

Probing into Hinterland Connectivity with a Web of Transport Modes and Logistics Nodes: A Case of Indian Container Ports

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Abstract

This article investigates the conceptual and empirical aspects of hinterland connectivity, focusing on container ports in India as a case study. It aims to clarify the complex and multidimensional nature of hinterland connectivity within the context of container ports by addressing a key conceptual issue. The study proposes that port-hinterland connectivity goes beyond direct links and emphasises the strategic relationships with key logistics centres in the hinterland. By employing centrality measures from social network analysis, the study evaluates the overall connectivity of Indian container ports, considering both direct and indirect connections from 2009 to 2021, to identify which ports have robust connections to key logistics centres. The results obtained by using eigenvector centrality reveal that an extensive hinterland network does not necessarily guarantee better hinterland connectivity for container ports. Additionally, the quality of connections, particularly to hubs with high betweenness centrality, is crucial for achieving a high degree of hinterland connectivity. These findings provide valuable policy insights, highlighting the importance of ports fostering closer relationships with key logistics hubs to effectively enhance their connectivity. Based on these findings, the paper offers policy recommendations for India aimed at improving connectivity in alignment with corresponding market shares. This research will serve as a foundation for further exploration of the interplay between port-hinterland connectivity and port market shares from a hinterland perspective, especially in a country like India, where hinterlands significantly overlap.

Keywords: Transport mode; Logistics node; Overlapped hinterland; Port-hinterland connectivity; Indian container port; Social network analysis.

1. INTRODUCTION

A seaport, serving as a central trading hub and vital link in global supply chains, must be well-connected to its hinterland¹, where traded goods are consumed or processed. In this way, the port plays a crucial role in determining the logistical performance of a country or region. This is particularly significant for countries that rely heavily on ports for their international trade. Previous studies have repeatedly emphasized the importance of effective hinterland connectivity as an extended function of ports. The quality of this connectivity can directly impact a port's operational efficiency and its competitive position against rivals in common or overlapping hinterland markets (Wang et al., 2016). Improving hinterland connectivity has been shown to be a key factor in enhancing the competitiveness of ports (Yeo et al., 2011).

In the context of port competition, the concept of port-hinterland connectivity (PHC) is examined from two distinct perspectives. The first perspective views PHC as an integral part of the port's overall connectivity, encompassing both seaside and landside transport links (Yeo et al., 2008; Wang et al., 2016). This approach primarily focuses on key factors such as land transportation costs, availability and capacity of transport modes to and from the port and transport infrastructure in the region. The flow of cargoes to and from the port to various destinations is a significant consideration in analysing PHC from this perspective. Ports that are effectively connected to numerous inland destinations (e.g., industrial clusters or major cities) at minimal cost and with maximum capacity (i.e., a high number of departing transport services) are considered to possess efficient hinterland connectivity. This perspective can therefore be labelled an economic perspective on PHC (Wang and Cullinane, 2008, 2016). However, this perspective has certain limitations. The studies mentioned have broad scopes, covering port efficiency, accessibility, and global connectivity, rather than solely analysing PHC. Some studies (e.g., Yeo et al., 2008 and 2011) were conducted with subjectively expressed opinions from industry stakeholders, potentially leading to an incomplete picture of the issue. Despite being insightful within their contexts, these studies may overlook essential elements such as the complex intermodal networks between ports and hinterlands.

On the other hand, the second perspective focuses on the port's intermodal network, which includes multiple modes of transportation such as rail, road, and inland waterways (Wang et al., 2016; Halim et al., 2016; Zhang et al., 2018). Studies adopting this perspective delve into the breadth and coverage of the intermodal network extending from the port to various destinations in its hinterland. Compared to the first perspective, this approach provides a more detailed geographical understanding of PHC, hence termed a topological perspective (Wang and Cullinane, 2008, 2016). Ports that have connections to a wide array of logistics nodes, mainly dry ports (Roso, 2007) and inland container depots (Sagarmala, 2016), are generally regarded as having higher levels of hinterland connectivity. The topological perspective effectively covers the intermodal network, but it's important to recognize that within this framework, the primary analytic focus has been on the 'first layer' of port hinterland connectivity. This foundational layer mainly comprises a limited range of transport services, such as rail or inland waterways, directly linked to a few inland logistics nodes, mainly inland container depots and dry ports. In practice, however, there exists a 'second layer' characterized by a diverse array of inland logistics nodes. These nodes have indirect connections to seaports via the first layer, encompassing facilities such as container freight stations, distribution centers, warehouses, and intermodal terminals. Additionally, Wang et al. (2016) and Zhang et al. (2018) have analysed the 'undirected' flows of transport services and freight movements between seaports and dry ports. Generally, these studies depict the relationship between a port and its hinterland as a static network that includes both physical connections (modes of transport) and logistical centers, with a particular focus on dry ports and inland container depots.

Nevertheless, the connectivity between a port and its hinterland cannot be structured solely in a static form. If we include the frequency of transport services along the connections to different logistics nodes between the port and the hinterland into the equation, a different picture might emerge regarding the possible connectivity between ports and their hinterlands. This complex nature of PHC presents a challenging point for definitively categorizing the aforementioned studies as either 'port-hinterland network' or 'port-hinterland connectivity'. This complexity may stem from the distinction that the

¹ Hinterland: An inland area from where the port draws its business (Kronbak and Cullinane 2011).

concepts of ‘network’ and ‘connectivity’ are separate entities that warrant individual evaluation, as noted by network scientists Wasserman and Faust (1994). While a network analysis centers around the question of ‘who is connected to whom’, the concept of connectivity focuses on ‘how often who is connected whom.’ A comprehensive understanding of connectivity between a port and its hinterland should therefore consider not only the breadth of the network but also the frequency of connections within the network. This type of analysis will enable a better understanding of the concept and pave the way for fairer comparisons between ports in a PHC context.

Building on the aforementioned discussion, this paper primarily aims to explore the conceptual model of port-hinterland network and connectivity. Based on this developed conceptual model, the paper seeks to structure and measure the port-hinterland network and connectivity of Indian container ports as a case study. India has been chosen as a case study because, in recent times, the Indian government has identified the hinterland connectivity of container ports as a weak point in the country's extensive logistics structure. In response, a substantial budget (USD 130 billion in 2016) has been allocated to improve this connectivity and link the ports with the wider hinterland (Sagarmala, 2016). This emphasis on hinterland connectivity and the consequent actions taken by the government makes Indian container ports a compelling case for examination. The paper is structured to address three key questions: (i) Conceptually, what defines port-hinterland connectivity? (ii) Empirically, how can port-hinterland connectivity be effectively measured? And (iii) Does a port with an extensive 'hinterland network' necessarily have high 'hinterland connectivity'? In pursuit of answers, this paper undertakes a literature review to capture recent progress in this field. A conceptual model is then developed, focusing on the hinterland connectivity of container ports, using centrality measures from social network analysis to empirically validate the proposed model. The concluding part contains a set of policy recommendations based on the results.

2. LITERATURE REVIEW

2.1 Two Perspectives on Port Hinterland Connectivity

In the context of port competition, numerous prior studies have underscored the significance of the connection between a port and its hinterland. Nonetheless, there exists a variety of terms used across these studies to describe this linkage. These terms encompass concepts such as 'port inland connectivity', 'inland transport network' (Wilmsmeier et al., 2006), 'transport network' (Yeo et al., 2008), 'port accessibility [land side]' (Cullinane et al., 2009), 'transport and terminal network' (Rodrigue et al., 2009), 'port hinterland system' (Wang and Ng, 2011), 'intermodal freight transport network' (Thill, 2010), 'intermodal accessibility' (Thill, 2010), 'intermodal link,' 'inland transport network' (Yeo et al., 2011), 'port hinterland accessibility' (Ferrari et al., 2011), 'port hinterland network' (Halim, 2016; Low et al., 2009), and 'hinterland connectivity' (Wang et al., 2016; Deng et al., 2022). Despite the varied terminology, all these expressions fundamentally pertain to the connectivity (or accessibility) between a port and its hinterland. Across these studies, the discussion and evaluation of this connectivity have occurred from diverse perspectives. However, as noted in the preceding section, these different dimensions can be categorised into two primary viewpoints: economic and topological.

Economic Perspective

From an economic standpoint, the connection between a port and its hinterland is commonly assessed based on three pivotal parameters: transportation costs, transit time, and the capacity of the transportation infrastructure linking the port with its hinterland. For instance, in their analysis of port characteristics, Wilmsmeier et al. (2006) identified inland transport infrastructure as a significant factor affecting [international maritime] transportation expenses. A proficient and cost-efficient land transport network can play a pivotal role in the competition among ports, as demonstrated by Yeo et al. (2008) concerning the competitiveness of container ports in Korea and China. Similarly, Tang et al. (2011) and Low et al. (2009) regarded the availability of intermodal facilities, such as rail, highways, and inland waterways, as a crucial factor in formulating a model for the port selection behaviour of shipping lines. Moreover, Cullinane and Wang (2009), in developing an index for container port accessibility, identified overall inland transportation costs—largely dependent on the transport network – as a pivotal

determinant. Additionally, Rodrigue and Notteboom (2009) emphasised how the amalgamation of transportation networks and terminals impacts the time taken for cargo to traverse from the port to its ultimate destination in the hinterland, elucidating the process of supply chain terminalization. In assessing the competitiveness of container ports from a logistics perspective, Yeo et al. (2011) underscored the significance of intermodal links and the associated logistics costs as crucial components. Collectively, these studies underscore the economic dimension of port-hinterland connectivity and emphasise the essential role that efficient and cost-effective inland transportation infrastructure plays in securing competitive advantages for ports.

