Analyzing Maritime Shipping Routes With Higher-order Network Analysis

Timothy LaRock
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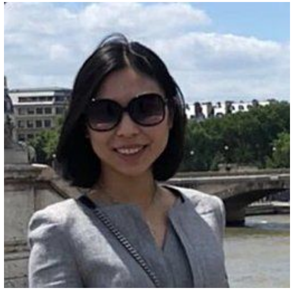
In collaboration with



Mengqiao Xu
Dalian University of Technology

Tina Eliassi-Rad
Northeastern University

Northeastern University
Network Science Institute

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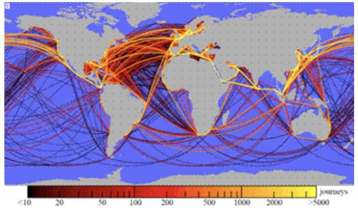
Global Liner Shipping Network

The Global Shipping Network Is Finally Revealed

Despite carrying 90 percent of the planet's trade, nobody has mapped the network of links between the world's ports. Until now.

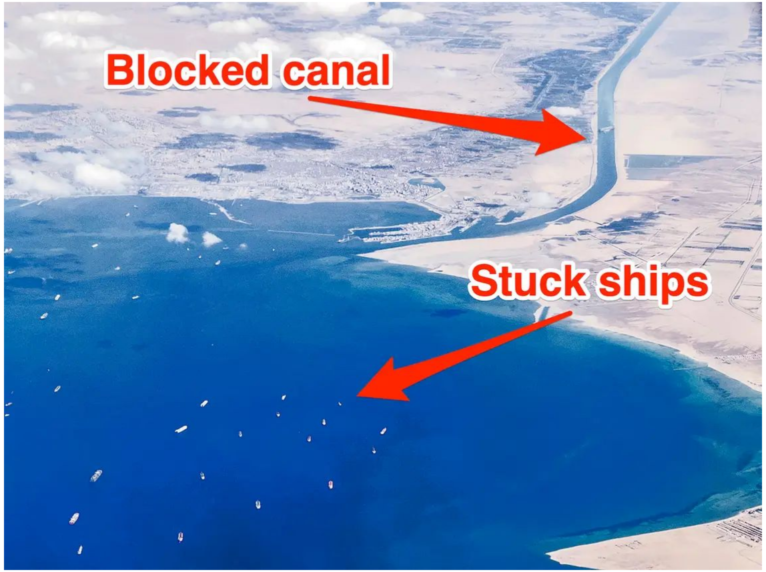
by **Emerging Technology from the arXiv** January 15, 2010

The International Maritime Organization based in London estimates that 90 percent of the world's trade is moved around the planet by sea. Given the fascination that complexity scientists have with rail, air and road networks, it seems strange that so little attention has been paid to the maritime network.



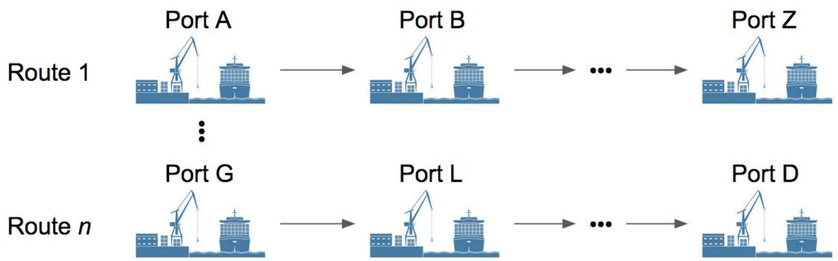
The maritime shipping network is the backbone of global trade.

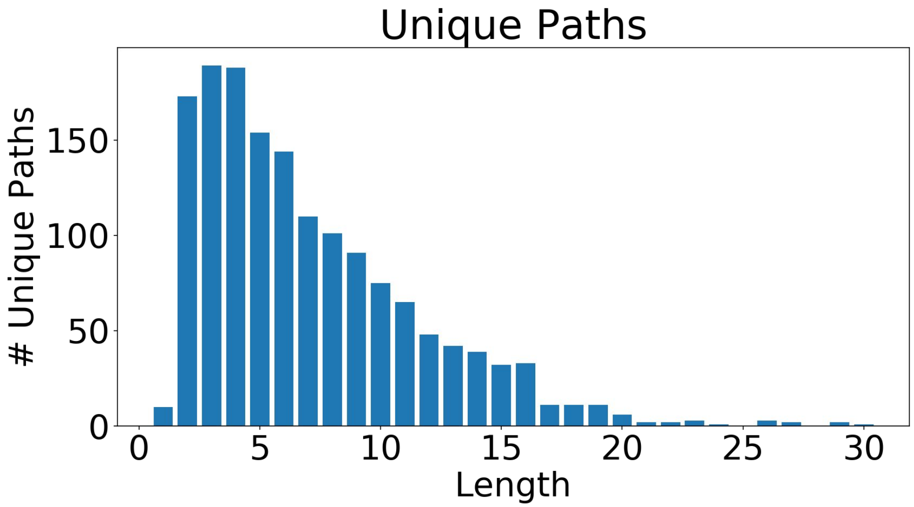
Global Liner Shipping Network



Understanding of the network structure and function is important for studying economic relationships between nations and regions, as well as more practical concerns like robustness to failures.

This Work: Shipping Route Data





1549 planned container shipping vessel routes from 2015
977 ports
5,268 directed edges

Data provided by Alphaliner (https://www.alphaliner.com/) by agreement with Prof. Xu

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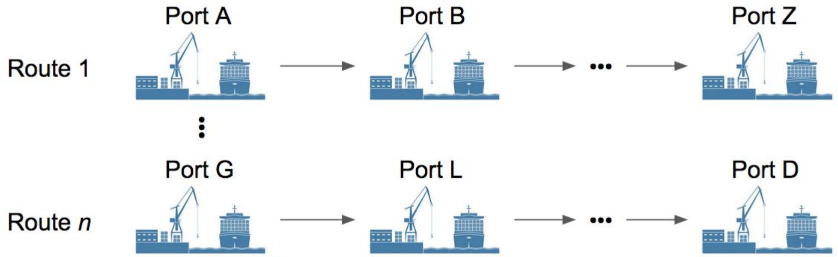

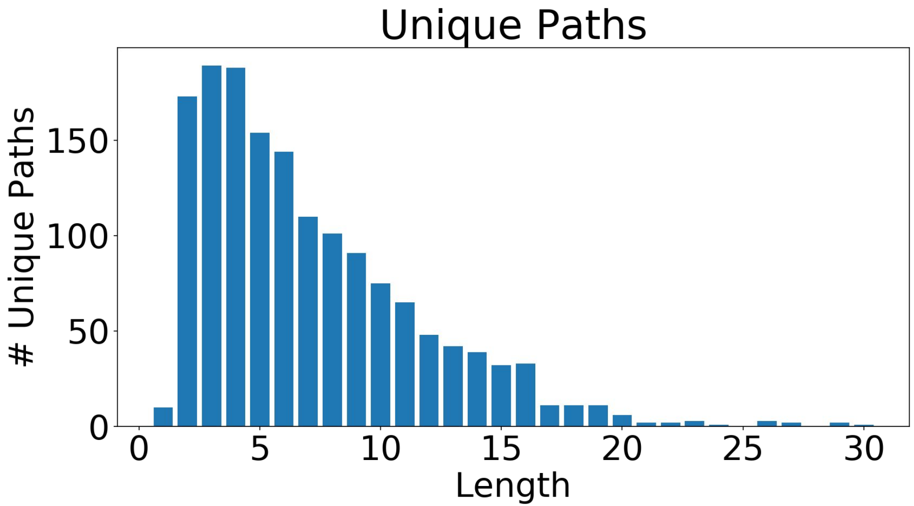

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Our goal: Quantify the role of a (previously defined) *structural core* in the network, taking advantage of the the sequential information in the routes themselves.

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Previous Work: Structural Core Analysis

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https://doi.org/10.1038/s41467-020-16619-5 OPEN

Modular gateway-ness connectivity and structural core organization in maritime network science

Mengqiao Xu[1,4]✉, Qian Pan[1,4], Alessandro Muscoloni[2], Haoxiang Xia[1]✉ & Carlo Vittorio Cannistraci[2,3]✉

Key contributions for our purposes:

1. Defining a *structural core* of ports in the container shipping network
2. Quantifying the role of this core in routing containers through the network

