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Research Article

Optimizing Intermodal Transport and Hub Location Problem for ECOWAS in the Context of Improving Intra-African Trade

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Trade within Africa is at an all-time low, with a lack of an optimal intermodal transportation network and a high cost of business serving as a deterrent to trade. This research studies Intra-African Trade within ECOWAS using a hierarchical spatial aggregation process to identify 27 nodes. Distance-based weighted centrality measures employed TOPSIS to model a ranked node centrality of Economic Community of West African States (ECOWAS) intermodal transport of railway, road, and waterway networks. The ten highest-ranking nodes identified from the mixed-integer linear program adopted as candidate hubs, thus selecting Ibeshe ferry terminal in Lagos and Tema Harbour in Accra for waterway; Thies, Ibadan, Conakry, Monrovia and Thies for railway; and Thies and Ibadan for road. We conclude with sensitivity analysis and a discussion of management implications for ECOWAS. This paper demonstrated that a limited number of transshipment hubs would encourage interregional trade and cut point-to-point transportation costs and lead to economic growth and development.

1. Introduction

Intermodal transportation, serving as a vital link between raw materials, goods, services, and opportunities, is a crucial component of intraregional trade, which has been noted as one of the key methods for rapid economic growth, poverty alleviation, and a means of breaching the wealth gap. African Continental Free Trade Agreement (AfCTA) is an ambitious move availing a vast potential as the world's first largest free-trade area after the World Trade Organization (WTO) and has immense potential for economic growth. Regrettably, this potential will continue to be constrained as the most intermodal transportation modes across Africa are in a deplorable state often underutilized with outmoded technologies, abandoned with corresponding low-quality operations, and colossal high transportation costs. Amtadi and Azta [1] concluded that transport costs in Africa, in most cases, were a higher barrier to trade than import tariffs or trade restrictions. Ogunkola [2], Amtadi and Azta [1] and AERC [3, 4] looked closely at the potential Africa has to trade within and concluded that Africa has a vast untapped potential for intraregional trade. Unfortunately, intraregional trade in Africa remains the lowest globally with the high cost of transportation being one of the biggest deterrents to trade. Over 12 years, as shown in Figure 1, intraregional trade within Africa has been growing within its various trade blocs. However, the rate of growth is minimal.

In July 2019, Africa enrolled the African Transport Network Project worth over $430.3 billion with a focus on railway, road, and bridges linking Africa with its markets [5]. Notwithstanding this huge potential and strong momentum, the average cost of intra-African trade is still higher than that in other regions, over 65% higher when compared to Latin America and 95% higher than the south and east of Asia. United Nations Conference on Trade and Development (UNCTAD) [6] and Teravaninthorn et al. [7] showed that just a 1% decrease in transportation cost could lead to an over 10% increase in the overall GDP and trade efficiency, with prospects of the lowest transportation costs in the world due to its low wage levels. These issues have led traders and consumers preferring alike to buy imported products at a

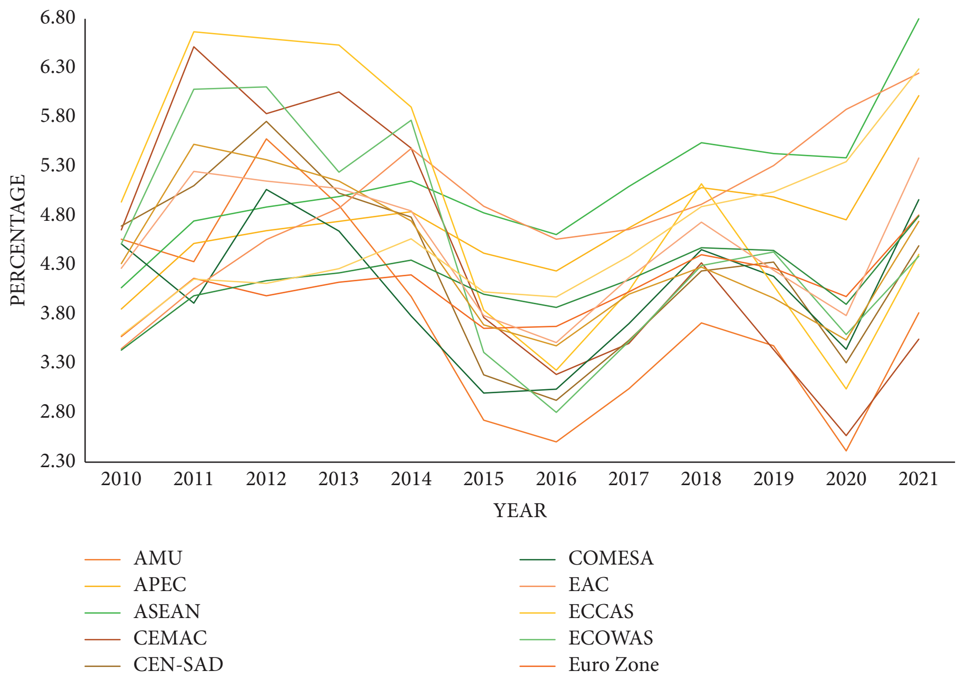


Figure 1: Intraregional trade comparison based and calculated by UNCTAD data. https://unctadstat.unctad.org/wds/TableViewer/tableView.aspx.

lower price defeating the purpose of intraregional trade, lowering the competitiveness of African goods on the market and putting pressure on governments to subsidize transportation costs to boost trade.

To address these issues, some researchers have proposed short, cost-efficient, and reliable intermodal transport between a limited number of prominent African transshipment hubs across Africa, such as the study of Contreras et al. [8], Meng and Wang [9], Alumur et al. [10], Adler et al. [11], Mokhtar et al. [12], Zhao et al. [13], and Zhao et al. [14], which would provide frequent, economic, and dependable transportation, and encourage interregional trade, capitalize on the considerable potential for economic growth, and solve high interregional trade costs. In these researches, an intermodal collection and distribution service will then connect hubs to cargo origins and destinations with the optimized cost. This will then reduce Africa's massive cost in setting up hub facilities and creates transportation links across Africa to encourage trade. However, achieving these effects is possible only if cities within trade blocs in Africa enjoy interconnected regional and international transport infrastructures. This implies the creation of a complex supply chain relationship consisting of consolidation hubs, operational nodes, and transportation routes between nodes and hubs. In this complex network, each origin node transfers freight volumes to a hub, where cargoes from multiple other origin node cities using various intermodal transport modes are unloaded and then merged into a single load transported via an optimal transport mode choice to various destinations.

The Economic Community of West African States (ECOWAS) is one of the most active trade and growth potential regions in Africa. To make this research to have a theoretical significance and more practical value, the region of ECOWAS is chosen as a pilot unit to design and optimize the intertransportation network in Africa. As this network evolves both in theory and practice, we foresee impacts on the choice of optimal hubs that can support continuous growth and evolution of the logistical and supply chain network and as such presents quite a tricky problem. To this effect, this research seeks to solve these research questions:

(1) How can ECOWAS countries choose optimal origin nodes and consolidation hub locations to improve intra-African trade?

(2) How can ECOWAS utilize its transportation infrastructure to plan a suitable railway plan?

(3) How can ECOWAS interconnect its new optimized network to facilitate trade?

This research will provide novel contributions to the growing field of the hub-and-spoke research. Also, most research to date utilizes integer programming methods to select node candidates assuming that all nodes play significant roles within the network while ignoring the actual characteristics of the network structure and the fundamental role each node and edge actually plays within the network structure. Moreover, previous researches concentrated on individual transportation modes ignoring the intermodal aspect of transportation modes and their effect on the resulting network structure. In this paper, we extend distance-based weighted centrality measures as used by Zhao et al. [14] to quantify significant nodes within the ECOWAS network, analyze the ECOWAS intermodal transportation network, to identify an ideal hub location, and propose a cost-effective establishment of railway transportation across ECOWAS for a hub location model.

