pink curves and control points in Figure 10(a). The maximum longitudinal gradient was treated as a constraint, and the optimization aimed to obtain feasible alignments rather than balance multiple objectives.

The final branch alignments are shown in Figure 10(b). The corresponding earthwork quantities are summarized in Table 2, with a total cut volume of 137,064.47 m^3, a fill volume of 129,647.73 m^3, and a volume balance of −7,416.74 m^3.

Table 2. Mass balance of secondary roads earthworks

Earthwork	Cut (-) [m^3]	Fill (+) [m^3]	Mass balance [m^3]
Volume	137,064.47	129,647.73	-7,416.74

5 Conclusion and Future Work

5.1 Conclusions

This study proposed an automated optimization framework for construction-stage planning of access road networks in onshore wind farm projects. The framework integrates terrain-aware analysis, parametric road modeling, earthwork evaluation, and stage-wise optimization into a unified computational workflow. Both primary and secondary access roads are generated through a hierarchical optimization strategy that incorporate practical engineering constraints, including longitudinal gradient limits, road geometry, deviation control from turbine locations, connectivity requirements, and cut-and-fill earthwork characteristics.

Through an illustrative example, the proposed framework demonstrates its capability to generate construction-feasible access road networks under complex terrain conditions. The results show that the framework can systematically support early-stage route selection, earthwork estimation, and network configuration, providing quantitative information for construction planning and decision support. The optimization process combines constraint enforcement (e.g., gradient limits) with local objective-based refinement, enabling efficient solution generation without relying on global weighting factors. The proposed approach is particularly suited for preliminary evaluation and scenario exploration rather than detailed design.

5.2 Future Work

Future work will further extend the current framework beyond the illustrative 495 × 495 m case to larger-scale terrains, with particular attention to computational efficiency and scalability. This extension will also enable systematic comparison with expert-designed road alignments to evaluate the practical performance of the proposed framework. In this context, data-driven approaches, such as reinforcement learning, could be explored to enhance cost-oriented optimization under more complex conditions.

In addition, more realistic earthwork modeling can be considered by introducing non-unity cut–fill conversion factors. The current interpolation-based approach may also be refined by incorporating explicit geometric constraints, such as minimum turning radius.

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