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An advanced optimization framework for cross-docking site selection in global supply chains using an enhanced k-means clustering algorithm integrated with geographic information systems

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ABSTRACT

This study introduces a novel mathematical framework for the optimal placement of cross-docking facilities within international logistics networks. The model employs an extended K-means clustering algorithm integrated with Geographic Information Systems (GIS) to enhance spatial decision-making. A comprehensive review of the existing literature highlights that transportation and warehousing costs represent the most substantial components of overall logistics expenditures. In international land transportation, direct point-to-point delivery is often impractical, thereby necessitating intermediate transshipment through cross-docking facilities. Inefficient selection of these intermediary nodes can result in elevated storage and transportation expenses. Accurate identification of optimal cross-docking locations, therefore, has significant potential to reduce both transport distances and associated costs in global logistics operations. To examine this premise, two comparative scenarios were developed. The first assumes that cross-docking operations are conducted at national borders prior to international shipment, while the second applies the proposed extended K-means clustering algorithm integrated with GIS to determine optimal cross-docking points beyond the border within the broader international supply chain network. Both scenarios were subjected to numerical simulations and analytical assessments to evaluate their relative performance in minimizing transportation distances. The results reveal that the GIS-supported extended K-means approach produces substantially shorter international transport routes compared with the border-based cross-docking strategy. These findings emphasize the strategic importance of accurately locating cross-docking facilities in international logistics planning. By optimizing cross-docking placement, logistics managers can enhance transportation efficiency, reduce operational costs, and strengthen organizational competitiveness in the increasingly dynamic global marketplace.

1. Introduction

According to the 2024 Report on Thailand's Gross Domestic Product (GDP), logistics expenditures accounted for approximately 14% of the national GDP. Within this proportion, transportation costs represented 6.7%, equivalent to over 1.2 trillion baht, while inventory carrying costs comprised 6.4%, exceeding 1.1 trillion baht. Road transport remains the predominant mode of freight movement, constituting more than 80% of total transport activity. This segment alone contributes roughly 3% to the country's GDP and has experienced a 4.6% growth in export-oriented freight volume. Notably, both transportation and inventory costs have exhibited a consistent upward trend, partially attributed to a 0.3% increase in labor wages within the transport and warehousing sectors (Office of the National Economic and Social Development Council, 2024). Furthermore, the sharp escalation in fuel prices rising by 30% in 2022 compared to 2021 has significantly amplified road transportation expenses (Office of the National Economic and Social Development Council, 2023; Department of Foreign Trade, 2023). These trends suggest that the escalating costs of transportation and inventory management are directly reflected in overall international freight and storage expenditures, thereby exerting financial pressure on shippers and manufacturing

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enterprises. Consequently, it is imperative to explore optimal warehouse location strategies, as these facilities function as critical transshipment nodes within international supply chains and have profound implications for overall logistics efficiency.

The designation of transshipment points plays a pivotal role in facilitating cross-border road freight operations. Among the various warehousing configurations, cross-docking logistics has emerged as a vital mechanism for the rapid redistribution of inbound goods. This system enables the swift sorting and consolidation of products prior to dispatch, thereby maximizing logistical efficiency and transport utility (Lee et al., 2025; Nogueira et al., 2025; Shams-Shemirani et al., 2024). Since international overland freight movement typically cannot be completed within a single day—due to the need for cargo aggregation from multiple domestic origins before cross-border transit—the strategic placement of cross-docking facilities at both origin and destination points becomes essential. Inadequate facility placement often results in unnecessary detours, extended travel distances, increased fuel consumption, and significant time losses.

A key challenge for international trade operators, therefore, lies in the strategic identification of optimal domestic transshipment points where goods can be efficiently consolidated prior to forwarding to international hubs. Such optimization facilitates the shortest possible transport routes to end destinations, enhances operational efficiency, and strengthens competitiveness within the global logistics sector. Moreover, precise transshipment planning fosters greater production connectivity and significantly improves overall supply chain performance.

The determination of these transshipment points involves identifying optimal central locations—either near production sources for export consolidation or close to consumer concentrations for final distribution. The objective is to minimize the total transportation distance. This methodological framework closely aligns with the principles of K-Means Clustering, wherein the centroids of numerous geographical locations are calculated to determine optimal cluster centers. The process requires specifying a predefined number of clusters corresponding to anticipated warehouses or hubs, followed by calculating the shortest Euclidean distances between all relevant sites—whether production or distribution points to derive the optimal centroids (Gantassi et al., 2025; Nweje & Taiwo, 2025; Raesi & Reisi, 2025). Consequently, applying K-Means Clustering to the designation of international transshipment points not only enhances logistical efficiency by minimizing route lengths but also reinforces the competitiveness of cross-border transport operators and strengthens supply chain performance.

In the contemporary business environment, information serves as the lifeblood of supply chain management. Information technology now plays a crucial role in mitigating temporal and spatial constraints (Zhu et al., 2022; Lysons & Farrington, 2020; Stock & Manrodt, 2020). The movement of raw materials and finished goods within the supply chain depends heavily on the accessibility and effective utilization of real-time information. This is exemplified by the growing adoption of application programming interfaces (APIs) and online platforms that support a wide array of operational functions, including order processing, procurement data management, complaint handling, and service quality feedback collection (Miehle et al., 2019; Pal, 2017; Kodali, 2016). Accelerating the flow of operational data through such applications thus enhances the responsiveness, efficiency, and overall performance of logistics and transportation systems.

Historically, the K-Means clustering algorithm has been widely applied in transportation and travel analysis to identify central points across geographic coordinates. Traditional implementations estimate distances between latitude–longitude pairs using the Pythagorean theorem to calculate the Euclidean distance (Suwanda et al., 2020; Liberti & Lavor, 2017). For global-scale or long-distance routing, the Great Circle Distance has been employed to account for the Earth's curvature, representing the shortest path between two points on a sphere. The Haversine formula, derived from trigonometric principles, further refines this measure to yield more accurate arc-based distances between terrestrial locations (Prasetya et al., 2020; Yang et al., 2019). However, these techniques provide only approximate estimations, as they do not reflect actual traversable distances constrained by road networks or terrain.

Recent research has sought to extend the K-Means algorithm to better capture the complexities of real-world transportation networks. Conventional clustering methods, which rely solely on geometric coordinates, often overlook practical geographic and infrastructural constraints. Even when theoretical centroids are identified, their implementation may prove infeasible due to non-Euclidean accessibility arising from topographical, urban, and infrastructural variations. Therefore, integrating K-Means clustering with geographic information systems (GIS) can substantially improve the accuracy and applicability of transport hub localization, leading to more realistic and efficient logistical planning.

GIS provides a sophisticated technological framework for collecting, managing, analyzing, and visualizing geospatial data. By integrating spatial data (e.g., maps and coordinates) with non-spatial attributes (e.g., demographic, environmental, and infrastructural information), GIS enables comprehensive insights to support evidence-based decision-making. Modern implementations such as Google Maps algorithms exemplify GIS applications by offering real-time route optimization and travel condition assessment (Ganiyev et al., 2023; McQuire, 2019; Mehta et al., 2019). Despite these advancements, there remains a significant research gap in integrating GIS with K-Means clustering for identifying optimal freight transfer nodes under dynamic and real-world constraints.

Accordingly, this study proposes the development of an Extended K-Means Clustering integrated with GIS (EKM-GIS) framework to enhance the strategic determination of logistics hubs within international supply chains. Such an integrated approach holds considerable potential to improve the operational efficiency of Thailand's cross-border freight enterprises by reducing transportation costs and travel times while increasing reliability. Moreover, the adoption of EKM-GIS may confer sustainable competitive advantages and strengthen the connectivity and resilience of the broader international supply chain ecosystem.

2. Literature review

The determination of optimal cross-docking locations within the framework of international supply chain management (LCDL-ISCM: Locating Cross-Docking Logistics in an International Supply Chain Context) represents a complex and multifaceted decision-making problem. Conceptually, this challenge builds upon the foundational principles of K-means clustering. In operational practice, multiple manufacturers transport goods by truck to domestic cross-docking centers, where consolidation and container loading occur. Fully loaded trailers are subsequently dispatched across national borders to foreign cross-docking facilities, where the cargo is unloaded and redistributed via local trucking networks to reach final destinations. The LCDL-ISCM framework thus extends the traditional K-means clustering methodology, which fundamentally seeks to partition spatial locations or entities into a predefined number of groups. Recently, numerous studies have applied K-means clustering–based approaches to address related optimization problems, as summarized below.

The research trajectory in this domain initially focused on the integration of K-means clustering with transportation routing optimization. Tari et al. (2018), for instance, combined the K-means algorithm with Genetic Algorithms (GA) to optimize the allocation of heterogeneous vehicle types within a transportation network, with the principal objective of minimizing total transportation costs. Utilizing hypothetical distance data between origin–destination pairs, the analysis implemented through the CPLEX solver demonstrated that the proposed hybrid clustering approach not only effectively solved the optimization problem but also substantially reduced computational time relative to conventional exact optimization methods.

More recent developments have advanced this integration. Thomas et al. (2024) investigated the incorporation of drone technology with the K-means clustering algorithm for single-vehicle delivery operations, aiming to optimize both scheduling and routing efficiency in parcel and mail delivery systems. Their data preprocessing employed a heuristic (holistic) filtering technique prior to clustering. In parallel, Sun et al. (2024) formulated a nonlinear mixed-integer optimization model designed to minimize transportation costs while enhancing the operational efficiency of medical supply vans under urgent delivery conditions. Their approach combined K-means clustering with an improved adaptive genetic algorithm (IAGA). The findings of both studies converge on a shared conclusion: integrating clustering with advanced metaheuristic techniques can significantly improve delivery efficiency by reducing operational completion time. These results underscore the considerable potential of hybrid K-means approaches for enhancing solution quality in real-world logistics environments.