While these studies offer valuable insights into PHC, they predominantly treat this connectivity as one among several factors in port competition. This means that they don't exclusively focus on the analysis of PHC. As a result, the methods and variables employed to measure PHC vary significantly from case to case. For example, Wilmsmeier et al. (2006) utilised regression analysis, while Wang and Cullinane (2008) employed the principal eigenvector method. Cullinane and Wang (2009) opted for social network analysis, whereas Yeo et al. (2011) used the fuzzy method. Tang et al. (2011) and Low et al. (2009) respectively utilised the network-based choice evaluation model and the network-based connectivity index, Valls et al. (2020) use nested logit model approach,

These diverse approaches relied on distinct variables and parameters, such as transport costs, time, mode availability and basic transport infrastructure to assess PHC. Although these approaches were suitable within their respective contexts, they might lack precision in empirically determining the exact connectivity of a port with its hinterlands. This underscores the necessity for a more encompassing and cohesive framework capable of comprehending the intricacies of PHC across various scenarios. Such a framework should consider the physical transport network and logistics infrastructure within the hinterland.

Topological Perspective

The understanding of the relationship between ports and their hinterlands from a topological perspective has evolved over time. Initially, the hinterland was viewed as an extension of the port's 'transport network,' where the port acted as a transfer point for goods moving between sea and land transport (Mayer, 1973). This perspective led to transport-oriented concepts in port-hinterland connectivity, such as mini-bridges and micro-bridges (Kuby and Reid, 1992), high-priority transport corridors (Taaffe et al., 1963), and intermodal networks (Hayuth, 1981; Fleming and Hayuth, 1994). Later, this view underwent a shift, recognising ports as intricate systems closely linked to an expansive 'network' of inland cargo centres (Slack, 1990). Scholars began to conceptualise the port-hinterland relationship as an integrated system where ports, inland transportation networks, and various inland cargo centres formed interconnected components of a comprehensive supply chain network (Van Klink, 1998; Van Klink and van Den Berg, 1998). More recently, the notion of a port's intermodal network has further expanded to encompass not only traditional modes such as rail, road, and inland waterways, but also a variety of inland logistics nodes, notably dry ports (Wang et al., 2016; Deng et al., 2022) and distribution centres (Halim et al., 2016). This interconnected network of ports, transportation systems, and logistics nodes is often referred to as the port-hinterland network (Halim et al., 2016; Deng et al., 2022) or port intermodal network (Crainic et al., 2015; Crainic and Kim, 2007). Numerous studies from above suggest that the extent of port-hinterland network is a critical determinant of a port's competitiveness.

Similar to the economic perspective, the diverse range of methods and variables used in topological studies to measure PHC highlights the intricate nature of the port and hinterland relationship. Each approach offers distinct insights into specific aspects of this complex structure. For example, studies by Thill and Lim (2010), Ferrari et al. (2011), Moura et al. (2017), employed gravity and Huff models in conjunction with Geographic Information System (GIS) tools. Whereas Garcia-Alonso et al. (2017) purely use GIS model to construct the port hinterland. They examined variables such as highway networks, travel distances, population density, and container throughput. Despite their differing perspectives, these studies share a common thread: analysing PHC by assessing the extent of the inland transport network from the port to the hinterland. Contrastingly, Dadashpoor and Arasteh (2020) chose social network analysis, emphasising commodity flows rather than transport networks. This offered an alternative outlook on the connectivity between Iranian ports and their hinterlands. However, recent

studies by Wang et al. (2016), Wei and Sheng (2018), and Deng et al. (2022) used a more conventional approach, focusing on the actual transport network between ports and their hinterlands. While analysing the hinterland connectivity of container ports in Bohai Bay, Wang et al. (2016) scrutinised the 'one-dimensional' transport network (i.e., from the port to dry ports) in the hinterland. They applied the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method to formulate an overall assessment index for three ports in the Bohai Bay. On the other hand, Wei and Sheng (2018) employed social network analysis to explore the logistical connectivity of six Chinese ports. They devised an 'undirected transport network' connecting ports and dry ports. Unlike Dadashpoor et al. (2020) and Wang et al. (2016), this approach didn't factor in cargo flow, transport services or frequency of transport services to and from ports. Moreover, recently Deng et al. (2022) considered the undirected network of dry ports and inland waterways along the Yangtze River when evaluating port-hinterland connectivity.

However, it's crucial to acknowledge that dry ports and/or distribution centres are not the only inland logistics nodes that connect to ports. Typically, a logistics centre is defined as a specific intermodal point in the transport system comprising various logistics facilities where different operators provide a range of services related to transport, logistics and distribution in a specific geographical area (Rimienė and Grundey, 2007). According to this definition, the spectrum of logistics nodes encompasses warehouses, inland container depots, distribution nodes, inland terminals, container freight stations, intermodal terminals, and more, are integral parts of this intricate hinterland network (Meidute, 2005; Notteboom et al., 2017). Each of these centres contributes to the overall business and operational dynamics of the port, presenting a more diversified view of the port-hinterland connectivity. To comprehensively assess a port's hinterland connectivity, it's imperative to consider all transport modes and inland logistics nodes linked to the port. This holistic approach ensures a comprehensive understanding of the port's reach and its ability to efficiently serve its customers further within the hinterland.

From the discussions presented in above studies, it is clear that the discourse on port-hinterland connectivity largely oscillates between two perspectives, with the terms 'port-hinterland network' and 'port-hinterland connectivity' often used interchangeably. From the economic perspective, these terms refer to a port's level of accessibility to different hinterland regions, including industrial clusters and populated areas. In contrast, the second perspective zeroes in on the specific 'connectivity' between the port and entities like dry ports and distribution centres. However, a significant portion of the literature in this field has concentrated on analysing PHC through the lens of 'who is connected to whom'. These studies investigate the transportation links that anchor the port to its hinterland, essentially examining the 'network' between the ports and various regions within the country, or the dry ports or distribution centres within their hinterland. It is crucial to recognise, in line with the principles of network science, that a 'network' denotes a collection of interconnected objects or entities. 'Connectivity', on the other hand, represents the extent or degree to which these objects or entities within a network are interconnected (Barabási, 2016; Newman, 2018). Therefore, to thoroughly analyse the 'connectivity' between a port and its hinterland, it is essential to evaluate the *degree* of interaction between the components within the network, such as the port and various types of inland logistics nodes.

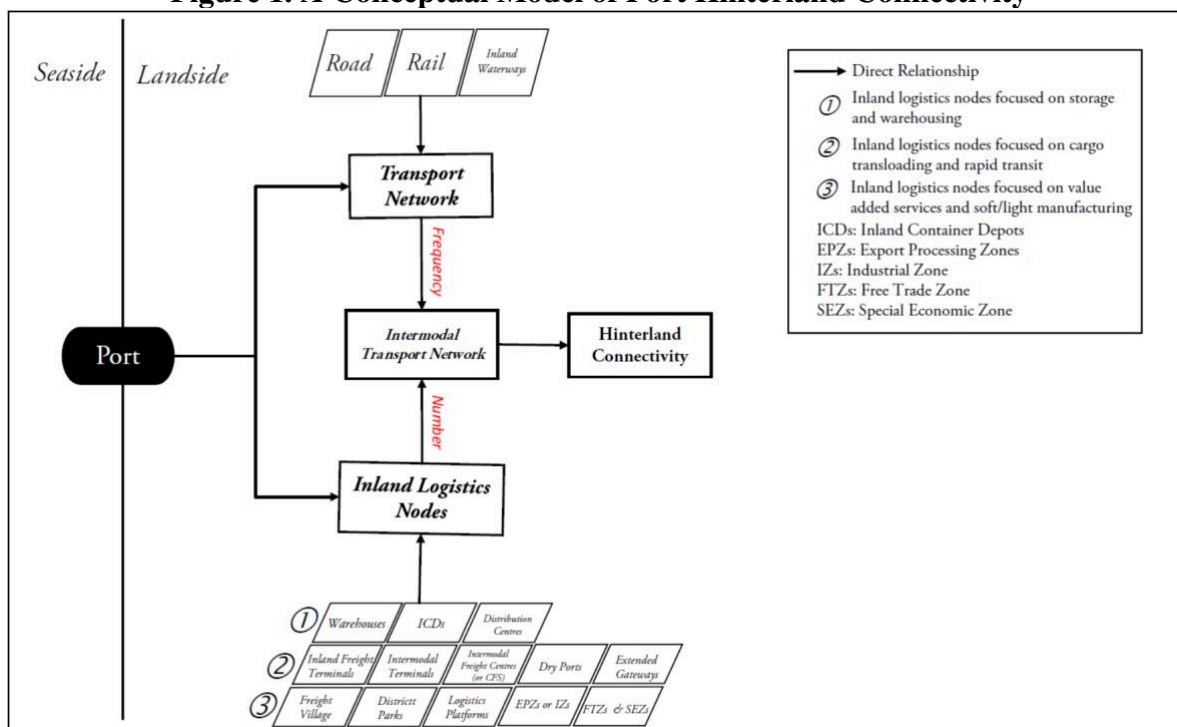
3. DEVELOPING A CONCEPTUAL MODEL

Building upon the discourse in Section 2, the concept of port-hinterland connectivity can be envisioned as a comprehensive matrix comprising two primary components: the 'transport network' and 'inland logistics nodes'. Each of these components can be further dissected into multiple segments. This delineation is illustrated in Figure 1, where the transport network is categorised into segments encompassing rail, road, and inland waterways. In parallel, the inland logistics nodes are categorised into three distinct types: (i) storage and warehousing nodes, (ii) cargo trans-loading and rapid transit nodes, and (iii) value-added service and soft/light manufacturing nodes. The first category, storage and warehousing nodes, encompasses diverse facilities such as inland container depots, distribution nodes, and both bonded and non-bonded warehouses. The second category, cargo trans-loading and rapid transit nodes, includes pivotal entities such as inland freight terminals (or container freight stations), intermodal terminals, intermodal freight nodes, dry ports, and extended gateways. Lastly, the third category, value-added services and soft/light manufacturing nodes, encapsulates freight villages, district

parks, logistics platforms, special economic zones, industrial zones, free trade zones, and export processing zones. The intertwined structure between these three modes of transport and the three types of inland logistic nodes, along with their respective sub-segments lays the foundation for the intermodal network (Crainic and Kim, 2007).

