

Optimal Supply Networks III: Redistribution

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Principles of Complex Systems, Vols. 1, 2, & 3D
CSYS/MATH 6701, 6713, & a pretend number, 2024–2025

The PoCverse
Optimal Supply
Networks III
1 of 49

Distributed Sources

Size-density law

Cartograms

A reasonable derivation

Global redistribution

Public versus Private

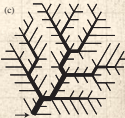
References

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Santa Fe Institute | University of Vermont



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Networks III
2 of 49

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Size-density law

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A reasonable derivation

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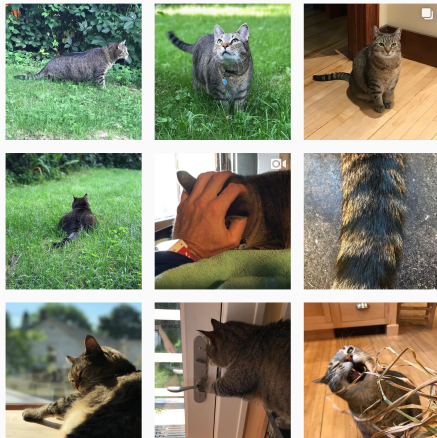
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The PoCverse
Optimal Supply
Networks III
3 of 49

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Size-density law

Cartograms

A reasonable derivation

Global redistribution

Public versus Private

References



Outline

Distributed Sources

Size-density law

Cartograms

A reasonable derivation

Global redistribution

Public versus Private

Distributed Sources

Size-density law

Cartograms

A reasonable derivation

Global redistribution

Public versus Private

References

References



Many sources, many sinks

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Cartograms

A reasonable derivation

Global redistribution

Public versus Private

References

How do we distribute sources?

- Focus on 2-d (results generalize to higher dimensions).
- Sources = hospitals, post offices, pubs, ...
- Key problem:** How do we cope with uneven population densities?
- Obvious: if density is uniform then sources are best distributed **uniformly**.
- Which lattice is optimal? The **hexagonal lattice**
- Q2:** Given population density is uneven, what do we do?
- We'll follow work by Stephan (1977, 1984) ^[4, 5], Gastner and Newman (2006) ^[2], Um *et al.* (2009) ^[6], and work cited by them.



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Public versus Private

References



Optimal source allocation: Size-density law

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Size-density law

Cartograms

A reasonable derivation

Global redistribution

Public versus Private


References

Solidifying the basic problem

- Given a region with some population distribution ρ , most likely uneven.
- Given resources to build and maintain N facilities.
- Q:** How do we locate these N facilities so as to **minimize the average distance** between an **individual's residence** and the nearest facility?





“Optimal design of spatial distribution networks” 
Gastner and Newman,
Phys. Rev. E, **74**, 016117, 2006. ^[2]

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Optimal Supply
Networks III
8 of 49

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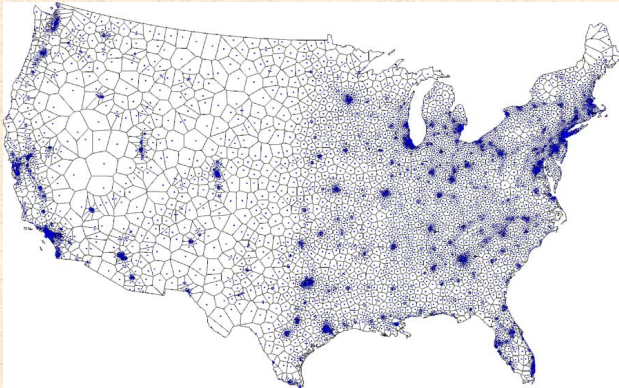
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-  Approximately optimal location of 5000 facilities.
-  Based on 2000 Census data.
-  Simulated annealing + Voronoi tessellation.



Optimal source allocation

Size-density law:



$$\rho_{\text{fac}} \propto \rho_{\text{pop}}^{2/3}$$



Why?




Again: Different story to branching networks where there was either one source or one sink.



Now sources & sinks are distributed throughout region.