Subsequent research extended the application of K-means clustering to activity classification and segmentation problems. Saha et al. (2019) analyzed alternative clustering methods derived from K-means principles, evaluating their performance through empirical observation and comparative analysis across various cluster quantities. Similarly, Sarkar et al. (2024) applied K-means clustering to strategic customer segmentation, using recency, frequency, and monetary (RFM) parameters as key criteria. Their comparative assessment between the conventional RFM model and K-means clustering revealed that integrating clustering with dimensionality reduction techniques can substantially enhance computational efficiency by shortening processing times and improving accuracy.

Further contributions have explored K-means clustering within multi-trip and large-scale routing contexts. Ferone et al. (2025) proposed a hybrid method for optimizing multi-trip medical supply delivery routes by incorporating temporal variables and metaheuristic algorithms. Their study, which monitored single-vehicle operations, found that this hybridized approach provided a robust and scalable alternative to traditional exact methods. Similarly, Kim et al. (2025) applied K-means clustering to waste collection routing, grouping collection points prior to route optimization using an ant colony algorithm. Their findings confirmed superior operational efficiency and a marked reduction in computational time compared to conventional methods. Collectively, these studies highlight K-means clustering's capacity to mitigate data heterogeneity and improve operational responsiveness in diverse logistics applications.

Recent investigations have also emphasized the method's potential in inventory and network design optimization. Raesi and Reisi (2025) examined inventory management in a steel manufacturing facility through a hybrid K-means–GA framework to identify optimal storage locations. Their model achieved approximately a 15% reduction in internal transportation and material handling distances. Complementarily, Deineko et al. (2025) developed a framework for urban transportation network design that combined K-means clustering with metaheuristic optimization. Through microscale simulations involving bicycles and electric vehicles, they demonstrated that their approach effectively reduced delivery points while improving the efficiency and utility of urban mobility systems. Together, these findings suggest that the successful application of K-means clustering requires consideration of contextual, operational, and environmental variables to maximize its practical impact.

Consistent with this trajectory, recent scholarship has focused on integrating K-means clustering with artificial intelligence (AI). Nweje and Taiwo (2025) applied AI to analyze workload distribution across supply chain nodes, improving the detection of latent operational factors. Their approach involved clustering nodes via K-means prior to processing demand forecasts and production capacity data using AI algorithms. Similarly, Gantassi et al. (2025) integrated K-means clustering with machine learning techniques for transportation route optimization, employing wireless sensors for data acquisition and pattern recognition. Both studies demonstrate that AI-assisted clustering enhances decision precision, operational efficiency, and adaptive learning capacity, indicating that the analytical power of K-means can be significantly strengthened when augmented with AI-based computational tools.

A holistic review of the existing literature reveals that, while numerous studies have examined K-means clustering in hybrid and technologically enhanced forms, a notable research gap persists. Specifically, few studies have addressed the complex logistical scenarios in which goods are consolidated from multiple domestic origins at internal transshipment points before being transported as full loads across borders to foreign hubs, and subsequently redistributed to final destinations. This cross-border, multi-stage logistical structure particularly when optimized using Geographic Information Systems (GIS) for route minimization introduces an intricate combination of clustering and routing challenges unique to the LCDL-ISCM domain. A central research question thus arises: how does the strategic determination of both domestic and international transshipment points influence overall system efficiency compared to traditional clustering methods relying on Euclidean or Pythagorean distance metrics? Addressing this issue requires an integrative understanding of logistical interdependencies and the development of an algorithmic framework that explicitly accommodates these complexities. The present study accordingly proposes a novel algorithmic design that incorporates these constraints, thereby extending the theoretical and practical frontiers of the LCDL-ISCM problem.

2.1 K-mean clustering

K-means clustering is a widely adopted unsupervised machine learning algorithm designed to partition a dataset into K distinct clusters according to the similarity of data attributes. The primary objective of this technique is to ensure that data points within the same cluster exhibit higher intra-cluster similarity compared to those belonging to different clusters. The algorithm aims to minimize the Within-Cluster Sum of Squares (WCSS), a metric that quantifies intra-cluster compactness, thereby enhancing the internal homogeneity of each cluster (Ferone et al., 2025; Kim et al., 2025; Sarkar et al., 2024). In essence, the K-means algorithm strives to position data points within each cluster as closely as possible to their corresponding centroid.

The operational procedure of the algorithm unfolds through the following iterative stages:

a) Determination of the number of clusters (K): The user specifies the desired number of clusters, a task that is inherently challenging and often necessitates the application of heuristic or statistical techniques such as the Elbow Method to identify an optimal K value.

b) Initialization of centroids: A set of K initial centroids is randomly selected from the dataset to serve as preliminary reference points for the clusters.

c) Assignment of data points to the nearest centroid: Each data point is allocated to the cluster represented by the nearest centroid, typically determined using the Euclidean distance metric.

d) Recalculation of centroids: Following the assignment phase, each centroid is recalculated as the mean position of all data points contained within its respective cluster.

e) Iteration until convergence: Steps (c) and (d) are repeated iteratively until the centroids stabilize, that is, when no substantial positional change is observed or until a predefined number of iterations is achieved.

The computation of the distance between individual data points and their respective centroids can be demonstrated through a two-dimensional analytical example, as illustrated below.

Parameters

F_j The location of each location when j $\in$ $\{1,2,3, \ldots \mathrm{n}\}$

fx_j The location of each location along the x axis

fy_j The location of each location along the y axis

$Cen_{.}$ The location of centroid among a number of data sets.

$Cenx_{.}$ The location of centroid along the x axis

$Ceny_{.}$ The location of centroid along the y axis

$Distance_j$ The distance between location F_j and centroid in case of designing by two dimensions

The Euclidean distance between each data point and the centroid is computed based on the Pythagorean theorem, as presented below.

$$Distance_j = \sqrt[2]{(fx_j - Cenx_{.})^2 + (fy_j - Ceny_{.})^2} \tag{1}$$

In summary, the K-means clustering algorithm is extensively utilized to determine the central position among a set of entities characterized by quantitative dimensions. Moreover, the resulting centroid represents not only the geometric center but also ensures that each connection between the centroid and individual data points corresponds to the shortest possible distance. Accordingly, it can be argued that identifying such a centroid among multiple locations facilitates the optimization of vehicle routes, thereby minimizing overall travel distance within the delivery network.

2.2 Problem statement

The formulation of the LCDL-ISCM problem focuses on a logistics process in which various manufacturers transport heterogeneous goods using one-ton pickup trucks to designated terminals. At these terminals, or at customs checkpoints along the national border, products from multiple suppliers are unloaded and subsequently reloaded onto other one-ton pickup trucks for delivery to diverse destinations. This operation closely resembles a cross-docking process, as the goods are transferred between carriers and the responsibility for their conveyance is shifted. Following the completion of cross-docking activities at border points, the heterogeneous products are transported by one-ton pickup trucks to their respective final destinations. This logistical configuration clearly illustrates the core challenge of identifying an optimized strategy that minimizes transportation distance and enhances efficiency within an international delivery network.

2.3 Classical Cross-Docking at the National Border: CCDNB

The term CCDNB refers to a conventional logistics practice involving the transshipment of goods at an official national border point between two countries prior to final delivery to their respective destinations abroad. Within this framework, multiple vehicles typically consolidate a diverse range of products sourced from various suppliers in the originating country and subsequently transport these consignments to the nearest designated border facility. Upon arrival, the goods are unloaded, transshipped, and cross-docked before being reloaded onto vehicles operating under the transportation system of the receiving country. These vehicles then proceed to distribute the shipments to their respective destinations. Fundamentally, the CCDNB process seeks to minimize the transportation distance between each supplier and the national border point prior to cross-docking operations, thereby enabling the most efficient distribution of goods to end destinations in the partner country. The following section presents a detailed scientific scenario that systematically models and analyzes the CCDNB framework.

2.3.1 To consolidate products, and then transport to the national border point before crossdocking

The producers in the first country are required to transport and deliver their products from small-scale manufacturing sites to national border points using one-ton pickup trucks. In this process, each manufacturer is individually responsible for managing its own transportation operations.

Parameters

K The total number of crossdocking points.

x_j The location of each supplier in the original country.

B_i The set of locations is needed to be crossdocking at the nearest border point i .

b_i The location of the nearest border point where each supplier requires transporting their products to crossdocking at that point.

$|| x_j - b_i||^2$ The distance between the location of each supplier x_j and the nearest border b_i following the Euclidian concept.

d_{ij} The distance between the location of each supplier x_j and the nearest border b_i following GIS concept.

A The summation of all distances from suppliers to the crossdocking point before crossing the country border. The transportation process from the original suppliers to the cross-docking facilities located at national border points is designed to determine the most efficient routing within the delivery network before transferring transport responsibilities to logistics providers in other countries. Furthermore, the primary objective of this approach is to achieve the minimum possible transportation distance, which can be formally expressed as follows.