1.1. ECOWAS Intermodal Transportation. The fundamental idea of intermodal transportation is to consolidate and regulate the efficient long-distance hauling of loads performed by large ocean vessels, and on land, primarily by rail and truck, through containerization [15]. Allate [16] has explored intermodal transport across ECOWAS and utilized a linear optimization model focusing on five main ports within ECOWAS. It shows high congestion levels as a significant challenge. Mostly, railways within ECOWAS are in deplorable conditions, utilizing outdated technologies and abandoned, low-quality operations [17]. This situation leaves road transport the predominant mode of transport within ECOWAS, making intermodal transportation within ECOWAS restricted with insufficient network flows, poor infrastructure, operating below capacity, resulting in considerable challenges in export and trade across Africa [17]. Fortunately, ECOWAS is still one of the potential areas to develop railway systems, which will afford higher efficiency and lower costs as compared to other modes of transportation [18].

1.2. Hub-and-Spoke Network. The traditional hub-and-spoke model was initially formulated by O'Kelly [19] as a quadratic integer programming model and improved by Campbell [20]. Campbell [20] referred to this model as the p-hub median problem aiding in selecting hub facilities allocating spoke nodes while routing freight flows. Many industries and researchers have utilized the hub-and-spook model to solve pressing issues of consolidation, cutting transport costs, and enjoying economies of scale to improve trade and interregion connectivity. Contreras et al. [8] evaluated the network hub location problem looking at a fixed number of hubs to be located through a mixed-integer programming model of the tree hub model, combining several aspects such as location, network design, and routing problems adopted to minimize transportation cost.

Other researchers in designing hub networks have traditionally overlooked the choice of mode of transportation with an assumption of one type of transportation mode for a hub network primarily focusing on a single transportation network, as shown in Table 1. Adler et al. [11] applied a gravity model to estimate intra-African trade growth of 8% in 2030 and proposed a hub-and-spoke design based on a modified multiairline p-hub median problem identifying three future hub locations within the African aviation network, namely, Cairo in Egypt, Addis Ababa in Ethiopia, and Johannesburg in South Africa. Here, the focus is primarily on air transport across East Africa but did not address airports within West Africa such as Nigeria and other modes of transport across Africa. Zhao et al. [13] introduced the study of evolutional transportation networks with an emphasis on the evolution of China Railway and utilizing a genetic algorithm interlinear programming and optimized the logistical network focusing on railway transport across China. Moreover, Zhao et al. [13] showed that as networks evolved, their logistical routes became more complex with a need for adopting a hybrid hub-and-spoke model to address these complexities. Sun et al. [21] focused on 48 origin cities utilizing TOPSIS with a cluster analysis to select 10 hub cities looking closely at China Railway Express.

Consequently, the vital aspect of designing hub networks in the real-life application and the complex nature of choices that exists between air, road, rail, and water transport is overlooked. In recent researches, many scholars seek to address this gap such as in Meng and Wang's study [9], they proposed a mathematical program that considered this thorny problem adapting equilibrium constraints (MPEC) model for the intermodal hub-and-spoke network design (IHSND). Meng and Wang [9] looked closely at multiple stakeholders and multitype containers. The model incorporates a parametric variational inequality (VI) that formulates the user equilibrium (U.E.) behavior of intermodal operators in route choice for any given network design. Moreover, implementing a hub-and-spoke network with an intermodal transportation network means creating intermodal nodes with a set of locations that promotes the efficiency of different transport networks with a higher level of integration. Zhao et al. [23] opting for 23 distribution node cities and applying the qualitative approach focused on assessing the importance of each freight transport (railway, highway, and waterway networks) and using the enhanced-entropy TOPSIS model selected six cities as final distribution centers.

Rodrigue [25] looked at intermodal node space in four functions: composition, transfer, interchanging, and decomposition. Also, Azizi et al. [26] and Li et al. [23] proposed a complex network model for an intermodal transport network looking closely at the backhaul problem in cereal distribution from Europe and Central Asia. Sibel Alumur et al. [10] considered the intermodal hub location and network design problem from the network design perspective focusing on linear mixed-integer programming. Subsequently, Zhao et al. [14] applied mixed-integer programming based on time constraints with penalties to address issues of less truckload and vacant trains between China and Europe within an intermodal transport system. Assessments of other researchers looking closely at intermodal transportation are Bontekoning et al. [27] and Mokhtar et al. [12].

Furthermore, another research gap relates to the need for railways across Africa studied by many researchers, World Bank [28], OECD [29], Markets [5], Africana [30], and Bayane and Yanjun [17]. None of these researchers has looked at the positive or negative impact investment in an active railway network across Africa which will or have simulated results based on this proposed network. Since this research is concerned with a hub-and-spoke network model and locating optimal hub facilities in an intermodal transport system, we will focus on the impact of active railway lines in hub location decisions in an intermodal network. Lastly, in ECOWAS, to the best of the researcher's knowledge, no research attempt has been made to consider intermodal transport utilizing weighted centrality measures.

Table 1: Transportation nodes and network topological structures.

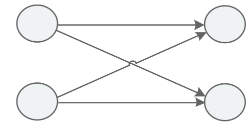
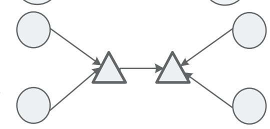
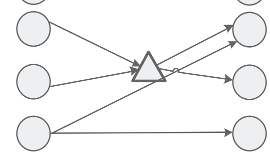
Type	Explanation	Network	Topological structures
Direct transportation	No transshipments on the way, fast travel speed, and more trains and trucks empty with less than truckload	Point-to-point network	
Pure hub-and-spoke transportation network	A higher proportion of trains and trucks carrying loads with potentially increased delays, unreliability, and poor timeliness of transportation	Hub-and-spook network	
Consolidation transportation	High proportions of trains and trucks carry loads, reduced overall transport time, and unreliability	Hybrid hub-and-spook	

Table 2: Descriptive macro economic statistics.

	2020			2021		
Variables	Average	Min	Max	Average	Min	Max
GDP (billion $)	44	2.7	20	46	17	34
Population (million)	39	2.8	25	41	3.4	27
Corruption index	0.35	0.18	0.45	0.35	0.21	0.45
Peace index	2	0	10	2	0	10

Table 3: Summary coefficients on gravity model estimates.

Variables	Coef.	Std. Err.	Sig
LN (GDP * GDP)	0.9810841	0.0065849	*
LN (Pop * Pop)	0.0069167	0.0059408	* * *
LN (ABS (GDP-GDP)	−0.0050114	0.0065017	* * *
LN (Distance)	−0.1599074	0.0590544	*
LN (CPI + CPI)	−0.2225097	0.0903401	*
LN (PI + PI)	0.0005157	0.0166238	* *
Common language	0.0001123	0.0013987	* * *
No. of obs		3,900	
Adj R-Squared		0.9247	

Note. *, * *, and * * * show the level of significance at 10%, 5%, and 1%, respectively.

The paper follows this structure; Section 1 introduces the research, gives the background of the study, the research problem, the research objectives, research questions, and the significance of the study; Section 2 models a network to select a small number of key nodes and hubs to reduce the problem size; Section 3 uses multicriteria decision-making techniques, which helps reduce the problem size by merging a set of distance-based weighted centralities into a single index multicriterion decision-making technique (MCDM); Section 4 defines the input parameters and optimizes the selected hub locations through a linear program to propose ten optimal hub locations with the highest total scores as our candidate hubs; Section 5 identifies optimal ECOWAS hubs and conducts a sensitivity analysis based on the proposed intermodal network; and finally, Section 6 concludes the study and suggests further studies.

2. Network Set-Up

This section of the paper will be divided into two portions: (1) Model the nodes and edges of ECOWAS transportation network using spatial aggregation in a qualitative clustering with data collected through OpenStreetMap (OpenStreetMap is an open source and free geographic data of the world) and (2) Selection of optimal node and hub locations using a series of distance-based weighted centrality measures, merging these measures into a single index utilizing multicriteria decision-making techniques (MCMD). Some researchers have considered unweighted centrality measures to analyze transportation networks, using weighted centralities by Opsahl et al. [31],which were developed due to the increasingly complex network analysis problem.

2.1. Model the Nodes and Edges

2.1.1. Selection of Optimal Nodes and Hub Location. This model is from the work of Zhao et al. [14] and models the nodes and edges utilizing spatial aggregation in a qualitative clustering procedure. First, we identify a comprehensive network of all the countries within the Economic Community of West Africa States (ECOWAS) using OpenStreetMap. Afterwards, we zero down to the core network, which identifies the most critical nodes and links ECOWAS, including rail, water, and road networks. For our research, we chose a maximum of three origin nodes per ECOWAS, making 26 cities and a total of 27 nodes as our origin nodes; we chose our candidate hubs from among our origin nodes. This paper employed several criteria in a spatial aggregation process to ensure the nodes selected are relevant (Figure 2).

