Investment in Infrastructure and Trade: The Case of Ports

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Introduction

- Transportation infrastructure is crucial for the smooth functioning of international trade
- Ports are vital links of the infrastructure network
  - $> 80\%$ of trade carried by ships
  - crucial determinants of trade costs
- This paper:
  - Port production function
    - Queueing theory; capture congestion dynamics
    - Input: infrastructure, labor, cranes; output: time
    - Congestion highly sensitive to demand shocks
  - Demand system for transportation services
    - Exporter-importer pairs decide which port to choose
    - Factors: time, distance, port prices, other port characteristics
    - Macroeconomic conditions shift demand over time
    - Agents sensitive to changes in time at port
  - Counterfactuals: welfare gains of port infrastructure investment
    - One additional ship for one port

Introduction

- Paper Findings
  - Port Investment $\rightarrow$ substantial trade and welfare gains only if targeted properly
  - Sizeable spillovers across ports
  - Macroeconomic volatility $\rightarrow$ returns to investment & geography
- Literature
  - transportation infrastructure on trade (e.g. Redding and Turner, 2015, Donaldson and Hornbeck, 2016, Redding, 2016, Donaldson, 2012, Fajgelbaum and Schaal, 2020, Allen and Arkolakis, 2022)
  - impacts of ports; shipping industry
  - congestion in the context of urban transportation (e.g. Durrmeyer and Martinez, 2022, Bordeu, 2023, Kreindler, 2023, Almagro et al., 2024)
  - supply chain disruptions
  - international trade, the role of geography, and the trade cost (e.g. Eaton and Kortum, 2002, Anderson and Van Wincoop, 2003, Melitz, 2003)

Background- Port Operation

- Procedures
  - ship waits in anchorage → enter the port to get serviced in berth → cargo loaded by workers & cranes and stored → cargo wait for trucks or trains to final destination → ship departs
- Port Infrastructure
  - Includes berth, cranes, storage areas, buildings, etc.
  - Port services: pilotage, cargo handling, towage; 40 services per ship per visit
  - Investment: $45 bi in 2012-2016; $163 bi scheduled in 2021-2025
    mix of private & local public funds in the US; serve local interests (e.g., high throughput, employment, and connectivity)
- Focus of This Paper
  - Dry bulk carriers- commodities and raw materials such as iron ore, steel, coal and grain; 1/2 total seaborne trade worldwide
  - 51 largest heterogeneous US ports

Data

- Port Production Function
  - Universe of port calls:
    AXS Marine (AXS Dry) Data for bulk carriers $>$ 10,000 DWT
    Vars: timestamp for vessel's arrival/ entry to and exit form the port, an indicator for whether the ship loaded/discharged, estimate for the commodity on board
  - Port Infrastructure:
    Miles of each berth, acres of storage space, and number of cranes from Google Maps and Google Earth Pro
  - Port Employment:
    Longshoremen union membership form the Department of Labor
- Port Demand
  - Monthly number of arrivals at each of the ports
    AXS Marine + Freight Analysis Framework Regional Database
  - Port charges for each service requested
    Anonymous provider; ˜ 35% global port calls Vars: berth dues, cargo handling dues, line handling, pilotage
- Port Infrastructure Expansion Cost
  - Dredging: site-specific cost estimates for dredging a new berth using cost projections from US Army Corp of Engineers
  - Acquisition of Land for Storage: land value estimates from Nolte, 2000 and industrial & commercial land data from OpenStreetMap

Data

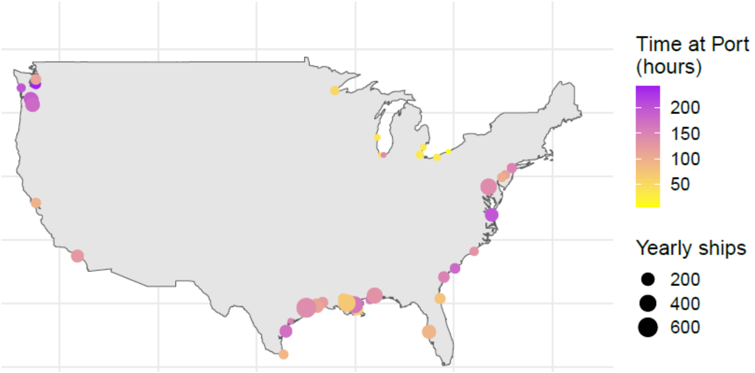
- Summary Statistics
  - Port calls (throughput in tons): total annual number of ships (total tonnage) that were handled at port

