Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private

References

Optimal Supply Networks III: Redistribution

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Complex Networks | @networksvox
CSYS/MATH 303, Spring, 2019

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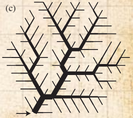
Dept. of Mathematics & Statistics | Vermont Complex Systems Center
Vermont Advanced Computing Core | University of Vermont



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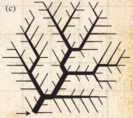

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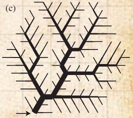

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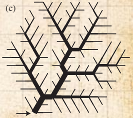
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private

References



Many sources, many sinks

How do we distribute sources?

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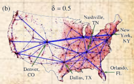
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private

References



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How do we distribute sources?

- Focus on 2-d (results generalize to higher dimensions).

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Size-density law
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A reasonable derivation
Global redistribution
Public versus Private

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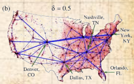

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Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private
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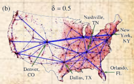

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- Key problem: How do we cope with uneven population densities?

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Size-density law
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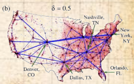
A reasonable derivation
Global redistribution
Public versus Private
References



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- Obvious: if density is uniform then sources are best distributed uniformly.

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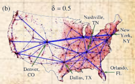
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private
References



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- Which lattice is optimal?

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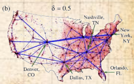
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private
References



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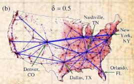
- Which lattice is optimal? The hexagonal lattice
- Q2: Given population density is uneven, what do we do?

Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private
References



Many sources, many sinks

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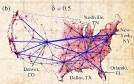
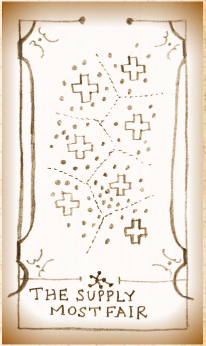
- Focus on 2-d (results generalize to higher dimensions).
- Sources = hospitals, post offices, pubs, ...
- Key problem: How do we cope with uneven population densities?
- Obvious: if density is uniform then sources are best distributed uniformly.
- Which lattice is optimal? The hexagonal lattice
- Q2: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

Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private

References




THE SUN
THE GOLDEN AGE OF REDUCTIONISM
THE MANIFESTO
WELL OF SCALES
THE LAWS OF DECAYING POWER
THE UNEXPECTED TRANSFIGURATION
MINISTRY OF RANDOM WALKS
THE RICH GET RICHER
THE DREAM OF EFFICIENT LANGUAGE
THE LAW OF DIGITS FIRST
THE SURPRISE OF BEING ROBUST YET FRAGILE
THE MISREADING OF THE BOOK OF SAND
THE MANY TALES OF MANY TAILS
THE MEASURING
THE DATA POOR
THE POURING DATA
THE CHARMS OF THE MANY WRONG PATHS
THE KNOWLEDGE OF DEAD MONKS
THE KNOWLEDGE OF DEAD MONKS
THE EMERGENCE OF STRUCTURE
THE EMERGENCE OF DESTRUCTION
THE EMERGENCE OF THINKING
THE EMERGENCE OF STORIES
THE MECHANICS STATISTICAL
THE THRESHOLDS OF PERCOLATION
THE NETWORKS COMPLEX
THE ELEMENTS OF WEBS
THE BIRDS OF A FEATHER
THE BIRDS OF NOT A FEATHER
THE ARC OF THE RANDOM NETWORK
THE STRANGENESS OF FRIENDS
THE SMALLNESS OF WORLDS
THE THEORY OF SIX DEGREES
THE NETWORKS FREE OF SCALE
THE CONTAGION
THE CONFUSION OF CONTAGIONS
THE DISEASE OF RANDOM MIXING
THE UNENDING PANDEMICS
THE THRESHOLDS OF THE MIND
THE SOCIAL WILD
THE SOCIAL CONTAGION
THE RATIO OF GAIN
THE MECHANICS OF FAME
THE TALK OF FAME
THE STORIES CONTAGIOUS
THE JOHN DORY
THE ADJACENT NARRATIVES
THE STORYTELLERS
THE PATHS OF UNIVERSALITY
THE DEPENDENT PATHS
THE TROUSERS OF BIFURCATING REALITIES
THE UNKNOWN MECHANISM
THE LANDSCAPES OF FORKING PATHS
THE NETWORKS OF BLOOD
THE TREES OF REALITY
THE ORDERS OF STREAMS
THE LAWS OF BRANCHING
THE SCALING OF BROKEN HIERARCHIES
THE BRAID OR THE BRANCH
THE LAW OF OPTIMAL FORKS
THE CHURCH OF QUARTEROLOGY
THE TRUTHICIDE
THE FAMILY OF PANCAKE COWS
THE FAMILY OF SPHERICAL COWS
THE IMPROBABLE PACHYDERM
THE ILL-SCALING OF ALLOMETRIC BODIES
THE SUPPLY TO THE MOST
THE DARK ART OF GENERATING FUNCTIONS
THE RANDOM SUM OF RANDOMNESS
THE TWO-SIDED WORLDS
THE STORIES AND THE TROPES
THE TRUTH OF DIFFUSION
THE UNVEILING OF HIDDEN POWERS
THE SCRYING FOR THE SHAPES OF THINGS
THE LIMITS OF ORGANIZATIONS
THE OVERCOMING OF CATASTROPHE
THE TROUBLES ILL-FORMED
THE NETWORKS OF MANY ILKS
THE CHAOS OF FETTERED CONTAGION
THE END