The first criteria help us identify and list a set of potential nodes, evaluates specific Economic Edge Gravity models based on the bilateral aggregate trade flows method by Tinbergen [32] which considered the GDP, the distance, population, and most importantly, the trade volumes between the various node cities. We select a node if the criterion results in one to three nodes per ECOWAS region.

2.1.2. City-Level GDP. Currently, there is no known standardized methodology for estimating city-level GDP, even though it has been used globally for infrastructural development. Often, we measure the relative affluence and purchasing power of people living in different cities in terms of per capital income: multiplying the average per capita GDP derived from the GSDP with the city's population [33]. The method assumes that the average per capita GDP and economic activities are uniform across all the cities in a state:

$$\text{City Level GDP} = \text{per capita GDP} \times \text{pop.of City}. \quad (1)$$

2.1.3. Bilateral Aggregate Trade Flows Method. Research by Tinbergen [32] proposed the gravity equation which was later expounded by Bergstrand [34] and has been adapted repeatedly to analyze trade between countries empirically and is regarded globally for its ability to approximate bilateral trade flows correctly. Researchers over time have adopted gravity models extensively to model trade flows such as Djankov et al. [35], Iwanow and Kirkpatrick [36], Chaney et al. [37], Cristea et al. [38], Kinder et al. [39], Adler et al. [11], Hassan Khayat [40], and Perez-Mesa et al. [41].

This model attempts to estimate the volume of traffic between two cities; the dependent variable is the natural logarithm of the sum of annual exports and imports in 2020 taken from IMF (The IMF (International Monetary Fund) publishes a range of time series data on financial indicators of IMF data) Directions of Trade for all major ECOWAS countries. This study utilizes panel data consisting of all ECOWAS significant cities.

$$Dd_{ij} = \ln\left(\frac{1}{T}\sum_{t=1}^{T}\left(\text{Import}_{ij} + \text{Export}_{ij}\right)\right), \quad (2)$$

where Dd_{ij} is the value of trade flows ($t = 1, 2, \ldots, T$). The model uses panel least squares and random effects to estimate variables because it is best suited for panel data and random effects (GLS) due to its efficiency in estimating and overcoming the ordinary least squares (OLS) model's loopholes. In addition, we consider generation or attraction variables, i.e., population, relative affluence, and purchasing power of people living in different cities (*GDP*), and resistivity factors such as political instability, transportation cost, and other regulatory issues. Given all the (i, j) possible combinations of the internal nodes where $(i \neq j)$, this research estimated this model:

$$\begin{aligned}\ln\left(Dd_{ij} + 1\right) = {} & \beta_1 \ln\left(GDP_i \times GDP_j\right) + \beta_2 \ln\left(Pop_i \times \text{Pop}_j\right) \\ & + \beta_3 \ln\left(\left|GDP_i - GDP_j\right|\right) + \beta_4 \ln\left(\text{Distance}_{ij}\right) \\ & + \beta_5 \ln\left(CPI_i + CPI_j\right) + \beta_6 \ln\left(\text{Peace Index}_i + \text{Peace Index}_j\right) \\ & + \beta_7 Dd_{ij}^{\text{Lang}},\end{aligned} \quad (3)$$

where Dd_{ij} represents the *O.D.* return demand, GDP is the gross domestic product of the city calculated in equation (1), Pop refers to the population of the *O.D.* cities, $|\text{GDP}_i - \text{GDP}_j|$ is the absolute size of the gap in wealth between the two cities adopted by researchers such as Adler et al. [11] and Beck [42]. The distance refers to the distance between the two nodes; the CPI refers to the corruption index. Transparency International is an institution that monitors corruption levels of countries using a CPI score. The CPI scores 180 countries and territories by their perceived levels of public sector corruption according to experts and businesspeople (http://www.transparency.org/cpi), and the Peace Index (Institute for Economics and Peace (IEP) is an independent institution focused on monitoring peace using an Index score. The Global Peace Index (GPI) measures the absence of violence or the fear of violence across three domains: safety and security, ongoing conflict, and militarization. GPI_2020_web.pdf (visionofhumanity.org)) measuring the safety and security of the two cities. We introduce a dummy, Dd_{ij}^{Lang}, to control for the common first language. The researcher assumes that the higher the GDP and population, the lower the distance and gap in wealth, and the higher the freight flow volumes between the cities [43], [38], [11], [41]. The lower the corruption index and conflict levels, the higher the peace index and economic stability and vice versa. As a positive contributor for trade, the research considers speaking of a common language.

Regression analysis was used to predict the β values with data management, and analysis was performed using STATA/SE 15.1. Higher trade flows existed between cities with higher GDP, population, lower conflict, and corruption index that share a common language. In contrast, the farther the distance, the more the dissimilar wealth, and the greater the level of corruption and conflicts, the lower the flow of trade.

Using the estimated parameters of (3), we forecasted O.D. demand for the next year, 2021. The estimated levels of GDP and population were gathered from World Bank Database, corruption index is estimated using an annual trend of 0.17% based on research by Adler et al. [11], indicating a gradual decrease in levels of corruption over time (10 indicating no corruption and 0 indicating extreme levels of corruption). Peace index remains the same as 2020 as potential changes in future is unknown. Based on the coefficients of Table 3, we calculated the forecast of intra-African O.D. demand for 2021.

For ECOWAS countries with more than three nodes, the following criterion was to check that the city is planned in the ECOWAS Master Plan for the Development of Regional Power Generation and Transmission Infrastructure 2019-2033 (sponsored by the European Union in 2018; https://www.ecowapp.org/sites/default/files/volume_0.pdf). For any other country or international organization plan, check for the cities with the highest transport modes and the cities with the highest transport modes. For example, rail transport in West Africa is limited and links only two capital cities with ports Abidjan (Cote d'Ivoire) to Ouagadougou (Burkina Faso) and Dakar (Senegal) to Bamako (MAli), and the city was supported by a country or international transportation plan. The rest of these rail infrastructures run within the countries; for this research, we assume that all railways found a link to various major cities. If these cities

