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Optimized routing of interconnected subsea pipelines using geospatial cost-surface modelling

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Abstract

This study presents an innovative, fully automated pipeline routing model that integrates multilayer geophysical and regulatory datasets into a single cost surface model. Unlike conventional techniques that rely on manual route selection or simplified cost estimates, the proposed method allows for a systematic assessment of tradeoffs among cost, length, safety, and environmental impact. The proposed method leverages Geospatial analysis tools to convert geophysical data, environmental restrictions, and platform locations into a detailed cell-based geophysical model. This model is used to generate a composite cost surface that reflects real-world challenges such as seabed topography, geohazards, and protected marine areas. Using graph-based optimization algorithms, the system computes the least-cost main and lateral pipeline routes that interconnect source and destination nodes. The approach was tested on actual offshore field scenarios, where it successfully identified optimal pipeline alignments that cut overall project cost by up to 15% compared to conventional routing methods. The system demonstrated a significant reduction in pipeline crossings and length and ensured full compliance with environmental and safety regulations. These results confirm the effectiveness of the geospatial cost surface approach in delivering robust, efficient, and sustainable subsea pipeline designs.

Keywords: Pipeline Routing; Cost Surface; Subsea Pipelines; Geospatial Analysis; Optimum Path; Geographical Information Systems

1. Introduction

1.1. Background and Motivation

Determining efficient and sustainable routing for subsea pipelines and subsea cables is one of the most critical and complex tasks when developing new offshore oil & gas fields. Traditionally, these routes have been identified through manual interpretation of available survey data and engineering judgment, which often leads to iterative design cycles and suboptimal outcomes [1]. Conventional approaches typically rely on overlay simplified cost assumptions, making it difficult to systematically assess the intricate trade-offs among capital expenditure (CAPEX), route length, constructability, regulatory compliance, safety, and environmental impact [1].

The significance of the proposed system arises with increasing the complexity of upgrading aging and congested offshore fields. In major oil & gas basins, such as those in the Arabian Gulf, the continuous expansion of production capacity has led to a dense network of subsea infrastructure [2]. The introduction of significant quantities of new subsea pipelines and power cables into this existing "spaghetti mesh" presents a three-fold challenge:

- **Exponential Cost Growth:** Inefficient routing in densely congested zones leads to unnecessarily long pipeline routes to avoid obstacles and frequent subsea crossings, which substantially increase material and installation of capital expenditures [2].

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- **Regulatory Compliance & Marine Approaches:** As fields become denser with existing facilities, adhering to strict marine regulations becomes more challenging, particularly for those related to platform approach corridors [1, 3]. Traditional manual planning methods often fail to identify routes that comply with mandatory safety distances and approach angles for new risers at existing platforms. This results in compliance risks or costly modifications later in the project lifecycle, especially after approval and during execution [1, 3].
- **Seabed Spatial Management:** Effective seabed organization is essential to reserve corridors for future expansion and vessel access. Without centralized planning, ad-hoc installations can limit flexibility and complicate long-term development and maintenance efforts [4].

1.2. Problem Statement

Current subsea pipeline planning faces significant challenges, primarily due to the complexity of overlaying diverse, multi-layers data sources such as detailed bathymetric maps, subsea geohazard assessments, seabed obstructions, and protected marine zones into a unified decision-making process [1]. This fragmented approach results in non-compliant routes, longer and more expensive pipelines, and increased environmental impact from crossings or proximity to ecologically sensitive areas. Finding a robust, scalable, and standardized decision-support system for offshore pipeline planning has become a necessity to fill the gap for consistent and objective route evaluation [1, 4].

1.3. Purpose Statement

This paper introduces an innovative, fully automated pipeline routing framework designed to overcome existing limitations in subsea route planning. The proposed method is a computer-driven approach that utilizes geospatial analysis tools of Geographic Information Systems (GIS) to identify optimal subsea pipeline routes. The distinct advantage of the new approach stems from the integration of multiple layers of geophysical and regulatory data into a unified cell-based composite cost surface model. The key innovation exists in combining this cost surface with geospatial optimization techniques to simultaneously evaluate and generate routes that are cost-effective, shortest in length, and most compliant within a single, objective-driven process.