	Mean	SD	25th percentile	75th percentile
Annual number of port calls	136	130	54	180
Annual throughput (tons)	7,295,140	7,355,597	2,602,124	9,970,174
Time at port (hours): average	117	54	74	153
Time at port (hours): st. dev. over time	88	41	58	118
Wait time (hours): average	39	39	2.9	58
Wait time (hours): st. dev. over time	58	50	16	101
Fraction of port calls with positive wait time	41%	30%	13%	70%
Port dues ($ per ton)	2.1	1.3	1.2	2.9
Port dues (in $) per port call	117,345	96,206	44,038	168,399
Length of berths (miles)	0.96	0.8	0.42	1.4
Storage space (acres)	176	176	55	234

  - Wait/Congestion time more volatile than service time
  - Ports do NOT specialize in specific commodities

Port Efficiency

- Time at Port
  - sum of total wait time; 22% total travel time



Model

- M/M/K queueing models:
  - ship arrivals follow a Poisson process and port service times are exponentially distributed
- **Port Technology**
  - Ship's expected total time at port:

$$\underbrace{T}_{\text{service time}} + \mathbb{I}\{Q \geq K\} \underbrace{(Q - K + 1)\frac{T}{K}}_{\text{wait time (queueing)}} \tag{1}$$

K: num of ships the port can handle at most at a time
T: expected service time at port
Q: (endogeneous) num of ships that the incoming ship finds ahead

$$T\left(\frac{L}{s}, \frac{c}{s}, \omega\right) \tag{2}$$

L: port's workers
s: num of ships currently serviced
c: cranes; ω: productivity

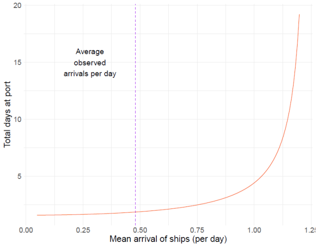
Model

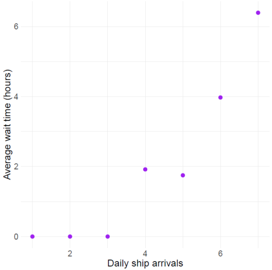
- **Port Technology**
  - Markov structure of endogenous evolution of the port queue
  - Prob $p_n(\tau)$ that in instant τ there are n total ships at port, either being serviced or waiting

$$\frac{dp_n(\tau)}{d\tau} = \begin{cases} -\lambda p_0(\tau) + \mu(0)\, p_1(\tau), & \text{if } n = 0, \\ -\left(\lambda + n\,\mu(n)\right) p_n(\tau) + \lambda p_{n-1}(\tau) + (n+1)\mu(n) p_{n+1}(\tau), & \text{if } 0 < n < K, \\ -\left(\lambda + K\,\mu(K)\right) p_n(\tau) + \lambda p_{n-1}(\tau) + K\,\mu(K) p_{n+1}(\tau), & \text{if } n \geq K. \end{cases} \tag{3}$$

λ: ship arrival rate
$\mu(s) = 1/T(s)$: rate at which ship completes service

- Convex Cost of Congestion (Simulation)





Model

- **Port Demand**
  - Payoff to shipment i between d and f from choosing port j in month t:

$$u_{ijt} = \beta_f \,\text{dist}(f,j) + \beta_d \,\text{dist}(j,d) - \beta_T TT_{jt} - \beta_p p_{jt} + \gamma_t + \gamma_f + \gamma_{l(j)} + \xi_{jft} + \epsilon_{ijt} \quad (4)$$