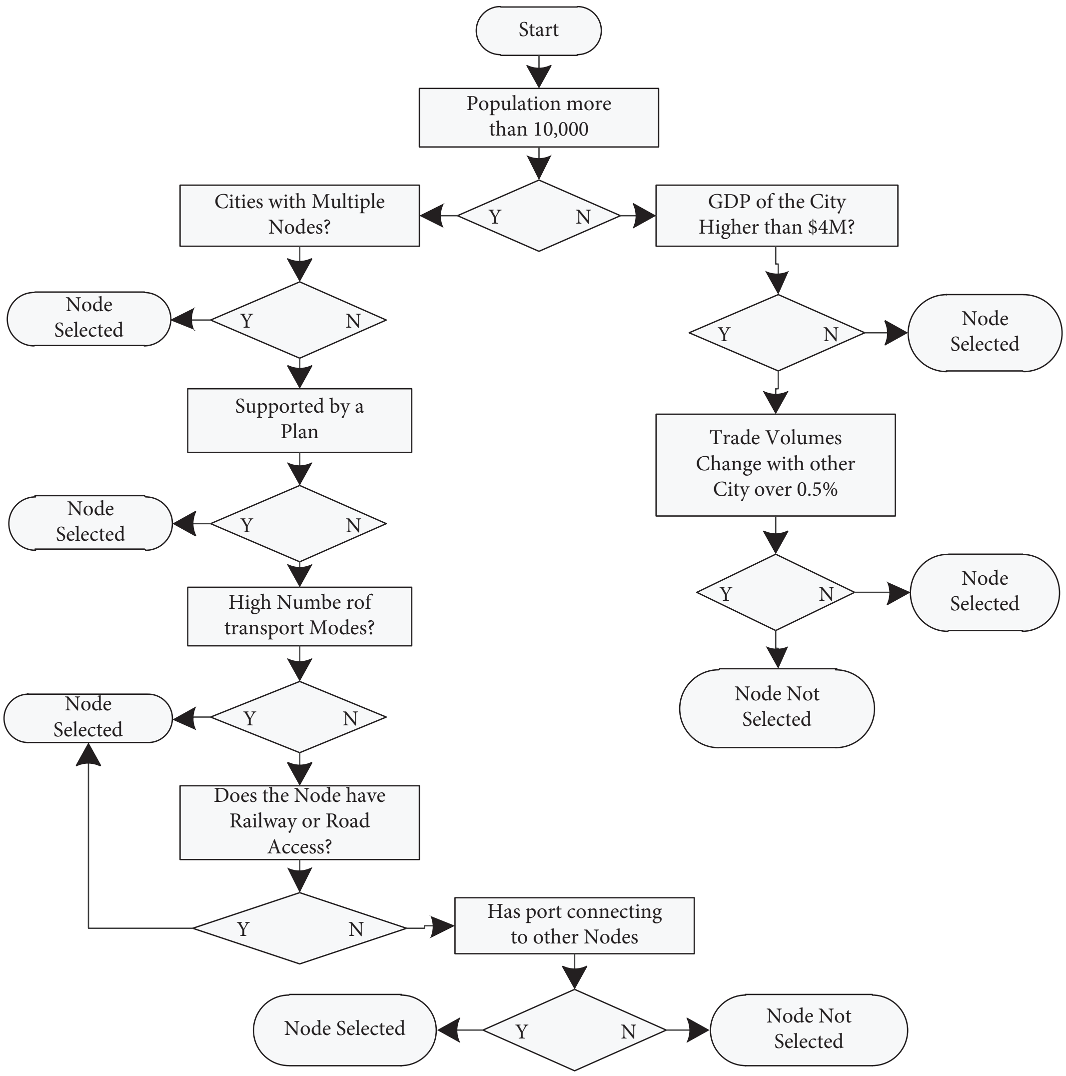


Figure 2: Objective selection of suitable origin nodes within ECOWAS.

have the same number of modes of transport, then we look at waterway access to these cities and select those with existing waterway access connecting that city to others. Finally, suppose several cities within ECOWAS countries meet all the above criteria, then we check to see if the city has an existing or planned railway line linking the town to its road network, and those cities are selected.

2.2. Setting Up the Network. This paper utilized OpenStreetMap discussed by Boeing [44] to provide a free and publicly editable map of the world, with a globally accepted high standard of data [45], [46] to model the transportation core network. In addition, it provided the distances for the roads, waterways, and railway networks within ECOWAS. Cape Verde is a member of the ECOWAS, but the paper excludes it due to lack of data and a well-defined transportation network linking it to the other countries. The network, three weighted undirected transportation subnetworks A_R, A_{RR}, A_W representing road, railway, and waterway networks, respectively, were obtained to set up the network, which was further combined to form a graph $G = (V, E)$, where V is the vertex set that represents all the nodes considered, E is the edge set that denotes the edges between the nodes $|V| = n$ and $|E| = m$.

3. Nodes Centrality and Ranking

3.1. Node Centrality. Centrality measures are essential tools in analyzing complex networks and have been looked at extensively by various researchers such as Rio et al. [47], Jiang et al. [48], Joseph and Chen [49], Zhao et al. [14], and Chebotarev and Gubanov [50]. Section 3 narrows our selected 27 nodes across 26 cities within the ECOWAS to a small set of candidate hubs utilizing four centrality measures;

3.1.1. Weighted Degree. Freeman [51] asserted that the degree of a node is the number of nodes that a focal node is connected to and can be used to find the core nodes in a network. Opsahl et al. [31], shows how a number of edges that connect a node is defined as the unweighted degree, while the node strength is the sum of the nodes edge weights. This research utilizes the weighted degree (WC_D) measure since research proves unweighted centrality measures are less suitable for studying transportation networks. Opsahl et al. [31] developed a weighted degree measure (WC_D) that uses a tuning parameter α to balance degree and strength, developing multiple values for α, where α: $\alpha = 1$, WC_D equals the strength s_i, and when $\alpha = 0$, then WC_D equals degree d_i. This paper uses $\alpha = 0.5$ to create a balance between both degree and strength, as evidenced by works in various fields [52], [53], [14].

$$WC_{D(i)} = d_i \times \left(\frac{s_i}{d_i}\right)^{\alpha}. \tag{4}$$

3.1.2. Shortest Path-Based Centrality Measures

Betweenness Centrality. It describes the frequencies of nodes in the shortest paths that pass through each node [54]. The basic idea is that connecting more nodes via a node implies that the node is more important. This equation shows how to find the total number of shortest paths between any two nodes, j and k, as well as to find out how many of these shortest paths go through a vertex $i\,(j \neq k \neq i)$:

$$\mathrm{BWC}(i) = \sum_{j \neq k \neq i} \frac{sp_{jk(i)}}{sp_{jk}}. \tag{5}$$

Closeness Centrality. It measures how close a vertex is to other vertices (the sum of the shortest path distances); the basic idea is that if a node can quickly reach others, that node is central to the network. It represents for each node a reciprocal of the sum of the shortest distances from node i (focal node) to any node j (all other nodes) [51] to all others in the network. For weighted networks, a Dijkstra algorithm sums the weights of all edges passed between nodes i and j to calculate the weighted distance $d_w\,(i, j)$ instead [31]:

$$\mathrm{WC}_{C\,(i)} = \left[\sum_{j}^{N} d_w\,(i, j)\right]^{-1}. \tag{6}$$

3.1.3. Topological Centrality. The above centralities focused on the nodes but did not account for the topological characteristics of the centrality. Topological centrality measures both the node and edges of a network. Zhuge et al. [55] showed that it combines the degree information and neighbor weights information. It is the relative measure of the extent to which a node shares neighbors with other nodes or between a pair of nodes, n, and m, divided by the number of neighbors of node n:

$$T_n = \frac{avg\,(J\,(n,m))}{k_n}. \tag{7}$$

The calculation of all four weighted measures is through the use of cytoscape [56].

3.2. TOPSIS Model for Merging of the Centrality of Indices. TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) analysis is to help make a calculated decision through an analytical and numerical method that looks at the multiple alternatives available. Many multicriteria techniques such as MAX MIN, SAW, AHP, SMART, and TOPSIS have been used by Hwang et al. [57], Pavić and Novoselac [58], Roszkowska and Wachowicz [59], and Zheng et al. [60]. Compared to other methodologies, the TOPSIS model will be adopted for this research because of its high accuracy [61]. Looking at the various centralities calculated based on [58] the TOPSIS method, weights w_j of the criteria x_j are given as

$$\sum_{j=1}^{n} w_j = 1. \tag{8}$$

It is necessary to select the most optimal option. Following the computation of the four centrality measures $\{X = x_1, x_2, x_3, x_4\} = W.C._D$, $W.C._B$, $W.C._C$, $T.C._C$ in Section 3.1 for each of the nodes $V = \{v_1, v_2, \ldots, v_N\}$ in the subnetwork A_R, A_{RR}, A_W. Following that, we combined the four centrality measures into one measure per transportation network. In each of the attribute matrices Y for the individual subnetworks, $v_i\,(x_j)$ represents the j-th centrality value of the i-th node, given numbers x_{ij} and balancing the matrix and generalizing the node attribute. Thus, the equation can be expressed as

$$Y = \begin{bmatrix} v_1(x_1) & v_2(x_2) & v_3(x_3) & v_4(x_4) \\ v_2(x_1) & v_2(x_2) & v_3(x_3) & v_4(x_4) \\ \vdots & \vdots & \vdots & \vdots \\ v_N(x_1) & v_N(x_2) & v_n(x_3) & v_N(x_4) \end{bmatrix}. \tag{9}$$

3.2.1. Standard Matrix Calculation. First, we calculate the normalized decision matrix since the indices have different scales and are challenging to work with if not normalized. If r_{ij} represents the normalized value of the j-th element in the i-th row, then

$$r_{ij} = \frac{v_i\left(x_j\right)}{\sqrt{\sum_{i=1}^{m}\left(v_1 x_j\right)^2}}, \quad i = 1, 2, \ldots, n, m\text{: } j = 1, 2 \ldots, n. \tag{10}$$

3.2.2. Index Weight Determining. Secondly, we compute weightage because the TOPSIS model needs weights to combine the indices. The weighting coefficient w_j is generated separately for each network and each index using the entropy method for weight determination.

