Division of Labor and Productivity Advantage of Cities: Theory and Evidence from Brazil

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Research question

- Why are firms more productive in larger cities?
  - Central question in urban economics
    - Enormous policy implications
  - Quantitatively important
- Hypothesis first suggested by Adam Smith (1776):

  Larger cities facilitate greater **division of labor within firms**,
  making firms there more productive

- Division of labor: extent of worker specialization within firms What is division of labor?
- Research question:

  Is ***division of labor within firms*** *an important mechanism driving* ***productivity advantage*** *in larger cities?*

Theoretical contribution

- Existing theories **silent** on relationship between *division of labor* and *city size* (Becker & Murphy, 1992; Costinot, 2008; Chaney & Ossa, 2013)
- New stylized fact:
  - Greater division of labor within firms in larger cities
- Model motivated by the stylized fact:
  - Embed division of labor into a spatial equilibrium model
- Two reduced-form assumptions:
  - Benefits of division of labor *higher* for firms with more *complex* products
  - Costs of division of labor *lower* for firms in *larger* cities (e.g., better matching between firm tasks and specialized workers)
- Model generates observed correlation through:
  - Selection: more complex firms locate in larger cities
  - Treatment: any given firm chooses greater division of labor in a larger city

Empirical contributions

1. Empirical support for proposed theory
    - Larger cities provide better ICT infrastructure $\implies$ greater division of labor (e.g., lower coordination or information frictions)
    - Model predictions: an improvement in ICT infrastructure
        - increases firms' division of labor
        - higher increases for more complex firms, and for firms in bigger cities
    - Quasi-experiment: gradual implementation of broadband infrastructure
        - Difference-in-differences: robust evidence for model predictions

2. Structural estimation: reduced-form evidence from (1) + cross-sectional data
    - Division of labor accounts for **15%** of productivity advantage in bigger cities
        - Same order of magnitude as *natural amenities* and *knowledge spillovers* (Ellison and Glaeser, 1999; Serafinelli, 2015)
    - Half due to selection, half due to treatment

Related Literature

- **Agglomeration economies**: Black and Henderson (1999), Duranton and Puga (2003), Rosenthal and Strange (2004), Melo et al. (2009), Eeckhout and Kircher (2011), Davis and Dingel (2015), Davis and Dingel (2016), De la Roca and Puga (2016), Behrens et al. (2015), Gaubert (2016)
  - I investigate an under-explored mechanism that explains productivity advantage in larger cities.
- **Theories of division of labor**: Becker and Murphy (1992), Costinot (2008), Chaney and Ossa (2013)
  - I develop the first theory of division of labor in a spatial equilibrium setting.
- **Empirical work on division of labor**: Baumgardner (1988), Garicano and Hubbard (2009), Duranton and Jayet (2011)
  - I provide the first economy-wide empirical evidence on the relationship between firm's division of labor and city size.
- **Impact of ICT infrastructure**: Sinai and Waldfogel (2004), Clarke and Wallsten (2006), Commander et al. (2011), Hjort and Poulsen (2016), Fort (2017), Almaida et al. (2017)
  - I study the role of ICT infrastructure in facilitating greater worker specialization within firms.

Outline

Stylized facts

Data

- *Relação Anual de Informações* (RAIS) 2010:
  - Linked employer-employee records covering all registered firms in Brazil
  - Worker-level: occupations, wage, etc.
    - detailed occupation codes and descriptions: 6-digit level, 2544 in total
  - Establishment-level: sector, location, etc.
  - Sample: privately owned establishments in tradable sectors
    - Agriculture, mining and manufacturing
  - N = 304,503

Definitions

- Division of labor: number of occupation codes involved in production process
  Definition
  - Remove managerial / supervisory occupations (keep all for robustness)
  - Specialization index: one minus Herfindal index across occupations (e.g., Michaels, 2007; Duranton & Jayet, 2011)
- Cities: microregions (e.g., Kovak, 2013; Costa et al., 2015)
  - A collection of economically integrated contiguous municipalities with similar geographic and productive characteristics (IBGE, 2002)
  - City size: population density (population for robustness)
- Sector-level complexity: Examples
  - Measure 1: number of intermediate inputs (Dietzenbacher et al., 2005; Levchenko, 2007)
  - Measure 2: export share of goods by the G3 (US, EU and Japan) economies (Hausmann et al., 2006; Wang and Wei, 2010)
    - ⋆ Goods exported by advanced economies are more complex