2.3.1.1 Objective function

$$min\ A = \sum_{i=1}^{k} \sum\nolimits_{x_j \in B_i} \sqrt{|| x_j - b_i||^2} \tag{2}$$

2.3.1.2 Constraint function

2.3.1.2.1 The summation of all set of locations is needed to be crossdocking at the nearest border point i is equal to the number of cross docking point.

$$\sum_{i=1}^{k} B_i = K \qquad \forall \mathrm{i} \in \{1,2,3,\ldots \mathrm{k}\} \tag{3}$$

2.3.1.2.2 The Euclidian distances are ideally replaced by the distance between two location following GIS concept, since the places on the land in the real world are connected by the road lines.

$$\sqrt{||\, x_j - b_i||^2} \cong d_{ij} \quad \forall \mathrm{i} \in \{1,2,3,\ldots \mathrm{k}\},\ \forall \mathrm{j} \in \{1,2,3,\ldots \mathrm{n}\} \tag{4}$$

2.3.2 To consolidate products from the national border point after crossdocking, and then transport to the destination in overseas country

Overseas transport providers first load goods after cross-docking at the national border, utilizing one-ton pickup trucks, and subsequently deliver each container to its designated destination in the foreign country. Furthermore, the objective of this program is to determine the shortest possible transportation distance, which can be formally represented as follows.

Additional parameters

y_q The delivery destination in the overseas country.

B_i The set of locations is needed to be crossdocking at the nearest border point i .

b_i The location of the nearest border point where each transport provider requires transporting their one-ton weight pick-up truck to crossdocking at that point.

$||\, y_q - b_i||^2$ The distance between the location of each destination y_q and the nearest border b_i following the Euclidian concept.

d_{iq} The distance between the location of each delivery destination y_q and the nearest border b_i following GIS concept.

E The summarization of all distances from the delivery destinations to the crossdocking points after crossing in another countries

The transportation from the border point to the final delivery destination following cross-docking overseas is designed to achieve the most efficient route within the delivery network. Furthermore, the objective of this framework is to determine the absolute shortest distance, which can be formally expressed as follows.

2.3.2.1 Objective function

$$min\ E = \sum_{i=1}^{k} \sum\nolimits_{y_q \in B_i} \sqrt{||\, y_q - b_i||^2} \tag{5}$$

2.3.2.2 Constraint function

2.3.2.2.1 The summation of all set of locations is needed to be crossdocking at the nearest border point i is equal to the number of cross docking point.

$$\sum_{i=1}^{k} B_i = K \qquad \forall \mathrm{i} \in \{1,2,3,\ldots \mathrm{k}\} \tag{6}$$

2.3.2.2.2 The Euclidian distances are ideally replaced by the distance between two location following GIS concept, since the places on the land in the real world are connected by the road lines.

$$\sqrt{||\, y_q - b_i||^2} \cong d_{iq} \quad \forall \mathrm{i} \in \{1,2,3,\ldots \mathrm{k}\},\ \forall \mathrm{q} \in \{1,2,3,\ldots \mathrm{z}\} \tag{7}$$

Finally, the cross-border transportation of goods using a one-ton pickup truck, following a conventional approach, aims to minimize the distance traveled by routing shipments through cross-docking facilities located at national border points between the two counties. Moreover, this transportation scenario can be mathematically formulated in terms of objective functions as follows.

$$CCDNB \left\{ \begin{matrix} Min\ A = \sum_{i=1}^{k} \sum_{x_j \in B_i} d_{ij} \\ Min\ E = \sum_{i=1}^{k} \sum_{y_q \in B_i} d_{iq} \end{matrix} \right. \tag{8}$$

or

$$CCDNB = \quad Min\,A + \; Min\,E \tag{9}$$

Accordingly, the objective functions (8) and (9) aim to determine the optimal scientific model of the Cross-Docking at the National Border (CCDNB) by establishing the cross-docking point at the national border between two countries. Specifically, the original producers are responsible for transporting their products via one-ton pickup trucks to the national border, where the goods are unloaded and cross-docked to an overseas transport provider. Subsequently, the products are delivered to their final destinations using one-ton pickup trucks. Notably, the operational framework of CCDNB is rigorously defined by the constraint functions (3)–(4) and (6)–(7).

2.4 Extended K-means clustering algorithm with GIS: EKM-GIS

EKM-GIS is proposed as an introductory mechanism for transshipping products at optimized cross-docking points between two countries prior to final delivery. Initially, manufacturers are responsible for transporting their products to the cross-docking point in the country of origin using one-ton pickup trucks. Following the first cross-docking process, products are consolidated and transported across the border to the destination country via ten-wheel trucks carrying a full load of 30 tons. It is noteworthy that the carrying capacities of the one-ton pickup trucks and ten-wheel trucks are strictly limited to 1 ton and 30 tons, respectively (Department of Highways, 2023). Upon arrival in the destination country, the ten-wheel trucks deliver the products to a second cross-docking point, from which local one-ton pickup trucks of overseas service providers distribute the products to the final delivery destinations. Subsequently, an alternative cross-docking scenario employing the extended K-means clustering integrated with GIS (EKM-GIS) was developed to enhance the efficiency of international logistics operations. This approach is articulated through three distinct stages of transportation, as detailed in the following sections.

2.4.1 The transportation from the original suppliers to the domestic crossdocking point in the primary country

Specifically, individual manufacturers are responsible for transporting their goods using one-ton pickup trucks to designated domestic consolidation points, where cargo from multiple suppliers is aggregated and subsequently loaded into containers. Each manufacturer independently manages and oversees the transportation of its products to these consolidation sites prior to initiating cross-docking operations. In practice, cross-docking points cannot be located outside the corporate premises or at open-air factory sites due to safety and security concerns. Therefore, for the purposes of this conceptual framework, cross-docking points are assumed to coincide with the original supplier locations, which effectively minimizes domestic transportation distances within the originating country. Furthermore, the corresponding mathematical model can be formally expressed as follows.

Additional parameters

C_i The set of the original supplier locations at the first country require transport their goods to the domestic crossdocking point i before going to across the country border to another nation.

x_j The original supplier location needs to transport its product to the domestic crossdocking point in group C_i.

μ_i The centroid for making the crossdocking activity for group i at the primary nation.

$|| x_j - \mu_i||^2$ The squared Euclidean distance between location x_j and the centroid μ_i at the primary nation.

$d1_{ij}$ The distance between the location of each supplier x_j and the centroid μ_i following GIS concept.

J The summation of all distances between location x_j and the centroid μ_i at the primary nation

The objective of transporting goods from the original suppliers to the domestic cross-docking point in the primary country is to minimize domestic transport distances, as illustrated below.

2.4.1.1 Objective function

$$min\,J = \sum_{i=1}^{k} \sum\nolimits_{x_j \in C_i} \sqrt{|| x_j - \mu_i||^2} \tag{10}$$

2.4.1.2 Constraint function

2.4.1.2.1 The original suppliers have to transport their products to the domestic crossdocking point when $n(\,)$ is the path number of transporting to the centroid μ_i in the primary nation.

$$\sum_{x_j \in C_i} j = n(|| x_j - \mu_i||^2) \tag{11}$$

2.4.1.2.2 The summation of all domestic transport distances from the original suppliers to the centroid within C_i has the lowest value.

$$min \sum_{x_j \in C_i} J = \sum\nolimits_{x_j \in C_i} \sqrt{||\, x_j - \mu_i||^2} \tag{12}$$

2.4.1.2.3 The Euclidian distances are ideally replaced by the distance between two location following GIS concept, since the places on the land in the real world are connected by the road lines.

$$\sqrt{||\, x_j - \mu_i||^2} \cong d1_{ij} \quad \forall \mathrm{i} \in \{1,2,3, \ldots \mathrm{k}\}, \;\; \forall \mathrm{j} \in \{1,2,3, \ldots \mathrm{n}\} \tag{13}$$

2.4.2 The transportation from the oversea crossdocking point to the destination in another country

Certainly, fully loaded 30-ton containers, transported by ten-wheeled trucks, are employed to deliver goods to cross-docking points in foreign countries, where the cargo is subsequently unloaded. From these points, further distribution to final destinations is carried out using local pick-up trucks with a one-ton capacity. Notably, each end-customer bears individual responsibility for arranging transportation of their goods from the cross-docking point within the destination country. In practical logistics operations, cross-docking locations cannot be designated outside the established business network or at outdoor delivery sites due to security concerns and potential hazards. Consequently, the cross-docking point in this conceptual framework is selected from destinations that facilitate the shortest possible distance in international transportation to the second country. Furthermore, the proposed systematic model can be illustrated as follows.

Additional parameters

L The total number of crossdocking points in the foreign country.

D_p The set of the delivery destination locations at the second country requires coming to transport goods at the crossdocking point p in other nation.

y_q the delivery destination locations at the second country need to transship its product at the crossdocking point in group D_p.

β_p The centroid for making the crossdocking activity for group p at the second nation.

$||\, y_q - \beta_p||^2$ The squared Euclidean distance between location y_q and the centroid β_p at the second nation.

$d2_{pq}$ The distance between the location of each supplier y_q and the centroid β_p following GIS concept.

Q The summation of all distances between location y_q and the centroid β_p at the primary nation

The objective of transporting goods from the overseas cross-docking point to delivery destinations in the second country is to minimize international transport distances, as illustrated below.