Xu et al. Approach to Structural Core

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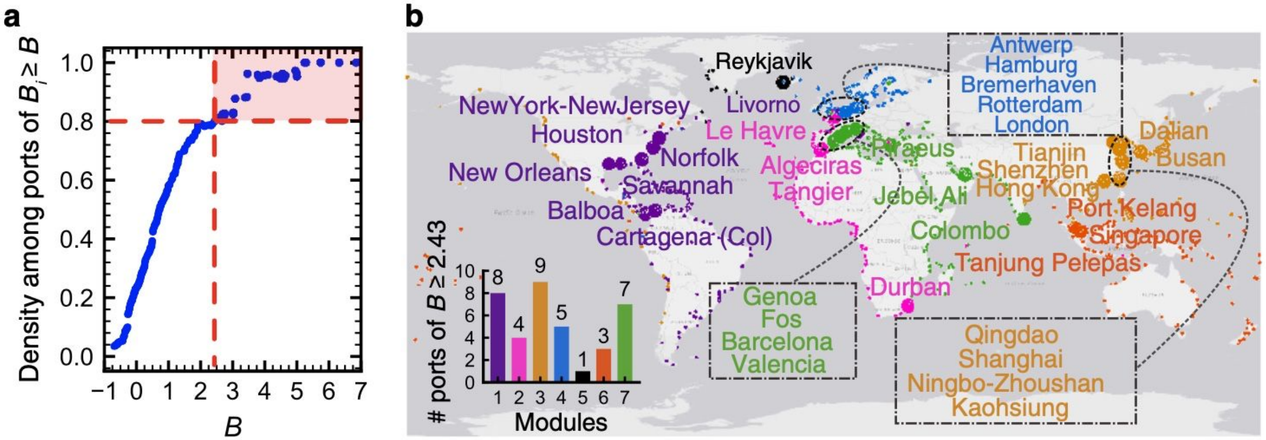
High-level: Define a set of nodes as a *structural core* if they are densely connected and mediate between different modules/communities of the network. Specifically:

- The density of connections between the nodes is > 0.8
- At least 1 node from each of the *modules* (as defined by the Louvain modularity maximization algorithm) in a representation of the network is present in the core



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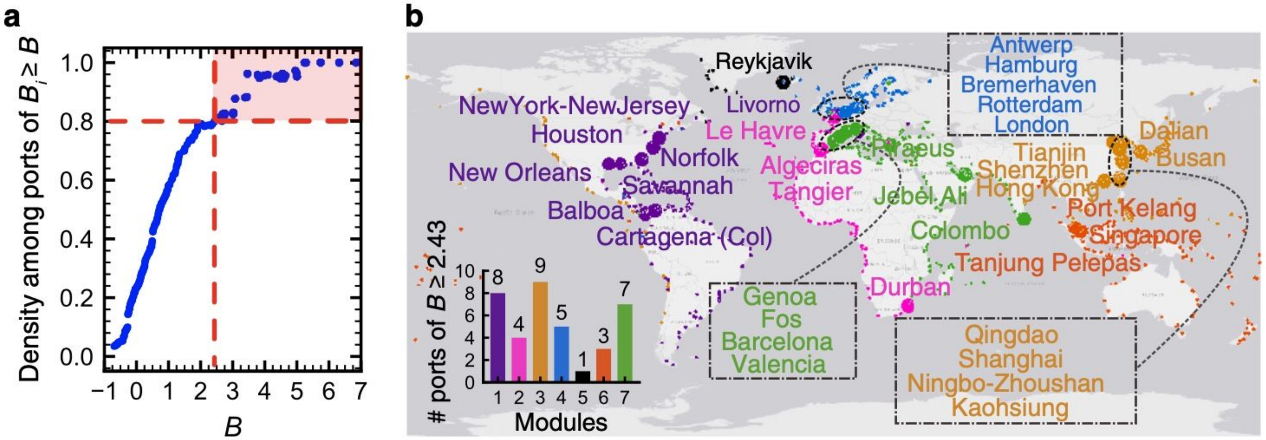

Xu et al. Representation

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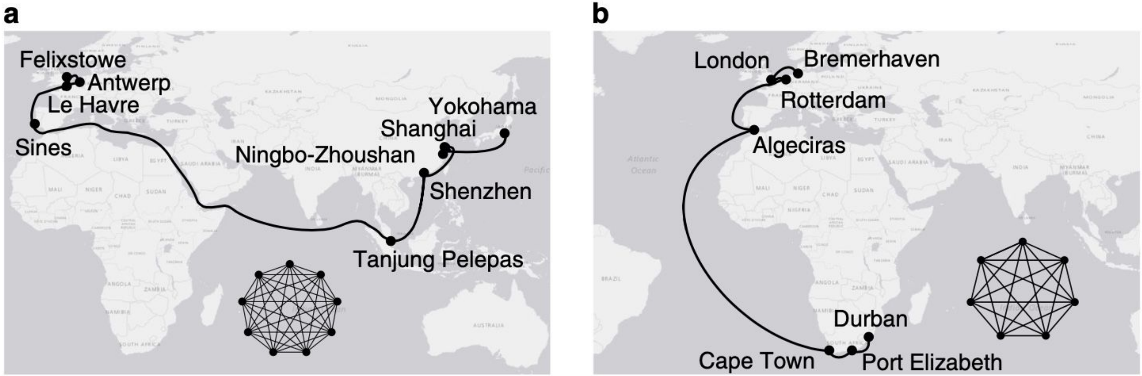
Representation: “Clique-graph”

- Turn every shipping route into an undirected clique, then union cliques



Quantifying the importance of the core

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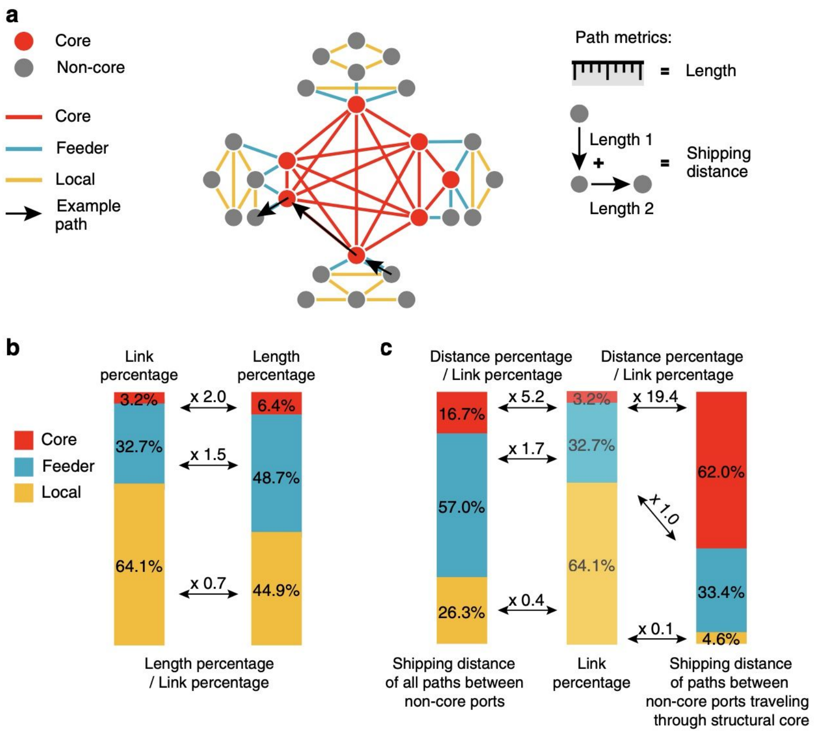
  - **Core:** both ports in structural core
  - **Feeder:** exactly one port in core
  - **Local:** neither port in core



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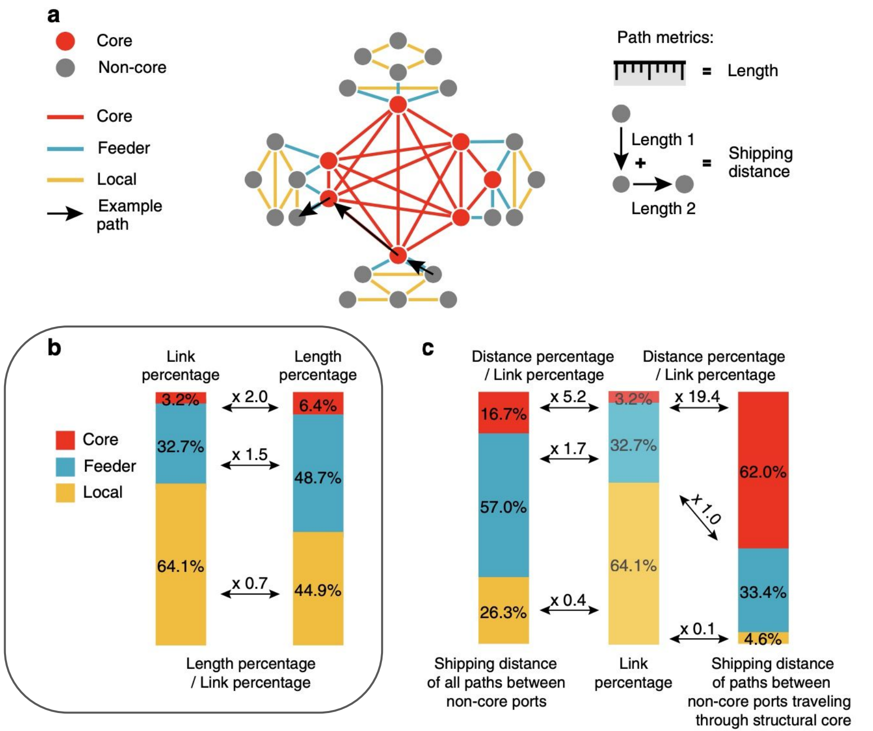