2. Literature Review

2.1. Challenges of Subsea Pipeline Route Selection

The process of selecting optimal offshore pipeline routes requires navigating significant engineering and environmental challenges that include: (1) High resolution Seabed topography and bathymetric data [5], (2) Congested brownfield environments [6], (3) Environmental constraints [7], (4) Regulatory and safety compliance, and (5) Data integration, quality, and uncertainty [8].

The selection of optimum subsea pipeline route requires high-resolution bathymetry and sub-bottom profiling data. Inadequate terrain data lead to route deviations and increased installation risk [1]. The fine-scale seafloor and topographic relief influence the feasibility, planning, and execution of trenching and burial depths for various applications like submarine cables and pipelines [9]. White and Cathie [4] highlighted the importance of seabed topography and geotechnical conditions in determining the feasibility and cost of pipeline installation.

The installation risk increases significantly with increasing the potential geohazards such as crossing with the existing facilities especially when upgrading existing offshore fields [1]. Mature basins such as the Arabian Gulf exhibit a dense "spaghetti mesh" of legacy pipelines and power cables [10]. Three-dimensional asset databases and encroachment detection tools are required to avoid costly re-routing for subsea pipeline routes [11].

Recently environmental considerations have gained increasing prominence in the selection process of subsea pipeline routes. A comparative analysis of pipeline routing practices across different jurisdictions showed noticeable variations in the implications of environmental compliance standards on route optimization [12]. The environmental impact assessments (EIAs) have a significant role in shaping pipeline routes, particularly in ecologically sensitive areas [13]. They emphasized the need for route selection processes to align with environmental protection policies. Omitting environmental concerns from technical routing models leads to project delays [14].

Adherence to national governance, safety, technical, and environmental standards is a significant challenge in selecting subsea pipeline routes [15]. Compliance with pipeline integrity and leak prevention standards add layers of design constraints that are not expressed in simple cost functions [16]. Routing studies should include detailed spatial overlays of protected species [16].

The current routing selection practices lack an integrated, data-driven framework capable of simultaneously evaluating technical feasibility, economic efficiency, environmental impact, and compliance across highly congested subsea environments [17]. The variation of data sources is one of the challenges for modelling pipeline routes as geophysical, environmental, regulatory, and asset management datasets often reside in disparate formats and coordinate systems [18]. The low data quality and inconsistency results in outdated bathymetry or missing hazard layers [19].

2.2. Conventional Method for Pipeline Route Selection

Traditionally, pipeline routes are selected based on visual assessment of supporting maps with different data types in a prolonged, time-consuming process. The pipeline routes are selected based on low-resolution datasets, with minimal consideration for bathymetries data and potential geohazards [1]. The process includes manually sketching several scenarios of the possible routes and conducting multiple review meetings and workshops with different stakeholders to agree on the final selection. After proposing the routes, a detailed geophysical survey is conducted along the corridors of the proposed routes to identify free span areas, complete geohazard assessment, and estimate implementation cost [1]. Selecting pipeline routes based on high-level data and before appropriate cost estimation and risk assessment can cause revisions to the design, resulting in significant increase in time and resources cost [20]. As described by Davince et al. [21], the manual techniques required significant domain expertise to interpret and translate into route planning decisions. The accuracy of the manual evaluation was heavily dependent on the experience of the geoscientists and engineers involved [21].