“Territorial division: The least-time constraint
behind the formation of subnational boundaries” 

G. Edward Stephan,
Science, **196**, 523–524, 1977. ^[4]



We first examine Stephan’s treatment (1977) ^[4, 5]



Zipf-like approach: invokes **principle of minimal effort**.



Also known as the Homer Simpson principle.



Optimal source allocation

- Consider a region of area A and population P with a single functional center that everyone needs to access every day.
- Build up a general cost function based on time expended to **access and maintain center**.
- Write **average travel distance** to center as $\langle d \rangle$ and assume **average speed of travel** is $\langle v \rangle$.
- Assume **isometry**: average travel distance $\langle d \rangle$ will be on the length scale of the region which is $\sim A^{1/2}$
- Average time expended per person in accessing facility is therefore

$$\langle d \rangle / \langle v \rangle = cA^{1/2} / \langle v \rangle$$

where c is an unimportant shape factor.



Optimal source allocation


- Next assume facility requires regular maintenance (person-hours per day).
- Call this quantity τ .
- If burden of maintenance is shared then average cost per person is τ/P where P = population.
- Replace P by $\rho_{\text{pop}}A$ where ρ_{pop} is density.
- Important assumption: uniform density.
- Total average time cost per person:

$$T = \langle d \rangle / \langle v \rangle + \tau / (\rho_{\text{pop}}A) = cA^{1/2} / \langle v \rangle + \tau / (\rho_{\text{pop}}A).$$


- Now Minimize with respect to A ...




Optimal source allocation

 Differentiating ...


$$\begin{aligned}\frac{\partial T}{\partial A} &= \frac{\partial}{\partial A} \left(cA^{1/2} / \langle v \rangle + \tau / (\rho_{\text{pop}} A) \right) \\ &= \frac{c}{2 \langle v \rangle A^{1/2}} - \frac{\tau}{\rho_{\text{pop}} A^2} = 0\end{aligned}$$

 Rearrange:

$$A = \left(\frac{2 \langle v \rangle \tau}{c \rho_{\text{pop}}} \right)^{2/3} \propto \rho_{\text{pop}}^{-2/3}$$

 # facilities per unit area ρ_{fac} :

$$\rho_{\text{fac}} \propto A^{-1} \propto \rho_{\text{pop}}^{2/3}$$

 Groovy ...

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Global redistribution


Public versus Private

References







Optimal source allocation

An issue:

 Maintenance (τ) is assumed to be **independent** of population and area (P and A)

 Stephan's online book
"The Division of Territory in Society" is here .

 (It used to be here .)

 The Readme  is well worth reading (1995).



Cartograms

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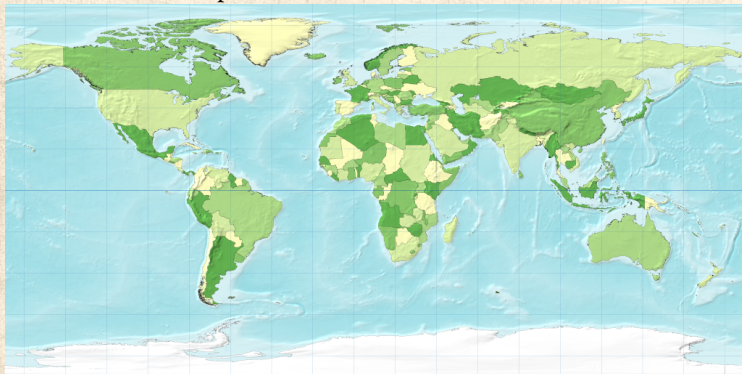
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Standard world map:



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Cartogram of countries 'rescaled' by population:



Cartograms

Diffusion-based cartograms:

- ❏ Idea of cartograms is to **distort areas** to more accurately represent some local density ρ_{pop} (e.g. population).
- ❏ Many methods put forward—typically involve some kind of physical analogy to **spreading or repulsion**.
- ❏ Algorithm due to Gastner and Newman (2004)^[1] is based on **standard diffusion**:

$$\nabla^2 \rho_{\text{pop}} - \frac{\partial \rho_{\text{pop}}}{\partial t} = 0.$$

- ❏ Allow density to diffuse and trace the movement of individual elements and boundaries.
- ❏ Diffusion is constrained by boundary condition of surrounding area having density $\langle \rho \rangle_{\text{pop}}$.