Nonetheless, in order to assess the 'connectivity' within this port-hinterland network, it becomes imperative to delve into the matrix formed by the three transport modes and the three different types of inland logistics nodes (along with their respective sub-segments) in conjunction with the frequency of intermodal services linking them. The interaction between these components, including the port, transpire at varying transport frequencies, underscoring the significance of incorporating the frequency of intermodal transport services into the evaluation. Consequently, it can be inferred that the *degree* of interaction between the port and the hinterland hinges on the '*frequency*' of intermodal services connecting the port and the '*number*' of diverse logistics nodes. Thus, the assessment of a port's hinterland connectivity is depending on a blend of the frequency of intermodal services emanating from the port and the number of logistics nodes in the hinterland. This multifaceted approach can yield a more comprehensive and nuanced understanding of port-hinterland connectivity.

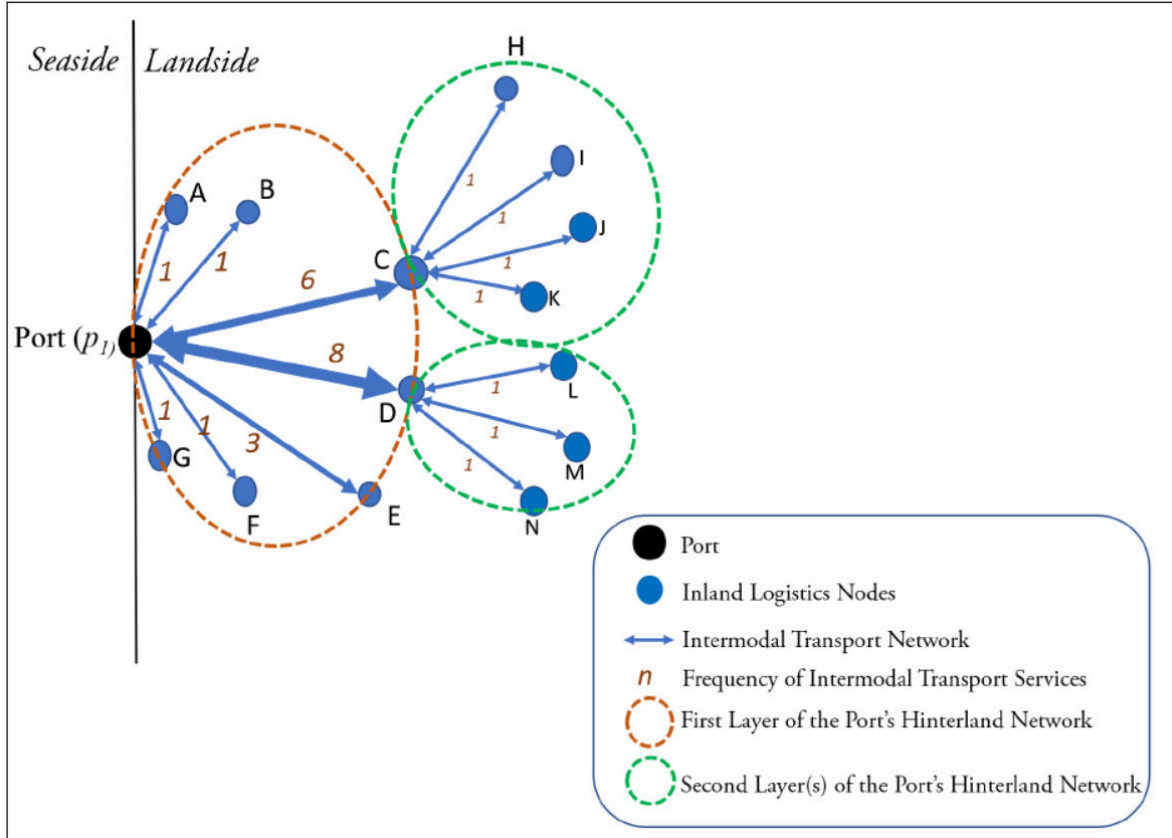
Figure 1. A Conceptual Model of Port Hinterland Connectivity



Source: Drawn by the authors

To analyse 'connectivity' within the port-hinterland network, the network must first be structured. However, as explained earlier, in extensive hinterlands such as India, not all inland logistics nodes have direct connections to the port, especially those in distant areas. Yet, they play a crucial role in handling containerised import and export cargo, contributing significantly to port container throughput. These nodes are integral to the extended hinterland, providing vital logistical services that facilitate smooth goods movement across the country or region. Distant inland logistics nodes, like smaller warehouses or container freight stations (CFSs), connect to the seaport via intermediary nodes such as inland container depots (ICDs) or dry ports, forming a 'second layer' of port-hinterland connectivity. Refer to Figure 2 for visualisation, where dash-line circles of distinct colours depict different layers of the port-hinterland network. The first layer comprises nodes directly linked to the port, while the second layer involves nodes indirectly connected via first-layer intermediaries. For a comprehensive analysis of PHC, both layers must be considered together. Note that in various regions, the port-hinterland network may have more than two layers. However, in the Indian container port network, these two layers predominantly prevail.

Figure 2. Port Hinterland Network: First and Second Layer



Source: Drawn by the authors

4. METHOD

To accurately assess the connectivity of the port-hinterland network, we used social network analysis (SNA), a method that analyses the interactions among nodes and links within complex networks (Scott and Carrington, 2011). SNA has been applied in numerous studies on transport, including maritime, air and road transport (e.g., Cheung et al., 2020; Cullinane and Wang, 2009; Arvis and Shepherd, 2016; Ando et al., 2021) and has been shown to be particularly effective in constructing and analysing complex networks. A crucial aspect of SNA is the use of 'centrality measures' to determine the importance and interconnectedness of nodes within the network. In our study, we used three major centrality indices: degree centrality, which quantifies the number of direct connections a node has (Shaw, 1954; Garrison, 1960; Nieminen, 1973); betweenness centrality, which emphasises the role of a node as a bridge within the network (Freeman, 1977); and eigenvector centrality, which considers both direct and indirect connections. This metric measures the overall connectivity of a node based on its connections to other influential nodes. Values from 0 to 1 are assigned to indicate the overall connectivity of a node within the network. Nodes with higher eigenvector centrality values are considered extensively connected because they are closely linked to other highly connected nodes (Bonacich, 2007; Ruhnau, 2000). These metrics are important for identifying central nodes and understanding the overall structure of the network, which is essential for understanding the dynamics of port-hinterland connectivity. In this study, ports and logistics nodes are defined as 'nodes' connected by different means of transport, the so-called 'links'. Using this framework, we first constructed the port hinterland network and then analysed the connectivity of these ports within the hinterland network.

4.1 Degree Centrality

The degree of centrality in a port-hinterland network is typically a measure of the number of transport links a port has with inland logistics nodes. However, for a more comprehensive analysis of port-hinterland connectivity, it's crucial to consider not just the connections but also the extent of interaction

between the port and inland logistics nodes. This means factoring in the frequency of transport services between the port and the inland nodes. In this context, the port-hinterland network is envisioned as a 'value-based network' within SNA. In such a network, when calculating a port's degree of centrality, the frequency of intermodal transport services is incorporated as the 'weight' or 'value' of each inbound and outbound connection to inland logistics nodes. This approach considers both the number of connections and the sum of all inbound intermodal frequencies, offering a more comprehensive measure of the port's connectivity within its hinterland network. The formulation of this value-based port-hinterland network can be represented by a specific equation (1).

$$G_w = (N, L, W) \quad (1)$$

Where

- G_w Represents the value (or weight) based port-hinterland network.
- N is the number of ports and inland logistics nodes in the network, i.e. $(n_1, n_2, n_3 \dots n_j)$.
- L is the number of transport services (e.g. rail, road and inland waterways) connecting all the inland logistics nodes, i.e. $(l_1, l_2, l_3 \dots l_L)$.
- W is weight of the port-hinterland network determine by the frequency of transport services connecting between ports and inland logistics nodes $(w_1, w_2, w_3 \dots w_L)$.