A key component of the conventional approach is the use of corridor screening, where potential routes are manually evaluated within a defined corridor that avoids major obstacles and high-risk areas. This approach was widely used in the North Sea and Gulf of Mexico during the 1970s–1990s, where engineers would manually delineate preferred paths based on bathymetric data and known geohazards [22]. Another conventional technique involves the use of checklists and scoring systems to qualitatively rank route options. These checklists typically consider factors such as water depth, soil stability, proximity to existing infrastructure, and environmental sensitivity [16, 23]. Hamid-Mosaku et al. [23] noted that such scoring systems were commonly used in early pipeline projects to support decision-making, especially in data-scarce environments. While effective in simplifying complex decisions, these methods were often limited by the lack of quantitative data integration and the potential for human bias. In addition to corridor screening and scoring systems, manual route selection historically relies on analog geophysical and geotechnical survey data. Seismic profiles, sub-bottom profiler data, and sediment sampling reports were manually analyzed to infer seabed conditions along potential routes [8, 24].

Despite its limitations, the manual conventional method of route selection has contributed significantly to the development of best practices in subsea pipeline engineering. It laid the groundwork for modern decision support systems by identifying the core criteria that influence pipeline routing, such as geohazards, environmental impact, and constructability [25]. Despite the increasing use of sophisticated technologies such as GIS, artificial intelligence (AI), and remote sensing, conventional methods remain relevant in certain contexts and continue to shape current practices [22]. The conventional methods remain valuable in situations where digital data is limited or where rapid assessments are needed, particularly in remote or frontier regions. However, the manual approach is increasingly being supplemented or replaced by more advanced methodologies that incorporate digital data integration, spatial analysis, and automated optimization [25].

2.3. Using Geospatial Analysis in Pipeline Route Selection

GIS and related geospatial techniques have become the backbone of modern workflows of subsea pipeline route selection. Integrating heterogeneous spatial datasets such as bathymetry, sub-bottom geology, environmental habitats, regulatory zones, and legacy assets enables engineers and planners to evaluate multiple route options that have the most technically and environmentally feasible alignment [26, 27]. This integration supports multi-criteria decision analysis, allowing engineers to assess trade-offs between cost, risk, and environmental impact [28]. GIS enables engineers to move from heuristic, paper-based sketches to data-driven, reproducible routing decisions. GIS can play a significant role in multi-objective spatial decision support systems by facilitating the use of weighted overlay methods and least-cost path modeling to identify optimal pipeline corridors [27, 29].

The GIS spatial analysis techniques are particularly valuable in offshore environments where data complexity and environmental sensitivity are high [27]. GIS facilitates environmental constraint mapping by allowing planners to overlay protected marine areas, fishing zones, and navigational corridors. This capability supports the identification of routes that avoid or minimize ecological disruption while complying with regulatory requirements [30, 31]. GIS-based spatial modeling of the hydrographic data supports the identification of high-energy zones and informs decisions on burial depth, trenching, and protective measures such as rock-dumping [32]. Several case studies demonstrated the effectiveness of GIS in subsea pipeline route selection. A GIS-based tool for offshore routing that uses spatial multi-criteria analysis can reduce project cost/effort by up to 30% [33]. Some researchers explored the use of GIS in offshore pipeline integrity management, concluding that GIS supports not only initial route selection but also long-term monitoring of pipeline exposure due to seabed changes and environmental impacts [34].

Cost surface analysis is a raster-based analysis where each cell receives a weighted sum of penalty values for its depth, slope, and habitat sensitivity. A unified raster cost surface combines bathymetry, seismic sub-bottom profiles, and habitat maps [35]. The approach sets out a model for treating disparate continuous and categorical layers within a single analytical framework. Compliant geospatial databases can store pipeline and power cable geometries together with attribute level metadata such as installation depth, material, and inspection history [36]. This structure facilitates encroachment detection in brownfield environments. The literature shows a clear shift from purely deterministic shortest path techniques toward evolutionary and hybrid metaheuristics that can handle multiple, conflicting, objectives [37]. These applied studies confirm that GIS-driven routing can deliver tangible cost and risk reductions across diverse geological and regulatory settings, but they also reveal a dependence on high resolution, up-to-date spatial data [38].