Calculate the proportion x_{ij} of the index value of the subnetwork under index j by

$$x_{ij} = \frac{r_{ij}}{\sum_{i=1}^{m} r_{ij}}, \quad j = 1, 2, 3, 4. \tag{11}$$

Next, calculating the entropy e_j is done by

$$e_j = -h \sum_{i=1}^{m} x_{ij} \ln x_{ij}, \quad j = 1, 2, 3, 4, \ldots n, \tag{12}$$

where m is the number of alternatives and can calculate h as $h = 1/\ln m$.

Calculating the weight vector w_j of index j, where $d_j = 1 - e_j$, is the degree of diversification, and w_j is the objective weight of the criteria:

$$w_j = \frac{1 - e_j}{\sum_{j=1}^{n} \left(1 - e_j\right)}, \; j = 1,\ 2,\ 3,\ 4, \ldots n \tag{13}$$

Following, we build the standardized matrix of weight by calculating the standardized value v_{ij} of weight as

$$V_{ij} = r_{ij} \times w_j. \tag{14}$$

Determine the ideal best solution and ideal worst solution values according to the standardized value v_{ij} of weight. A^+ and A^- are then given as

$$A^+ = \begin{cases} \max\{r_{i1}\}, \ldots, \{\max\{r_{i4}\}\} \\ i \in \{1, 2, \ldots N\} i \in \{1, 2, \ \ldots N\} \end{cases} = \{v_1^+,\ v_2^+,\ v_3^+,\ v_4^+\}, A^- = \begin{cases} \min\{r_{i1}\}, \ldots, \{\min\{r_{i4}\}\} \\ i \in \{1, 2, \ \ldots N\} i \in \{1, 2, \ldots N\} \end{cases} = \{v_1^-, v_2^-, v_3^-, v_4^-\}. \tag{15}$$

For the next step, we calculate for the Euclidean distance, which is the distance between each objective ideal best (S^+) and ideal worst (S^-) solution, which is calculated as

$$S_i^+ = \left[\sum_{j=1}^{m} \left(V_{ij} - V_j^+\right)^2\right]^{(1/2)},$$
$$S_i^- = \left[\sum_{j=1}^{m} \left(V_{ij} - V_j^-\right)^2\right]^{(1/2)}. \tag{16}$$

Next, we calculate the performance score or closeness degree of the ideal solution where C_i^* is between 0 and 1:

$$C_i^* = \frac{S_i^-}{S_i^+ + S_i^-}, \quad 0 \le C_i^* \le 1,\ i = 1, 2, \ldots n. \tag{17}$$

3.3. Comprehensive Ranking. This section combines the four centrality indices obtained previously into a comprehensive node centrality ranking using each subnetwork's modal share as a weight. The modal share is calculated as the average proportion of the total trade volumes transported via each transportation network mode within the selected cities with the various network nodes, using the average trade volumes of the 27 chosen cities modal shares resulting in the modal weights $\delta_i = \{0.003, 0.030, 0.014\}$, for road, rail, and waterway networks, respectively. The comprehensive node centrality ranking CC_i is calculated as the sum of a node's three C_i^* values multiplied by their corresponding modal weight δ_i, with m representing the number of indices j and n representing the number of nodes i:

$$CC_i = \sum_{j=1}^{m} \delta_i C_i^*, \quad i = 1, 2 \ldots, n. \tag{18}$$

Figure 3 represents the calculated node ranks against its corresponding node centrality scores. The node rank is defined as origin nodes ranked by their CC_i; here, the highest score for rank = 1. Calculations show that most of the nodes were evenly distributed, with ten selected nodes with the highest scores chosen as our hub candidates. The difference between the tenth and the eleventh node is 0.000205143, which is the highest difference recorded among the various nodes. Most of our selected hubs remain within countries bordering the Atlantic are attributed to the access of waterway transportation and high economic interactions due to the closeness of borders and population factors as shown in Figure 4. Also, to some extent, these countries have better-developed transportation infrastructures than their surrounding countries, most of them being landlocked, such as Niger.

4. Hub Location Model for ECOWAS

4.1. Defining the Constraints. Here, the input data regarding our hub location model is defined based on literature and research reports. Input data are chosen as a close approximation to real-time data as possible for ECOWAS's current operational environment.

4.1.1. Transportation-Related Parameters. Transportation times and costs for the ECOWAS origin-hub phase was based on the average transportation cost data, as shown in Table 1, and speed data for rail, road, and waterways adopted from the calculations of Zhao et al. [14] were 42.83 (km/h), 62.80 (km/h), and 11 (km/h) respectively.

Freight cost before and after the consolidation is combined with the distances, as shown in Section 2.2; freight cost before b_1 is calculated as the distance between node I and hub H multiplied by transportation cost [14] multiplied by total trade volumes between node I and destination J using transportation mode $mb_1 = l_{ih}^m d_{ih}^m w_{ij}$, and freight cost after

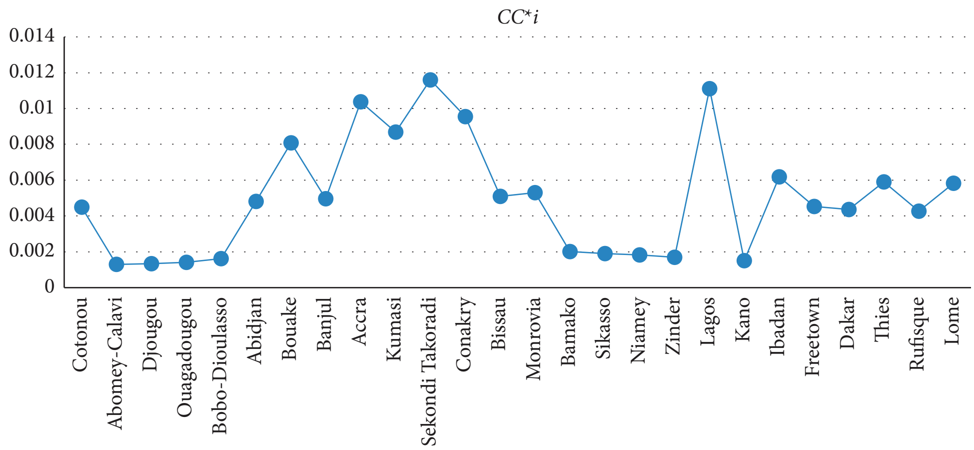


Figure 3: Node ranks of the various cities.

consolidation at hub H between hub h and destination j using transportation mode m is defined as $b_2 = l_{hj}^m d_{hj}^m w_{ij}$. The value of time μ is calculated as the sum of handling time divided by handling capacity of the hub multiplied by the trade volumes between node i and destination j added to total transportation time between node i and hub H that is defined as d_{ih}^m/θ_{ij}^m, and transportation time from hub H to destination J is defined as d_{hj}^m/θ_{ij}^m. Transportation cost per mode is shown in Table 4. Handling cost and set up cost are shown in Table 5.

4.1.2. Demand. Current demand will be estimated as the calculated trade volumes in a million tons to measure intracommunity current freight volumes of EOWAS countries from Section 3.1.3.

4.1.3. Constraints Related to Candidate Hubs. Set up cost (ease of doing business provides objective measures of business regulations by the World Bank, pages 10–14). C_h was estimated using the World Bank [65] data and represents the official costs without bribes. The underlying assumptions of the logistics facilities include that we set it on a 10,000 square feet plot of land. With two stories and a total constructed area of approximately 14,000 square feet, with two levels with each floor, an estimated 3 meters height is estimated at 50 times income per capital for all hub cities. Handling cost (ease of doing business provides objective measures of business regulations by the World Bank, pages 59–65 and pages 100–110). k_h is calculated based on the cost of hiring a laborer per month who is assumed to be a logistics facility worker with an average of senior high school education on a full-time basis and is a nonmember of the union World Bank [65], which is divided by eight hours per day^{-1}, which will then be divided by 15 metric tons of demand to arrive at the unit handling cost per ton.

