
Optimizing Route Selection for Inter-Island CPO Pipeline: A Corridor Study from Riau to Selangor via the Strait of Malacca

Abstract

Route selection is the most critical stage in pipeline system planning, particularly for cross-border subsea installations. This study examines the optimization of a crude palm oil (CPO) pipeline route from Riau to Selangor via the Strait of Malacca using a corridor-based route planning approach. The methodology includes a comparative analysis of several alternative alignments and a multi-criteria evaluation covering technical, economic, environmental, and operational aspects. The study also references global pipeline projects such as the Trans-Alaska Pipeline System and the Druzhba Pipeline as benchmarks. The results indicate that the shortest route is not always optimal, and that a corridor-based approach can produce routes with lower risk and better long-term cost efficiency.

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1. Introduction

In recent decades, crude palm oil (CPO) has emerged as one of the most strategic global commodities, playing an increasingly dominant role across various industrial sectors, ranging from food production to renewable energy. Indonesia, particularly the Riau region, is recognized as a major CPO producer with production capacity that continues to grow annually. On the other hand, Selangor has developed into a key hub for downstream processing and distribution of palm oil derivatives, integrated with international markets. This situation creates a highly dynamic yet complex cross-border supply chain, particularly in terms of transporting raw materials from production areas to processing centers [1].

Currently, the distribution of CPO between these regions is predominantly carried out through maritime transportation via the Strait of Malacca, one of the busiest shipping lanes in the world. Although this mode is capable of handling large volumes, several limitations have become increasingly significant concerns, including maritime traffic congestion, dependency on weather conditions, fluctuations in fuel costs, and the risks of accidents and oil spills that can negatively impact the environment. With the growing global demand for CPO, this conventional distribution system is increasingly considered inefficient and vulnerable to operational disruptions [2].

In the field of fluid transportation engineering, pipeline systems are often identified as a more efficient solution for the large-scale, long-distance transport of liquids. Previous studies have shown that pipeline systems offer advantages such as continuous flow, higher energy efficiency, and relatively lower long-term operational costs compared to ship-based

transportation [3]. Furthermore, pipeline infrastructure plays a critical role in improving the efficiency of global energy distribution systems [4]. Case studies such as the Trans-Alaska Pipeline System and the Druzhba Pipeline demonstrate that pipeline systems are capable of overcoming complex geographical and operational challenges through proper route planning.

However, despite the extensive literature highlighting the advantages of pipeline systems, there remains a gap in research specifically addressing their application to cross-border CPO distribution in Southeast Asia. Most previous studies have focused primarily on fluid flow mechanics or general economic analyses, without thoroughly examining the route selection process as a key determinant of project success. Additionally, there is a common tendency in early planning stages to assume that the shortest route is the most optimal, even though numerous studies have shown that such an approach often neglects critical factors such as risk, environmental conditions, and installation complexity [5].

This research gap becomes particularly relevant in the context of the Riau–Selangor corridor, which traverses the Strait of Malacca. The characteristics of this region including high shipping traffic density, varying seabed depths, and the presence of ecologically sensitive areas necessitate a more comprehensive planning approach. Therefore, a method is required that not only considers distance but also integrates technical, economic, and environmental parameters simultaneously [6].

Based on these challenges, this study aims to analyze and optimize the route selection of a cross-border CPO pipeline using a corridor-based route planning approach. This method enables the identification of corridor zones as flexible solution spaces for evaluating multiple route alternatives, thereby facilitating the selection of an optimal route in terms of cost, safety, and operational sustainability. Specifically, this study seeks to address the following research questions: (1) what are the characteristics of an optimal corridor for a CPO pipeline between Indonesia and Malaysia, (2) to what extent is the corridor-based approach superior to the shortest-path approach, and (3) which factors most significantly influence the determination of an optimal route under complex marine conditions.

To achieve these objectives, this article is structured as follows. The second section presents a literature review covering the fundamental concepts of route selection and insights from global pipeline projects. The third section describes the research methodology, including the multi-criteria analysis approach. The fourth section discusses the results of the analysis and evaluates the proposed route alternatives. Finally, the fifth section provides conclusions and recommendations for future research. Through this structure, the study aims to contribute to the development of a more efficient and sustainable CPO distribution system at the regional level.

2. Academic Perspective

From an academic perspective, the development of a subsea crude palm oil (CPO) pipeline from Riau to Selangor via the Strait of Malacca can be understood as a fundamental transformation in liquid commodity distribution systems from a discrete, ship-based transport approach to a continuous flow system. This transition theoretically enhances supply chain efficiency by reducing dependence on ports as bottleneck points, minimizing the need for temporary storage (buffer stock), and enabling a more stable and predictable distribution process. In the context of regional integration, such a system also has the potential to strengthen industrial connectivity between production areas and downstream processing centers.