    $\text{dist}(f,j)$: distance between the foreign location f and port j
    TT_{jt}: (endogenous) total time at port j in period t
    p_{jt}: price that port j charges for its services in month t
    γ_t: month fixed effects- macro economic fluctuations
    γ_f & $\gamma_{l(j)}$: origin & destination fixed effects
    ξ_{jft}: unobserved demand shocks for period t
    ϵ_{ijt}: iid shipment-specific shock; Type I EV distribution
  - Advantages
    measure the welfare cost of delays- $\beta_T TT_{jt}$
    substitutions patterns depend on foreign and domestic locations
- **Macroeconomic Volatility**
  - Macroeconomic conditions affect overall demand for ports:

$$\gamma_t = \rho_0 + \rho_1 \gamma_{t-1} + \epsilon_t \quad (5)$$

    $\epsilon_t \sim N(0, \sigma_\epsilon^2)$

Model

- **Trade Flows**
  - Probability that a pair trading between foreign location f and domestic location d chooses port j:

$$\sigma_{jfdt} \equiv \Pr(j \mid f, d, t) = \frac{\exp(\delta_{jft} + \beta_d \, \mathsf{dist}(j, d))}{1 + \sum_l \exp(\delta_{lft} + \beta_d \, \mathsf{dist}(l, d))} \tag{6}$$

$$\delta_{jft} \equiv \beta_f \, \mathsf{dist}(f, j) - \beta_T TT_{jt} - \beta_p p_{jt} + \gamma_t + \gamma_f + \gamma_{l(j)} + \xi_{jft} \tag{7}$$

  - Problem: σ_{jfdt} not directly observable, use:

$$\sigma_{jft} \equiv \underbrace{\Pr(j \mid f, t)}_{\text{observed ship flows}} = \sum_d \Pr(j \mid f, d, t) * \underbrace{\Pr(d \mid f, t)}_{\text{observed US regional trade flows}} \tag{8}$$

  - Monthly total trade/ship flow through port j:

$$\lambda_{jt} = \sum_f \sum_d \sigma_{jfdt} M_{df} \tag{9}$$

assume a ship arrives at port j at Poisson rate λ_{jt}

Estimation Strategy- Production

- **Port Technology**
  - **Service Time**- CES

$$T_{jt} = \omega_{jt} \left(\alpha \left(\frac{L_{jt}}{s_{jt}} \right)^{\eta} + (1-\alpha) \left(\frac{c_{jt}}{s_{jt}} \right)^{\eta} \right)^{-\frac{1}{\eta}} \tag{10}$$

  - Endogeneity: inputs are not orthogonal to realized productivity
    IVs: 1. labor- local wages in related occupations
    2. changes to the labor force and to % the population above 65
    3. lagged inputs
    GMM estimation: $\mathbb{E}(\nu_{jt} z_{jt}) = 0$, where $\log \omega_{jt} = \log \omega_j + \delta t + \nu_{jt}$
  - **Port Capacity**- Leontief

$$K_j = \min \left\{ \frac{B_j}{\kappa_1}, \frac{A_j}{\kappa_2} \right\} \tag{11}$$

B_j: port j's total length of its berths
A_j: acreage of storage space
κ_1: median number of miles of berth per ship (B_j/K_j)
κ_2: median storage acreage per ship (A_j/K_j)