Recent advancements in remote sensing, autonomous underwater vehicles (AUVs), and machine learning are enhancing the quality and resolution of spatial data used in GIS-based pipeline routing [39]. The advancement in cloud-based GIS and open-source geospatial tools has a significant effect on data accessibility and collaboration across multidisciplinary teams involved in offshore pipeline projects [40]. Nevertheless, uncertainty of handling, data standardization, scalable optimization, and inclusion of broader socioeconomic factors remain open to challenges. Addressing these gaps will be essential for the next generation of GIS-enabled routing tools, especially as offshore development moves deeper, farther, and into increasingly congested brownfield environments.

3. Methodology

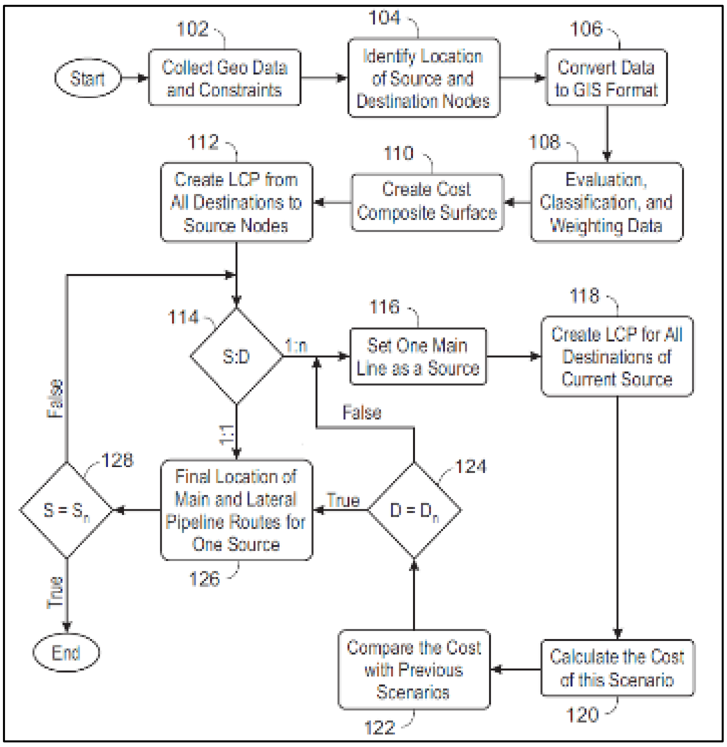

Figure 1 Workflow of the proposed framework

The proposed methodology utilizes a multi-stage process rooted in GIS and spatial analysis tools. The framework consists of four core components: (1) The cell-based geophysics model, (2) The composite cost surface generation, (3) The LCP analysis and path optimization engine, and (4) The centralized rule of Engine. Figure 1 shows a diagram for the workflow of the proposed framework.

3.1. Data Integration and Cell-Based Modeling

The foundation of the system is the transformation of input data into a digital environment.

- **Inputs:** The system ingests high-resolution bathymetry, seabed features/obstructions, and regulatory boundaries. A Geospatial database was the source of all data collected by hydrographic survey organizations. Hydrographic survey techniques such as echo sounder and LiDAR were used to capture the bathymetric data, and seabed features as Digital Terrain Model (DTM) vector format. The collected data included bathymetric data, existing subsea facilities, geohazard constraints, environmental constraints, and geotechnical constraints. ESRI ArcGIS Pro software was used to convert the data into GIS-compatible formats. The source and destination data were selected from the existing well-head platforms as sources and tie-in platforms as destinations.
- **Grid Generation:** These inputs were rasterized into a uniform grid (cell-based model). Raster resampling techniques such as nearest (neighbor) interpolation were applied to address the differences in resolution of the data. The resolution of the grid (cell size) was determined by the required fidelity of the survey data. The previous steps for data input and grid generation are shown in Figure 1 as (102, 104,106).

3.2. Composite Cost Surface Generation

The core innovation of this approach is the creation of a "Composite Cost Surface." In this context, "cost" does not strictly refer to currency, but rather an "impedance value" or "penalty" associated with traversing a specific cell on the grid. The analysis cell size is set to 20m to standardize the analysis for all input data layers.