4.2. Formulation of the ECOWAS Hub Location Model. The parameters and variables are shown in Table 6.

$$T.C\text{: Min} = \sum_{i\in I}\sum_{h\in H}\sum_{m\in M}\sum_{j\in J}\mu\left\{\left(\frac{t_h}{a_h}\right)\times\sum w_{ij}X_{ih}+\sum\frac{d_{ih}^m}{\theta_{ih}^m}+\sum\frac{d_{hj}^m}{\theta_{hj}^m}\times H_h^m\right\}+\sum_{m\in M}\sum_{h\in H}\sum_{i\in I}\sum_{j\in J}l_{ih}^m d_{ih}^m w_{ij}X_{ih}H_h^m+\sum_{i\in I}\sum_{h\in H}\sum_{m\in m}\sum_{j\in J}l_{hj}^m d_{hj}^m w_{ij}X_{ih}+\sum_{m\in M}\sum_{h\in H}c_h^m H_h^m+\sum_{i\in I}\sum_{j\in J}\sum_{h\in H}w_{ij}k_h, \quad (19)$$

is subject to

$$\sum_{h\in H} X_{ih} = 1, \quad \forall i \in N, \quad (20)$$

$$X_{hj} = X_{jh}, \forall j, i \neq j, \quad (21)$$

$$X_{ih} \le H_h^m \forall i \in N,\ h \in H, \quad (22)$$

$$H_h^m \in \{0,1\}, \forall j, \quad X_{ih} \in \{0,1\} \forall i \in N, h \in H, \quad (23)$$

$$\sum_{m\in M}\sum_{h\in H} c_h^m H_h^m, \quad < C, \quad (24)$$

$$i \in I, \forall i, \quad j \in J, \forall j, \quad m \in M, \forall m. \quad (25)$$

The objective function comprises the waiting cost at start node i, transportation cost from node i to hub h, the waiting and handling cost at hub h, the transportation cost from hub h to destination, utilizing the various modes of transport and the total fixed cost of establishing hubs. A constraint (20) ensures that each demand node must and can only be allocated to one hub node. Every demand node is assigned to a hub node utilizing the classical single allocation constraints in the hub location. Condition (21) ensures the transport modes is a two-mode network that considers both imports

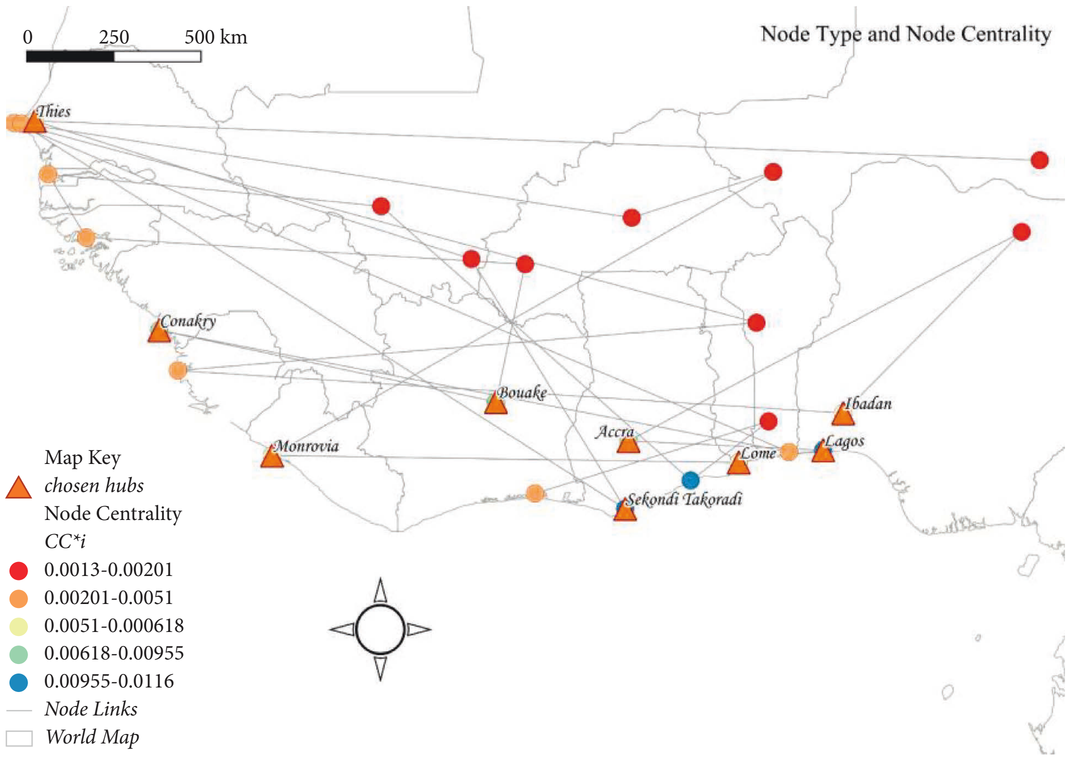


Figure 4: Node type and node centrality.

Table 4: Transportation cost per mode.

Source	Road (**US**)	Rail (**US**)	Waterway (**US**)
PLANCO consulting [62], Teravaninthorn and Raballand [7]	60–70	18.5–6.5	1.462
Transport Canada [63]	26.058–5.918	0.31–0.155	0.28–0.088
Troch et al. [64]	0.030–0.080	0.020–0.030	0.0010–0.050
Average (l_{ihm})	27.014	4.2525	0.3762

Table 5: Handling cost and set up cost by World Bank (2020).

Hub candidate	Handling cost (\$/(h **ton**$^{-1}$))	Set-up cost (\$)
Sekondi Takoradi	0.3786	85,189.97
Lagos	0.4683	82,291.02
Accra	0.3756	85,189.97
Conakry	0.4042	37,360.52
Kumasi	0.3758	85,189.97
Bouake	0.8808	84,456.78
Ibadan	0.4683	82,291.02
Thies	4.5458	75,776.70
Lome	0.7808	34, 626.57
Monrovia	1.1783	25,026.38

and exports. Rule (22) provides that a hub route is from origin node i to hub h. In Constraint (24), C is \$7.5 billion, which ensures the investment within the permission of policy support (Africa Transport and Connectivity Task Force, Towards an enhanced Africa-EU Cooperation on Transport and Connectivity [R], European Commission, 2020, page 49; https://transport.ec.europa.eu/news/africa-europe-alliance-better-transport-and-mobility-between-africa-and-european-union-2020-02-20_en). The remainder of the constraints defines non-negativity constraints and constraints negative binary variables. Based on data from literature [13], unit waiting cost is assumed to be the opportunity cost incurred as a result of waiting and is $\mu =$.

Unfortunately, transport modes within ECOWAS operate below capacity and are abandoned. For this research, we assume that the transport modes within ECOWAS are standardized and perform at optimal speeds. For the rail service, we take a busy heavy rail line (10 cars/train) which operates through a central transfer station (1.8-*ton p*/*ft*, 75 *ft*/*car*) with long station dwell-times (15 mins) which will be adopted for cities with uncertain rail transport and it is assumed that a single trail run's daily capacity = (load in tons per car) × (cars per train) × (trains per day)× (PHF) × (365 days). For our research, we introduced a parameter of peak hour factor (PHF) set at 0.80 [66]. Also, this research adopts a Pontoon Ferry common in developing countries for waterway transport and an assumption of a heavy-duty freight truck for road transport. To solve this model, we utilized a selection algorithm written by the researchers to find optimal results.

4.3. Results and Discussion

4.3.1. Hub Location and Material Flows. As opposed to the current railway structure of ECOWAS, which research deems underutilized and unconnected, we utilized a well-connected and proposed railway structure connecting all the identified major cities within ECOWAS. Although we assume that ECOWAS had operating railway linkages across all selected significant cities, waterway and road networks remained the same for this simulation. The model identified optimal hubs for each mode of transport; for waterway transportation, it identifies two optimal hubs located in Accra and Lagos. The railway based on the proposed structure identified four optimal hubs: Conakry, Monrovia, Ibadan, and Thesis. The road network identified two optimal hub locations: Thesis and Ibadan. The choice of the population size was random, with a trade-off between efficiency and effectiveness. Too small a population will limit the exploration space of the research, and too large a population would impair the model's efficiency [67]. The algorithm parameters were a maximum number of 5000 iterations, with a population size of 1000, a mutation probability of 0.5, an elite ratio of 0.01, a crossover probability of 0.5, a parent's portion of 0.3, a uniform crossover type, and a maximum of 1000 iteration was allowed without improvement.