Estimation Result- Production

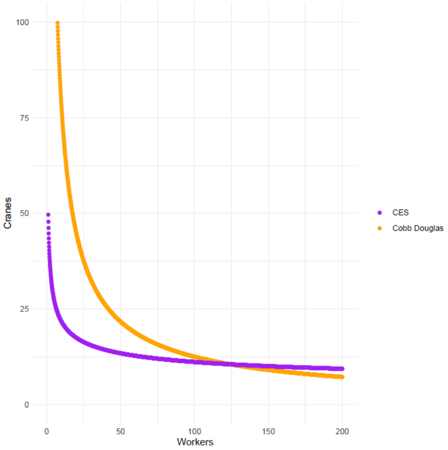


Figure: Port Service Time

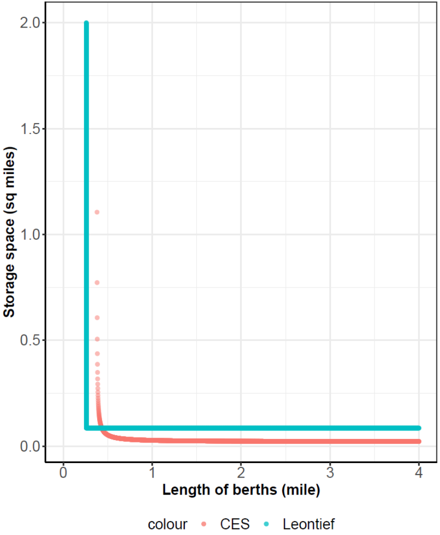


Figure: Port Capacity Function

Estimation Strategy- Demand

- **Micro Likelihood**

$$\mathcal{L}^{\text{micro}}(\delta, \beta_d) = \sum_{f,t} \sum_j n_{ft}^j \log\left(\Pr(j \mid f, t)\right) \tag{12}$$

$$= \sum_{f,t} \sum_j n_{ft}^j \log\left(\sum_d \Pr(j \mid f, d, t) \Pr(d \mid f, t)\right) \tag{13}$$

$$= \sum_{f,t} \sum_j n_{ft}^j \log\left(\sum_d \frac{\exp(\delta_{jft} + \beta_d \,\mathsf{dist}(j,d))}{1 + \sum_l \exp(\delta_{lft} + \beta_d \,\mathsf{dist}(l,d))} \Pr(d \mid f, t)\right) \tag{14}$$

- Problem: Endogeneity of TT_{jt}

  IVs: 1. unexpected disruptions in port j's service operations at t
  residuals from a regression of service time on a number of controls

  Moment conditions: $\mathbb{E}\left(\xi_{jft} z_{jft}\right) = 0$

- **Macro Likelihood**

$$\mathcal{L}^{\text{macro}}(\delta, \beta_d) = \sum_{\text{year}} \sum_{f,d,j} \left(\sigma_{fjd,\text{year}}\right)^{n_{fjd,\text{year}}} \tag{15}$$

  Purpose: identify β_d

  $n_{fjd,\text{year}}$: annual flow from f to d through j

Estimation Strategy- Demand

- **Objective Function**

$$\arg\min_{\beta_\delta,\beta_d,\delta} \mathcal{L}^{\text{micro}}(\delta,\beta_d) + \frac{1}{2} m(\delta,\beta_\delta)' W m(\delta,\beta_\delta) + \alpha \mathcal{L}^{\text{macro}}(\delta,\beta_d) \tag{16}$$

- $m(\delta,\beta_\delta)$: empirical analog of $\mathbb{E}\left(\xi_{jft} z_{jft}\right) = 0$

$$m(\delta,\beta_\delta) = \sum_{f,t}\sum_{j} z_{jft}\left(\delta_{jft} - \beta_f \operatorname{dist}(f,j) + \beta_T TT_{jt-1} + \beta_p p_{jt} - \gamma_t - \gamma_f - \gamma_{l(j)}\right) \tag{17}$$

- Enrich with macroeconomic shocks

$$\gamma_t = \beta y_t + \epsilon_t \tag{18}$$

y_t: Baltic Dry Index, commodity prices, Industrial Price Index

Estimation Result- Demand

	Demand Estimates
Average time at port	-1.44
	(0.49)
Port price per ton	-1.60
	(0.02)
Foreign distance (days of travel)	-0.71
	(0.15)
Domestic distance (log days of travel)	-1.2
	(0.05)
East Coast FE	-0.98
	(2.10)
Great Lakes FE	-15.89
	(4.57)
Gulf FE	-8.22
	(3.73)
Foreign location FE	Yes
Month FE	Yes
Instruments	Unexpected disruptions to port operations