From a pipeline engineering standpoint, the designed route does not simply follow the shortest straight line but instead adopts a corridor-based route planning approach that considers a range of technical and environmental parameters. This reflects the principle that route optimization is not solely focused on minimizing distance, but rather on minimizing total risk throughout the project lifecycle. In marine corridors such as the Strait of Malacca, which is characterized by high shipping traffic density and variable seabed conditions, this approach becomes essential for avoiding high-risk zones such as major shipping lanes and areas with low seabed stability [7].

From a hydraulic perspective, the relatively high viscosity of CPO requires careful planning of flow parameters, including pipeline diameter, operating pressure, and the potential use of heating

systems to maintain flowability. In addition, energy losses due to friction along the pipeline are a key factor affecting operational efficiency, meaning that route design must also account for pipeline length and geometric conditions that minimize flow resistance [8].

From an installation and operational perspective, the subsea segment represents the most critical component, as it is exposed to external risks such as anchor interference, ocean currents, and other maritime activities. Therefore, protection strategies such as pipeline burial, the application of protective coatings, and route selection that avoids high-density activity zones are essential design considerations. Furthermore, limited accessibility for inspection and maintenance in cross-border systems necessitates the implementation of real-time monitoring technologies to ensure long-term system reliability [9].

From an engineering economics perspective, although the initial capital investment for pipeline construction is relatively high, the system offers advantages in terms of lower long-term operational costs compared to repeated maritime transport. These efficiencies become increasingly significant at large distribution volumes and under continuous operation, resulting in overall benefits when evaluated using lifecycle cost analysis [10].

Overall, the subsea CPO pipeline represents not only a technical infrastructure project but also a complex system involving interactions among engineering, economic, environmental, and geopolitical aspects. Consequently, the success of its implementation is highly dependent on the accuracy of the route selection process, which serves as the primary determinant in ensuring efficiency, safety, and sustainability in cross-border distribution systems.

3. Results

The route selection analysis identified several potential corridors connecting Riau and Selangor across the Strait of Malacca. Rather than evaluating a single direct route, the corridor-based approach generated multiple route alternatives that could be assessed according to technical, environmental, economic, and operational criteria. This approach allows planners to identify route segments with lower overall risk while maintaining acceptable transportation efficiency.

The evaluation results indicate that route performance is influenced by a combination of seabed conditions, shipping traffic density, installation complexity, and expected operational requirements. Consequently, route optimization cannot be based solely on minimum distance, as several longer alternatives demonstrated lower risk levels and better long-term feasibility.

3.1 Corridor Identification

Three conceptual corridor alternatives were identified between Riau and Selangor. Corridor A represents the shortest route and passes through areas with high shipping density. Corridor B follows a slightly longer alignment that avoids major navigation channels. Corridor C represents the longest alternative but traverses areas with relatively lower maritime activity and fewer environmental constraints.

The preliminary assessment shows that Corridor A offers advantages in terms of shorter installation distance but faces higher operational risks. Corridor B provides a balance between distance and risk exposure, while Corridor C offers the lowest external risk but requires substantially higher construction costs due to its longer length.

3.2 Comparison of Alternative Routes

A comparative analysis was conducted using multiple evaluation criteria including route length, installation complexity, shipping traffic exposure, environmental sensitivity, and operational risk. The results indicate that no single route performs best across all criteria.

The shortest route demonstrates favorable capital expenditure characteristics but receives lower scores in safety and operational reliability. Conversely, longer routes generally achieve better performance in risk reduction and maintenance accessibility. This finding confirms that route optimization requires a multi-criteria decision-making approach rather than a simple distance-based assessment.

3.3 Technical Constraints in the Strait of Malacca

Several technical constraints were identified within the proposed pipeline corridor. The Strait of Malacca is characterized by intense commercial shipping activity, creating significant risks associated with anchor interference and accidental impacts. In addition, variations in seabed morphology may affect installation methods and pipeline stability [11].

Environmental conditions such as currents and sediment transport also influence route feasibility. Areas with high sediment mobility may require additional protection measures, including trenching or burial, which can increase project costs. Therefore, these factors must be incorporated into route evaluation and optimization processes [12].

3.4 Corridor Optimization Results

Based on the overall assessment, Corridor B was identified as the most suitable alternative for the proposed CPO pipeline. Although it is not the shortest route, it provides the best balance between construction cost, operational safety, environmental considerations, and long-term reliability.

The findings demonstrate that corridor-based planning enables more comprehensive decision-making by considering multiple risk factors simultaneously. This approach supports the development of safer and more sustainable cross-border pipeline infrastructure while reducing the likelihood of costly operational disruptions throughout the project lifecycle.

4. Discussion

The results of this study indicate that a corridor-based route planning approach provides a more effective framework for subsea CPO pipeline development than the conventional shortest-path method. Although minimizing distance can reduce initial construction costs, route selection based solely on length often overlooks critical operational and environmental risks. The findings demonstrate that pipeline performance is strongly influenced by external factors such as shipping density, seabed conditions, and long-term maintenance requirements. Therefore, route optimization should be viewed as a multi-criteria decision-making process rather than a simple geometric problem.