2.4.2.1 Objective function

$$min\, Q = \sum_{p=1}^{L} \sum\nolimits_{y_q \in D_p} \sqrt{||\, y_q - \beta_p\, ||^2} \tag{14}$$

2.4.2.2 Constraint function

2.4.2.2.1 One-ton weight pick-up truck s assigned to collect goods from the consignee must transport the cargo from only a single designated crossdocking point in the respective foreign country when $n(\,)$ *is the path number of transporting to the centroid* β_p *in the second nation.*

$$\sum_{y_q \in D_p} q = n(||\, y_q - \beta_p||^2) \tag{15}$$

2.4.2.2.2 The summation of all oversea transport distances from the delivery destination to the centroid within D_p *has the lowest value.*

$$min \sum_{y_q \in D_p} Q = \sum\nolimits_{x_j \in C_i} \sqrt{||\, y_q - \beta_p||^2} \tag{16}$$

2.4.2.2.3 The Euclidian distances are ideally replaced by the distance between two location following GIS concept, since the places on the land in the real world are connected by the road lines.

$$\sqrt{\left|\left| y_q - \beta_p \right|\right|^2} \cong d2_{pq} \quad \forall \mathrm{p} \in \{1,2,3,\dots \mathrm{l}\},\ \forall \mathrm{q} \in \{1,2,3,\dots \mathrm{m}\} \tag{17}$$

2.4.3 The transportation from the domestic crossdocking point in the primary country to the oversea crossdocking point in another country

Certainly, this process is initiated upon the completion of cross-docking activities in the primary country, after which the goods are transported as 30-ton full truckload shipments via ten-wheel trucks across international borders. Upon arrival at a designated cross-docking facility in the destination country, the shipments are unloaded and subsequently distributed to their respective final destinations. Within the framework of this research, the cross-docking facility in the origin country is selected from among multiple supplier locations, whereas the facility in the destination country is chosen from a set of delivery destinations. Furthermore, the corresponding scientific scenario can be formally established as follows.

Additional parameter

$d3_{ip}$ The distance between the location of domestic centroid μ_i and the oversea centroid β_p following GIS concept, which is the actual path along the road line between crossdocking points in the different countries.

R The summation of all distances between centroid μ_i and the centroid β_p in the dissimilar countries

T_{ip} The total transport times between centroid μ_i and the centroid β_p in the dissimilar countries

The objective of transporting goods from the domestic cross-docking facility in the primary country to the overseas cross-docking facility in the secondary country is to minimize the transportation distance, as illustrated below.

2.4.3.1 Objective function

$$\min R = \sum_{i=1}^{K} \sum\nolimits_{p=1}^{L} T_{ip} \sqrt{\left|\left| \mu_i - \beta_p \right|\right|^2} \tag{18}$$

2.4.3.2 Constraint function

2.4.3.2.1 A trailer departing from a domestic cross-docking facility is required to deliver goods to a single overseas cross-docking point. This restriction, enforced in the present study, aligns with international freight regulations, which mandate that shipments be directed to only one destination.

$$\sum_{i=1}^{K} i = \sum_{p=1}^{L} p \tag{19}$$

2.4.3.2.2 The summation of all transport distances from the domestic crossdocking point in the primary country to the oversea crossdocking point in the second country has the lowest value.

$$\min \sum_{i,p \in K,L} R = \sum\nolimits_{i,p \in K,L} \sqrt{\left|\left| \mu_i - \beta_p \right|\right|^2} \tag{20}$$

2.4.3.2.3 The Euclidian distances are ideally replaced by the distance between two location following GIS concept, since the places on the land in the real world are connected by the road lines.

$$\sqrt{\left|\left| \mu_i - \beta_p \right|\right|^2} \cong d3_{iq} \quad \forall \mathrm{i} \in \{1,2,3,\dots \mathrm{k}\},\ \forall \mathrm{p} \in \{1,2,3,\dots \mathrm{w}\} \tag{21}$$

2.4.3.2.4 A ten-wheel truck possesses a carrying capacity approximately 30 times greater than that of a one-ton pickup truck. Consequently, the total number of transport trips required between the cross-docking facility in the primary country and those in the other countries can be expressed as follows.

$$T_{ip} = \left(\frac{1}{30}\right) \sum\nolimits_{x_j \in C_i} x_j \tag{22}$$

Or

$$T_{ip} = \left(\frac{1}{30}\right) \sum\nolimits_{y_q \in D_p} y_q \tag{23}$$

Consequently, this schoolwork addresses the consolidation of goods from multiple origins to domestic transshipment hubs and their subsequent distribution to international transshipment points for final delivery to end customers. The objective is to determine the optimal locations of both domestic and international transshipment hubs under the constraint of minimizing the overall transportation distance. This is achieved through the application of the Extended K-Means (EKM) clustering method an enhancement of the traditional K-Means clustering algorithm integrated with Geographic Information Systems (GIS). The entire process can be formalized within a mathematical modeling framework as follows.

$$EKM - GIS \text{ covers} \qquad \begin{aligned} min\,J &= \sum_{i=1}^{k} \sum\nolimits_{x_j \in C_i} d1_{ij} \\ min\,Q &= \sum_{p=1}^{L} \sum\nolimits_{y_q \in D_p} d2_{pq} \\ min\,R &= \sum_{i=1}^{K} \sum\nolimits_{p=1}^{L} T_{ip} d3_{ip} \end{aligned} \tag{24}$$

Or

$$EKM - GIS = \quad Min\,J + \ Min\,Q + \ Min\,R \tag{25}$$

Eq. (24) and Eq. (25) constitute the mathematical formulation of the EKM-GIS model, providing a foundational framework for the development of an algorithm aimed at efficiently identifying optimal logistics cross-docking points. The model delineates the transportation process in which individual producers employ one-ton pick-up trucks to deliver goods to domestic transshipment centers, where shipments are consolidated and subsequently loaded onto ten-wheel trucks with a full capacity of 30 tons for cross-border transport. Upon reaching international transshipment points, the goods are unloaded and distributed to their respective final destinations using one-ton pick-up trucks. The operation of the EKM-GIS model is governed by a set of constraints specified in Eqs. (11-13), Eqs. (15-17), and Eqs. (19-23).

2.5 Geographical Information System: GIS

A Geographic Information System (GIS) constitutes a computational framework for the acquisition, storage, analysis, and management of spatially referenced data. By enabling the identification of patterns, spatial relationships, and contextual geographic insights within datasets, GIS serves as an indispensable tool across diverse domains, including field excursion planning, environmental monitoring, and transportation systems analysis.

In the present study, the assessment of transportation route conditions is conducted utilizing GIS-derived data. The analytical process involves calculating distances between various transport nodes by extracting real-time information from the Google Maps database. Google Maps, developed by Google Inc., represents a significant advancement in navigational technology, offering the capability to determine the shortest path between two geographical points. The platform employs structured map data and a graph-based routing algorithm specifically Dijkstra's algorithm which identifies all feasible paths before computing the shortest route. This process integrates real-time GPS signals to account for prevailing traffic conditions, thereby providing accurate travel time estimates (Ganiyev et al., 2023; McQuire, 2019; Mehta et al., 2019).

Such node-based spatial analysis not only enables precise distance computation but also facilitates reliable estimation of travel durations, serving as a proxy for current traffic conditions. Within this study, both distance and travel time are adopted as key indicators of transportation and logistics performance (Dadsena et al., 2023; Argiyantari et al., 2022; Pathak et al., 2019). Moreover, the study proposes the development of an application designed to strategically identify optimal freight transfer points. This approach integrates an enhanced K-means clustering algorithm within a GIS framework, aiming to optimize logistical efficiency by minimizing transport distances and travel times. Simultaneously, such optimization is anticipated to strengthen stakeholder confidence in the performance and reliability of international supply chains.

2.6 Conceptual framework

In the context of international supply chains, the foundation of land-based freight transport and cargo handling operations rests on each enterprise's commitment to ensuring that goods are delivered to their designated destinations in accordance with customer requirements. Nonetheless, logistics service providers frequently face rising operational costs and increasing logistical complexities. Such challenges often stem from efforts to maintain elevated service levels in response to customer demands—for instance, the absence of optimally designated transshipment points due to time constraints or the necessity of providing immediate responses to client inquiries. These circumstances frequently necessitate longer travel distances, thereby extending delivery times and amplifying operational costs, which in turn are reflected in the overall cost structure, resulting in higher total expenditures.

Accordingly, one of the primary objectives of this study is to evaluate transport operational performance with respect to distance optimization. Specifically, the study compares two approaches: Classical Cross-Docking at the National Border (CCDNB) and an integrated methodology combining the Extended K-Means (EKM) clustering technique with Geographic Information Systems (EKM-GIS) to determine cross-docking locations. The purpose is to examine whether the application of such advanced analytical tools can enhance logistical efficiency by reducing transportation distances. The conceptual framework underlying this research entails the development of a scientific model for the efficient determination of cross-docking points, utilizing the EKM clustering method in conjunction with GIS technology, within the broader framework of international supply chain logistics, as illustrated in Fig. 1. Consequently, EKM-GIS has been systematically developed based on insights from CCDNB and is anticipated to enable transport planners to identify shorter transportation routes within international supply chains. The research framework for this investigation is presented in Fig. 1.

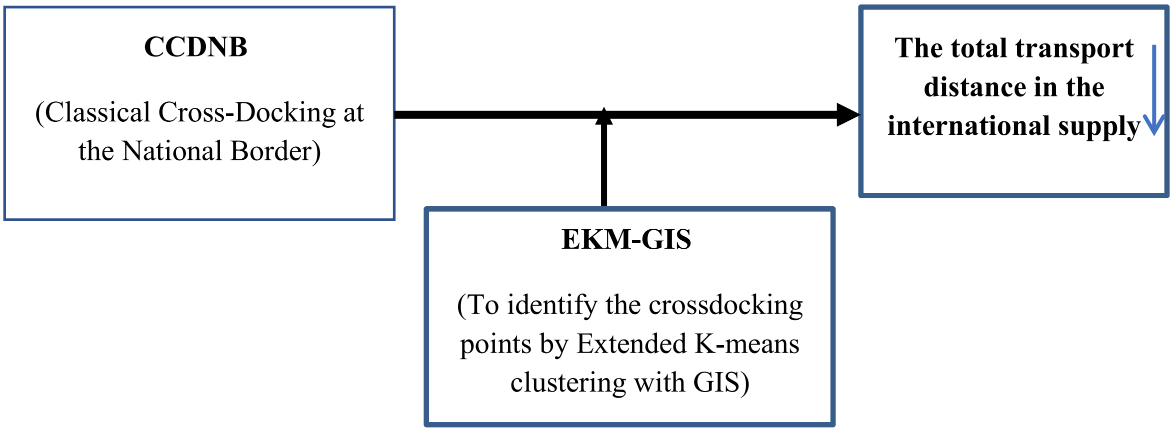

Fig. 1. The research model. Source: the Authors

3. Research method

3.1 Initial population

This study seeks to assess transportation efficiency by comparing cumulative transport distances generated from the CCDNB and EKM-GIS models within the context of international supply chain logistics. To establish a representative cross-border scenario, a set of locations was randomly selected from land-connected regions of Thailand and Cambodia. These locations were drawn from official sources, namely the Provincial Statistical Reports of Thailand (National Statistical Office, 2024) and the administrative database of the Kingdom of Cambodia (Department of Local Administration, 2024). Accordingly, at this stage of the analysis, all supplier sites within the primary country and all delivery destinations in the secondary country were systematically identified, providing a comprehensive framework for subsequent logistical evaluation.