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Cartograms

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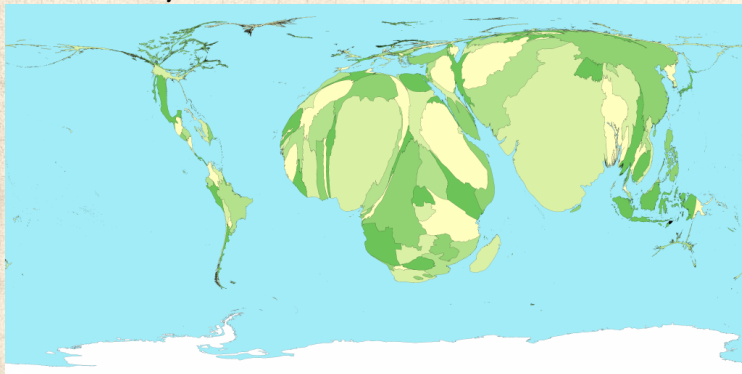
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Child mortality:



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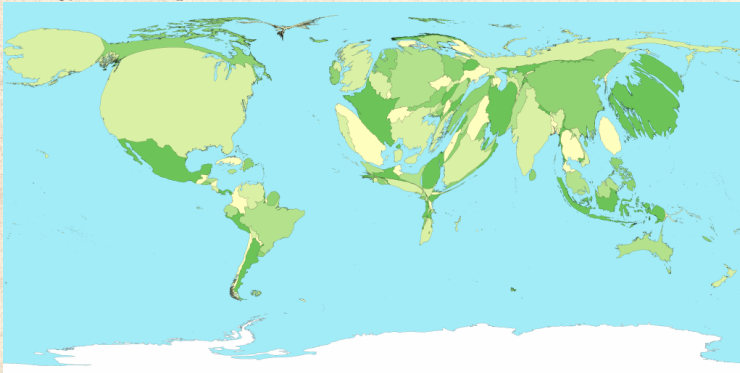
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Energy consumption:



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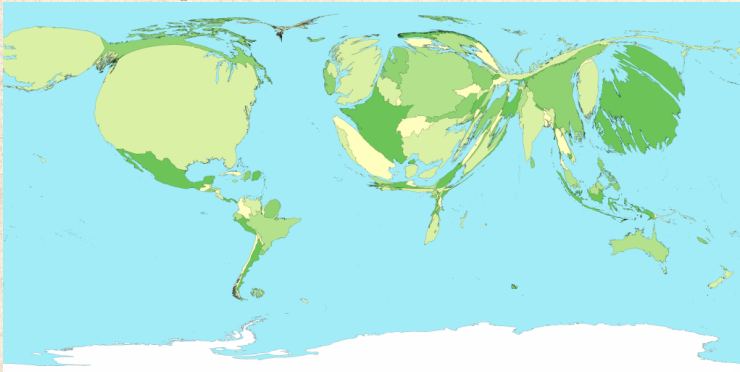
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Gross domestic product:



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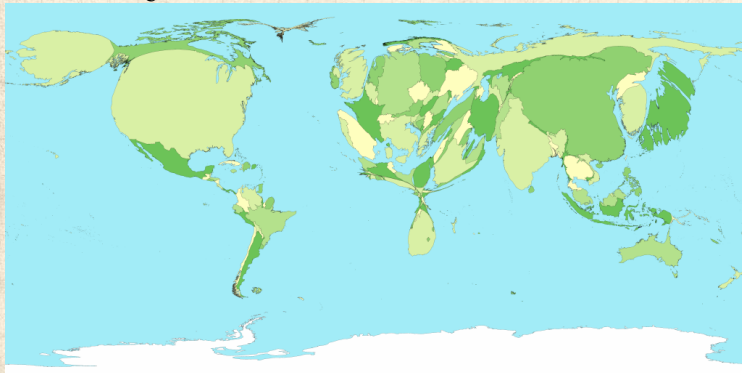
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Greenhouse gas emissions:



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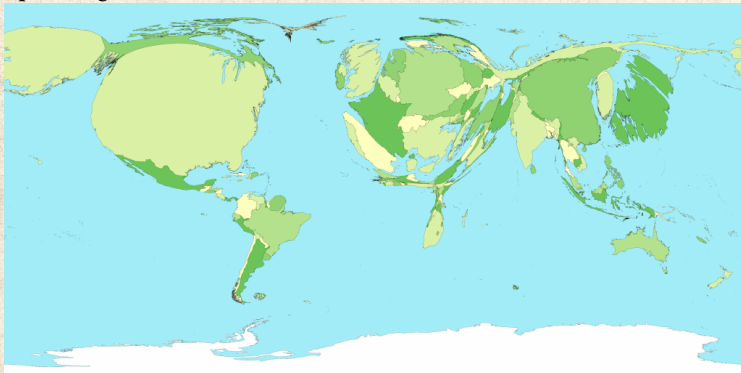
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Spending on healthcare:



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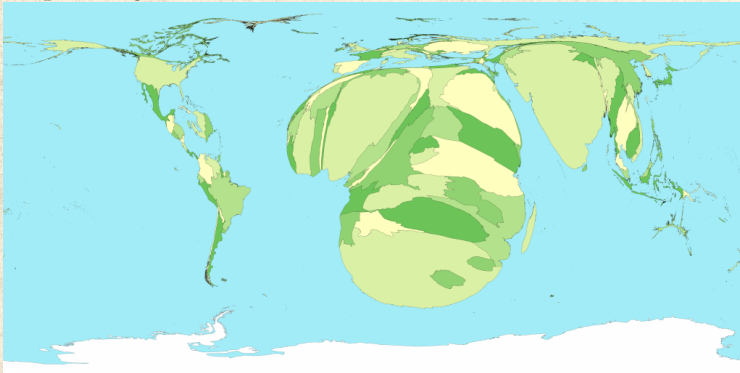
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People living with HIV:



Cartograms

 The preceding sampling of Gastner & Newman's cartograms lives here .

 A larger collection can be found at worldmapper.org .

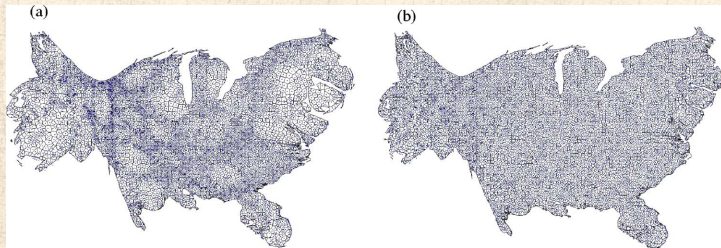






“Optimal design of spatial distribution networks” ↗


Gastner and Newman,

Phys. Rev. E, **74**, 016117, 2006. [2]

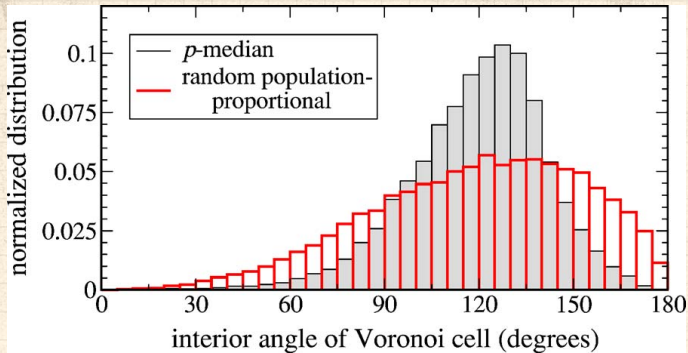


 **Left:** population density-equalized cartogram.

 **Right:** (population density)^{2/3}-equalized cartogram.

 Facility density is uniform for $\rho_{\text{pop}}^{2/3}$ cartogram.








From Gastner and Newman (2006) [2]






Cartogram's Voronoi cells are somewhat hexagonal.