Furthermore, equations (2) and (3) serve as instrumental tools for computing the degree centrality of a port and its corresponding degree centrality index within a value-based port-hinterland network.

$$c_D^w(n) = \sum_{j=1}^N w_{jn} \quad (2)$$

$$I_{CD}^w(n) = \frac{c_D^w(N)}{L_w} \quad (3)$$

Where

- $c_D^w(n)$ weighted degree centrality of port n .
- w is 'weight or value' of adjacency port-hinterland network determined by the frequency of transport services.
- w_{jn} is a connectivity from the port n to the inland logistics node j .
- $w_{jn}=1$, if port n is connected to inland logistics node j in the port-hinterland network.
- $w_{jn}=0$, if port n is not connected to inland logistics node j in the port-hinterland network.
- I_{CD}^w is a degree centrality index (or connectivity) of n^{th} port in a weight directed port-hinterland network.
- N is to the number of actors (i.e., ports and inland logistics nodes) in the port-hinterland network.
- L_w sum of the weights of the transport services connected to the N (actors) in the port-hinterland network.

The equations previously discussed focus solely on the direct connections to and from the port, effectively mapping out the first layer of port-hinterland connectivity, as illustrated in Figure 2. This layer captures the immediate, direct links between the port and inland logistics nodes. However, it's essential to recognise that this layer often includes several intermediary nodes that play a pivotal role in facilitating access between the port and the more complex, second layer of nodes. To gain a comprehensive understanding of the port-hinterland connectivity, identifying and analysing these intermediary nodes is crucial, as they significantly influence the overall connectivity within the network.

4.2 Betweenness Centrality

The key distinction between degree centrality and betweenness centrality lies in their focus areas within network analysis. Degree centrality assesses an actor's position based on the number of direct connections it has within the network. On the other hand, betweenness centrality evaluates how significantly an actor functions as an intermediary in facilitating communication between other actors (Freeman, 1977; Wasserman and Faust, 1994).

In the context of port-hinterland networks, intermediary nodes in the first layer play a vital role in connecting the port with the more complex second layer. This layer often includes inland logistics nodes that, lacking direct intermodal connections to a seaport, rely on nearby intermediary nodes for such connectivity. This structure mirrors a hub-and-spoke model, where major logistics nodes act as hubs, aggregating and transporting containers to and from the seaport. Identifying these critical hubs or important nodes is essential for a comprehensive understanding of port-hinterland connectivity. These nodes, as intermediaries, are pivotal in managing the flow of containers between the port and the hinterland. To pinpoint these crucial nodes, the betweenness centrality of each hinterland logistics node in the Indian hinterland is calculated using equations (4) and (5).

$$C_B(i) = \sum_{j < k}^N \frac{N_{jk}(i)}{N_{jk}} \quad (4)$$

$$I_i^{CB} = \frac{2C_B(i)}{(N-1)(N-2)} \quad (5)$$

Where

- $C_B(i)$ is the betweenness centrality of inland logistics node i .
- N number of actors (ports and inland logistics nodes) in the port-hinterland network.
- $N_{jk}(i)$ is the number of shortest paths connecting actor j and actor k that must pass through actor i .
- N_{jk} total number of shortest paths connecting actor j and actor k .

Equation (5), which standardises the betweenness centrality value between 0 and 1, facilitates the comparison of betweenness centralities across different nodes. Represented as I_i^{CB} for node I in a network of N nodes, this equation allows for measuring the relative betweenness centrality of each inland logistics node, shedding light on its role within the complex and overlapping ports' hinterland network. However, computing betweenness centrality is inherently more complex than degree centrality due to its focus on a node's intermediary role in facilitating network flow. A significant debate in the field revolves around the inclusion of edge weights, which represent the intensity or frequency of communication, in betweenness centrality calculations (Newman, 2004; Noh and Rieger, 2002). While some scholars advocate for incorporating edge weights to gain a more nuanced understanding of communication flows (Opsahl et al., 2010), others argue that focusing on the direction of flow without considering edge weights suffices (Barrat et al., 2004; Newman, 2004).

In the context of a port-hinterland network, the inclusion of edge weights can lead to complexity and potential misinterpretation, especially when comparing nodes with different numbers of links and frequencies. For example, comparing a node with 10 links, each with a frequency of 1, to a node with a single link with a frequency of 10 could lead to misleading results. Some studies have used tuning parameters (e.g., Wang and Cullinane, 2016), but they require a uniform data set therefore may not be applicable to all networks. In this study, the betweenness centrality of each inland logistics node within the port-hinterland network is determined without considering edge weights. The subsequent betweenness index derived from equation (5) allows the assessment of the respective betweenness (or

important) position of each inland logistics node within the port-hinterland network, taking into account the different types of nodes connected to it via different transport links.

4.3 Eigenvector Centrality

Eigenvector centrality is a metric used in network analysis that evaluates the importance of a node by considering both its direct and indirect connections. Unlike simpler metrics that only account for a node's immediate connections, eigenvector centrality assesses a node's influence based on its connectivity to other significant nodes within the network. This means a node is deemed important not only if it has many connections but also if it is connected to other nodes that are themselves have higher connectivity. The centrality values assigned range between 0 and 1, with higher values indicating greater overall connectivity and influence within the network (Ruhnau, 2000; Ando et al., 2021).

In the context of a port-hinterland network, eigenvector centrality is particularly useful for identifying ports with higher direct and indirect connectivity within the hinterland network. This network comprises ports and inland logistics nodes such as warehouses, distribution centers, and transport hubs. A port with a high eigenvector centrality score is well-connected not just directly to many inland nodes, but also to inland nodes that are themselves highly connected within the hinterland. Therefore, eigenvector centrality can highlight ports that are critical in the broader logistical network, accounting for both immediate connections and the importance of those connections. For instance, a port linked to major inland logistics node (which in turn are well-connected to other nodes) will score high in eigenvector centrality, reflecting its pivotal role in facilitating second layer of logistics networks. This measure provides a comprehensive understanding of port connectivity by considering both the quantity and quality of connections. It moves beyond merely counting connections to assessing their significance within the entire network structure.

By applying eigenvector centrality, we gain a nuanced insight into how central or influential a port is within the port-hinterland network. This dual consideration of connection quantity and quality offers a richer analysis of port connectivity and strategic importance in logistics. Eigenvector centrality of each port can be gauged by applying equation (6).

$$v_i = \frac{1}{\lambda} \sum_{j=1}^n w_{ij} \cdot v_j \quad (6)$$

Where

- v_i is the weighted eigenvector centrality score of node i .
- w_{ij} represents the weight of the connection between node j and node i .
- n is the total number of nodes in the network.
- λ is a constant representing the largest eigenvalue of the network W .

5. DATA

In recent years, India has risen to become the fifth largest economy in the world (IMF, 2023), a milestone largely attributed to numerous development initiatives by the Indian government. One of these initiatives is the ambitious Sagarmala project, which translates to 'Garland of the Sea'. This initiative aims to improve the performance of the country's logistics sector. The maritime sector, which has long been the backbone of Indian trade, has experienced significant growth in recent years. The Sagarmala project aims to fully harness India's 7,517 km of coastline, 14,500 km of potentially navigable waterways and its strategic location on key international maritime trade routes. The project aims to unlock the potential of the waterways and coastline for international trade. The project also has the vision of reducing logistics costs for both domestic and EXIM (export-import) freight traffic by expanding the infrastructure. The studies conducted under the Sagarmala project have identified opportunities to

reduce overall logistics costs, thereby improving the efficiency and competitiveness of the Indian manufacturing sector in the global market (Sagarmala, 2016).

The project, with an impressive budget of USD 130 billion, targets three critical areas of the logistics sector: modernisation of seaports, setting up of port-linked industrial units and development of hinterland connectivity to container ports. Among these areas, the government has recognised that the link between ports and hinterland is the weakest aspect of the country's logistics sector. Therefore, a significant portion of the budget (USD 36 billion in 2016) has been allocated to improve hinterland connectivity of ports to various regions of the country (Sagarmala, 2016). This focus on hinterland connectivity and the resultant measures taken by the government makes Indian container ports an interesting case study for this research. In compiling the hinterland network of Indian container ports, data for the period from 2009 to 2020 was carefully collated from the sources listed in Table 1. This period was chosen to accurately represent port-hinterland connectivity in India during a significant period of economic expansion after the 2008 financial crisis and before the outbreak of the pandemic in 2019.

Table 1. Summary of Data Sets

<i>Dataset</i>	<i>Years</i>	<i>Observations</i>	<i>*Sources</i>
Number of Ports	FY 2009-2010 to FY 2020-2021	15	IPA (2023) and IPPTA (2023)
Inland Logistics Nodes	FY 2009-2010 to FY 2020-2021	349	CONCOR (2022) and CBITC (2022)
Monthly frequency of rail and barge services from ports to inland logistics nodes	FY 2009-2010 to FY 2020-2021	228	CONCOR (2022)
Monthly frequency of rail and barge services from inland logistics nodes to Ports	FY 2009-2010 to FY 2020-2021	228	CONCOR (2022)
Total		12 years	820

Note: *IPA: Indian Ports Association; IPPTA: Indian Private Ports and Terminal Associations; CBITC: Central Board of Indirect Taxes and Customs; CONCOR: Container Corporations of India

Container Ports: This dataset captures active container ports in the Indian hinterland, along with inland logistics nodes involved in maritime trade activities, particularly imports and exports. The primary data sources are the Indian Port Association (IPA) and the Indian Private Ports and Terminals Association (IPPTA).

Active Inland Logistics Nodes: Information on operational inland logistics nodes comes from the Container Corporation of India Limited (CONCOR) and the Central Board of Indirect Taxes and Customs (CBITC). In India, import and export containers are predominantly processed through government-owned Inland Container Depots (ICDs), and privately owned Container Freight Stations (CFSs) and bonded warehouses, as per customs regulations.