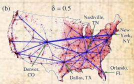

THE SUPPLY MOST FAIR

Optimal source allocation

Solidifying the basic problem

Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private

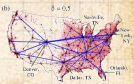
References



Optimal source allocation

Solidifying the basic problem

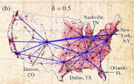
- Given a region with some population distribution ρ, most likely uneven.



Optimal source allocation

Solidifying the basic problem

- Given a region with some population distribution ρ, most likely uneven.
- Given resources to build and maintain N facilities.

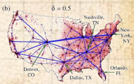


Optimal source allocation

Distributed Sources
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?

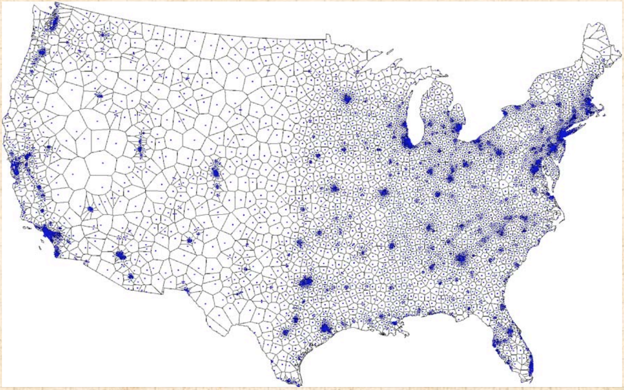


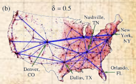
“Optimal design of spatial distribution networks”

Gastner and Newman,
Phys. Rev. E, **74**, 016117, 2006. [?]

Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private

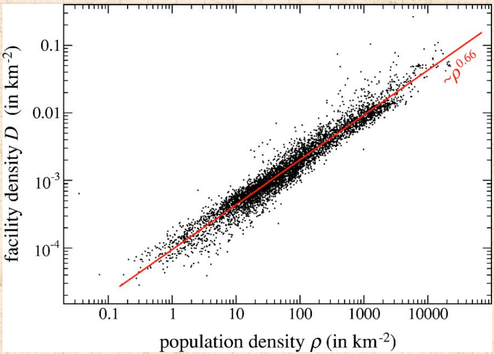
References



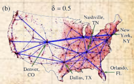


- Approximately optimal location of 5000 facilities.
- Based on 2000 Census data.

Optimal source allocation



- Optimal facility density ρ_{fac} vs. population density ρ_{pop}.