Deriving the optimal source distribution:



-  **Basic idea:** Minimize the average distance from a random individual to the nearest facility. [2]
-  Assume given a fixed population density ρ_{pop} defined on a spatial region Ω .
-  Formally, we want to find the locations of n sources $\{\vec{x}_1, \dots, \vec{x}_n\}$ that minimizes the **cost function**


$$F(\{\vec{x}_1, \dots, \vec{x}_n\}) = \int_{\Omega} \rho_{\text{pop}}(\vec{x}) \min_i \|\vec{x} - \vec{x}_i\| d\vec{x}.$$


-  Also known as the p-median problem, and connected to cluster analysis.
-  Not easy ...in fact this one is an NP-hard problem. [2]
-  Approximate solution originally due to Gusein-Zade [3].



Approximations:


 For a given set of source placements $\{\vec{x}_1, \dots, \vec{x}_n\}$, the region Ω is divided up into Voronoi cells , one per source.

 Define $A(\vec{x})$ as the **area** of the Voronoi cell containing \vec{x} .

 As per Stephan's calculation, estimate typical distance from \vec{x} to the nearest source (say i) as

$$c_i A(\vec{x})^{1/2}$$


where c_i is a shape factor for the i th Voronoi cell.

 Approximate c_i as a constant c .





Size-density law

Carrying on:


 The cost function is now


$$F = c \int_{\Omega} \rho_{\text{pop}}(\vec{x}) A(\vec{x})^{1/2} d\vec{x}.$$

 We also have that the **constraint** that Voronoi cells divide up the overall area of Ω : $\sum_{i=1}^n A(\vec{x}_i) = A_{\Omega}$.

 Sneakily turn this into an integral constraint:

$$\int_{\Omega} \frac{d\vec{x}}{A(\vec{x})} = n.$$

 Within each cell, $A(\vec{x})$ is constant.

 So ...integral over each of the n cells equals 1.

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Size-density law

Cartograms

A reasonable derivation

Global redistribution

Public versus Private

References



Now a Lagrange multiplier story:

By varying $\{\vec{x}_1, \dots, \vec{x}_n\}$, minimize

$$G(A) = c \int_{\Omega} \rho_{\text{pop}}(\vec{x}) A(\vec{x})^{1/2} d\vec{x} - \lambda \left(n - \int_{\Omega} [A(\vec{x})]^{-1} d\vec{x} \right)$$

I Can Haz Calculus of Variations ↗

Compute $\delta G / \delta A$, the functional derivative ↗ of the functional $G(A)$.

This gives

$$\int_{\Omega} \left[\frac{c}{2} \rho_{\text{pop}}(\vec{x}) A(\vec{x})^{-1/2} - \lambda [A(\vec{x})]^{-2} \right] d\vec{x} = 0.$$


Setting the integrand to be zilch, we have:

$$\rho_{\text{pop}}(\vec{x}) = 2\lambda c^{-1} A(\vec{x})^{-3/2}.$$





Size-density law

Now a Lagrange multiplier story:


 Rearranging, we have

$$A(\vec{x}) = (2\lambda c^{-1})^{2/3} \rho_{\text{pop}}^{-2/3}.$$

 Finally, we identify $1/A(\vec{x})$ as $\rho_{\text{fac}}(\vec{x})$, an approximation of the local source density.

 Substituting $\rho_{\text{fac}} = 1/A$, we have

$$\rho_{\text{fac}}(\vec{x}) = \left(\frac{c}{2\lambda} \rho_{\text{pop}} \right)^{2/3}.$$

 Normalizing (or solving for λ):

$$\rho_{\text{fac}}(\vec{x}) = n \frac{[\rho_{\text{pop}}(\vec{x})]^{2/3}}{\int_{\Omega} [\rho_{\text{pop}}(\vec{x})]^{2/3} d\vec{x}} \propto [\rho_{\text{pop}}(\vec{x})]^{2/3}.$$

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Size-density law

Cartograms

A reasonable derivation

Global redistribution

Public versus Private

References



Global redistribution networks

One more thing:

- How do we supply these facilities?
- How do we best redistribute mail? People?
- How do we get beer to the pubs?
- Gastner and Newman model: cost is a function of basic maintenance and travel time:

$$C_{\text{maint}} + \gamma C_{\text{travel}}.$$

- Travel time is more complicated: Take 'distance' between nodes to be a composite of shortest path distance l_{ij} and number of legs to journey:

$$(1 - \delta)l_{ij} + \delta(\#\text{hops}).$$

- When $\delta = 1$, only number of hops matters.