3.2 Data collection

All transportation routes connecting the location pairs analyzed in this study were extracted using the Google Maps application. As a publicly accessible and cost-free platform, Google Maps enables precise measurement of distances between geographical points, in accordance with Geographic Information Systems (GIS) principles. Moreover, the distance estimates provided by the platform are generated from real-time data collected via the Global Positioning System (GPS) and are informed by a substantial volume of active road users, particularly drivers. Consequently, these measurements can be regarded as analytically representative of the shortest feasible routes between locations, benefiting from aggregated user data and exhibiting a high degree of reliability for road network analysis in logistics and supply chain applications.

3.3 Data analysis

All secondary datasets employed in this study were rigorously analyzed using quantitative methodologies. Initially, the Google Maps application functioned not only as a tool for the random selection of locations but also as a critical instrument for calculating inter-site distances, encompassing all relevant transportation routes in accordance with the conceptual frameworks of CCDNB and EKM-GIS, respectively. Following the acquisition of data including randomized districts and associated transportation networks, these datasets were systematically evaluated within the parameters of the established research framework.

Subsequently, the analytical results obtained from this study offer valuable insights for the formulation of innovative strategic guidelines aimed at enhancing the efficiency of international transportation systems. In particular, these findings may facilitate the optimization of cross-docking operations by reducing transport distances through the improvement of road network linkages. Furthermore, the complete dataset was subjected to additional analysis using the Solver Add-in in Microsoft Excel 2024, a computational tool employed to implement optimization algorithms. Finally, the numerical applications of the CCDNB and EKM-GIS methodologies were systematically executed and are illustrated in Fig. 2 and Fig. 3, respectively.

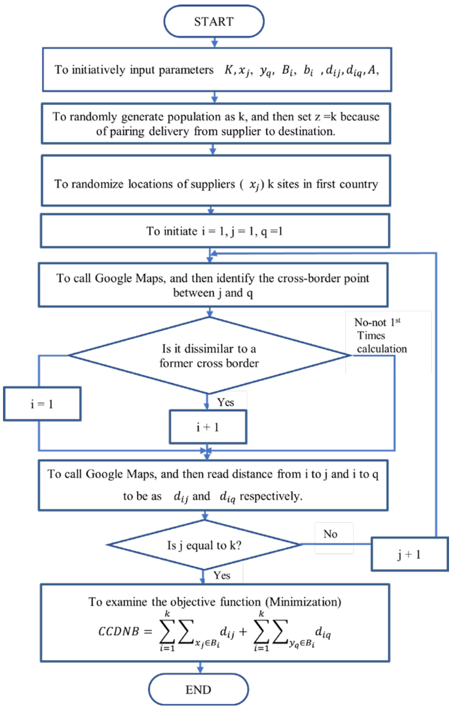

Fig. 2. Flow chart of Classical Cross-Docking at the National Border. Source: The Authors

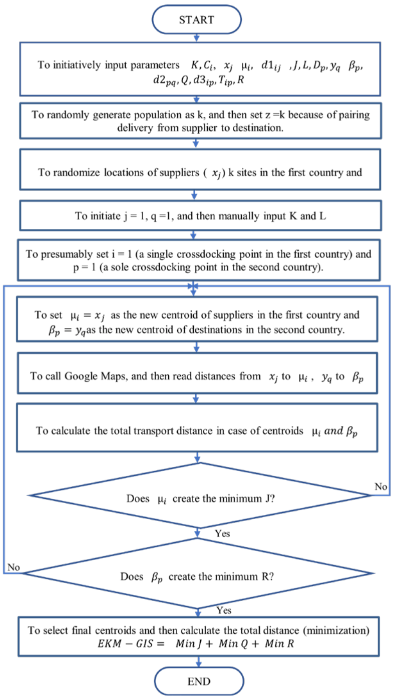

Fig. 3. Extended K-means clustering algorithm with GIS. Source: The Authors

4 Results

4.1 Initial population

This study employed a randomized sampling strategy to identify representative locations by integrating data from the Google Maps platform with official statistics from the Provincial Statistics of Thailand (National Statistical Office, 2024) and the administrative framework of the Kingdom of Cambodia (Department of Local Administration, 2024).

Table 1

The random of the supplier locations and the delivery locations. Source: the Authors

j	Supplier location in Thailand (x_j)	q	Delivery destination in Cambodia (y_q)
1	Phangnga	1	Puok
2	Sa Kaeo	2	Svay Leu
3	Loei	3	Banteay Srei
4	Phatthalung	4	Kampong Chhnang
5	Samut Sakon	5	Soutr Nikom
6	Kalasin	6	Koh Kong
7	Bungkan	7	Phnom Penh
8	Chanthaburi	8	Stung Treng
9	Bangkok	9	Takéo
10	Uttaradit	10	Svay Rieng
11	Surat Thani	11	Sisophon
12	Phra Nakhon Si Ayutthaya	12	Battambang
13	Phuket	13	Kratié
14	Amnat Charoen	14	Chi Kraeng
15	Pathum Thani	15	Pailin
16	Nong Khai	16	Ratanakiri
17	Udon Thani	17	Preah Vihear
18	Nakhon Ratchasima	18	Siem Reap
19	Trang	19	Srei Snam
20	Nakhon Si Thammarat	20	Prasat Bakong
21	Saraburi	21	Angkor Chum
22	Mae Hong Son	22	Preah Sihanouk
23	Pattani	23	Pou Pir Daeum
24	Narathiwat	24	Kampong Speu
25	Krabi	25	Kralanh
26	Phetchaburi	26	Prey Veng
27	Roi Et	27	Pursat
28	Kamphaeng Phet	28	Banteay Meanchey
29	Ubon Ratchathani	29	Kandal
30	Lamphun	30	Tboung Khmum

Specifically, thirty distinct supplier sites in Thailand and an equal number of corresponding delivery destinations in Cambodia were identified through a randomized computational procedure facilitated by Google Maps. Subsequently, the complete set of direct delivery routes between each supplier–destination pair was established using a computer-assisted, randomized mapping approach. All geographic locations were classified according to provincial or district-level nomenclature, deliberately avoiding any reference to personally identifiable or proprietary site information. The resulting dataset, encompassing all international delivery pairings transported via one-ton pickup trucks from Thai suppliers to Cambodian recipients, is comprehensively presented in Table 1. Distances between each supplier–destination pair were obtained from the Google Maps application, while supplier capacities and customer demand quantities were generated randomly during this phase.

4.2 Distribution following the procedure of CCDNB

To evaluate the implications of this conceptual framework, domestic suppliers were required to initiate delivery operations using their one-ton capacity pickup trucks, with the national border serving as the preferred cross-docking hub prior to transferring transport responsibility to international counterparts employing similarly equipped vehicles. Additionally, it was essential to identify the most proximate border crossing for each supplier–destination pair. This location, denoted as (B_i) was selected as the cross-docking hub based on its ability to simultaneously minimize the distance from the supplier (d_{ij}) and the distance to the destination (d_{iq}). To support this process, the Google Maps application was employed as a Geographic Information System (GIS) tool to determine the nearest border crossings and calculate the corresponding distances, the results of which are summarized in Table 2.

Table 2
The nearest border point and the relative distances following CCDNB. Source: the Authors

j	q	Delivery trip	i	The nearest border point (B_i)	d_{ij}(Kms)	d_{iq}(Kms)
1	1	x_1 to y_1	1	Krong Poi Pet	1005	135
2	2	x_2 to y_2	5	Ban Klong Luk Border	58	215
3	3	x_3 to y_3	10	Sisaket Immigration Checkpoint	524	106
4	4	x_4 to y_4	1	Krong Poi Pet	1093	318
5	5	x_5 to y_5	1	Krong Poi Pet	286	192
6	6	x_6 to y_6	2	Ban Hat Lek Border	680	10.4
7	7	x_7 to y_7	4	Nam Yuen District	594	454
8	8	x_8 to y_8	8	Kamrieng	76.4	503
9	9	x_9 to y_9	1	Krong Poi Pet	246	54.3
10	10	x_{10} to y_{10}	1	Krong Poi Pet	650	527
11	11	x_{11} to y_{11}	1	Krong Poi Pet	885	46.7
12	12	x_{12} to y_{12}	1	Krong Poi Pet	260	113
13	13	x_{13} to y_{13}	1	Krong Poi Pet	1088	484
14	14	x_{14} to y_{14}	7	Chong Sangam Customs House	258	187
15	15	x_{15} to y_{15}	6	Ban Pakkad Border Checkpoint	329	24.8
16	16	x_{16} to y_{16}	4	Nam Yuen District	548	404
17	17	x_{17} to y_{17}	9	Kantharalak District	443	133
18	18	x_{18} to y_{18}	3	Chong Chom border crossing	216	169
19	19	x_{19} to y_{19}	1	Krong Poi Pet	1078	131
20	20	x_{20} to y_{20}	1	Krong Poi Pet	1025	182
21	21	x_{21} to y_{21}	1	Krong Poi Pet	230	132
22	22	x_{22} to y_{22}	2	Ban Hat Lek Border	1187	233
23	23	x_{23} to y_{23}	1	Krong Poi Pet	1286	60.3
24	24	x_{24} to y_{24}	2	Ban Hat Lek Border	1544	259
25	25	x_{25} to y_{25}	1	Krong Poi Pet	1019	96.6
26	26	x_{26} to y_{26}	1	Krong Poi Pet	376	477
27	27	x_{27} to y_{27}	3	Chong Chom border crossing	203	342
28	28	x_{28} to y_{28}	3	Chong Chom border crossing	601	139
29	29	x_{29} to y_{29}	4	Nam Yuen District	125	475
30	30	x_{30} to y_{30}	1	Krong Poi Pet	837	428
				Total	18750.4	7031.1