Frequency of Intermodal Transport Services: This dataset focuses on the frequency of rail and inland waterways services connecting ports to inland logistics nodes. Data is sourced from CONCOR (via e-mail), accounting for 80% of container traffic, and other private companies contributing to 14% of the traffic (Gangwar et al., 2012). Road connectivity data, without specific frequency details, identifies links between nodes and ports, sourced from inland logistics companies' websites.

According to IPA (2023) and IPPTA (2023), 18 operational container ports were identified in India, equally distributed between the west and east coasts. The study includes data for 15 of these ports (11 public, 4 private), with 3 ports unavailable for analysis. Furthermore, 349 inland logistics nodes were

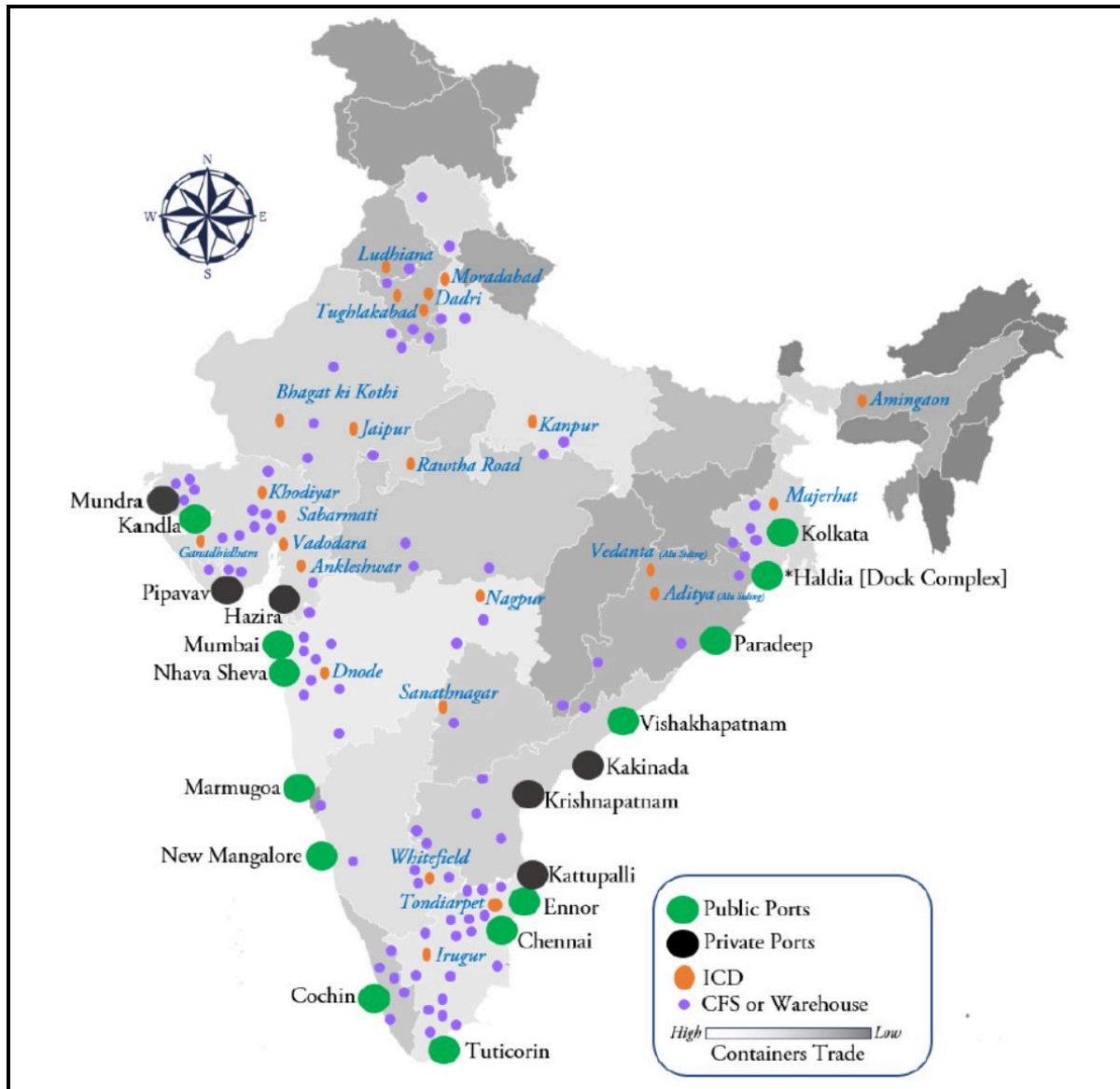
incorporated, representing about 96% of India's container trade as per CBITC (2022). Table 2 presents the list of Indian container ports incorporated in this study. Concurrently, Figure 3 illustrates the tentative geographical locations of these ports and inland logistics nodes in India.

Table 2. Container Ports in India

<i>Sr. No.</i>	<i>Port</i>	<i>Coast</i>
1	Kandla	West
2	Nhava Sheva	West
3	Marmugoa	West
4	New Mangalore	West
5	Cochin	West
6	Pipavav	West
7	Hazira	West
8	Mundra	West
9	Vishakhapatnam	East
10	Paradeep	East
11	Haldia	East
12	Kolkata	East
13	Tuticorin	East
14	Chennai	East
15	Krishnapatnam	East

Source: Indian Port Association (2023) and Indian Private Ports and Terminals Association (2023)

Figure 3. Container Ports and Inland Logistics Nodes in India

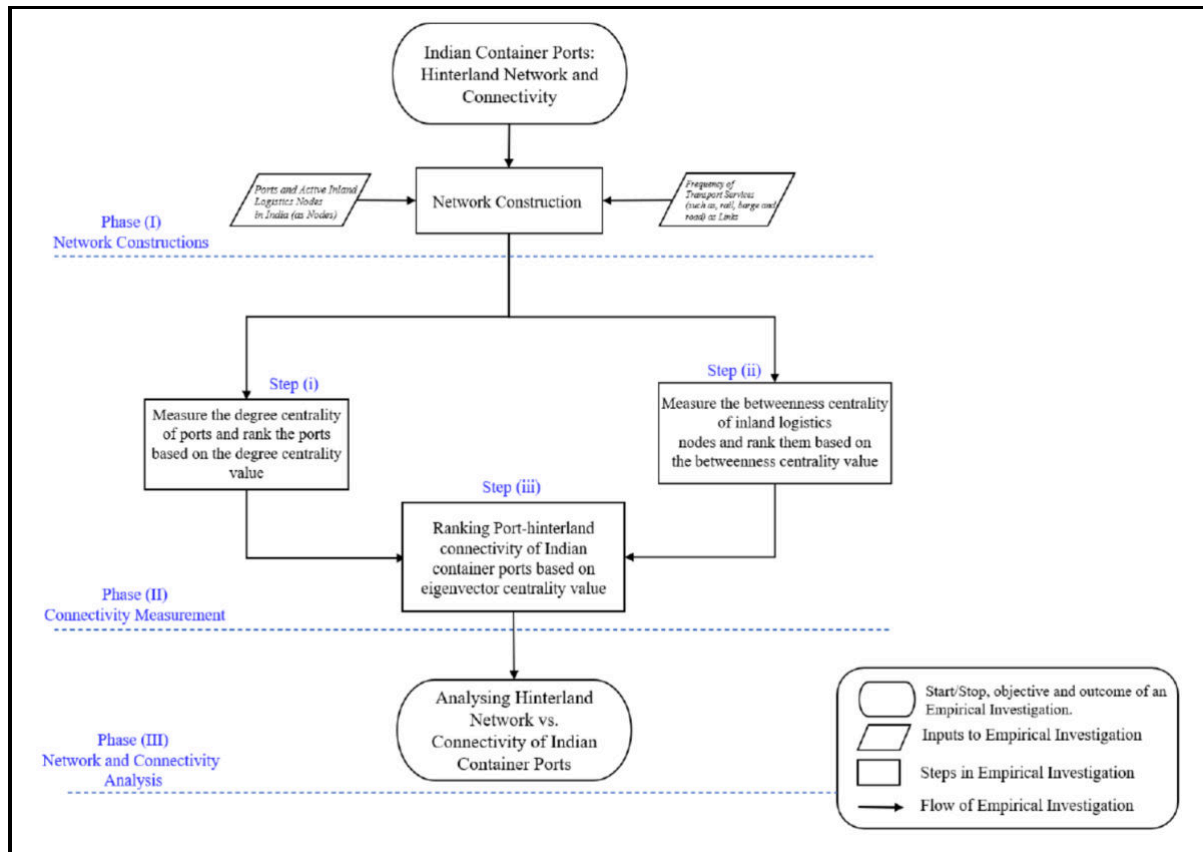


Note: * The Haldia Dock Complex is a separate container port located 150km from the Port of Kolkata, but managed by the Port Trust of Kolkata; this is why it is named a dock complex.

Source: Modified from Sagarmala Project Report (2016)

The empirical investigation of this study is structured into three distinct phases, as depicted in Figure 4, focusing on the analysis of port-hinterland connectivity in the context of Indian container ports:

Figure 4. The Steps of Empirical Investigations



Source: Drawn by the authors

Phase (I) Network Construction: In this initial phase, the construction of the hinterland network was centred around data from 15 container ports and 349 inland logistics nodes. Utilizing monthly data over a 12-year period (FY 2009-2010 to FY 2020-2021), the study delineated the connections between these ports and inland logistics nodes. Various transport modes, including rail, barge, and road, were considered. While assigning frequencies for rail and inland waterway transport was relatively straightforward, the frequency of road transport (trailers) posed certain challenges. To simplify, the study assumed a constant frequency of road connections between each port and its corresponding inland logistics nodes. This assumption, albeit a simplification, facilitated the formation of a coherent network representing road connections.