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Size-density law

Cartograms

A reasonable derivation

Global redistribution

Public versus Private

References



Global redistribution networks

Distributed Sources

Size-density law

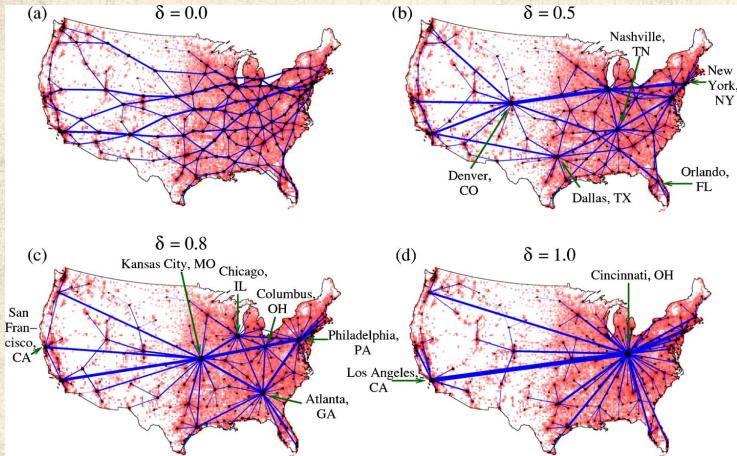
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A reasonable derivation

Global redistribution

Public versus Private

References



From Gastner and Newman (2006) [2]



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Optimal Supply
Networks III
39 of 49

Distributed Sources

Size-density law

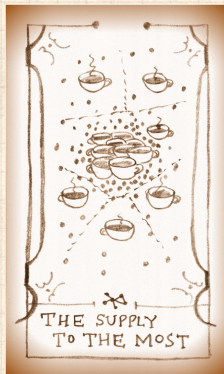
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A reasonable derivation

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Public versus Private

References



Public versus private facilities

Beyond minimizing distances:

🧱 “Scaling laws between population and facility densities” by Um *et al.*, Proc. Natl. Acad. Sci., 2009. [6]

🧱 Um *et al.* find empirically and argue theoretically that the connection between facility and population density

$$\rho_{\text{fac}} \propto \rho_{\text{pop}}^{\alpha}$$

does not universally hold with $\alpha = 2/3$.

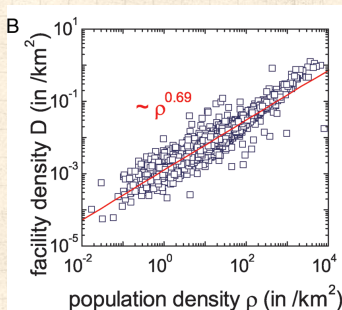
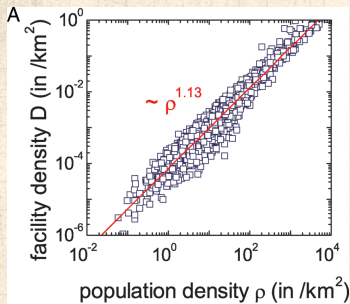
🧱 **Two idealized limiting classes:**


1. For-profit, commercial facilities: $\alpha = 1$;
2. Pro-social, public facilities: $\alpha = 2/3$.

🧱 Um *et al.* investigate facility locations in the United States and South Korea.




Public versus private facilities: evidence



 **Left plot:** ambulatory hospitals in the U.S.

 **Right plot:** public schools in the U.S.

 **Note:** break in scaling for public schools. Transition from $\alpha \simeq 2/3$ to $\alpha = 1$ around $\rho_{\text{pop}} \simeq 100$.