Estimation Result- Elasticities & Substitution

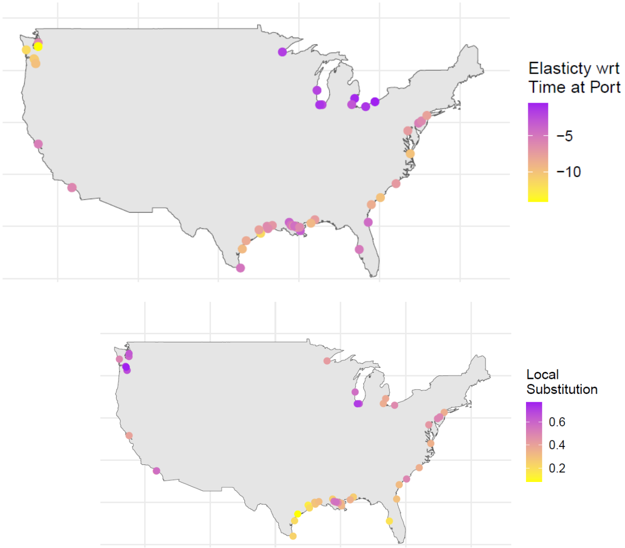


Figure 8: Local Substitution. For each port j this figure plots the fraction of shipments through j that is diverted away from j to a local port (i.e. to one of the 10 closest ports), conditional on shippers choosing to switch following a small increase in time at port.

Welfare Gains from Infrastructure Investment (Counterfactuals)

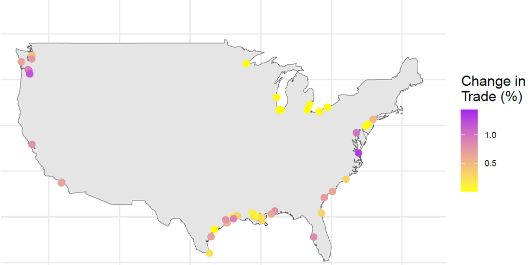
- Investment: one additional ship for each port $K_j \to K_j + 1$
  - assume j's labor and crane also increase
  - 30 years for this counterfactual
- Treated Ports
  - Congestion first declines due to higher capacity; then increases due to higher demand
  - On average (median) trade increases by 42% (38%) at the treated port; congestion declines on average (median) by 4.1% (3.7%)
- Other Ports
  - Substitution effects: lose demand
  - Feedback effect: de-congestion boost demand
  - On average trade decreases by 0.19%, while congestion declines on average by 0.6%
- Welfare Measure

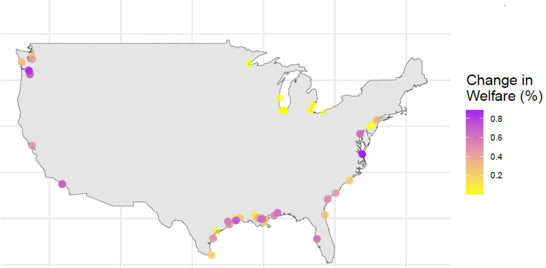
$$\sum_t \beta^t W\left(TT_t, \gamma_t\right) \tag{19}$$

Where

$$W\left(TT_t, \gamma_t\right) = \frac{1}{\beta_p}\left[\sum_{d,f} \log\left(\sum_j \exp\left(\beta_T TT_{jt} + \gamma_t + x_{jfd}\right) + 1\right) M_{df} + \gamma^{\text{euler}}\right] \tag{20}$$

Welfare Gains from Infrastructure Investment (Counterfactuals)





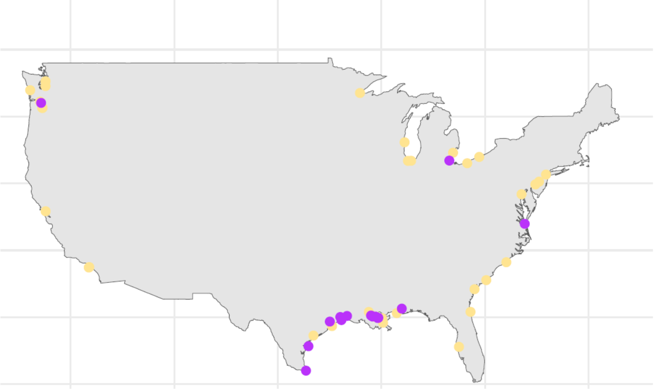
Net Returns from Infrastructure Investment

- Cost for Port:

$$C_j^d + C_j^l + C_j^b \tag{21}$$

  C_j^d: dredging cost
  C_j^l: land purchasing cost
  C_j^b: cost of constructing a bulkhead to support the new berth

- $NetReturn = Welfare - Cost$



Findings

- Port Investment $\rightarrow$ substantial trade and welfare gains only if targeted properly
- Sizeable spillovers across ports
- Macroeconomic volatility $\rightarrow$ returns to investment & geography

Thank you!

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