From a technical perspective, the Strait of Malacca presents unique challenges due to its status as one of the busiest maritime corridors in the world. High vessel traffic increases the probability of anchor interference, accidental impacts, and operational conflicts during both construction and operation phases. Consequently, route alternatives that avoid heavily trafficked navigation channels may provide significant long-term benefits despite requiring slightly greater installation distances. This finding supports the principle that risk reduction can often generate greater value than distance minimization alone [11].

The study also highlights the importance of seabed characteristics in route planning. Variations in seabed morphology, sediment composition, and bathymetric conditions directly influence installation methods and pipeline stability. Routes crossing areas with unstable sediments or significant seabed irregularities may require additional engineering measures such as trenching, stabilization systems, or protective structures. These requirements can substantially increase project costs and operational complexity throughout the pipeline lifecycle [13].

From a hydraulic standpoint, the transportation of crude palm oil presents additional challenges compared to conventional water pipelines. The relatively high viscosity of CPO can increase friction losses and pumping energy requirements, particularly over long distances. As a result, route selection indirectly affects operational efficiency because longer routes may require greater pumping power, while routes with fewer operational risks may provide better reliability and lower maintenance costs. Achieving an optimal balance between hydraulic efficiency and operational safety therefore becomes an important consideration in corridor evaluation [14].

Economic considerations further reinforce the advantages of the corridor-based approach. Although certain route alternatives may involve higher initial investment costs, these expenditures can be offset by lower operational risks, reduced maintenance requirements, and improved system reliability over time. This perspective aligns with lifecycle cost analysis principles, which emphasize the evaluation of total project costs throughout the infrastructure lifespan rather than focusing

exclusively on construction expenses [15].

The findings are also consistent with lessons learned from major international pipeline projects. The Trans-Alaska Pipeline System demonstrates the importance of adapting route alignment to challenging environmental conditions, while the Druzhba Pipeline illustrates the benefits of flexible corridor planning across multiple regions. Similar principles can be applied to the proposed Riau–Selangor CPO pipeline, where route selection must accommodate technical constraints, environmental considerations, and operational requirements simultaneously [16].

In addition to engineering and economic factors, environmental considerations should be integrated into route optimization. The Strait of Malacca contains ecologically sensitive marine areas that may be affected by construction activities or accidental releases. Consequently, route selection should seek to minimize environmental disturbance by avoiding sensitive habitats whenever possible. Such an approach supports sustainable infrastructure development while reducing potential regulatory and social challenges [17].

Overall, the study demonstrates that corridor-based route planning offers a more comprehensive and sustainable approach for cross-border subsea pipeline development. By integrating technical, hydraulic, economic, operational, and environmental considerations into a single planning framework, decision-makers can identify routes that provide the most favorable balance between efficiency and long-term reliability. These findings suggest that future pipeline projects in Southeast Asia could benefit significantly from adopting similar corridor-based planning methodologies.

5. Conclusions

This study concludes that route selection is a critical factor in the development of cross-border subsea pipeline systems, particularly for the transportation of crude palm oil (CPO) between Riau and Selangor through the Strait of Malacca. The findings demonstrate that the conventional shortest-path approach is not necessarily the most suitable option in complex marine environments. Although shorter routes may reduce initial construction distance, they often expose the pipeline system to greater operational and environmental risks.

The analysis further indicates that a corridor-based planning approach provides a more comprehensive framework for route optimization. By evaluating multiple route alternatives using technical, economic, environmental, and operational criteria, decision-makers can identify routes that offer a better balance between efficiency and safety. Among the evaluated alternatives, Corridor B was found to provide the most favorable overall performance by minimizing exposure to high-risk areas while maintaining acceptable construction and operational costs.

The study also highlights the importance of considering external risk factors such as shipping traffic density, seabed conditions, and installation complexity during route selection. These factors were shown to have a greater influence on long-term pipeline performance than distance alone. Consequently, successful route planning requires a holistic assessment that incorporates lifecycle considerations rather than focusing solely on initial investment requirements.

Furthermore, the results emphasize that the development of a subsea CPO pipeline should be viewed not only as an engineering project but also as an integrated system involving economic, environmental, and operational dimensions. The adoption of corridor-based route planning can contribute to improved infrastructure reliability, reduced operational disruptions, and enhanced sustainability in regional commodity distribution networks.

Future research should incorporate more detailed spatial and engineering analyses, including Geographic Information System (GIS) applications, bathymetric surveys, hydrodynamic modeling, and quantitative risk assessment. The integration of these tools would improve route optimization accuracy and provide stronger support for decision-making in future cross-border pipeline projects. Overall, the corridor-based approach presented in this study offers a valuable foundation for the planning and development of efficient, safe, and sustainable CPO transportation infrastructure in Southeast Asia.

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