As presented in Table 2, the analysis indicates that the delivery scenario involved eight designated border locations functioning as cross-docking hubs prior to the handover of goods to international transport providers operating one-ton capacity pickup trucks. The initially assigned cross-docking points included Krong Poi Pet, Ban Hat Lek Border, Chong Chom Border Crossing, Nam Yuen District, Ban Klong Luk Border, Ban Pakkad Border Checkpoint, Chong Sangam Customs House, Kamrieng (Kantharalak District), and the Sisaket Immigration Checkpoint. These sites served as transitional logistics nodes within the distribution network. Among these, Krong Poi Pet emerged as the most frequently utilized cross-docking point, appearing in 15 instances, whereas Ban Klong Luk Border, Ban Pakkad Border Checkpoint, Chong Sangam Customs House, Kamrieng, Kantharalak District, and the Sisaket Immigration Checkpoint were each used only once.

Regarding transportation distances, the cumulative domestic transport distance within the primary country, managed by suppliers using one-ton pickup trucks, was approximately 18,750.4 kilometers, mathematically expressed as: $Min\ A =$

$\sum_{i=1}^{k}\sum_{x_j \in B_i} d_{ij}$. In contrast, the total overseas transport distance, carried out by international providers with comparable vehicles, was estimated at 7,031.1 kilometers: $Min\ E = \sum_{i=1}^{k}\sum_{y_q \in B_i} d_{iq}$. Accordingly, the implementation of the CCDNB (Cross-docking Consolidation Distribution Network-Based) model resulted in a combined transport distance of approximately 25,781.5 kilometers.

4.3 Distribution following the procedure of EKM-GIS

In line with the established framework, it was essential first to identify and analyze the domestic cross-docking hub in the primary (home) country and the international cross-docking hub in the foreign country, before performing a computational optimization of transportation distances, as prescribed by the objective function embedded within the EKM-GIS methodology. It is noteworthy that the geographical coordinates of all supplier origins and international destinations were previously specified in Table 1. This analysis was subsequently conducted under the operational constraints of K = 1 and L = 1.

The investigation began with the determination of the domestic centroid. To this end, Google Maps was employed to calculate the pairwise distances among the thirty supplier locations within the primary country. The resulting domestic distance matrices are systematically presented in Table 3(a) and Table 3(b). Analysis further revealed that all supplier nodes, denoted as x_j, were optimally routed through a central cross-docking facility located in Saraburi, Thailand (x_{21}), as this configuration minimized the cumulative transport distance to the centroid. Quantitatively, this outcome is expressed by the minimization function: $min\,J = \sum_{i=1}^{k}\sum_{x_j \in C_i}\sqrt{||\,x_j - \mu_i||^2}$ resulting in an aggregate transport distance of approximately 15,739.6 kilometers. Subsequently, the Google Maps application was utilized to determine the inter-location distances among thirty designated destinations in the second country. The resultant international distance matrix is systematically documented in Table 4(a) and Table 4(b). Notably, all customer locations (y_q) were found to be optimally served by one-ton capacity pickup trucks transporting goods to the cross-docking facility in Siem Reap, Cambodia (x_{18}). This configuration achieved the minimal aggregate transport distance to the centroid, mathematically expressed as: $min\,Q = \sum_{p=1}^{L}\sum_{y_q \in D_p}\sqrt{||\,y_q - \beta_p\,||^2}$ with a total distance of approximately 6,462 kilometers. At this stage, the geographic distribution of cross-docking nodes across the two countries was delineated, indicating that the initial cross-docking facility was located in Saraburi, Thailand, while the corresponding node in the second country was established in Siem Reap, Cambodia. Further analysis determined that the inter-facility distance between these two nodes, as measured via Google Maps, was approximately 376 kilometers.

Table 3(a)

The supplier distance matrix (unit in Kilometer) connecting by the road line (1/2). Source: the Authors

x_j	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}	x_{11}	x_{12}	x_{13}	x_{14}	x_{15}
x_1		947	1295	303	722	1274	147	994	764	1231	161	832	120	1361	798
x_2	948		509	1035	229	431	631	158	189	587	826	197	1028	457	179
x_3	1297	509		1384	578	301	324	667	542	243	1175	492	1377	484	511
x_4	305	1035	1384		810	1362	1562	1082	852	1319	225	920	340	1449	886
x_5	720	229	577	807		555	755	275	44.8	513	597	114	800	642	79.1
x_6	1275	429	303	1362	556		269	538	520	501	1152	473	1355	187	489
x_7	1471	625	322	1558	752	271		784	717	542	1349	669	1551	404	685
x_8	994	158	667	1081	274	548	789		251	713	871	307	1074	582	265
x_9	765	189	544	852	45.4	522	722	249		480	642	81.1	845	610	43.2
x_{10}	1244	588	243	1331	525	498	546	709	486		1122	409	1325	681	456
x_{11}	161	827	1175	224	602	1153	1353	873	643	1111		712	241	1240	677
x_{12}	840	197	487	927	121	467	667	304	80.7	407	717		920	555	51.1
x_{13}	122	1030	1378	345	805	1356	1556	1076	846	1314	238	915		1444	881
x_{14}	1365	460	480	1452	646	183	394	577	610	678	1242	563	1445		579
x_{15}	797	180	512	884	77.6	490	690	263	40.8	459	674	53.3	877	577	
x_{16}	1367	521	175	1454	648	208	151	680	613	395	1245	565	1448	361	581
x_{17}	1317	471	157	1404	597	157	166	629	562	377	1194	514	1397	310	530
x_{18}	1017	166	342	1105	298	262	462	324	263	467	895	215	1098	350	231
x_{19}	238	1021	1369	57	796	1347	1547	1067	837	1305	210	906	282	1434	871
x_{20}	255	967	1315	110	742	1293	1493	1013	783	1251	141	852	305	1380	817
x_{21}	867	167	430	954	147	411	612	330	112	402	744	50.7	947	499	80.2
x_{22}	1565	908	697	1652	846	914	1001	1030	806	461	1443	730	1645	1098	777
x_{23}	499	1229	1577	200	1003	1555	1755	1275	1045	1513	418	1114	534	1642	1079
x_{24}	611	1341	1689	312	1116	1667	1868	1387	1157	1625	531	1226	646	1755	1192
x_{25}	120	961	1309	187	736	1287	1488	1007	777	1245	157	846	163	1375	812
x_{26}	630	318	667	717	93.3	645	845	365	135	602	508	203	711	732	169
x_{27}	1263	373	348	1351	544	76.7	348	491	509	546	1141	461	1344	131	477
x_{28}	1119	462	331	1206	400	514	635	584	360	169	996	283	1199	698	330
x_{29}	1369	427	495	1456	650	218	467	545	614	693	1246	566	1449	94.1	582
x_{30}	1431	775	449	1518	712	704	752	896	673	213	1309	596	1512	887	643

Table 3(b)

The supplier distance matrix (unit in Kilometer) connecting by the road line (2/2). Source: the Authors