- **Weighting Factors:** The system assigns weights to various spatial layers. For example, a flat seabed with no hazards has a base cost (1.0), while a steep slope or a pockmark has a significantly higher multiplier (e.g., 10.0 or 100.0).
- **Exclusion Zones:** Areas such as environmental sanctuaries or safety zones around existing platforms were assigned infinite costs, rendering them non-traversable.
- **The Composite Layer:** These layers were mathematically stacked to produce a single surface where "low values" represent desirable paths, and "high values" represent high-risk or expensive areas. Weighted Sum method was used to incorporate relative importance of each surface. The previous steps for generating the composite cost surface are shown in Figure 1 as (108, 110).

3.3. Spatial Analysis Optimization Algorithms

Once the cost surface is generated, the problem shifts from geographical analysis to mathematical optimization. The grid is treated as a graph where each cell is a node connected to its neighbors.

- **Path Finding:** The system employs advanced path finding algorithms to calculate the Least Cost Path (LCP) between a designated source and destination.
- **Compliance Verification:** The algorithm ensures that the generated path adheres to curvature constraints (minimum bend radius) and incident angles for crossing existing pipelines. To ensure that the generated path adheres to curvature constraints, a smoothing line algorithm (Bezier Interpolation) was applied to output routes. Figure 1 shows the generation of LCP steps as (112).
- **Iteration for Inter-Connected Routes Scenario**
  For each set of destinations that are connected to the same single source, different scenarios for identifying main and lateral pipeline routes can be evaluated. In each scenario, one route will be selected as a main line. The selected main line will act as the source for the other destinations within this scenario. The LCP analysis will be performed for each scenario to determine the least cost route for each destination node within this scenario to any location on the selected main line of this scenario. Finally, the cost of all scenarios will be calculated and compared to determine the least cost scenario for the whole set of pipeline routes for a single source. Steps 114-122 in Figure 1 shows the iteration process for inter-connected routes scenario. Figure 2, 3 shows the difference between direct route and inter-connected routes scenario.

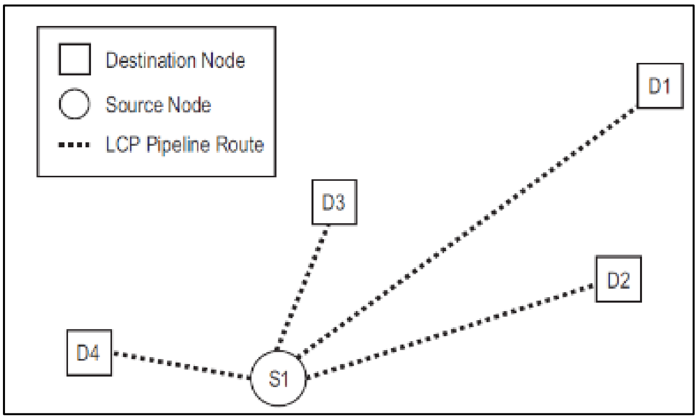

Figure 2 Direct Route Scenario

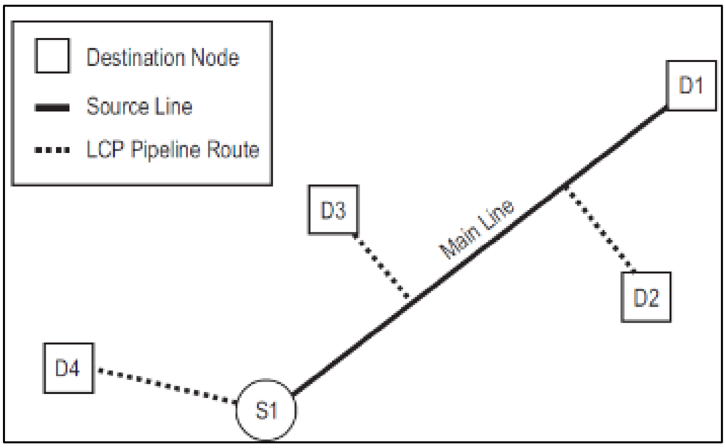

Figure 3 Interconnected Routes Scenario

3.4. Centralized Planning with Embedded Compliance

To resolve the chaotic nature of ad-hoc routing in congested fields, the system acts as a centralized planning hub. A key feature of the framework is the integration of a "Rule Engine" that embeds the operator's specific engineering standards directly into the routing logic. Instead of relying on individual engineers to remember and apply complex marine standards, the system automatically enforces constraints such as:

- Standardized platform approach corridors and riser guard zones.
- Mandatory crossing angles and minimum separation distances from existing assets.
- Specific exclusion zones for jack-up rig footprints and anchor patterns.