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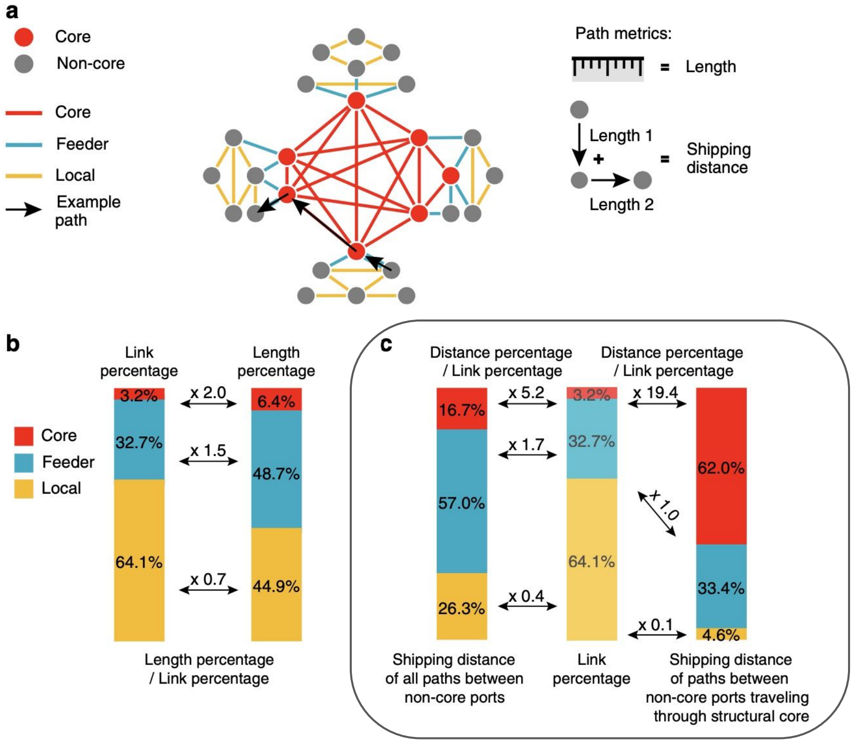
- Compute % of *links* and % of *shipping length* in the network by category
- Compute shortest paths through the clique-graph and the contribution of lengths from edges in each category to these paths



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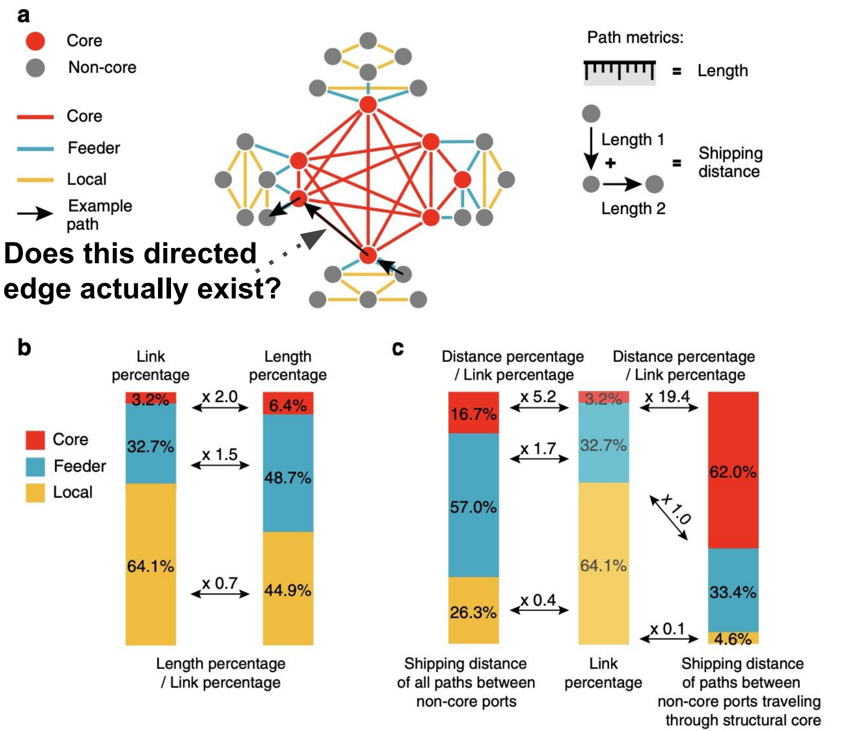
Problem: Paths through the clique-graph **do not represent actual navigation trajectories!**

Solution: Define a set of more realistic paths using the shipping routes directly.



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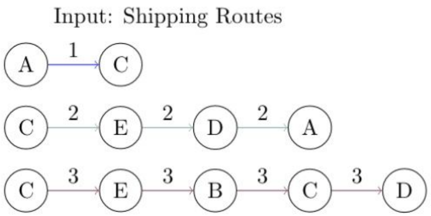
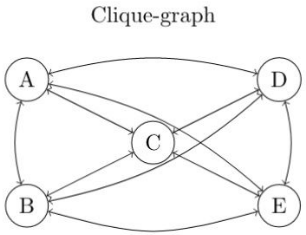
Constructing realistic navigation paths

We are not satisfied with using shortest-paths through the clique graph.





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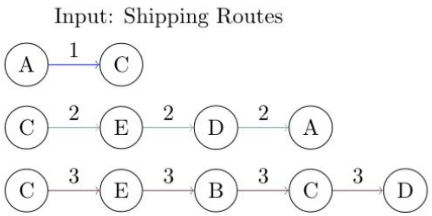

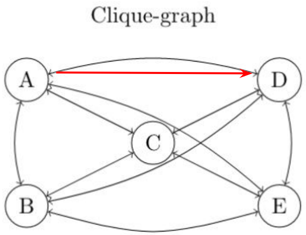

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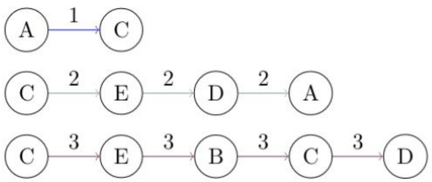
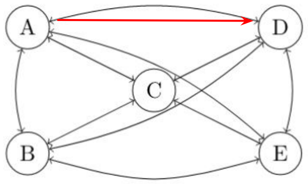
Our idea: Minimum-route paths

- Path between ports *s* and *t* is *minimum-route* if it reaches *t* from *s* using the minimum number of different shipping routes (e.g. transfers from one vessel to another)
- Why?
    - Trade-off between number of port calls and number of ship transfers, transfers more important because they are more costly
    - Shortest paths may minimize the wrong objective!

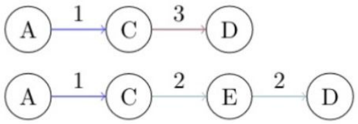
Input: Shipping Routes



Clique-graph



Minimum-route paths from A to D



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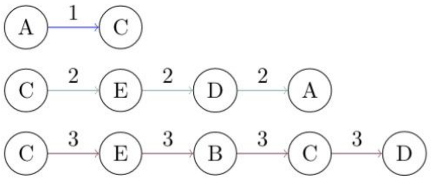

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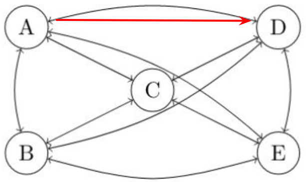
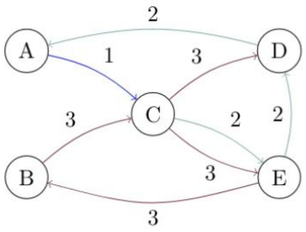


Path-graph



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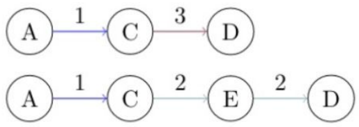


Computing Minimum-route Paths

Algorithm 1 IterativeMinRoutes(R)

Input: R (set of shipping routes)
Output: mr (minimum route paths)

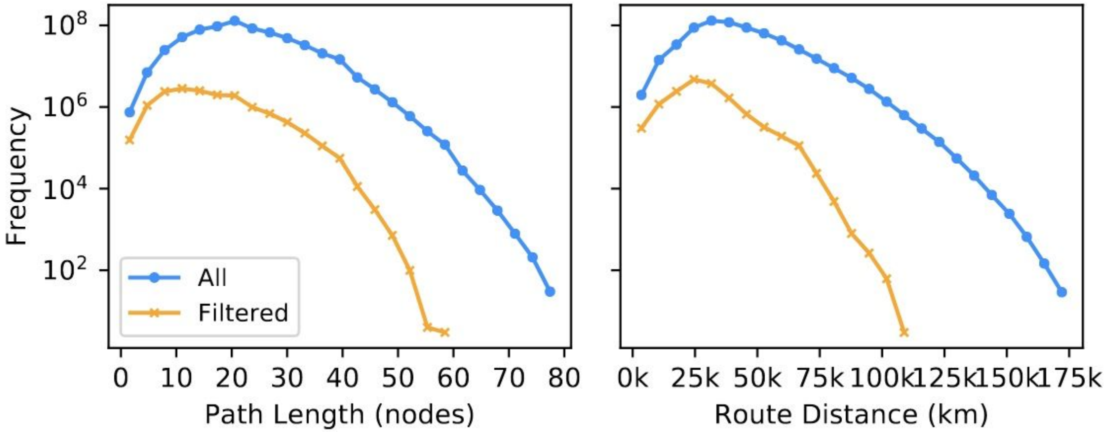
Construct the graph $G = (V, E)$ from routes R
Assign to P_R the set of all reachable (s, t) pairs from G (BFS)
Initialize $d \leftarrow 1$
for all routes $r \in R$ **do**
    if r is open **then**
        Add all paths from i to j in r s.t. $i < j$ to $mr[d][i][j]$
        Remove all $(i, j) \in r, i < j$ from P_R
    else
        Add all paths between all pairs $(i, j) \in r, i \neq j$ to $mr[d][i][j]$
        Remove all $(i, j) \in r, i \neq j$ from P_R
Construct co-route graph G_c
Compute shortest path length $dist[s, t]$ in G_c for all $(s, t) \in P_R$
while $|P_R| > 0$ **do**
    $d \leftarrow d + 1$
    for $(s, t) \in P_R$ s.t. $dist[s, t] = d$ **do**
        for $w \in mr[d-1][s]$ **do**
            if $t \in mr[1][w]$ **then**
                Concatenate all paths from s to w with all paths from w to t and add to $mr[d][s][t]$
        Remove (s, t) from P_R