Back

Correlation: division of labor and city size

$$\log N_{jms} = \alpha_0 + \alpha_1 \log L_m + \mathbf{X}_{jms} + \varepsilon_{jms}$$

where:

- N_{jms}: number of occupations within establishment j in city m and sector s (proxy for division of labor)
- L_m: size of the city m
- $\mathbf{X_{jms}}$:
  - Establishment size
  - Industry FE
  - Market access Definition
  - Size of local employment in sector s
  - Skill intensity
  - State FE

Fact 1: Greater division of labor within firms in larger cities

Dependent variable	Log no of occupations within an establishment				
	All tradable		Export intensive	Mono-estb firms	Homogeneous
	(1)	(2)	(3)	(4)	(5)
Log (city size)	.0501*** (.0032)	.0214*** (.0038)	.0219*** (.0037)	.0195*** (.0029)	.0173*** (.0082)
Controls	No	Yes	Yes	Yes	Yes
Obs	304503	304503	115449	284592	34058
R-sq	.13	.842	.836	.853	.821

Standard errors clustered by city in parentheses. Significance levels: * 10%, ** 5%, ***1%. All regressions include state and sector FEs. Establishment-level controls are establishment size and skill intensity within the firm. City-level controls are share of high-skilled workers, average wage, sector diversity, and the size of local sectoral employment. Occupations are measured by 6-digit Brazilian CBO codes. Sectors are measured by 5-digit Brazilian CNAE codes. Homogeneous sectors include corrugated and solid fiber boxes, white pan bread, carbon black, roasted coffee beans, ready-mixed concrete, oak flooring, motor gasoline, block ice, processed ice, hardwood plywood, and raw cane sugar (Foster, Haltiwanger and Syverson, 2008).

- Both division of labor and production location are endogenous

Example | Plots | Specialization index | 4-digit occupation codes | Bins of firm sizes | Population size | Variation of tasks within firms

Correlation: division of labor and complexity

$$\log N_{jms} = \alpha_0 + \alpha_1 \log c_s + \mathbf{X}_{jms} + \varepsilon_{jms}$$

where:

- c_s: complexity of sector s Definition
- $\mathbf{X_{jms}}$:
  - Establishment size
  - Size of local employment in sector s
  - Skill intensity
  - City FE
  - 2-digit Industry FE

Fact 2: Greater division of labor within firms in more complex sectors

Dependent variable	Log no. of occupations					
	No. of intermediate inputs			G3 export share		
	All tradable		Mono-estb firms	All tradable		Mono-estb firms
	(1)	(2)	(3)	(4)	(5)	(6)
Log (complexity)	.0423***	.0363***	.0372***	5.481***	.5388***	.632***
	(.0145)	(.0043)	(.0043)	(.5432)	(.1756)	(.1376)
Controls	No	Yes	Yes	No	Yes	Yes
Obs	304503	304503	284592	304503	304503	284592
R-sq	.035	.787	.79	.039	.787	.79

Standard errors clustered by sector in parentheses. Significance levels: * 10%, ** 5%, ***1%. All regressions include a city FE and a 2-digit industry FE. Occupations are measured by 6-digit Brazilian CBO codes. Sectors are defined at 4-digit Brazilian CNAE codes.