x_i	x_{16}	x_{17}	x_{18}	x_{19}	x_{20}	x_{21}	x_{22}	x_{23}	x_{24}	x_{25}	x_{26}	x_{27}	x_{28}	x_{29}	x_{30}
x_1	1365	1316	1013	243	252	864	1557	497	611	117	630	1263	1106	1367	1410
x_2	523	474	169	1023	968	166	912	1229	1344	966	319	374	461	427	765
x_3	178	157	343	1372	1317	431	665	1578	1693	1315	668	348	332	508	449
x_4	1454	1404	1101	57	111	952	1645	199	314	183	718	1351	1194	1455	1498
x_5	647	597	294	795	740	145	838	1001	1116	738	90.7	544	387	648	691
x_6	206	157	262	1350	1295	410	908	1556	1671	1293	646	71.5	517	219	707
x_7	147	179	459	1546	1491	606	965	1752	1867	1489	842	345	631	473	748
x_8	681	631	327	1068	1013	334	1038	1275	1389	1011	364	498	587	552	892
x_9	614	565	261	839	784	112	806	1046	1160	782	135	512	355	615	659
x_{10}	400	379	465	1319	1264	405	429	1526	1640	1262	615	545	168	705	213
x_{11}	1245	1196	892	212	143	743	1436	419	533	155	510	1143	985	1246	1290
x_{12}	559	510	206	914	859	57.4	733	1121	1235	857	210	457	282	560	586
x_{13}	1448	1399	1095	288	305	946	1640	539	653	163	713	1346	1189	1449	1493
x_{14}	360	311	352	1440	1385	500	1085	1646	1761	1383	736	134	695	94.1	884
x_{15}	582	532	229	871	816	80.2	784	1078	1193	814	167	479	333	583	637
x_{16}		50.9	355	1442	1387	502	818	1649	1763	1385	738	280	484	428	601
x_{17}	49.4		304	1391	1336	452	800	1598	1712	1334	687	229	466	377	583
x_{18}	354	305		1092	1037	153	865	1299	1413	1035	388	252	414	378	673
x_{19}	1439	1389	1086		131	937	1630	250	365	124	704	1336	1179	1440	1483
x_{20}	1385	1336	1032	132		883	1576	274	389	153	650	1283	1125	1386	1430
x_{21}	503	454	150	941	886		746	1148	1262	884	237	401	295	504	599
x_{22}	854	834	857	1640	1585	741		1846	1961	1583	936	961	457	1121	221
x_{23}	1647	1597	1294	250	274	1145	1838		116	376	912	1544	1387	1648	1691
x_{24}	1759	1710	1406	363	387	1258	1951	114		489	1024	1657	1500	1760	1804
x_{25}	1379	1330	1026	130	154	878	1571	381	495		644	1277	1120	1380	1424
x_{26}	737	687	384	705	650	235	928	912	1026	648		634	477	738	781
x_{27}	284	234	251	1338	1283	399	953	1545	1659	1281	634		562	159	752
x_{28}	488	468	411	1193	1139	294	463	1400	1515	1137	490	562		721	316
x_{29}	425	375	375	1443	1388	504	1099	1650	1765	1386	740	157	709		899
x_{30}	606	585	671	1506	1451	607	221	1713	1827	1449	802	751	323	911	

Table 4(a)

The destination distance matrix (unit in Kilometer) connecting by the road line (1/2). Source: the Authors

y_a	y_1	y_2	y_3	y_4	y_5	y_6	y_7	y_8	y_9	y_{10}	y_{11}	y_{12}	y_{13}	y_{14}	y_{15}
y_1		79	48.6	354	57.5	429	334	311	413	418	89.6	149	349	80.7	208
y_2	81.6		57.4	352	48.7	605	325	233	404	409	168	227	369	71.9	286
y_3	50.9	57.7		364	60	477	336	290	415	421	137	197	352	83.2	255
y_4	354	353	364		322	355	94	404	165	215	274	202	270	296	276
y_5	60.1	48.7	60	321		573	293	281	372	378	147	206	309	40.2	265
y_6	429	606	617	355	574		297	657	328	427	349	268	523	549	293
y_7	336	325	336	94	293	296		376	74.6	122	362	290	242	267	364
y_8	314	233	290	403	281	656	376		455	334	400	459	135	304	518
y_9	416	405	416	165	373	333	74.9	456		181	433	361	322	347	435
y_{10}	421	410	421	215	378	427	122	332	182		483	410	198	352	485
y_{11}	89.2	168	137	273	146	349	361	400	432	482		68.1	438	169	127
y_{12}	148	227	196	202	205	268	290	459	361	411	68.1		466	229	77.5
y_{13}	352	369	352	269	309	522	242	135	321	199	439	465		283	539
y_{14}	83.3	71.9	83.1	295	40.2	548	267	304	347	352	170	229	283		288
y_{15}	207	286	255	278	264	293	366	518	437	487	127	78.9	542	287	
y_{16}	480	399	455	539	447	792	511	166	591	469	566	625	271	470	684
y_{17}	175	94.6	151	375	143	628	347	181	427	432	262	321	317	166	380
y_{18}	17.9	63.4	35.3	346	42	444	318	295	397	403	104	163	334	65.2	222
y_{19}	73.1	120	99.3	349	130	425	437	348	508	491	85.1	144	422	153	203
y_{20}	50.3	65.5	52.4	348	44	600	320	297	399	405	137	196	336	67.2	255
y_{21}	32.1	111	86	350	89.1	426	365	343	444	450	86.1	145	381	112	204
y_{22}	535	524	535	272	492	223	215	575	245	345	541	468	441	466	542
y_{23}	98.3	177	146	263	155	338	350	409	421	472	18.1	57.2	447	179	109
y_{24}	374	363	374	111	331	248	54.2	414	81.8	184	379	306	280	306	381
y_{25}	39	118	87.2	315	96.1	391	403	350	474	457	51	110	388	119	169
y_{26}	353	341	352	159	310	376	91.4	306	151	80.9	427	355	172	284	429
y_{27}	269	348	318	107	326	238	194	505	266	315	189	117	371	350	191
y_{28}	109	187	157	295	166	370	382	419	454	504	21.2	89.4	458	189	148
y_{29}	357	346	357	99.3	314	271	35.1	397	78.9	151	367	295	263	288	369
y_{30}	296	285	296	170	253	417	131	245	213	126	383	366	111	228	440

Table 4(b)
The destination distance matrix (unit in Kilometer) connecting by the road line (2/2). Source: the Authors

y_a	y_{16}	y_{17}	y_{18}	y_{19}	y_{20}	y_{21}	y_{22}	y_{23}	y_{24}	y_{25}	y_{26}	y_{27}	y_{28}	y_{29}	y_{30}
y_1	477	173	15.6	71	47.7	32.3	532	96.2	372	39.3	350	268	109	354	294
y_2	399	94.6	63.7	150	65.5	111	523	175	363	118	341	347	188	346	285
y_3	456	152	35.1	99.3	52.5	86	535	144	374	87.2	352	316	157	357	296
y_4	540	376	369	350	349	351	273	263	111	316	166	106	295	100	171
y_5	447	143	42.3	128	44	89.4	492	153	331	96.4	309	325	166	314	253
y_6	792	629	444	425	601	426	223	338	249	391	382	237	370	272	418
y_7	511	347	318	438	320	365	215	351	54.2	404	91.2	194	383	35.1	131
y_8	166	181	296	348	298	343	575	407	414	350	308	504	420	397	246
y_9	591	427	398	509	400	445	251	422	81.8	475	151	265	454	77.1	212
y_{10}	467	432	403	489	405	450	345	472	185	457	80.6	315	504	151	126
y_{11}	566	262	104	84.8	136	85.8	540	11.5	378	50.8	433	188	21.2	367	383
y_{12}	625	321	163	144	196	145	469	57.2	307	110	362	117	89.3	296	367
y_{13}	271	317	334	420	336	381	440	445	280	388	174	369	458	263	112
y_{14}	470	166	65.4	151	67.2	113	466	176	306	120	284	349	189	288	228
y_{15}	684	380	222	203	255	204	545	109	383	169	438	192	148	372	443
y_{16}		347	462	514	463	509	710	573	550	516	443	639	586	532	382
y_{17}	347		158	235	159	205	546	269	386	212	364	475	294	368	308
y_{18}	461	157		85.9	32.2	47.2	517	111	356	54.2	334	283	124	339	278
y_{19}	514	235	88.2		120	26.7	616	91.6	454	34.7	423	264	104	443	366
y_{20}	463	159	32.4	118		79.6	519	143	358	86.6	336	316	156	341	280
y_{21}	509	204	47.2	26.7	79.3		564	92.7	403	35.8	382	265	105	386	325
y_{22}	710	546	517	616	519	564		530	166	582	300	372	562	189	336
y_{23}	575	271	113	93.9	146	94.9	530		367	59.9	422	177	39.3	356	427
y_{24}	549	386	356	455	358	404	166	368		421	139	211	400	27.5	175
y_{25}	515	211	54.1	34.6	86.3	35.6	582	57.6	420		389	230	70.4	409	332
y_{26}	442	364	335	421	337	382	294	416	134	389		259	448	121	63.1
y_{27}	640	442	284	265	317	266	374	178	211	231	266		210	200	272
y_{28}	585	293	124	104	156	105	562	32.7	399	70.3	454	209		389	402
y_{29}	532	368	339	443	341	386	189	356	26.6	409	121	199	389		161
y_{30}	380	308	279	364	280	326	336	428	175	333	63.1	270	402	159	

The inter-country transport operation, under parameters K=1 and L=1, was assumed to be executed using a ten-wheeled truck with a maximum payload capacity of 30 tons. The total inter-centroid transport distance for this segment was quantified as: $min\ R = \sum_{i=1}^{K} \sum_{p=1}^{L} T_{ip} \sqrt{|| \mu_i - \beta_p ||^2}$ yielding an estimated distance of 376 kilometers. Consequently, the EKM-GIS model computed the cumulative transport distance across the entire operation to be approximately 22,577.6 kilometers.

In summary, the international transportation process analyzed within this study, under the guidance of the EKM-GIS framework, can be succinctly described as follows: Initially, all suppliers transported their heterogeneous product lines from their respective manufacturing facilities to the strategically designated cross-docking hub in Saraburi, Thailand, using one-ton capacity pickup trucks. The optimal location of this hub was algorithmically determined through the EKM-GIS optimization model. Upon arrival, the goods underwent a cross-docking process, which entailed unloading, systematic reorganization, and consolidation of cargo. Subsequently, the consolidated goods were loaded onto a ten-wheel truck with a payload capacity of 30 tons. This fully laden vehicle then proceeded directly to the secondary cross-docking facility in Siem Reap, Cambodia, crossing a single border checkpoint. Upon reaching the terminal destination, a second cross-docking operation was performed, involving unloading, sorting, and redistribution. Finally, the goods were dispatched via one-ton pickup trucks for last-mile delivery to multiple customer destinations.