4.3.2. Selection of Consolidation Centers. Optimizing the total cost across networks revealed optimal routes with their associated hubs for each mode of transport. The result is shown as Figure 5.

5. Sensitivity Analysis

Conducting a sensitivity analysis for several parameters effects further explores the factors that are noted as affecting selection results. For this sensitivity analysis, the figures are estimated as close to real-life circumstances as possible to evaluate the efficiency of the model as stated by Saltelli et al. [68].It looks at ECOWAS connected by railways to its major cities and other modes of transport to analyze if an investment in railway transport is beneficial for exploring the vast trade potential of the free-trade zone.

5.1. Value of Time (VOT). Value of time for trade volumes measured sensitivity to delivery time and speed. Transporting goods through rail and ferries leads to VOT being lost compared to the road, and it is not an optimal choice for time-sensitive and perishable goods. Also, in Figure 6 an increasing VOT showed a corresponding increase in total cost and more hubs needing to be set up to avoid congestion. With VOT increasing, goods need to be cleared from hubs at an increasing rate, but this leads to congestion at hubs and increases hub handling time. To curb this, more hubs are needed to be set up to reduce congestion at hubs and ensure the value of time. An increasing VOT implies limited choice in the mode of transportation mostly with the most time-sensitive mode of transport being chosen; with the transport capacity of rail transport averaged at 1500 tons per train, investing in time-sensitive speed freight trains would increase the value of time of rail transport.

A decreasing VOT leads to more flexibility in the choice of mode of transport and reduces transportation costs. This is suitable for industrial and mechanical goods in nature for which customers are unwilling to pay extra for timely delivery. Moreover, as intraregion trade increases within ECOWAS, and VOT will also increase. Therefore, it is advisable to invest in more time-sensitive rail transport with higher speed, expand hubs, and reduce waiting time. As an incentive for increasing trade within ECOWAS, it is advised that attention should be given to maintaining peace and reducing corruption within ECOWAS, thus reducing the bottlenecks, reducing the overall cost of trade, and ensuring increased intraregional trade.

5.2. Transportation Cost and Hub Set-Up Cost. To understand the significant impact of rail transport, we analyzed the impact of the transportation cost on the number of hubs set and total cost (Figure 7). From our sensitivity analysis, we noted that lower transportation costs led to fewer hubs being established and lower transportation costs, and as transportation cost increases, the number of hubs set also increased, and the overall total cost increases. As such, to increase trade, it is advised that governments regulate the cost of transportation by introducing favorable policies that regulate transportation costs such as subsidizing the cost of transportation. Moreover, railways have higher loading capacity than road or waterway; as such, transporting higher volumes through rail results in enjoying economies of scale from the origin to selected hubs and destinations, reducing overall total cost. Therefore, massive investment in improving the overall connectivity of ECOWAS through focused on investing in railways, waterways, and better road access; most especially highways will lower the cost of trade and improve intraregional trade.

5.3. Hub Set-Up Cost. Reducing the hub set-up cost C_h increased the number of hubs established. In Figure 8, with no set-up cost, the model established an increased number of hubs with a reduced total cost; as set-up cost increases, we observed a decline in the number of hubs established and a rapid increase in total cost. With increasing intraregional trade, more hubs are needed to be set up to accommodate growing trade flows. To ensure this, it is necessary for policies to be set that ensures a smooth flow of trade between various cities and planned budgetary adjustments to accommodate for this increasing cost as more hubs are needed.

5.4. Handling Cost. Our analysis considered the impact of changes in handling cost, reducing handling cost, and reduced total cost. As shown in Figure 9, the higher the

Table 6: Explanation of variables.

Symbol	Definition
	Sets
I	Set of ECOWAS cities origin nodes, indexed by i
J	Set of ECOWAS cities destinations, indexed by j
H	Set of hubs, indexed by h
M	Set of transportation modes, indexed by $m = RR$ which represents rail, $m = R$, represents road and, $m = W$ represents waterway
	Parameters
W_{ij}	Trade volume from origin i to destination j
l_{ih}^m	Unit transportation cost of unit flow between nodes $i \in N$ and $h \in N$ using the transportation mode $m \in M$
l_{hj}^m	Unit transportation cost of unit flow between nodes $h \in N$ and $j \in N$ using the transportation mode $m \in M$
c_h^m	Set-up cost for establishing a hub h at node $h \in H$ with the transportation mode $m \in M$
μ	Value of time
b_1	Freight cost per t-km before consolidation
b_2	Freight cost per t-km after consolidation
θ_{ij}^m	Transportation speed between nodes $i \in N$ and $j \in N$ using the transportation mode $m \in M$
k_h	Unit handling cost at hub h
a_h	Maximum handling capacity at hub h
d_{ih}^m	Distance between nodes $i \in N$ and hub h using the transportation mode $m \in M$
d_{hj}^m	Distance from hub h to destination j via the transportation mode m
t_h	Handling time at hub h
θ_{hj}^m	Transportation speed between nodes $h \in N$ and $j \in N$ using the transportation mode $m \in M$
θ_{ih}^m	Transportation speed between nodes $i \in N$ and $h \in N$ using the transportation mode $m \in M$
	Decision variables
X_{ih}	1 if node $i \in N$ is allocated to the hub at node $h \in H$; otherwise, 0
H_h^m	1 if a hub is established at node $h \in H$ using transportation mode $m \in M$; otherwise, 0

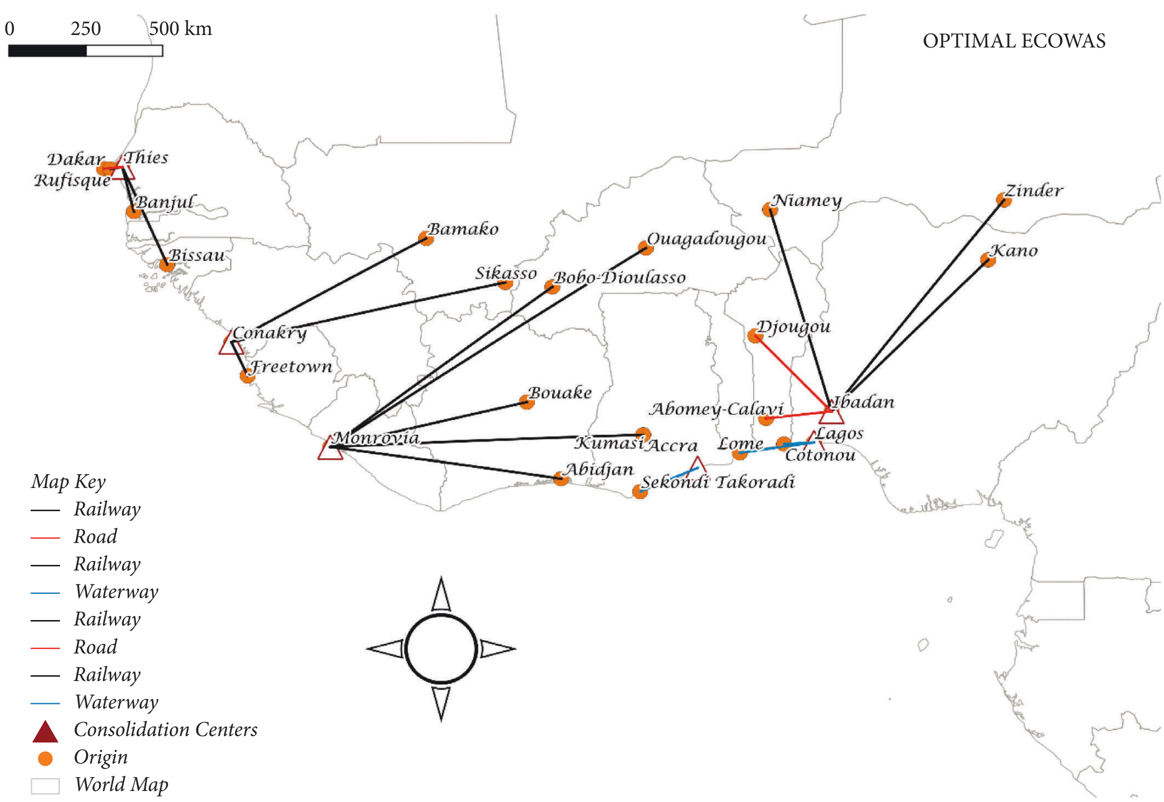


Figure 5: Optimal ECOWAS for logistic network.