Results using specialization index Results using 4-digit occupation codes

Two stylized facts:

1. Positive correlation between *division of labor* and *city size*
2. Positive correlation between *division of labor* and *complexity*

Theory

Cities

- Continuum of homogeneous sites:
  - Cities emerge endogenously
  - L indexes both city and population size
  - Constrained in housing land supply $\leftarrow$ congestion force
- Occupied by mobile workers and firms

Workers

- Homogeneous workers consume housing and a bundle of freely traded goods

Worker's problem

$$U = \left(\frac{h}{1-\eta}\right)^{1-\eta}\left(\frac{X}{\eta}\right)^{\eta}, \quad \text{where } X = \prod_{s=1}^{S} X_s^{\xi_s}$$

- Within each sector s, a CES aggregate of a continuum of varieties z

$$X_s = \left[\int x_s(z)^{\frac{\sigma_s - 1}{\sigma_s}} dz\right]^{\frac{\sigma_s}{\sigma_s - 1}}, \quad \text{where } \sigma_s > 1 \qquad (1)$$

- Given spatial mobility, same utility across space in equilibrium Derivation

$$w(L) = \bar{w}\left((1-\eta)L\right)^{\frac{1-\eta}{\eta}}, \quad \text{where } \bar{w} = \bar{U}^{1/\eta} P \qquad (2)$$

Firms

- Firms are monopolistically competitive
- Single product: freely traded across space
- Exogenously assigned to:
  - a sector $s \in \{1, \ldots, S\}$
  - a firm-specific production technology
- Difference: *product complexity*
  - Across sectors, c_s: *Computer* vs *Shoe*
  - Within sector, z: *Nike* vs *local shoe factory*

Optimal Division of Labor

- A firm chooses division of labor N:
  - increases productivity, raises "costs" (e.g., coordination costs, Becker & Murphy, 1992)
- Output is:

$$Q_s(z) = A(N, z, c_s)H(N, L)l$$

- **Assumption 1:** $A(N, z, c_s)$
  - Increasing in N Preferences
  - Log-supermodular in (N, z) and (N, c_s): more complex firms benefit more from greater division of labor Microfoundation An example
- **Assumption 2:** $H(N, L)$
  - Decreasing in N
  - Log-supermodular in (N, L): larger cities lower costs Microfoundation: infrastructure Microfoundation: learning

Optimal City Size

Firm chooses the optimal city of size L:

- lower costs of division of labor, higher labor costs

Lemma

Within a sector s, high-z firms sort into larger cities. More formally, given c_s, the matching function $L_s^*(z)$, is increasing in z.

- Log-supermodularities: (N, z) and (N, L)
- When N optimally chosen, log-supermodularity (z, L) (Topkis, 1978)
- Positive assortative matching between z and L in equilibrium

Firm's problem | First-order conditions
Spatial Eqm Definition | GE quantities | Existence and Uniqueness | Stability

Equilibrium characteristics

Proposition

In equilibrium, within a sector, firm's division of labor, profit, revenue, and productivity all increase with city size.

- In equilibrium, high-z (complex) firms sort into larger cities
- N is higher in larger cities
  - Selection: high-z firms occupy larger cities, choosing larger N
  - Treatment: larger cities reduce cost of increasing N for all firms
- Firms located in larger cities are bigger (in revenue) and more productive

Descriptive evidence | Cross-sector Characteristics

Impact of ICT infrastructure improvement

- Larger cities provide better ICT infrastructure in equilibrium Microfoundation
- Hypothesis: facilitate greater division of labor, e.g., by reducing coordination or information frictions (Bolton and Dewatripont, 1994; Bloom and Garicano, 2008; Garicano and Heaton, 2010)

Proposition

In equilibrium, in response to an ICT improvement,

(i) *all firms increase their division of labor;*

(ii) *the increase is larger for firms in high-c_s sectors; and*

(iii) *the increase is larger for firms located in bigger cities.*

- (N, c_s), (N, z): Improvement in ICT infrastructure benefits more complex firms more

  $\Longrightarrow$ Larger increase for firms in high-c_s sectors and for high-z firms

- (N, L): High-z firms locate in bigger cities

  $\Longrightarrow$ Larger increase for firms in bigger cities

Illustration

Empirical support for proposed theory

Broadband Internet Infrastructure in Brazil

- Plausibly exogenous variation in ICT infrastructure from a quasi-experiment:
  - Gradual improvement of broadband infrastructure in Brazil
- Up to 2010, broadband access in Brazil closely reflected variation in population density Broadband access
- National Broadband Plan (*Programa Nacional de Banda Larga*, PNBL)
  - Largest ICT infrastructure project in Brazil: $14.7bil USD investment
  - Major initiative: 48,000km of new broadband backbone into remote, low-density areas What's a backbone?
  - Staggered implementation between 2012 and 2014
- Difference-in-differences estimation New backbones