Minimum-route Paths

Result: About 650 million minimum-route paths between 900,000 pairs of ports

Filter based on (1) distance and (2) redundancy

13.8 million paths after filtering



Redundancy filtering: A path between *s* and *t* is removed if there is a shorter path that intersects completely with the longer path

Ex: A-B-C-D-E is redundant if A-B-E exists, but A-X-Y-Z-E is not

Distance filtering: A path between port *s* and *t* is removed if its total shipping distance (sum of edge distances) is 1.5x the minimum distance among all paths between *s* and *t*

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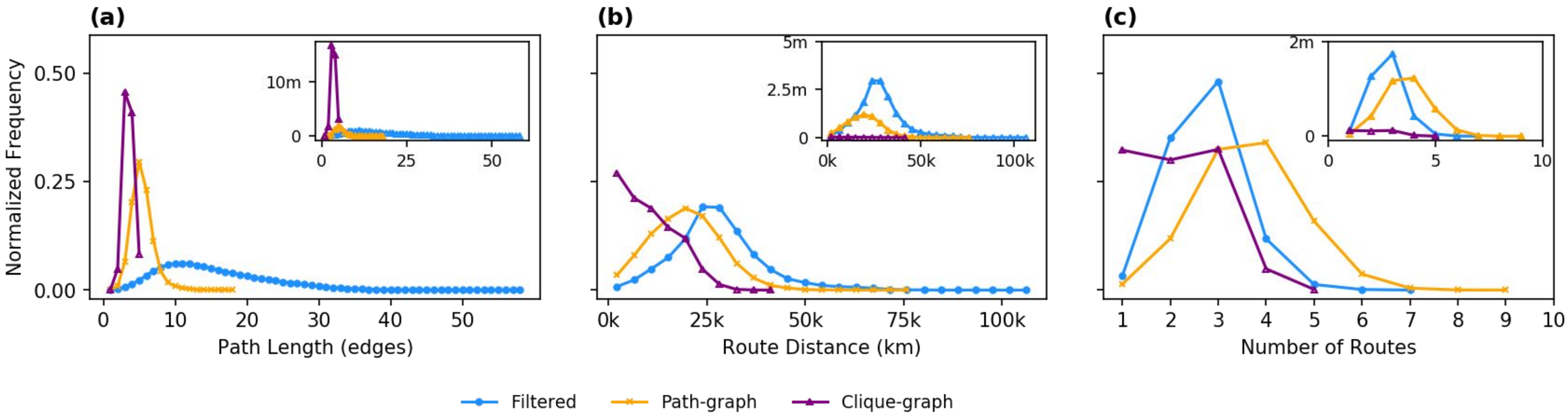
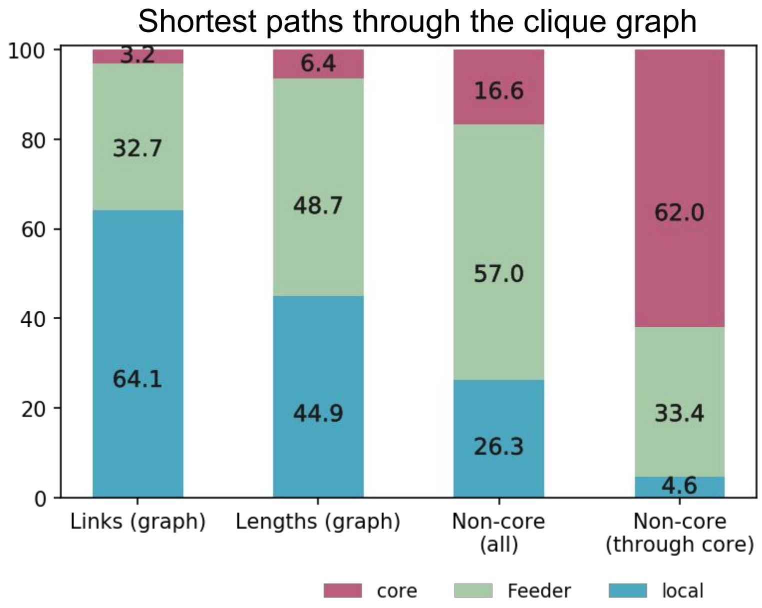
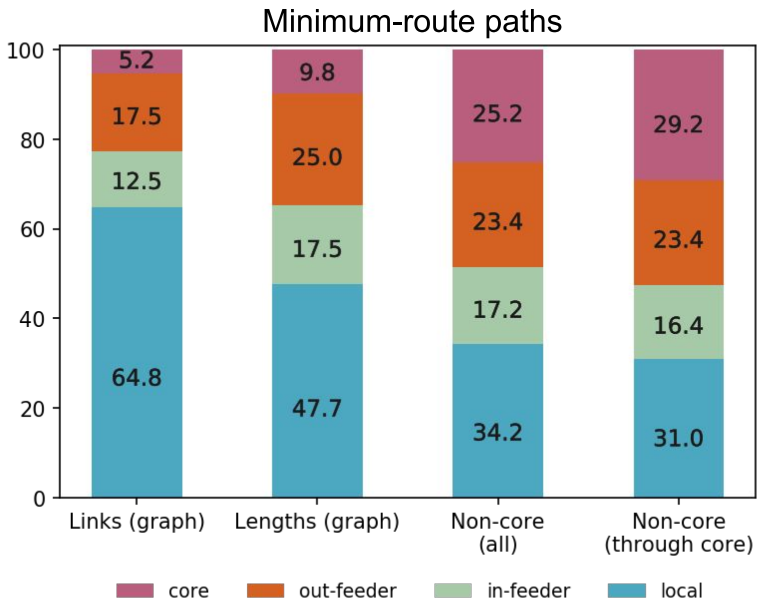
Comparison of Routes



Key takeaway: Shortest paths and minimum-route paths are noticeably different in terms of network length, shipping distance, and number of transfers required!

Comparison of Structural Core Analysis





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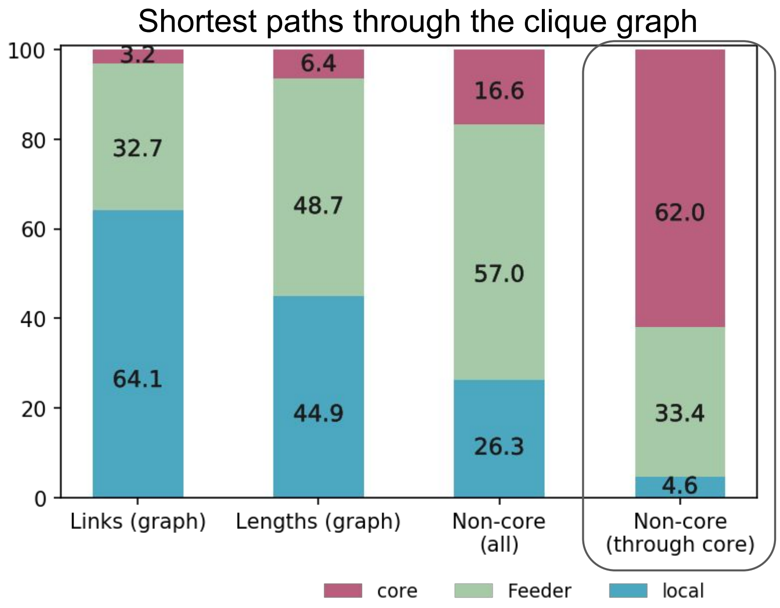

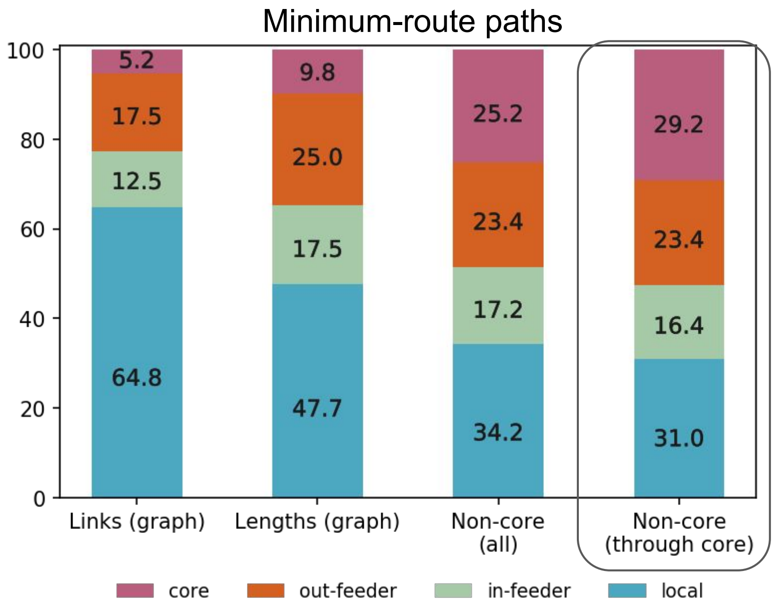

The role of core links appears to have been amplified in the clique graph, and the role of local links was suppressed.