Public versus private facilities: evidence

US facility	α (SE)	R^2
Ambulatory hospital	1.13(1)	0.93
Beauty care	1.08(1)	0.86
Laundry	1.05(1)	0.90
Automotive repair	0.99(1)	0.92
Private school	0.95(1)	0.82
Restaurant	0.93(1)	0.89
Accommodation	0.89(1)	0.70
Bank	0.88(1)	0.89
Gas station	0.86(1)	0.94
Death care	0.79(1)	0.80
* Fire station	0.78(3)	0.93
* Police station	0.71(6)	0.75
Public school	0.69(1)	0.87

SK facility	α (SE)	R^2
Bank	1.18(2)	0.96
Parking place	1.13(2)	0.91
* Primary clinic	1.09(2)	1.00
* Hospital	0.96(5)	0.97
* University/college	0.93(9)	0.89
Market place	0.87(2)	0.90
* Secondary school	0.77(3)	0.98
* Primary school	0.77(3)	0.97
Social welfare org.	0.75(2)	0.84
* Police station	0.71(5)	0.94
Government office	0.70(1)	0.93
* Fire station	0.60(4)	0.93
* Public health center	0.09(5)	0.19

Rough transition between public and private at $\alpha \approx 0.8$.

Note: * indicates analysis is at state/province level; otherwise county level.

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Size-density law

Cartograms

A reasonable derivation

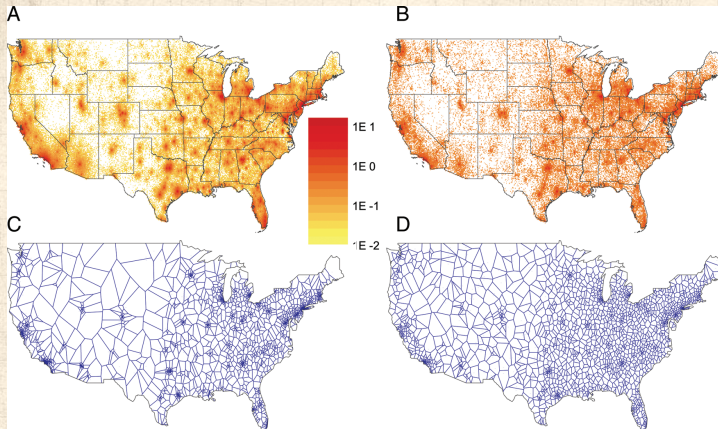
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Public versus private facilities: evidence



A, C: ambulatory hospitals in the U.S.; **B, D:** public schools in the U.S.; **A, B:** data; **C, D:** Voronoi diagram from model simulation.



Public versus private facilities: the story

So what's going on?

- 🧱 Social institutions seek to **minimize distance of travel**.
- 🧱 Commercial institutions seek to **maximize the number of visitors**.
- 🧱 Defns: For the i th facility and its Voronoi cell V_i , define
 - 🧱 n_i = population of the i th cell;
 - 🧱 $\langle r_i \rangle$ = the average travel distance to the i th facility.
 - 🧱 A_i = area of i th cell (s_i in Um *et al.* [6])
- 🧱 Objective function to maximize for a facility (highly constructed):


$$v_i = n_i \langle r_i \rangle^\beta \text{ with } 0 \leq \beta \leq 1.$$

🧱 Limits:



- 🧱 $\beta = 0$: purely commercial.
- 🧱 $\beta = 1$: purely social.



Public versus private facilities: the story





-  Either proceeding as per the Gastner-Newman-Gusein-Zade calculation or, as Um *et al.* do, observing that the cost for each cell should be the same, we have:

$$\rho_{\text{fac}}(\vec{x}) = n \frac{[\rho_{\text{pop}}(\vec{x})]^{2/(\beta+2)}}{\int_{\Omega} [\rho_{\text{pop}}(\vec{x})]^{2/(\beta+2)} d\vec{x}} \propto [\rho_{\text{pop}}(\vec{x})]^{2/(\beta+2)}.$$

-  For $\beta = 0$, $\alpha = 1$: commercial scaling is linear.
-  For $\beta = 1$, $\alpha = 2/3$: social scaling is sublinear.



References I

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