Details of PNBL

Estimating equations I

To establish existence of one possible explanation (ICT infrastructure):

$$\log N_{jt} = \alpha + \beta Backbone_{jt} + \delta_j + \delta_t + \varepsilon_{jt}$$

- $Backbone_{jt}$: dummy variable with value 1 if j is "served" by a new backbone at time t, and zero otherwise.
- δ_j, δ_t: establishment, year FEs
- Define "served" based on geographic distance (e.g. Hjort and Poulsen, 2016)
  - Connectivity is lower further away from the backbone: range 100km-400km (IGIC, 1994; Collins, 2015; Maskara, 2017)
  - Baseline: "served" if the distance to the backbone is closer than **250km**
  - Robustness: varying the radius
- Model prediction: $\beta > 0$

Estimating equations II

To test complementarity assumptions

$$\log N_{jt} = \alpha + \beta Backbone_{jt} + \gamma Backbone_{jt} \times \log L_{c(j),t_0} + \delta_j + \delta_t + \varepsilon_{jt}$$

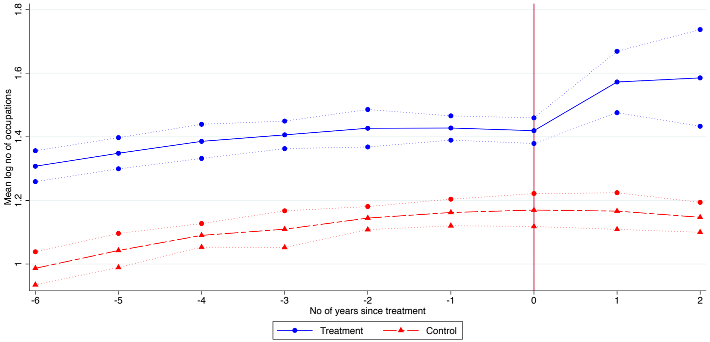
$$\log N_{jt} = \alpha + \beta Backbone_{jt} + \omega Backbone_{jt} \times \log c_{s(j),t_0} + \delta_j + \delta_t + \varepsilon_{jt}$$

- $\log L_{c(j),t_0}$: city size
- $\log c_{s(j),t_0}$: sector complexity Definition
- Model predictions: $\gamma > 0$, $\omega > 0$

Identifying assumptions I

- Identifying assumption: common trend
  - **Parallel trends** in log N_{jt} before the program
  - **No systematically different shocks** after the program

- No significant difference in pre-trends:



Specialization index

Identifying assumptions II

- Alignment of new backbones pre-determined
- The order in which locations are served approximately geographically determined

Broadband availability increases the division of labor

- Number of occupations increase by 1.3% for firms in treated areas, relative to others
- Increases significantly higher for
  - firms in larger cities
  - firms producing more complex products
- Same qualitative results using specialization index

Dependent variable	Log (No of occs)				Specialization index			
	(1)	(2)	(3) Interm. inputs	(4) G3 exp share	(5)	(6)	(7) Interm. inputs	(8) G3 exp share
$Backbone_{jt}$	.0127***	.0015	.0015	.0074**	.0855***	.0116	.0728***	.0805***
	(.0028)	(.003)	(.0038)	(.0032)	(.017)	(.0085)	(.014)	(.016)
$Backbone_{jt} \times \log L_{ct_0}$		.0077***				.0141***		
		(.0008)				(.0033)		
$Backbone_{jt} \times \log c_{st_0}$			.0139***	.004***			.0156***	.0064***
			(.0031)	(.0012)			(.0044)	(.0013)
Mean of outcome	1.45	1.45	1.45	1.45	.43	.43	.43	.43
Obs	777096	777096	777096	777096	777096	777096	777096	777096
R-sq	.853	.853	.853	.854	.717	.718	.717	.717

Robust standard errors clustered by municipality in parentheses. Significance levels: * 10%, ** 5%, ***1%. All regressions include a constant term, establishment and year FEs.