Conclusions

Previous work may have over-emphasized the role of the structural core in the shipping network.

We built on this work by choosing a more accurate network representation and set of paths to analyze.

Minimum-route paths (a) preserve directionality, (b) correspond to real navigation trajectories based on the shipping routes, and (c) optimize for fewer cargo transfers rather than port calls alone.

Defense expected December 2021

Seeking postdoctoral research opportunities, especially in the northeastern US or remote!

Thank you!

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Interests:

Methods for analyzing sequential/pathway data with higher-order networks

Growth and evolution of networks

Infrastructure and logistics networks

Networks in nature

Science and technology studies

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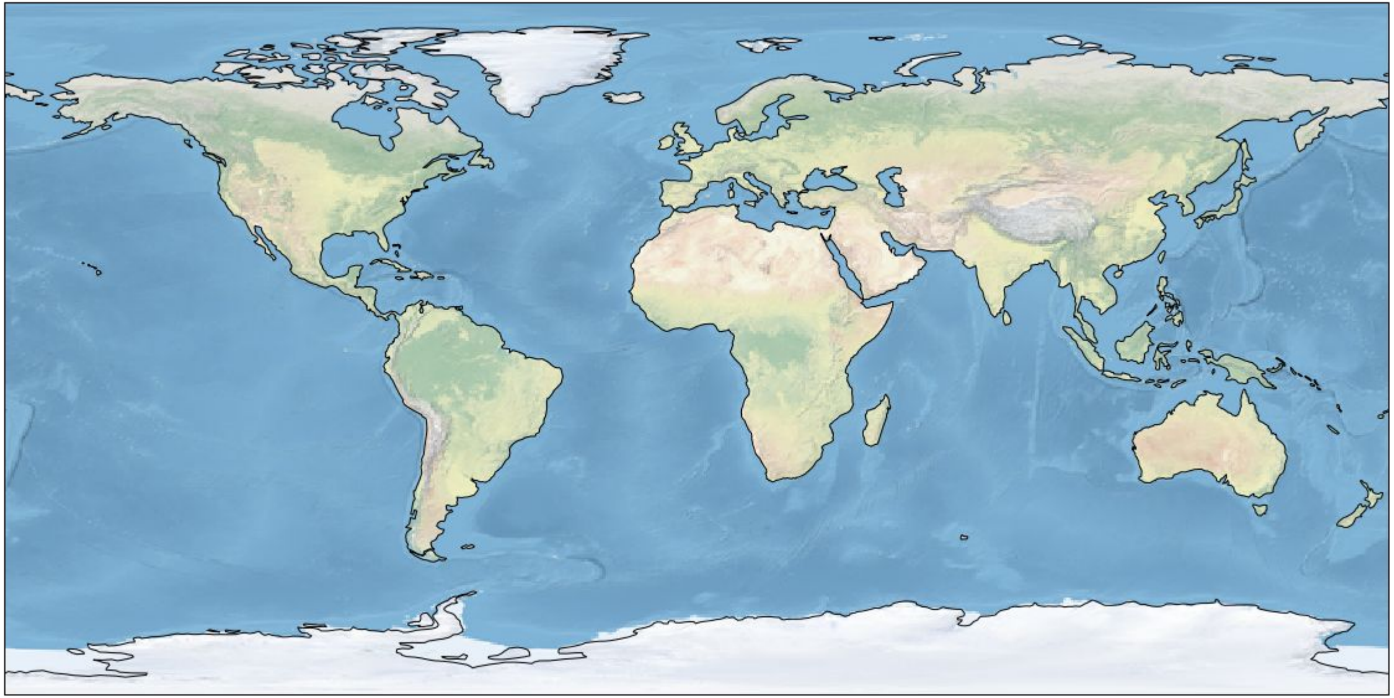
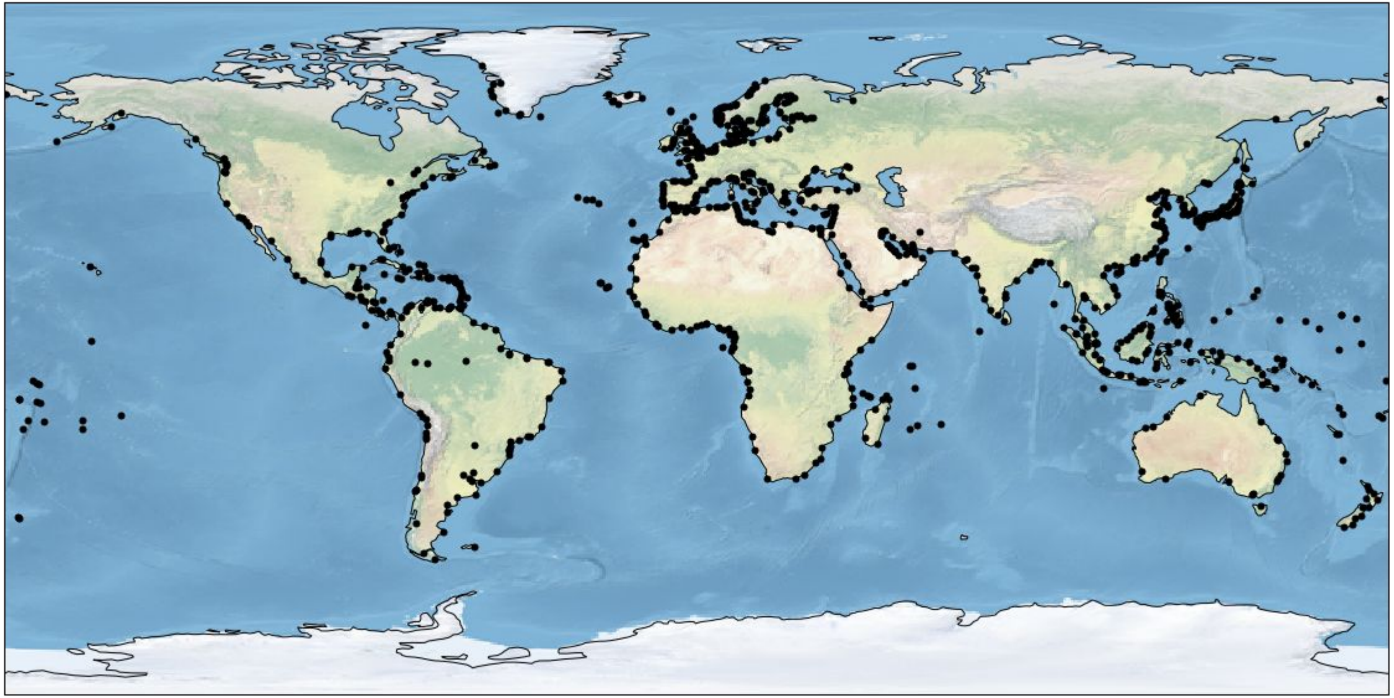


Data: Global Liner Shipping

Nodes: 510 Ports



Data: Global Liner Shipping

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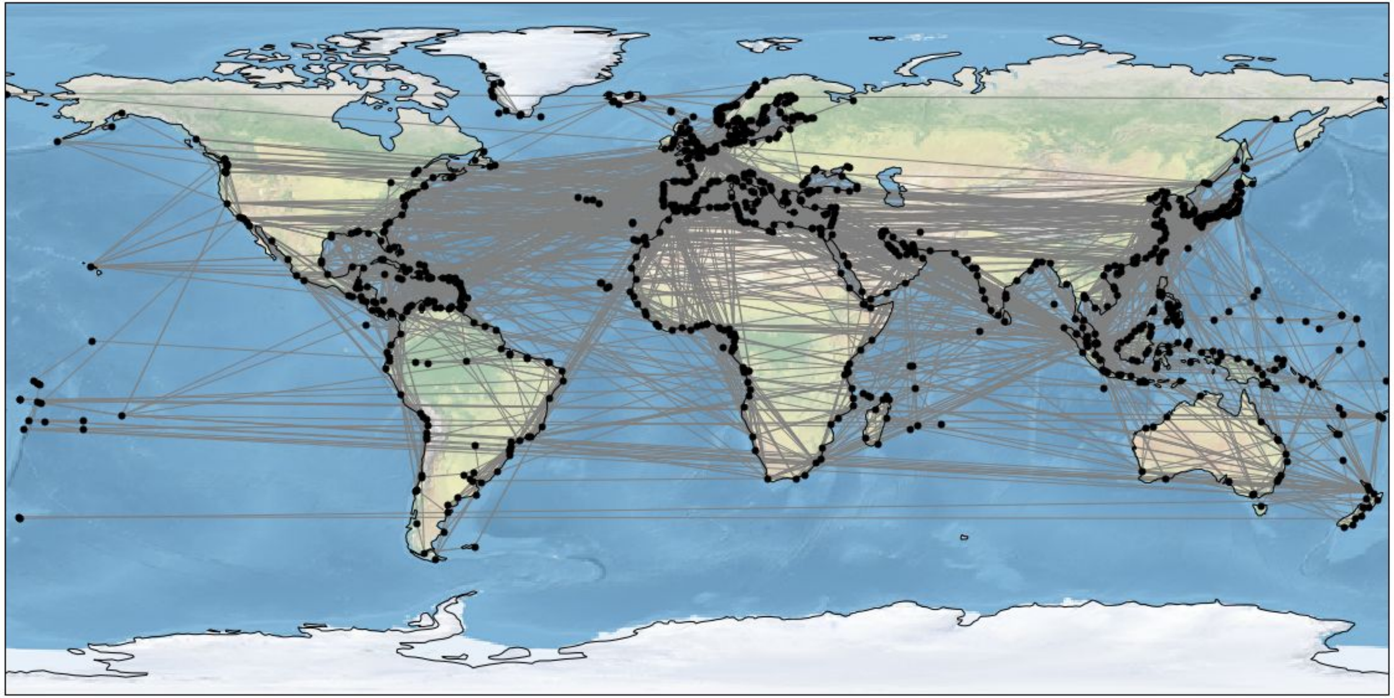
Edges: 5271