4.4 Effective comparison

This section presents a comparative analysis of outcomes arising from the implementation of international transport operations using two distinct methodologies: Classical Cross-Docking at the National Border (CCDNB) and Extended K-Means integrated with Geographic Information Systems (EKM-GIS). The analysis primarily focuses on assessing total transport distance, which represents the central objective of this study. Moreover, the approach demonstrating superior efficiency is highlighted as a strategic recommendation, aimed at informing and optimizing managerial decision-making in international logistics planning, particularly in the coordination of delivering heterogeneous products from multiple suppliers in the country of origin to a diverse array of recipients in the destination country.

Table 5
The comparison of effectiveness between CCDNB and EKM-GIS. Source: the Authors

Description	CCDNB	EKM-GIS	Discrepancy assessment	
			(CCDNB) – (EKM-GIS)	Rate (%)
1. Domestic Transport distance (kms)	18,750.4	15,739.6	-3,010.8	-16.1
2. Oversea Transport distance (kms)	7,031.1	6,462	-569.1	-8.1
3. Transport distance from Domestic crossdocking point to Oversea crossdocking point (kms)	0	376	376	N/A
4. Total transport distance	25,781.5	22,577.6	-3,203.9	-12.4

Remark: N/A means Not Assessable

As presented in Table 5, a comparative analysis was undertaken between the Classical Cross-Docking at the National Border (CCDNB) framework and the Extended K-Means integrated with Geographic Information Systems (EKM-GIS), focusing specifically on various categories of transport distances. Initially, both models were evaluated in the context of domestic transportation within the country of origin. The results demonstrated that the strategic placement of the cross-docking node according to the EKM-GIS methodology led to a significant reduction of approximately 16.1% in total domestic transport distances for suppliers, relative to the CCDNB framework.

Subsequently, the performance of the two models was assessed with respect to international (overseas) transport distances. The findings indicated that situating the cross-docking facility in the recipient country under the EKM-GIS approach resulted in an approximate 8.1% decrease in international transport distances.

Notably, although the EKM-GIS approach entailed an increase of approximately 376 kilometers in transport distance between domestic and overseas cross-docking points compared to CCDNB, it nonetheless achieved a substantial net reduction in total transport distance, amounting to approximately 3,203.9 kilometers, or 12.4%. Collectively, these empirical results underscore the superior transport efficiency of the EKM-GIS framework, demonstrating its effectiveness in minimizing overall logistics distances relative to the conventional CCDNB model.

5. Discussion

In the domain of international logistics, this study develops alternative mathematical models to address the complex challenge of transporting heterogeneous products across national borders. Such consignments require cross-docking at border checkpoints before final delivery to recipients in a different country. The necessity for these logistical interventions stems from the extended durations characteristic of international freight movements, which frequently exceed a single day.

Prolonged transnational distances inherently increase transportation costs, thereby encouraging the adoption of cross-docking operations at border locations. By strategically transferring logistical responsibility to regional carriers, the cumulative travel burden is mitigated, albeit at the expense of increased overall transit time. Within this context, transport distance emerges as a critical variable, warranting rigorous evaluation within the study's analytical framework. Accordingly, a scientifically grounded model is proposed to serve as a strategic tool for optimizing cross-border product delivery through road-based logistics.

Two mathematical modeling approaches were subsequently examined in detail: one representing conventional methodologies and the other incorporating a purpose-built, enhanced framework. These models were applied to the delivery of diverse products from multiple suppliers in one country to corresponding clients in another. The modeling process was supported by secondary data acquisition, specifically geospatial distance data obtained from Google Maps. Numerical methods were employed iteratively to analyze the models, culminating in a comparative assessment of their effectiveness in optimizing transport distances.

The study's findings provide valuable insights with broad implications for both academic discourse and practical logistics management. They contribute to the advancement of theoretical and operational understanding in the planning and execution of international road-based freight transportation.

5.1 Research implications

In addressing the central research questions and aiming to propose an optimized methodology for the alternative positioning of cross-docking points within international transportation operations, this study established its research framework based on empirical logistics practices observed in cross-border product distribution. Anchoring the analysis in real-world operations enabled the identification and adaptation of a novel optimization strategy designed to determine the most efficient cross-docking locations, thereby minimizing total transportation distances across the distribution network.

The investigation utilized two distinct analytical models. The first, referred to as the conventional model, reflects the prevailing practice of product transshipment at official national border checkpoints prior to final delivery within the destination country. In contrast, the second model introduces an innovative framework, advocating transshipment at strategically optimized intermediary cross-docking points located between the two countries. For this study, potential cross-docking locations were randomly selected along the geographic corridor connecting Thailand and Cambodia, with transportation routes between each pair of locations derived from the Google Maps platform. These data were subsequently subjected to rigorous numerical analysis.

The findings indicate that the integration of the Extended K-Means Clustering Algorithm with Geographic Information System (EKM-GIS) technology substantially outperforms the traditional Cross-Docking at the National Border (CCDNB) approach in reducing total transportation distance. While individual international delivery routes may experience distance reductions when optimized in isolation, network-wide transport efficiencies are most effectively realized through a holistic optimization strategy, as enabled by the EKM-GIS methodology. These results corroborate the conceptual framework presented in **Fig. 1** and demonstrate that EKM-GIS offers a strategic advantage for transport planners seeking to minimize distances within international supply chains.

These outcomes support the research hypothesis that relying on a single, fixed cross-docking location is inadequate for achieving optimal transportation efficiency in international logistics. Rather, dynamically positioning cross-docking points through the application of advanced geospatial and optimization technologies can significantly enhance overall transport effectiveness. Moreover, this study contributes novel insights to the literature on international supply chain management, particularly in the context of road-based cross-border networks.

5.2 Practical implications

As shown in Table 5, the principal logistical challenge in international transportation involving heterogeneous products destined for diverse global clientele lies in strategically optimizing the total transportation distance across the distribution network. The comparative implications of the Classical Cross-Docking at the National Border (CCDNB) and the Extended K-means clustering algorithm integrated with Geographical Information Systems (EKM-GIS) are systematically evaluated. It becomes apparent that restricting cross-docking operations to the national border is insufficient to achieve optimal transport efficiency, particularly with respect to minimizing total distance when managing a variety of products for distinct international customers. Therefore, transportation planners must adopt a holistic network-wide perspective rather than addressing individual routes in isolation before determining cross-docking locations; such a comprehensive approach demonstrably leads to superior logistical outcomes. Moreover, in the context of international logistics operations incorporating cross-docking, the application of the EKM-GIS methodology offers significant advantages. Empirical evidence indicates that its integration can markedly enhance distance-based efficiency, underscoring its value as an effective tool for optimizing international transportation systems.

5.3 Limitation and future direction

This study is subject to several limitations that merit careful consideration. First, the secondary datasets employed in this analysis were selectively extracted from Google Maps, which constitutes only one of multiple platforms within the broader Geographic Information Systems (GIS) framework. Consequently, the adoption of alternative GIS-based data sources could potentially produce differing results in transport distance estimations. Second, the analytical datasets utilized herein were exclusively restricted to spatial distance metrics, thereby omitting other potentially relevant variables; integrating additional dimensions could lead to substantially different findings. Collectively, these methodological constraints highlight the necessity for further research, particularly to advance and refine the existing body of knowledge concerning international land transportation systems that incorporate cross-docking operations.

6. Conclusion

This study aims to develop an innovative scientific framework for optimizing the spatial allocation of cross-docking logistics within international supply chains. Specifically, the research implements an Extended K-means Clustering algorithm integrated with a Geographic Information System (EKM-GIS) and evaluates its distance-based efficiency relative to the conventional approach, which situates cross-docking nodes at national borders prior to transnational shipments.

The analysis considers a logistical scenario in which heterogeneous goods from multiple manufacturers are transported via one-ton pickup trucks to logistics terminals. At these terminals—whether intermediate hubs or border customs checkpoints—products from diverse suppliers are unloaded and subsequently reloaded onto different vehicles for final delivery to distinct destinations. The proposed mathematical model is designed to optimally determine cross-docking locations between two countries before allocating transport routes across the delivery network.

Traditionally, logistics operations consolidate various products within the country of origin and transport them to the nearest border crossing, where unloading, cross-docking, and reloading into foreign-registered vehicles occur prior to final distribution. Despite its widespread use, research investigating the optimization of cross-docking nodes located between countries—aimed at minimizing transnational transport distances—remains limited.

To support both conventional and alternative model formulations, an extensive literature review was conducted. Empirical data, including randomized locations of suppliers and destinations, were sourced from Thailand's provincial statistical reports and Cambodia's administrative datasets. Additional transport distance metrics were obtained using Google Maps in conjunction with GIS tools, thereby ensuring that the analytical framework reflects realistic spatial parameters. The overarching objective of this international cross-docking framework is to minimize the total transportation distance across the supply chain.

For empirical validation, all secondary datasets underwent numerical analysis using the Solver Add-in in Microsoft Excel 2024. Computations followed procedural frameworks for two models: the Classical Cross-Docking at National Borders (CCDNB) and the Extended K-means Clustering integrated with GIS (EKM-GIS). Results indicate that the proposed EKM-GIS model substantially improves distance efficiency compared with the conventional CCDNB approach.

Two key insights emerge from this study. First, cross-docking site selection in international supply chains should consider the comprehensive transport paths of all suppliers and destination points, rather than focusing solely on bilateral supplier–customer connections. Such integrative spatial optimization enhances overall transport performance, whereas the conventional practice of locating cross-docking nodes exclusively at border checkpoints fails to achieve minimal transport distances.

Second, the EKM-GIS model demonstrates strong potential as a decision-support tool for international transport logistics. By enabling planners to identify more effective cross-docking locations, the model achieves shorter aggregate transport distances compared with traditional approaches, particularly in overland road transport contexts. Consequently, the proposed framework represents a significant advancement in the pursuit of more efficient, data-driven international logistics strategies.

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