FIGURE 6: Impact of consolidation on total cost, value of time, and no. of hubs.

FIGURE 7: Impact of transportation price, total cost, and no. of hubs.

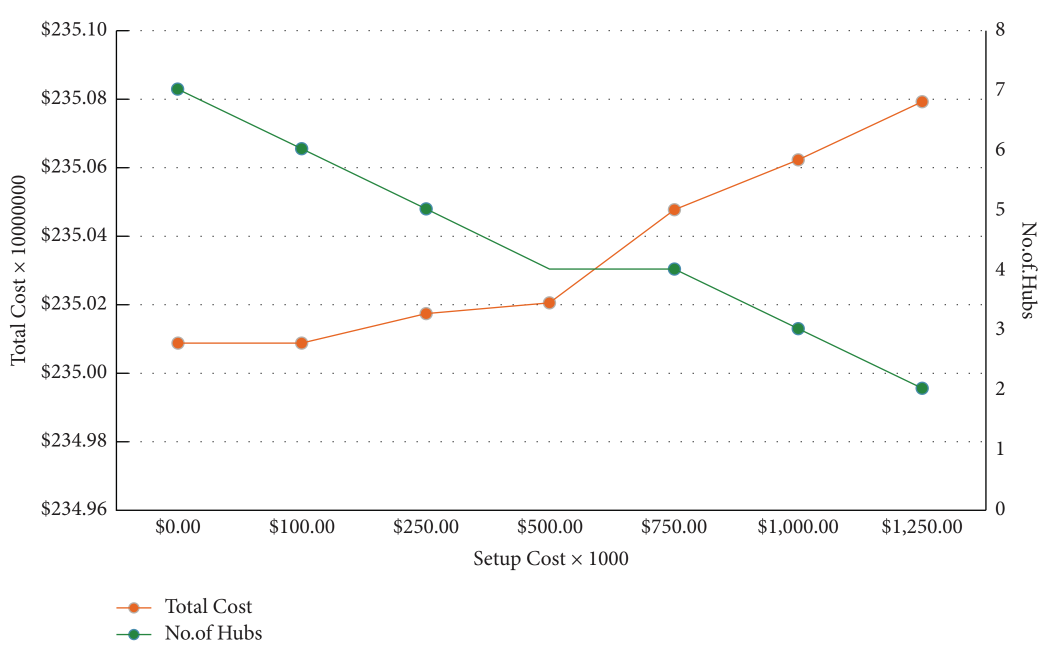


FIGURE 8: Impacts of set-up cost, total cost, and no. of hubs.

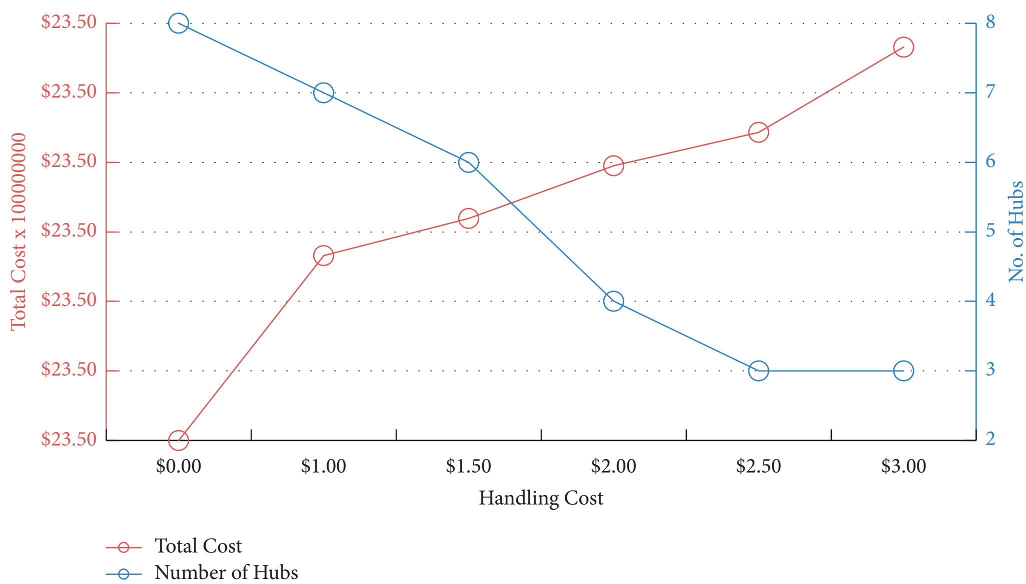


FIGURE 9: Impact of handling cost, total cost, and no. of hubs.

handling cost, the higher the total cost; to combat this, it is advisable to invest in subsidizing handling costs at the beginning of intraregional trade till ECOWAS is self-sufficient. Also, as handling cost increases, fewer hubs are set up, and this implies that as handling cost reduces, more cargoes will be directed to these hubs leading to congestion and a need for an increase in the number of hubs set-up. An increasing handling cost also offers a corresponding decrease in handling time and increased handling capacity, reducing waiting time and increasing time value as fewer cargoes are directed to these hubs. These results showed that adjusting the number of hubs setup caused subsidizing handling cost, and the handling capacity of these hubs can increase trade. In addition, as trade levels rise, a proposal of hub workers working in shifts or overtime during peak seasons to tackle congestion and rerouting specific trade volumes to other hubs to reduce congestion can be adopted.

It is advisable that to enjoy economies of scale and promote intraregional trade, ECOWAS invests in rail across its major cities to take advantage of the potential offered by the trade agreement. For an optimal solution, it is advisable that hubs increase their handling capacity and handling time by having employees work overtime during peak hours at the hub.

6. Conclusion

Above all, the introduction of active railways across ECOWAS showed a significant reduction in transportation costs. Moreover, it lowered the overall total price of the network, proving how vital economic link railway transportation is for substantial trade growth in Africa. We reached the following conclusions.

To begin with, the proposed optimal network will also centralize trade across ECOWAS, eliminate the high cost of point-to-point transportation, boost business, and lower the overall trade cost. This will ensure that goods traded within Africa will stand as competitive on the African market against imported goods. In addition, it leads to poverty alleviation by creating much-needed jobs as trade soars and paving the way for wealth creation, as seen in countries such as China, which boosts transportation efficiency as a source of trade growth and poverty reduction.

Secondly, utilizing a distance-based weighted centrality measure as a determinant of candidate hubs also ensured our choice of hubs was void of researcher bias and contributed to research in Africa. Unfortunately, to the best of our knowledge, no research across ECOWAS has yet utilized distance-based centrality measures to propose a hub location model or examine the intermodal transportation network within ECOWAS.

Finally, an optimal number of hubs were located and proposed; for the waterway, two optimal hubs were situated in Accra and Lagos. Based on the proposed structure, the model was identified for railway in Thies, Ibadan, Conakry, and Monrovia as optimal hubs and road network optimal hub locations in Ibadan and Thies. The sensitivity analysis conducted showed that the handling cost, hub set-up cost, and value of time affect the optimal location and the number of hubs set. These results provide management recommendations such as improving the overall security of certain cities to reduce overall cost and improving the operations of these hubs by adopting technological advancements to streamline operations.

This research has certain limitations: First, its implementation requires a substantial financial investment from all parties to roll out a successful railway system across ECOWAS to enjoy its results. Also, certain cities were excluded due to a lack of data and additional inputs to support their inclusion. Including these cities would affect the outcome and might lead to a broader selection of hubs. Finally, due to time restrictions and access to efficient and effective data, this research could not look at transportation across Africa. As such, it is recommended for future studies to include intermodal transportation modes across Africa [10, 22, 24, 61].

Data Availability

The data that support the findings of this study are openly available in data.4tu.nl at https://doi.org/10.4121/16790221.

Conflicts of Interest

The authors declare that they have no potential conflicts of interest.

Authors' Contributions

Jihui Shi and Kesewa Opoku Agyemang contributed equally to this study.

Acknowledgments

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