Density: 0.0055

Global Clustering: 0.20

Average Clustering: 0.26



Degree and Clustering

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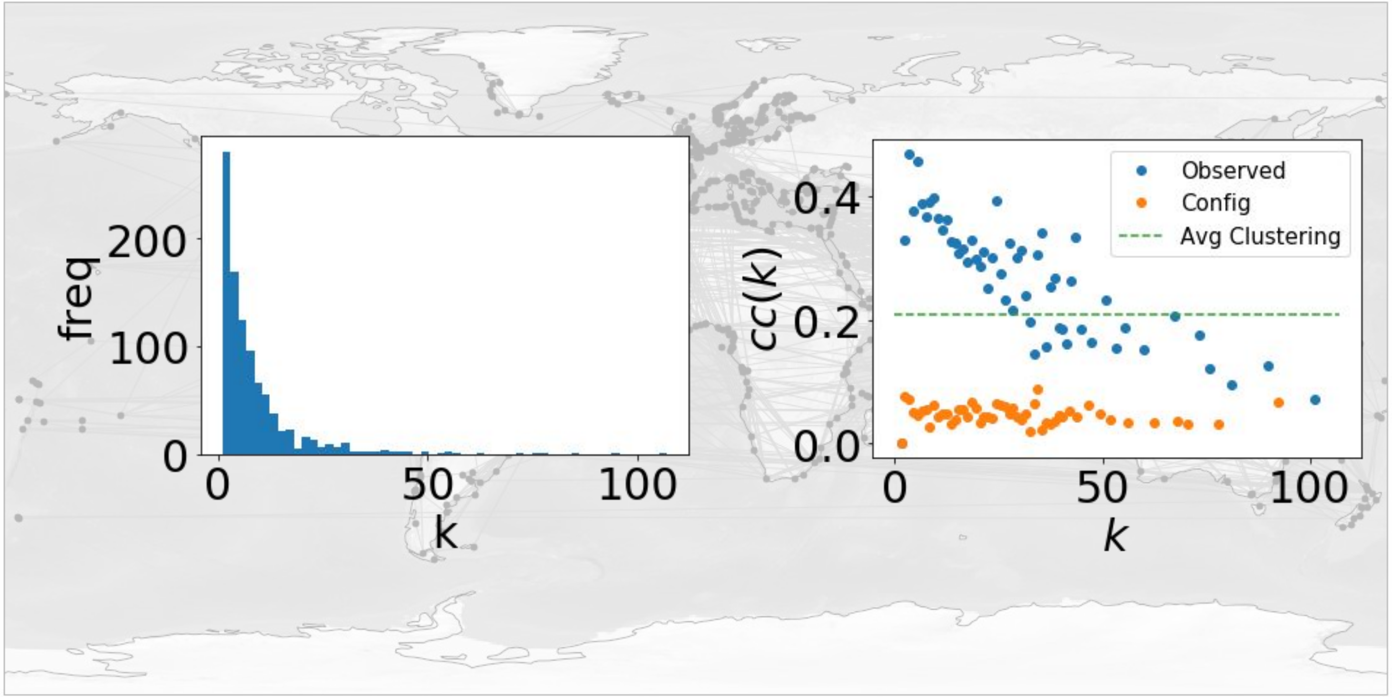

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What has been done?

Ducruet & Notteboom (2012) identify 4 research areas:

1. Geographic coverage of carrier networks (Bergantino and Veenstra 2002; Frémont 2007; Rimmer and Comtois 2005)

2. Network connectivity (Joy 1999; Ducruet et al. 2010b; McCalla 2004)

3. Network efficiency (Song et al. 2005; Tai and Hwang 2005; Zeng and Yang 2002)

4. Complex networks (Deng et al. 2009; Hu and Zhu 2009; Kaluza et al. 2010)

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Xu et al. Representation

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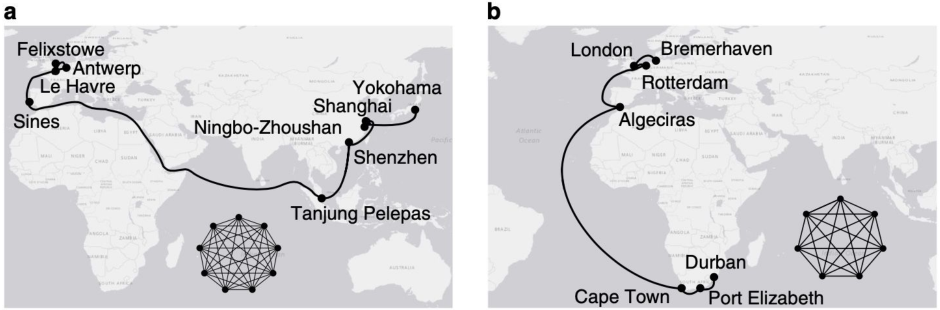
Representation: “Clique-graph”

- Turn every shipping route into an undirected clique, then union cliques
- Advantages:
  - If routes are navigated in both directions, then shortest path length between *s* and *t* in the clique-graph equals the number of routes required to get from *s* to *t*
- Disadvantages:
  - Throws away sequential information that we will argue can be valuable
  - Shortest paths not meaningful, since indirect connections are made direct
  - Directionality



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What has been done?

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The complex network of global cargo ship movements

Pablo Kaluza, Andrea Kölzsch, Michael T. Gastner and Bernd Blasius

Published: 19 January 2010 | https://doi.org/10.1098/rsif.2009.0495

Analyzes the port-to-port network based on GPS data of vessel movements

3 networks, each corresponding to a different kind of traffic: Bulk dry carrier, oil tanker, and container ship

Found evidence for the small world property, heavy tailed degree and strength distributions, centrality of canals, and more.

Two problems

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Problem 1: Connections in the clique-graph may not represent actually existing connections between ports

- This representation makes interpretation of modules difficult. Ports can be in the same module even if there is no route in which they appear together as a directed edge.

Solution: Use a path-based representation of the network, where an edge only exists if it appears exactly in at least one route

Problem 2: Modularity maximization is non-convex, making the choice of partitioning (and thus values of gateway-ness) arbitrary

- Partially addressed by showing that gateway-ness identifies cores in many partitionings, but specific choice still arbitrary

Solution: Compute 1000 (Leiden) partitions and count how many times each node appears in a valid* structural core. The structural core is defined to be nodes that appear in at least 80% of valid structural cores.

* Since the network representation changed, so did the criteria for a structural core:

- All modules represented –> at least 2/3 of modules
- density > 0.8 –> induced graph weakly connected