By centralizing these rules, the system ensures that every proposed route is inherently compliant with the Operator's marine and safety standards before it is even reviewed by human engineers.

4. Results and Discussion

4.1. Case Study and Validation

To validate the methodology, a model was developed using the ArcGIS Pro Model Builder. The developed model was applied on a real-world offshore brownfield development in the Arabian Gulf. The scenario involved connecting a new Wellhead Platforms (WHP) to an existing Tie-in Platform (TP) through a congested seabed corridor characterized by irregular bathymetry and multiple existing pipeline crossings.

4.1.1. Scenario Parameters

- Distance: Approx. 20 km.

- Constraints: Presence of protected marine coral zones, shallow water areas, and three existing pipelines requiring crossing.
- Objective: Minimize pipeline length while avoiding all geohazards and ensuring zero dredging.

Application: The GIS-based model successfully integrated the geophysical survey data. The cost surface highlighted high-risk areas (steep slopes) and exclusion zones (coral). The algorithm computed a primary route and two alternative lateral routes. The results from the developed model were compared to the manual-based output for the same field area, wellhead platforms, and tie-in platforms.

4.2. Quantitative Impact

The results in Table 1 shows that the automated routing analysis yielded significant tangible benefits compared to the baseline manual route initially proposed for the project:

- Cost and Distance Reduction: The optimized route reduced the total pipeline length and associated material costs by 15%.
- Crossing Optimization: The system identified a path that reduced the number of necessary pipeline crossings, thereby lowering installation complexity and risk.

Table 1 Quantitative comparison between manual and automated methods

	Manual Method	**Automated Method**	**Difference**
Length	60.7 km	54.5 km	6.2 km
Crossings	8	6	2
Violations	4	0	4
Total Cost	96.9 $MM	82.4 $MM	15%

4.3. Enhancing Sustainability and Environmental Stewardship

Beyond economic optimization, the system demonstrated a profound ability to enhance environmental compliance and sustainability. The GIS cost surface was configured to prioritize "Low Impact" routing by assigning prohibitive costs to sensitive environmental features. The system successfully delivered:

- Habitat Preservation: The algorithm automatically diverted routes away from identified marine habitats and coral clusters, ensuring zero direct impact on biodiversity.
- Dredging Avoidance: By incorporating bathymetric depth data into the cost function, the system identified routes that avoid shallow water areas. This significantly reduced the requirement for seabed dredging, thereby minimizing turbidity and protecting the marine ecosystem from sedimentation.
- Protected Area Compliance: Special protected zones were hardcoded as "non-traversable" barriers, ensuring that no generated route could accidentally encroach upon regulatory boundaries.

4.4. Operational Efficiency

The implementation of the centralized rule engine streamlined the planning process. Routes that typically require weeks of iterative adjustment to meet marine approach standards were generated in hours, with compliance built-in. This capability allows operators to arrange the seabed effectively and preserving corridors for future expansion.

5. Conclusion

This paper presented a novel approach for subsea pipeline routing using GIS-based cost surface analysis. By automating the integration of geophysical and regulatory data, the methodology moves the industry away from subjective manual design toward data-driven optimization. The results from the case study confirm that this approach can deliver up to 15% savings in project costs while ensuring rigorous adherence to safety and environmental standards. Furthermore, the system addresses the critical challenges of brownfield development by embedding regulatory compliance and centralized planning into the core of the routing logic. As the offshore sector continues to digitize, such objective decision-support tools will be critical for sustainable field development.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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