Phase (II) Connectivity Measurement: The second phase was subdivided into three steps: *Step (i)* involved measuring the 'direct connectivity' of each port using the degree centrality function, focusing on first-layer connectivity as shown in Figure 2. Ports were then ranked in descending order based on these centrality values. *Step (ii)* entailed the application of betweenness centrality to identify pivotal inland logistics nodes. Nodes with high betweenness centrality scores were categorized as important, serving as intermediaries in the container flow within both the first and second network layers. In *Step (iii)*, eigenvector centrality was employed to assess both direct and indirect connectivity within the overall hinterland network, with ports ranked from 1 to 15 based on their overall network connectivity.

Phase (III) Network and Connectivity Analysis: The final phase focused on evaluating the differences between the port-hinterland network and the actual port-hinterland connectivity for Indian container ports. Leveraging insights from Phases I and II, this phase was dedicated to addressing the third research question posed in the manuscript.

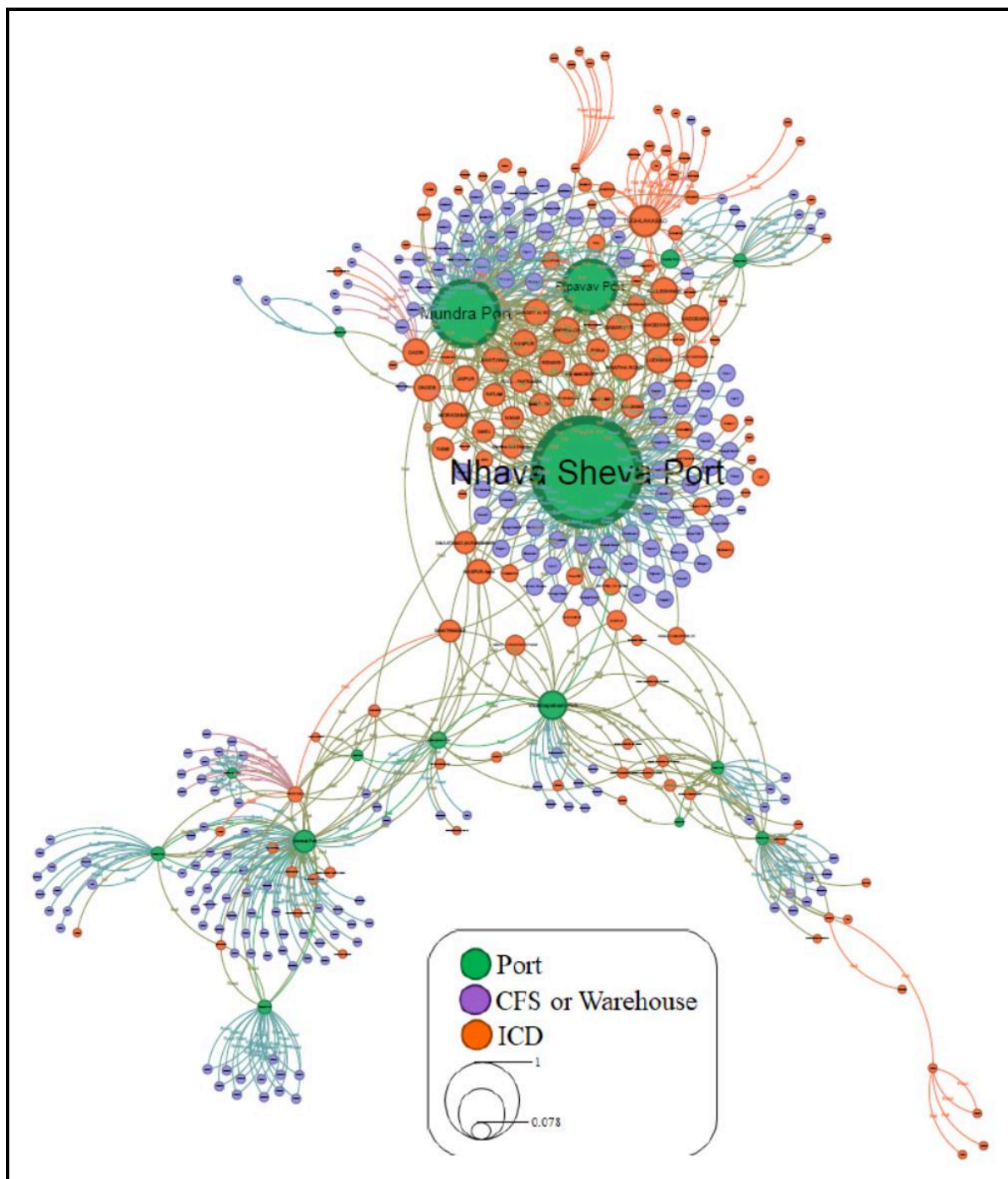
6. FINDINGS AND DISCUSSION

6.1 Degree Centrality of Ports

In Phase (I) of our study, we constructed the hinterland network for Indian container ports by analysing intermodal frequencies over a 12-year period. As depicted in Figure 5, the network diagram showcases the connections between 15 container ports and 349 hinterland logistics nodes. Table 3 further details the degree centrality (first layer connectivity) for each port. Among them, Nhava Sheva port emerges prominently with the highest degree centrality (0.4577), signifying its strong direct connectivity with 114 inland logistics nodes at a higher intermodal frequency. Following Nhava Sheva, the ports of Mundra, Pipavav, Chennai, and Kolkata also demonstrate substantial degree centrality, indicating their significant connectivity within the Indian hinterland network.

Interestingly, Pipavav port, though connected to fewer inland logistics nodes (48), exhibits a higher degree centrality than Chennai Port (69). This suggests more frequent intermodal interactions between Pipavav and its connected inland logistics nodes. Conversely, Chennai, while linked to a greater number of nodes, shows a lower intermodal frequency in its connections. A similar pattern is observed with the ports of Cochin and Haldia. Cochin, connected to only 17 nodes, has a degree centrality of 0.0042, while Haldia, linked to 21 nodes, records a centrality of 0.0034. Additionally, Hazira port, with connections to 10 inland logistics nodes, displays a lower degree centrality than the ports of Kandla and New Mangalore, each connected to 7 nodes. Marmugoa and Paradeep ports, with the least connections to inland logistics nodes (4 and 5, respectively), register the lowest degree centrality values (0.0003 and 0.002) as indicated in Table 3. These findings offer crucial insights into the direct connectivity between ports and inland logistics nodes, forming an integral part of the first layer analysis.

Figure 5. Hinterland Network of Indian Container Ports



Note: Scales are based on the eigenvector centrality value of nodes

Source: Generated from the equations (1)-(6)

Table 3. Degree Centrality of Indian Container Ports

<i>Rank</i>	<i>Port</i>	<i>No. of Nodes Directly Connected to the Port (First Layer Network)</i>	<i>*Degree Centrality</i>
1	Nhava Sheva	114	0.4577
2	Mundra	91	0.2671
3	Pipavav	48	0.1457
4	Chennai	69	0.0630
5	Kolkata	30	0.0280
6	Visakhapatnam	38	0.0158
7	Krishnapatnam	23	0.0073
8	Cochin	17	0.0042
9	Haldia	21	0.0034
10	Tuticorin	15	0.0027
11	New Mangalore	7	0.0010
12	Kandla	7	0.0010
13	Hazira	10	0.0007
14	Marmugoa	4	0.0003
15	Paradeep	5	0.0002

Source: Compiled from the results using equations (2) and (3).

Note: *Figures denote the degree centrality value of ports in the directional and weighted Indian hinterland network based on 12 years of data, (from FY 2009-2010 to FY 2020-2021).

6.2 Betweenness Centrality of Inland Logistics Nodes

The network diagram in Figure 5 illustrates the pivotal role of certain inland logistics nodes, especially Inland Container Depots (ICDs), within the Indian hinterland network. These ICDs are instrumental in facilitating container traffic flow between ports and various inland logistics nodes in the second-layer. As delineated in Table 4, among the 349 logistics nodes in the network, 53 exhibit a high level of betweenness centrality. Notably, the *Sanathnagar* ICD is at the forefront with a betweenness centrality value of 0.3229, whereas the *Diwana (Panipat)* ICD registers the lowest at 0.0001. These ICDs are strategically distributed across India, providing connections to diverse ports along the country's east and west coasts. Key ICDs such as *Sanathnagar*, *Whitefield*, and *Tughlakabad*, which are linked to over three ports, are identified as some of the most crucial nodes in the network.

These ICDs' significant position in the network underscores their essential function in managing container flows between the first layer (ports) and the second layer (other inland logistics nodes). By acting as crucial intermediaries, they not only enhance port connectivity in the secondary layer but also substantially influence the movement of containers between ports and various inland destinations across India. This, in turn, contributes significantly to the efficiency and overall effectiveness of the port-hinterland connectivity within the Indian context.