Examples | Alternative theories | Other outcome variables | Back to policy evaluation

Robustness I

- Varying distance around the backbone network used to define if an area is served
  - Served if distance $<$ 100km, 200km, 300km, 400km Results
- Adding *lead* variables: $t-1$ and $t-2$
  - insignificant coefficients $\implies$ supporting parallel trends assumption Results
- Firms may reorganize and reallocate resources across establishments in response to the new ICT infrastructure
  - Excluding multiple-establishment firms Results
- Origin and destination locations for the new backbones tend to be larger cities
  - Excluding terminal locations Results
- Locations near submarine cable landing points are typically in or near mega-cities
  - Excluding all establishments located within 100km of the landing points Results
- Areas connected to broadband networks before PNBL may be on a different growth path
  - Excluding firms connected to broadband network before PNBL Results
- Areas that were never treated may be on a different growth path
  - Restricting sample to establishments that are eventually treated Results
- Removing new workers hired after the program Results

Robustness II

- There may be city-specific time trends
  - Adding city-specific linear trends Results
- Results are driven by locations very near or far from the new backbone cables
  - Excluding municipalities that are either very near ($< 10th$ percentile) or very far ($> 90th$ percentile) from the backbone network Results
- Firms may have anticipated the change in ICT infrastructure
  - Excluding data from 2010 and 2011 Results
- Rural areas or mega cities may be on a different growth path compared to urban areas
  - Drop rural areas (density $<$ 400 persons/km^2) Results
  - Drop mega cities (density $>$ 90th percentile) Results
- Export-intensive firms may benefit more as the ICT infrastructure enhances international communication
  - Separate firms into two groups based on sector-level share of exports Results
- Possible spatial correlation biasing standard errors
  - Use Conley SE (Conley, 1999; Conley, 2008) Results
- Possible serial correlation biasing standard errors
  - Non-parametric permutation tests Results
- Combining two interaction terms in a single regression Results

Structural analysis

Model specification and assumption

- Recall productivity function:

$$\psi_s(z) = A(N, z, c_s)H(N, L)$$

- Assume:

$$\log \psi_s(z) \equiv (\log z)(1 + \log N)^{c_s} - (\log N)(1 + \log L)^{-\theta_s}$$

- $\log z\,(1 + \log N)^{c_s}$: worker productivity
  - c_s: relationship between z and N
  - $c_s = 0$: no complementarity
- $\log N\,(1 + \log L)^{-\theta_s}$: costs of division of labor
  - θ_s: relationship between L and N
  - $\theta_s = 0$: city size has no effect on division of labor
- z: complexity draw
  - log-normal distribution with variance ν_z

Three model extensions

$$\log \psi_{js} \equiv \log z \left(1 + \log N\right)^{c_s} - \log N \left(1 + \log L\right)^{-\theta_s} + \alpha_s \log L + \log z(1 + \log L)^{\upsilon_s} + \varepsilon_{jL}$$

1. Other agglomeration forces: $\alpha_s \log L + \log z(1 + \log L)^{\upsilon_s}$ Extension
   - Differences in natural amenities, knowledge spillovers, sharing of inputs, etc
   - α_s: strength of reduced-form agglomeration forces
   - υ_s: strength of direct interaction between z and L
   - $c_s = 0$ or $\theta_s = 0$: nest firm sorting model (e.g., Gaubert, 2017)
   - With also $\upsilon_s = 0$: nest traditional model (e.g., Allen and Arkolakis, 2014)
2. Imperfect sorting of firms: ε_{jL}
   - Idiosyncratic motives for choosing a location
   - i.id across city sizes and firms
   - Type-I extreme value distribution with mean 0 and variance ν_L
3. An equilibrium with discrete cities:
   - $\mathcal{N}$ cities: $L_n \in \mathcal{L}$, $n = 1, \dots, \mathcal{N}$

Estimation method and parameters

Method of simulated moments (e.g. Gouriéroux and Monfort, 1997; Eaton et al, 2011)