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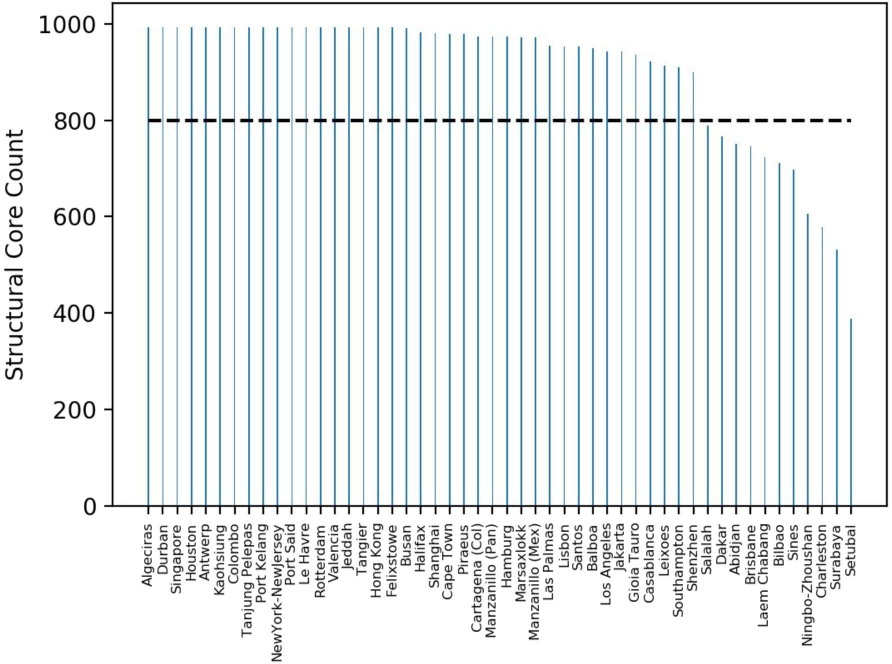
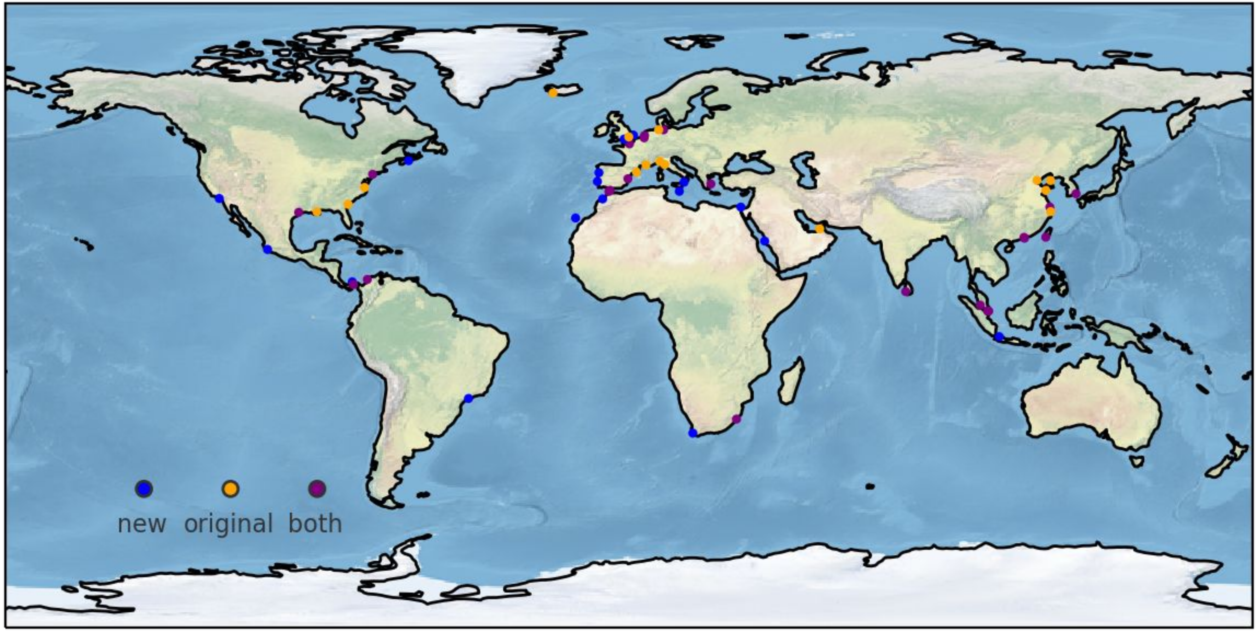
Structural Core Results



39 nodes, 22 of which were in the original core

Structural Core Results



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How is the global shipping network constructed?

"Container shipping features a complex combination of end-to-end services, linebundling services and pendulum services, which are connected to form extensive shipping networks. Port hierarchy in the container business is intrinsically linked to **shipping lines' design of these liner service networks** in terms of service variables such as service frequency, vessel capacity, fleet mix, vessel speed and **the number and order of port calls** (Fagerholt 2004; Notteboom 2006b)." Ducruet & Notteboom, 2012

Computing Minimum-route Paths

Algorithm 1 IterativeMinRoutes(R)

Input: R (set of shipping routes)
Output: mr (minimum route paths)

Construct the graph $G = (V, E)$ from routes R
Assign to P_R the set of all reachable (s, t) pairs from G (BFS)
Initialize $d \leftarrow 1$
for all routes $r \in R$ **do**
  if r is open **then**
    Add all paths from i to j in r s.t. $i < j$ to $mr[d][i][j]$
    Remove all $(i, j) \in r, i < j$ from P_R
  else
    Add all paths between all pairs $(i, j) \in r, i \neq j$ to $mr[d][i][j]$
    Remove all $(i, j) \in r, i \neq j$ from P_R
Construct co-route graph G_c
Compute shortest path length $dist[s, t]$ in G_c for all $(s, t) \in P_R$
while $|P_R| > 0$ **do**
  $d \leftarrow d + 1$
  for $(s, t) \in P_R$ s.t. $dist[s, t] = d$ **do**
    for $w \in mr[d-1][s]$ **do**
      if $t \in mr[1][w]$ **then**
        Concatenate all paths from s to w with all paths from w to t and add to $mr[d][s][t]$
    Remove (s, t) from P_R

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A-B-C-D   C-D-A-B   X

A-B-C-D-A   C-D-A-B   ✓

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Xu et al. Approach to Structural Core

ARTICLE
https://doi.org/10.1038/s41467-020-16619-5 OPEN
Check for updates

Modular gateway-ness connectivity and structural core organization in maritime network science

Mengqiao Xu[1,4✉], Qian Pan[1,4], Alessandro Muscoloni[2], Haoxiang Xia[1✉] & Carlo Vittorio Cannistraci[2,3✉]

High-level: Define a set of nodes as a *structural core* if they are densely connected and mediate between different modules/communities of the network. Specifically:

- The density of connections between the nodes is > 0.8
- At least 1 node from each of the *modules* (as defined by the Louvain modularity maximization algorithm) in a representation of the network is present in the core

Gateway hubs (nodes with *gateway-ness* > 1.5) were found to reliably identify structural cores

- Gateway-ness measures the extent to which a port's *out-module degree* is larger than that of other ports in the same module
- Put another way: ports that act as "brokers" in the clique-graph are a structural core

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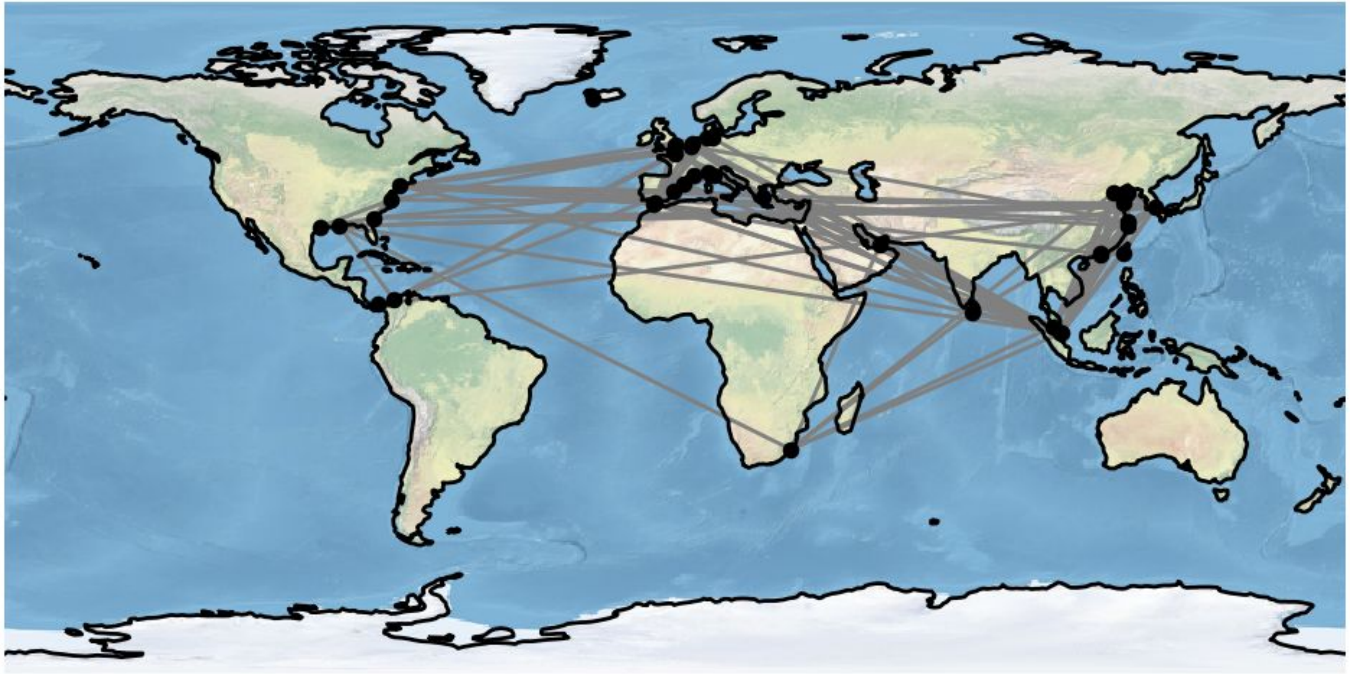