Table 4. Betweenness Centrality of Indian Logistics Nodes

<i>Rank</i>	<i>Node</i>	<i>Type</i>	<i>*Betweenness Centrality</i>	<i>Rank</i>	<i>Node</i>	<i>Type</i>	<i>*Betweenness Centrality</i>
1	Sanathnagar	ICD	0.3229	28	Ratlam	ICD	0.0040
2	White Field	ICD	0.1605	29	Amingaon	ICD	0.0040
3	Tughlakabad	ICD	0.0844	30	Jakhwada	ICD	0.0026
4	Raipur	ICD	0.0354	31	Tuticorin	ICD	0.0024
5	Dadri	ICD	0.0350	32	Vishakhapatnam-MMLP	ICD	0.0023
6	Nagpur (Ajani)	ICD	0.0270	33	Bhusawal	ICD	0.0023
7	Vedant Aluminium Siding	ICD	0.0268	34	Chinchwad (Pune)	ICD	0.0023
8	Ankaleshwar	ICD	0.0257	35	Malanpur-Gwalior	ICD	0.0020
9	Vadodara	ICD	0.0237	36	Jharsugad	ICD	0.0019
10	Concor KPOT	ICD	0.0205	37	Vadodara	ICD	0.0016
11	Jaipur	ICD	0.0202	38	D-Node	ICD	0.0014
12	Ludhiana	ICD	0.0202	39	Piyala	ICD	0.0012
13	Khodiyar	ICD	0.0196	40	Durgapur Termianl	ICD	0.0011
14	Bhagat ki Kothi	ICD	0.0178	41	Majerhat	ICD	0.0009
15	Kanpur	ICD	0.0155	42	Mandideep	ICD	0.0009
16	Bharat Aluminium Siding	ICD	0.0145	43	Mahan Aluminium Siding	ICD	0.0009
17	Daulatabad (Aurangabad)	ICD	0.0140	44	Khatuwas	ICD	0.0008
18	Moradabad	ICD	0.0138	45	Jindal Stainless Siding	ICD	0.0008
19	Ludhiana	ICD	0.0115	46	Varnama	ICD	0.0005
20	Aditya Aluminium Siding	ICD	0.0101	47	Pantnagar- SCICL	ICD	0.0004
21	Rewari	ICD	0.0093	48	Pithampur	ICD	0.0004
22	Shalimar Terminals	ICD	0.0081	49	Guntur	ICD	0.0003
23	Tondiapet	ICD	0.0070	50	Tumb –Valsad	ICD	0.0003
24	Agra	ICD	0.0057	51	Irugur	ICD	0.0001
25	Gandhidham	ICD	0.0054	52	Pali	ICD	0.0001
26	Sabarmati	ICD	0.0052	53	Diwan-Panipat	ICD	0.0001
27	Rawtha Road	ICD	0.0046				

Source: Compiled from the results using equations (4) and (5).

Note: *Figures denote the betweenness centrality value of inland logistics nodes in the undirected Indian hinterland network based on 12 years of data, (from FY 2009-2010 to FY 2020-2021).

6.3 Eigenvector Centrality of Ports

In the final step of Phase (III), we utilised equations (5) to assess the hinterland connectivity of Indian ports, considering both their direct and indirect (first and second level, as depicted in Figure 2) connections within the network. The eigenvector centrality function assigns a value ranging from 0 to 1 to each port, reflecting its level of connectivity in the Indian hinterland network. This metric accounts for the ports' direct and indirect linkages and the frequency of intermodal services to and from each port, thus offering a holistic view of each port's overall connectivity. The scoring process incorporates the port's connections to various 'important' nodes in the network and those nodes' subsequent links to other significant nodes, enabling the identification of ports with the highest connectivity based on their ties to these important nodes.

The outcomes of this analysis are presented in Table 5. Nhava Sheva emerges as the port with the highest connectivity, boasting an exceptional eigenvector centrality value of 1.0000. Mundra and Pipavav ports also display notable eigenvector centrality values (0.5860 and 0.4543, respectively), signifying their substantial connectivity across both layers of the network and ranking them 2nd and 3rd. Ports like Vishakhapatnam, Chennai, Kolkata, and Krishnapatnam, with moderate eigenvector centrality values, occupy the 4th, 5th, 6th, and 7th positions in terms of connectivity. Subsequently, Tuticorin, Cochin, Hazira, Kandla, and Haldia ports follow, each demonstrating average connectivity within the network as indicated by their eigenvector centrality scores. The ports of New Mangalore and Marmugoa, with lower eigenvector centrality values, are ranked 13th and 14th, respectively, suggesting lesser connectivity in both network layers. Lastly, Paradeep port, positioned at the bottom of the list (15th), holds the lowest eigenvector centrality value (0.0078), denoting minimal hinterland connectivity within the Indian port hinterland network.

Table 5. Eigenvector Centrality of Indian Container Ports

<i>Rank</i>	<i>Port</i>	<i>*Eigenvector Centrality</i>
1	Nhava Sheva	1.0000
2	Mundra	0.5860
3	Pipavav	0.4543
4	Visakhapatnam	0.1987
5	Chennai	0.1392
6	Kolkata	0.0988
7	Krishnapatnam	0.0843
9	Cochin	0.0547
8	Tuticorin	0.0529
12	Haldia	0.0522
10	Hazira	0.0465
11	Kandla	0.0450
13	New Mangalore	0.0197
14	Marmugoa	0.0163
15	Paradeep	0.0078

Source: Compiled from the results using equations (6).

Note: *Figures denote the eigenvector centrality value of ports in the directional and weighted Indian hinterland network based on 12 years of data, (from FY 2009-2010 to FY 2020-2021).

6.4 Analysing Indian Ports Hinterland Network and Connectivity

Our findings, as detailed in Table 5, reveal that Nhava Sheva port possesses the most extensive network in the Indian hinterland, comprising 114 nodes. This extensive reach grants it the highest degree of hinterland connectivity in the first-layer network, as evidenced by its leading degree centrality value of

0.4577. Furthermore, Nhava Sheva is intricately connected to 39 of the 53 'important' nodes in the network, identified by their high betweenness centrality. This extensive connectivity signifies Nhava Sheva's robust links not only in the first layer but also across the second layer of the Indian hinterland network. Consequently, Nhava Sheva is the most interconnected port in the network, as demonstrated by its highest eigenvector centrality value of 1.0000. Similarly, Mundra and Pipavav ports exhibit significant direct connections to 91 and 48 logistics nodes, respectively, reflected in their respective degree centrality values. Of these, 26 nodes connected to Mundra and 19 to Pipavav are recognised as important nodes due to their high betweenness centrality. As a result, both ports exhibit substantial eigenvector centrality values (0.5860 and 0.4542), ranking them as the second and third most connected ports in the Indian hinterland network, respectively. This pattern illustrates that an extensive hinterland network correlates with higher hinterland connectivity for the port.

Conversely, the ports of Vishakhapatnam and Chennai present an interesting divergence. Despite Chennai Port's connection to 69 nodes and a higher degree centrality, its eigenvector centrality (0.1392) is lower than that of Vishakhapatnam port (0.1986), which is connected to 38 nodes and exhibits a lower degree centrality. The key factor lies in their respective connections to 'important' nodes: Chennai is linked to only 6 such nodes, while Vishakhapatnam connects to 9. This disparity in strategic connections results in greater accessibility for Vishakhapatnam port in the second layer of the hinterland network, outperforming Chennai in overall hinterland connectivity. Thus, despite Chennai's broader network, its hinterland connectivity is surpassed by Vishakhapatnam, positioning them 4th and 5th in the Indian hinterland connectivity rankings. Following a similar connectivity pattern, Kolkata and Krishnapatnam ports also exhibit this trend and are ranked 6th and 7th, respectively, in the hinterland connectivity within the Indian hinterland network.

The analysis of the ports of Cochin, Tuticorin, and Haldia yields particularly intriguing results. It underscores that the quality of connectivity outweighs the sheer extent of a network in achieving superior hinterland connectivity. Despite Haldia being linked to a significant number of nodes (21) and boasting a higher degree centrality compared to Tuticorin port, as well as being connected to more key nodes (5) than Tuticorin (3), it still registers a lower eigenvector centrality (0.0522) against Cochin (0.0547) and Tuticorin ports (0.0529). The critical distinction in their connectivity patterns lies in the fact that both Cochin and Tuticorin are linked to one of the most crucial nodes, the Whitefield ICD, which holds the second highest betweenness centrality in the Indian hinterland network (refer to Annex-2). This connection grants these two ports a more expansive second-layer connectivity compared to Haldia. A comparable situation is observed with Hazira and Kandla ports. While Kandla Port's degree centrality surpasses that of Hazira, its overall hinterland connectivity (eigenvector centrality) is lower. Additionally, the ports of New Mangalore, Marmugoa, and Paradeep, having fewer direct connections to nodes, demonstrate lower hinterland connectivity within the Indian network.

The findings, as elaborated above and depicted in Figure 6, definitively answer the third question of this study. They reveal that a port's extensive network, characterised by numerous connections to inland logistics nodes, does not automatically equate to high hinterland connectivity. This emphasises the importance of strategic connections over mere network size in enhancing port hinterland connectivity.