- Allow parameters to vary by sector ($S = 21$) Summary statistics

$$\log \psi_{js} \equiv \alpha_s \log L + \log z_j (1 + \log L)^{\upsilon_s} + \log z_j \, (1 + \log N)^{c_s} - \log N \, (1 + \log L)^{-\theta_s} + \varepsilon_{jL}$$

- $6S$ parameters: $\chi_s = \{c, \theta, \alpha, \upsilon, \nu_L, \nu_z\}_s$
  - c: complementarity between $\log N$ and $\log z$
  - θ: complementarity between $\log N$ and $\log L$
  - α: reduced-form agglomeration force
  - υ: complementarity between $\log z$ and $\log L$
  - ν_L: variance of firm-city shocks ε_{jL}
  - ν_z: variance of firm complexities z

First stage estimation | Estimation details

Moments and identification

- Quasi-experiment + cross-sectional moments

1. Average city-level increase in division of labor Details
   - ★ firms in larger cities increase more in response to the ICT shock
   - ★ Greater increase for larger c and/or θ

$\Longrightarrow$ identifies $\frac{\theta}{1-c}$

2. Within-city variation in firm's division of labor Details

$\Longrightarrow$ separates c from $\frac{\theta}{1-c}$

3. Increase in average *division of labor* wrt city size Details
4. Increase in average *firm size* wrt city size Details
5. Firm-size distribution Details
6. Geographic distribution of firms across city sizes Details

$\Longrightarrow$ Identify α, υ, ν_L and ν_z (Gaubert, 2017)

Model fit

- Estimated model fits targeted moments well Results
- Moments not targeted:
  - Sector product complexity lines up well with empirical proxies Some examples Correlation
  - City-size distribution well-approximated by Zipf's Law Results
  - City-level changes in division of labor across all sectors Details

Quantitative Analysis

Division of labor and size advantage of cities

- Productivity advantages of larger cities:

$$\log \psi_{js} = \beta_0 + \beta_1 \log L_j + \delta_s + \iota_j \tag{3}$$

- $\hat{\beta}_1 = 0.083$: consistent with 0.02–0.10 estimates in the literature (Rosenthal and Strange, 2004; Melo et al., 2009)

- Shutting down division of labor N Details
  - $\triangle\hat{\beta}_1 = 0.013$
  - Division of labor: 15% of the productivity gains in larger cities
  - 7%–20% due to natural advantages (Ellison and Glaeser, 1999; Roos, 2005); 10% due to knowledge spillover (Serafinelli, 2015)

- Shutting down systematic choice of L Details
  - $\triangle\hat{\beta}_1 = 0.0064$
  - Sorting of firms: about 50% of the productivity differences through **division of labor**

Alternative approach Policy Implications

Conclusions

- I study how division of labor within firms relates to spatial productivity differences
- New fact: positive correlation between firm's division of labor and city size
- A parsimonious model generating the stylized fact in equilibrium
  - Sorting of firms + direct effect of city size $\Longrightarrow$ spatial distributions of the division of labor and productivity
- Quasi-experiment: strong empirical support for the proposed theory
- Structural analysis: the division of labor accounts for 15% of productivity advantages in larger cities
  - Half due to sorting of firms; half due to direct effect of city size

"**The greatest improvement in the productive powers of labour**, *and the greater part of the skill, dexterity, and judgment with which it is anywhere directed, or applied,* **seem to have been the effects of the division of labour**."

– Adam Smith, the Wealth of Nations (1776)

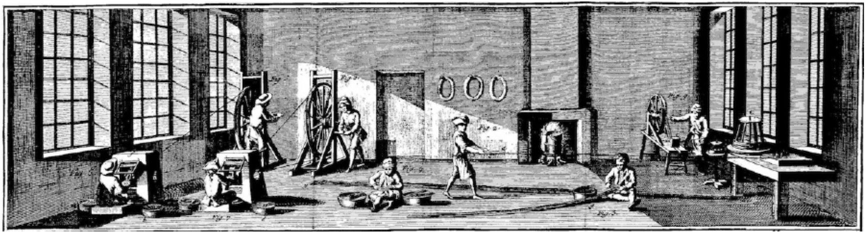


Illustration of the pin factory, Denis Diderot *Encyclopépie* (1772)