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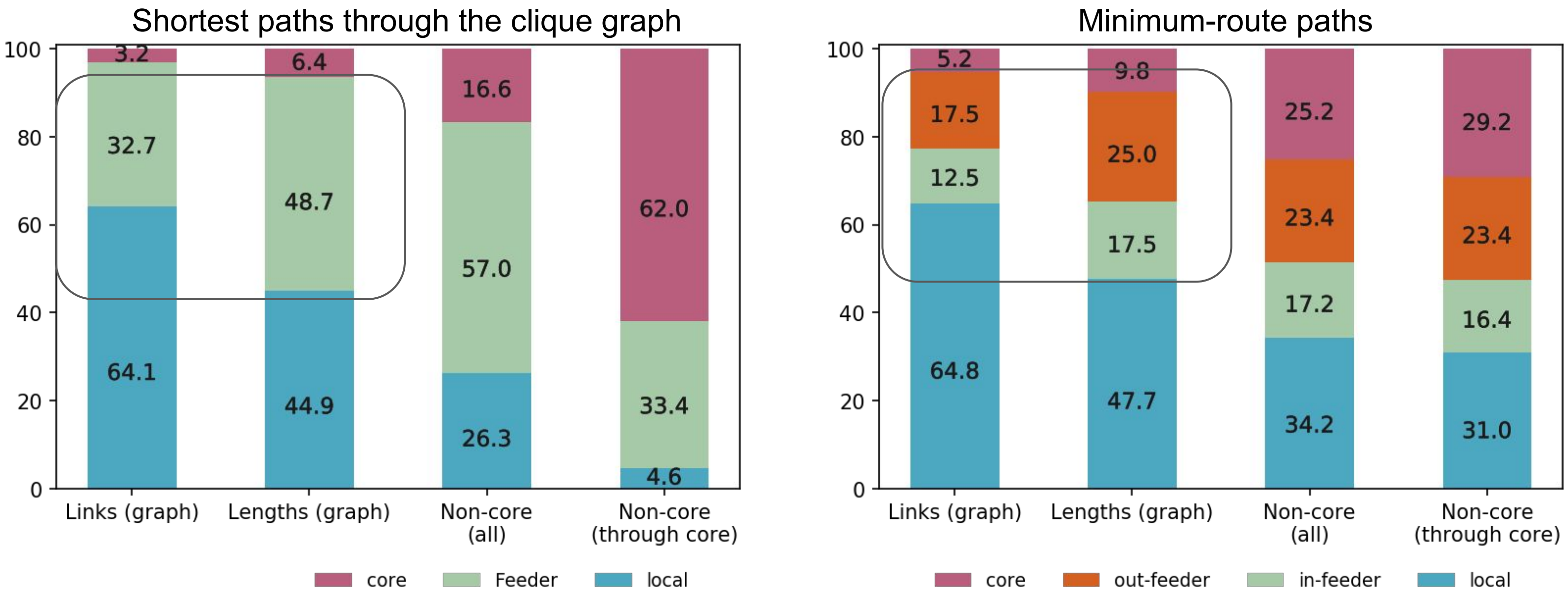
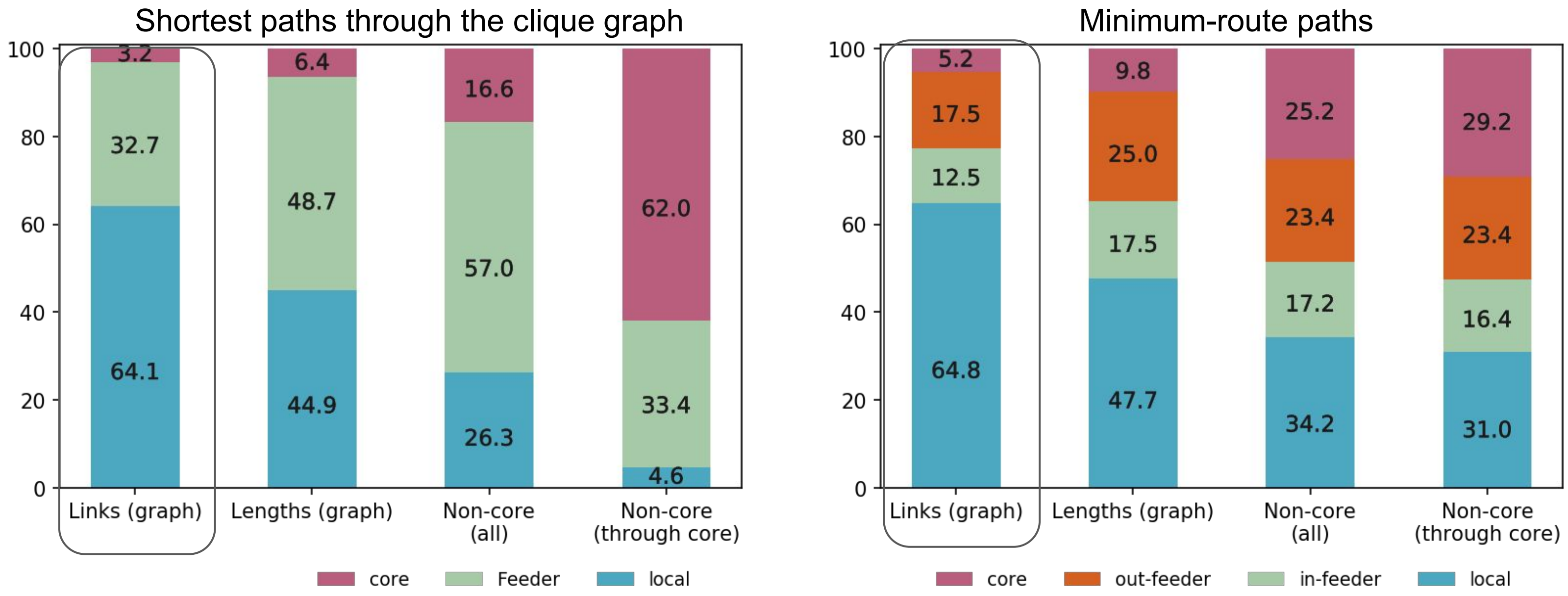
Comparison of Structural Core Analysis



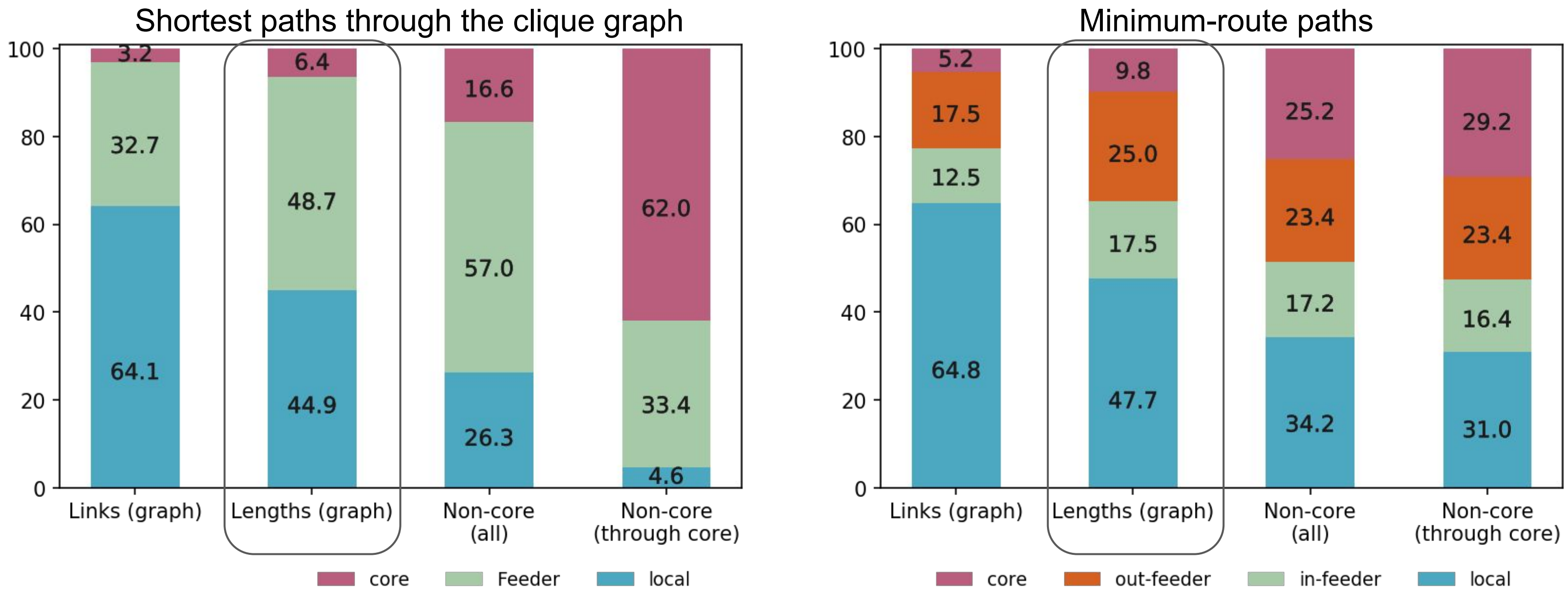
Observation 1: Since our representation preserves directionality, we can separate in vs. out feeders. Out-feeders are more prevalent in both link and length percentage.

Comparison of Structural Core Analysis



Observation 2: Link percentages in the graph are roughly similar between the clique-graph representation and the path-graph representation.

Comparison of Structural Core Analysis



Observation 3: The proportion of feeder and local length percentages in the graph reversed when using the minimum-route paths.

Northeastern University
Network Science Institute