Table 6. Port Hinterland Network vs. Port Hinterland Connectivity

Port	Port-hinterland Network		Port-hinterland Connectivity (**First Layer)		Port-hinterland Connectivity (§ First and Second Layers)	
	No. of Nodes Directly Connected to the Port	*No. of Important Nodes in the Network	Degree Centrality	Ranking based on Degree Centrality	Eigenvector Centrality	Ranking based on Eigenvector Centrality
Nhava Sheva	114	39	0.4577	1	1.0000	1
Mundra	91	26	0.2671	2	0.5860	2
Pipavav	48	19	0.1457	3	0.4543	3
Visakhapatnam	38	9	0.0158	6	0.1987	4
Chennai	69	6	0.0630	4	0.1392	5
Kolkata	30	6	0.0280	5	0.0988	6
Krishnapatnam	23	6	0.0073	7	0.0843	7
Cochin	17	3	0.0042	8	0.0547	8
Tuticorin	15	3	0.0027	10	0.0529	9
Haldia	21	5	0.0034	9	0.0522	10
Hazira	10	4	0.0007	13	0.0465	11
Kandla	7	5	0.0010	12	0.0450	12
New Mangalore	7	1	0.0010	11	0.0197	13
Marmugoa	4	1	0.0003	14	0.0163	14
Paradeep	5	0	0.0002	15	0.0078	15

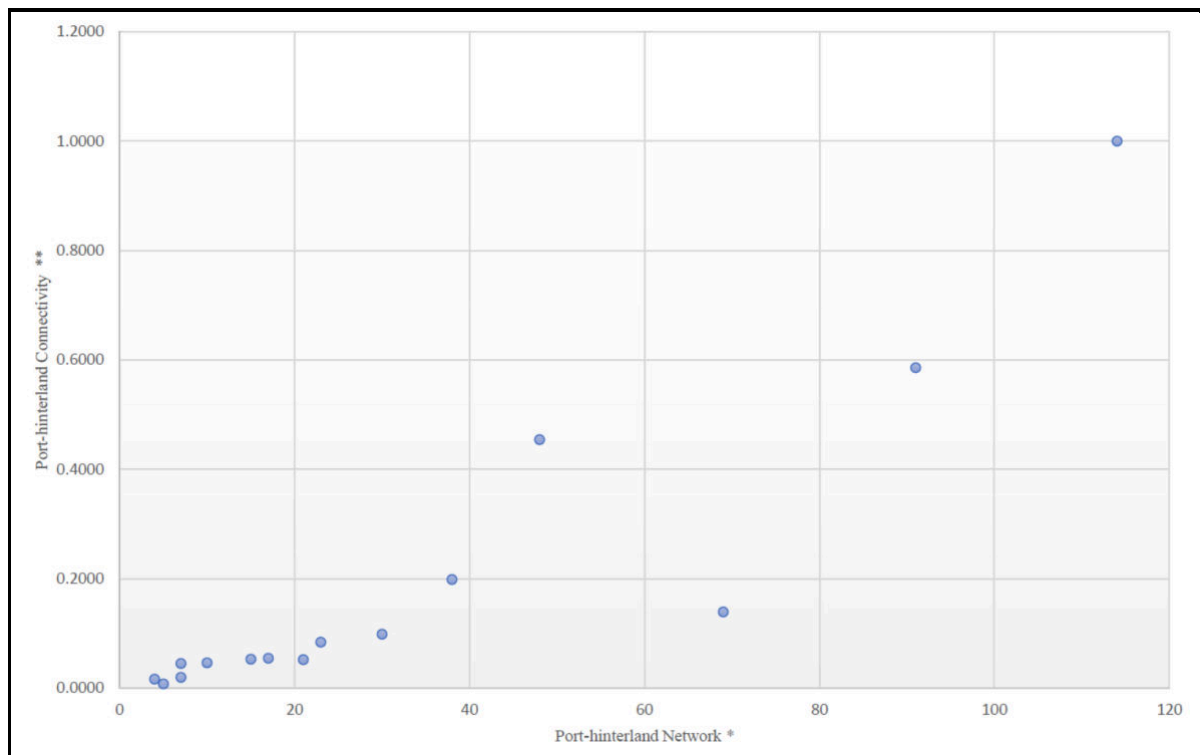
Source: Compiled from the results using equations (1), (2), (3), (4), (5) and (6).

Note(s): *These are the nodes (in the first layer) that have a higher degree of betweenness centrality [calculation from phase II, step (ii)] and act as intermediaries between the port and the inland logistics nodes in the second layer.

** Referring to Figure 2, the calculations are based on the number of nodes directly connected to the port [calculation from phase II, step (i)].

§ Referring to Figure 2, the calculations are based on the number of nodes directly and indirectly connected to the port [calculation from phase II, step (i)].

Figure 6. Indian Container Ports' Hinterland Network vs. Connectivity



Notes: * No. of inland logistics nodes directly connected to ports from Table 5.

** Eigenvector Centrality value of ports

7. POLICY IMPLICATIONS

While the Sagarmala project represents a crucial initiative by the Indian government to enhance the logistics sector's performance, certain aspects of its approach to port connectivity warrant reconsideration. The project's analysis predominantly focuses on the first layer of port connectivity, thereby overlooking a significant segment of the Indian hinterland in the connectivity planning. To effectively improve the connectivity of Indian container ports, it is imperative for the government to incorporate the second layer of inland logistics nodes, which includes a variety of nodes beyond inland container depots (ICDs).

The Sagarmala project's current prioritisation of first-layer analysis has steered significant infrastructure investment proposals towards regions where industrial clusters are already established. However, this strategy may not fully meet the broader connectivity needs across India. Specifically, the project's plans for infrastructure enhancement, particularly the development of dedicated freight corridors, seem to be centred around north-western ports, including Nhava Sheva, Mundra, Pipavav, Kandla, and Hazira. These ports, such as Nhava Sheva, Mundra, and Pipavav, already have high connectivity within the Indian hinterland network and share overlapping hinterlands. Although enhancing infrastructure in these areas is likely to reduce congestion, it might also intensify competition among these ports. Consequently, industrial growth could become excessively concentrated in these already-developed regions. This focus raises concerns that other regions, especially in Central and Eastern India, might not receive adequate opportunities for industrial growth and development. Thus, a more balanced approach in infrastructure investment is needed to ensure equitable economic advancement across different parts of India.

In contrast, the ports in the southern conical hinterland, including Chennai, Tuticorin, Cochin, and New Mangalore, share a common hinterland but, except for Vishakhapatnam port, demonstrate weak second-layer connectivity. This limits their reach into the central hinterland of the country. Additionally, eastern ports like Haldia and Paradeep exhibit relatively lower hinterland connectivity, largely restricted to their regional hinterland. The limited connectivity from certain inland logistics nodes in these regions, such as Kanpur, leads to a preference for connecting with Nhava Sheva and Mundra ports over closer eastern ports. Infrastructure enhancement in these less connected regions could extend their reach to the north-west, where a considerable number of industrial clusters are located.

Moreover, the Sagarmala project's focus has been primarily on the development of ICDs. To authentically enhance port connectivity, the government should also concentrate on developing other smaller but crucial nodes capable of serving distant hinterlands, such as distribution centres, container freight stations, and warehouses. Presently, a disproportionate number of logistics nodes are situated in the north-west and southern regions, leaving the central and eastern regions with a dearth of such facilities. This uneven distribution hampers the accessibility of container ports in these underserved areas, leading to a lack of comprehensive national connectivity. A more balanced and inclusive approach in the development of logistics infrastructure, addressing these regional disparities, is essential. Such an approach would not only enhance port connectivity but also contribute to equitable economic growth across India.

8. CONCLUSION

This paper has examined aspects of the complex port-hinterland connectivity with reference to Indian container ports. It was aimed at demystifying the complicated structure and nature of port-hinterland connectivity by examining its conceptual as well as empirical dimensions. Conceptually, the study stretched the boundary from the simplistic count of direct connections to inland logistics nodes or hinterland destinations. Having emphasised that port-hinterland connectivity encompasses the interlinked relationships and access to key hubs at multiple levels of the hinterland network, this paper put forwards an argument for a multi-layered understanding that embraces both the quantity and the quality of those connections in a single, rather than separate, framework.

The empirical analysis from the case of Indian container ports confirms the effectiveness of eigenvector centrality as a tool to assess the overall connectivity of the port-hinterland network. This metric not only considers direct connections but also recognises the importance of indirect connections to a few

important logistics hubs. The study shows that ports with a higher own-vector centrality have better hinterland connectivity, largely due to their strategic connections to those key hubs. These results underline that the quality of those connections, especially to nodes with high betweenness centrality, proves to be the case for a port's hinterland connectivity in an effective manner.

Having once again recognised that port-hinterland connectivity is a complex, multi-dimensional concept, this paper suggests that ports should prioritise building strategic links with key logistics nodes and hubs in their hinterland in order to effectively improve their connectivity. Using eigenvector centrality as a metric allows ports to fully understand their role within the network and consider both direct and indirect connections. This approach also allows ports to simulate scenarios to identify hinterland nodes that could potentially improve their connectivity and thereby have a positive impact on their operational and business performance. In terms of policy implications, this study provides an insight for projects like Sagarmala and emphasises the need for a comprehensive and differentiated approach when developing transport and logistics strategies in line with hinterland connectivity for Indian ports.

The study's findings suggest that while an extensive network doesn't guarantee higher connectivity for a port, there's a need to delve deeper into understanding how network and connectivity influence port market shares. Future research could focus on analysing the impact of network configuration and connectivity on market shares, exploring which configurations of transport networks and logistics nodes are most conducive to gaining market share. Additionally, investigating the role of port administration in enhancing hinterland connectivity could provide valuable insights. This could involve examining whether public or private ports are more aggressive in expanding connectivity into the hinterland and what strategies they employ to achieve this. By addressing these questions, researchers can offer valuable insights to port authorities and policymakers aiming to optimise port performance and enhance regional connectivity.

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