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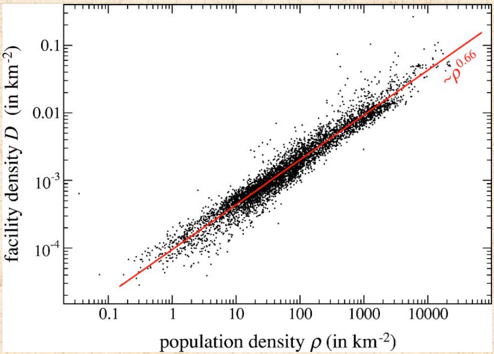

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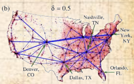
- Fit is $\rho_{\text{fac}} \propto \rho_{\text{pop}}^{0.66}$ with $r^2 = 0.94$.



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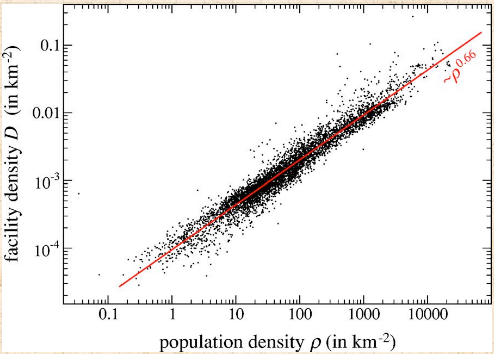
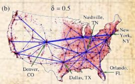


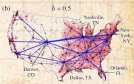
- Optimal facility density ρ_{fac} vs. population density ρ_{pop}.
- Fit is $\rho_{\text{fac}} \propto \rho_{\text{pop}}^{0.66}$ with $r^2 = 0.94$.
- Looking good for a 2/3 power ...



Outline

Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private

References



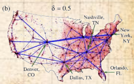
Optimal source allocation

Size-density law:

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

Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private

References



Optimal source allocation

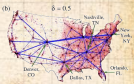
Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private

References

Size-density law:

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

- Why?



Optimal source allocation

Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private
References

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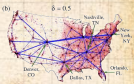
- Again: Different story to branching networks where there was either one source or one sink.



Optimal source allocation

Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private
References

Size-density law:

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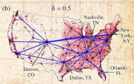
- Again: Different story to branching networks where there was either one source or one sink.
- Now sources & sinks are distributed throughout region.



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Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private

References

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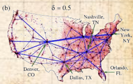

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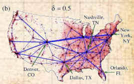

Optimal source allocation

Distributed
Sources

Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private

References

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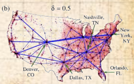

Optimal source allocation

Distributed
Sources

Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private

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- "Territorial Division: The Least-Time Constraint Behind the Formation of Subnational Boundaries" (Science, 1977)
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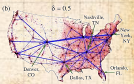
- Also known as the Homer Simpson principle.

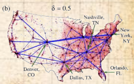


Optimal source allocation

- Consider a region of area A and population P with a single functional center that everyone needs to access every day.

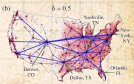
Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private

References



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.



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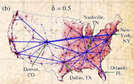
Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private
References



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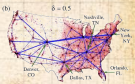

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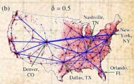
- Write average travel distance to center as $\bar{d}$ and assume average speed of travel is $\bar{v}$.
- Assume isometry: average travel distance $\bar{d}$ will be on the length scale of the region which is $\sim A^{1/2}$
- Average time expended per person in accessing facility is therefore

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

where c is an unimportant shape factor.

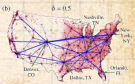


Optimal source allocation

- Next assume facility requires regular maintenance (person-hours per day).

Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private

References



Optimal source allocation

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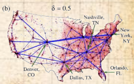
- Call this quantity τ.

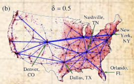
Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private
References



Optimal source allocation

- Next assume facility requires regular maintenance (person-hours per day).
- Call this quantity τ.
- If burden of mainenance is shared then average cost per person is τ/P where P = population.

Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private
References



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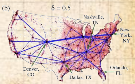
- Replace P by $\rho_{\text{pop}} A$ where ρ_{pop} is density.

Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private

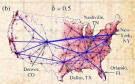
References



Optimal source allocation

- Next assume facility requires regular maintenance (person-hours per day).
- Call this quantity τ.
- If burden of mainenance 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.

Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private
References

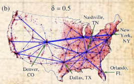


Optimal source allocation

- Next assume facility requires regular maintenance (person-hours per day).
- Call this quantity τ.
- If burden of mainenance 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:

$$T = \bar{d}/\bar{v} + \tau/(\rho_{\text{pop}}A)$$

Distributed
Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private
References



Optimal source allocation

Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private

References

- Next assume facility requires regular maintenance (person-hours per day).
- Call this quantity τ.
- If burden of mainenance is shared then average cost per person is τ/P where P = population.
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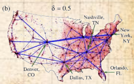
- Important assumption: uniform density.
- Total average time cost per person:

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



Optimal source allocation

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- Total average time cost per person:

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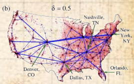
- Now Minimize with respect to A …

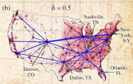


Optimal source allocation

- Differentiating ...

$$\frac{\partial T}{\partial A} = \frac{\partial}{\partial A}\left(cA^{1/2}/\bar{v} + \tau/(\rho_{\text{pop}}A)\right)$$

Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private
References

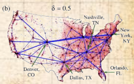


Optimal source allocation

- Differentiating ...

$$\frac{\partial T}{\partial A} = \frac{\partial}{\partial A}\left(cA^{1/2}/\bar{v} + \tau/(\rho_{\text{pop}}A)\right)$$

$$= \frac{c}{2\bar{v}A^{1/2}} - \frac{\tau}{\rho_{\text{pop}}A^2}$$



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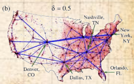
Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private

References



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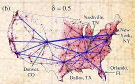
- Rearrange:

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



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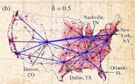
$$A = \left(\frac{2\bar{v}\tau}{c\rho_{\text{pop}}}\right)^{2/3} \propto \rho_{\text{pop}}^{-2/3}$$

Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private
References



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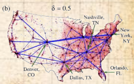
- # facilities per unit area ρ_{fac}:

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

Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private
References



Optimal source allocation

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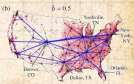
- Groovy ...

Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private
References



Optimal source allocation

Distributed
Sources

Size-density law

Cartograms

A reasonable derivation

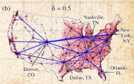
Global redistribution

Public versus Private

References

An issue:

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

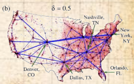


Optimal source allocation

An issue:

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

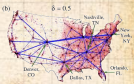
- Stephan's online book "The Division of Territory in Society" is here.
- (It used to be here.)
- The Readme is well worth reading (1995).



Outline

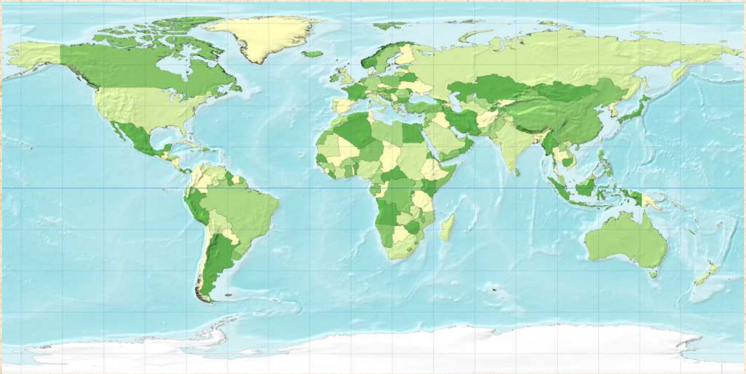
Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private

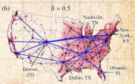
References



Cartograms

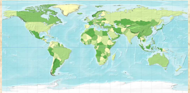
Standard world map:





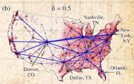
Cartograms

Cartogram of countries 'rescaled' by population:



Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private

References

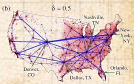


Cartograms

Diffusion-based cartograms:

Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private

References



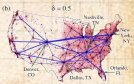
Cartograms

Diffusion-based cartograms:

- Idea of cartograms is to distort areas to more accurately represent some local density ρ_{pop} (e.g. population).

Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private

References



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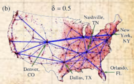
Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private

References



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- Algorithm due to Gastner and Newman (2004) [?] is based on standard diffusion:

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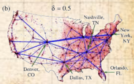
Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private
References



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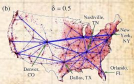
- Allow density to diffuse and trace the movement of individual elements and boundaries.

Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private
References



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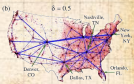
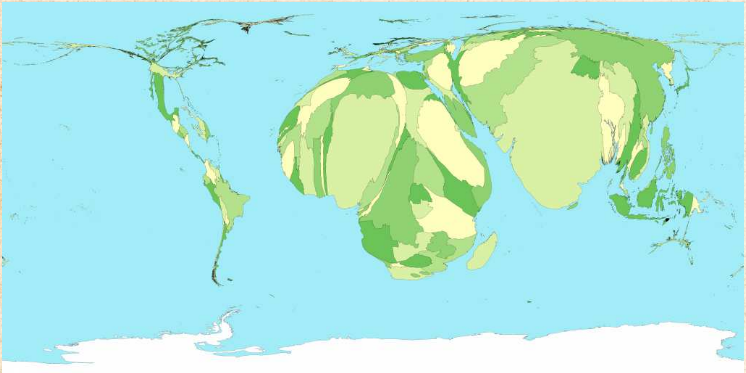
- Allow density to diffuse and trace the movement of individual elements and boundaries.
- Diffusion is constrained by boundary condition of surrounding area having density $\bar{\rho}_{\text{pop}}$.

Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private
References

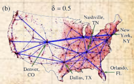


Cartograms

Child mortality:

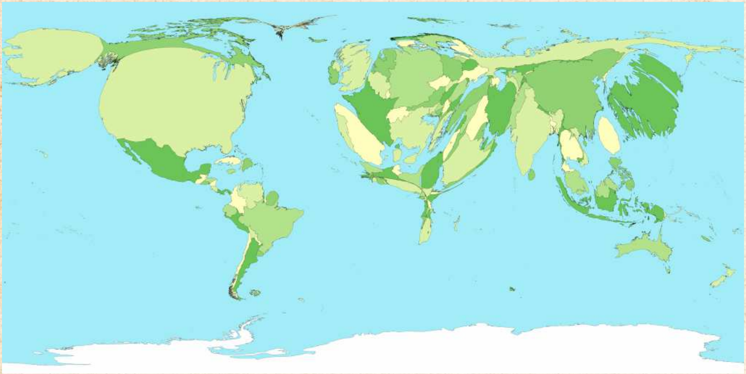


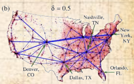
Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private
References



Cartograms

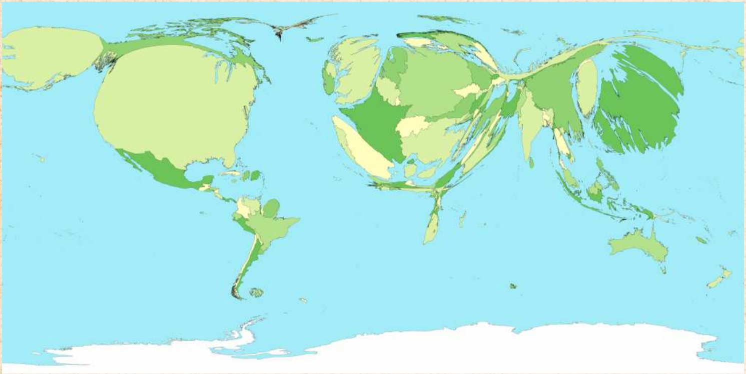
Energy consumption:

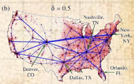




Cartograms

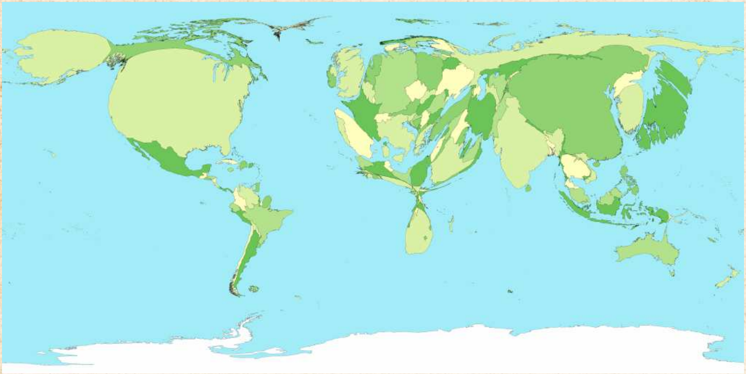
Gross domestic product:



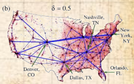


Cartograms

Greenhouse gas emissions:

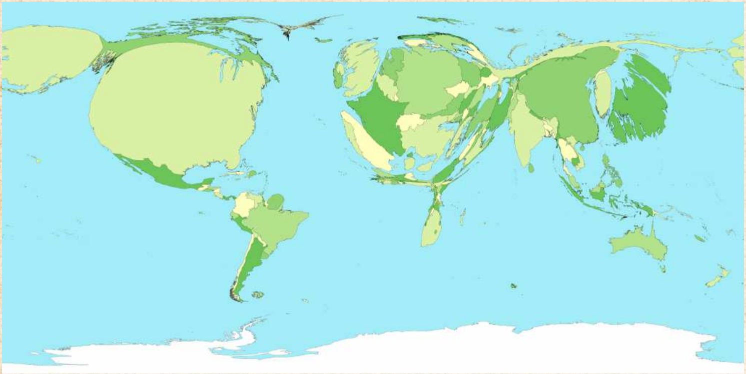


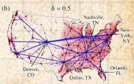
Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private
References



Cartograms

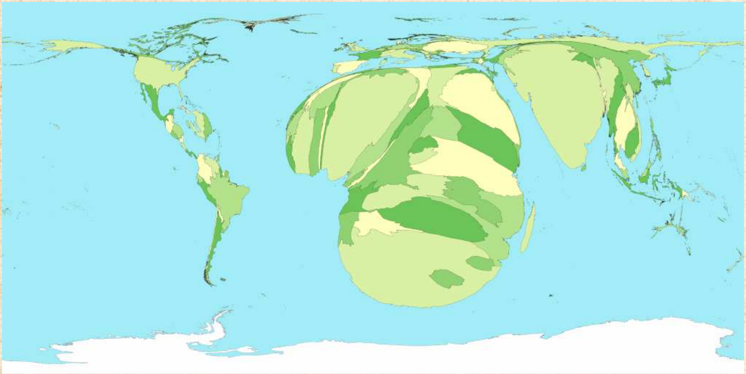
Spending on healthcare:



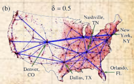


Cartograms

People living with HIV:



Distributed
Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private
References



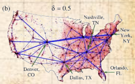
Cartograms

Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private

References

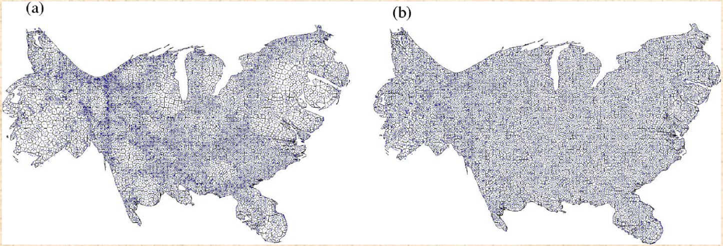
- The preceding sampling of Gastner & Newman's cartograms lives here.
- A larger collection can be found at worldmapper.org.

WORLDMAPPER The world as you've never seen it before



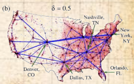
Size-density law

"Optimal design of spatial distribution networks"
Gastner and Newman,
Phys. Rev. E, **74**, 016117, 2006. [?]



Left: population density-equalized cartogram.

Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private
References



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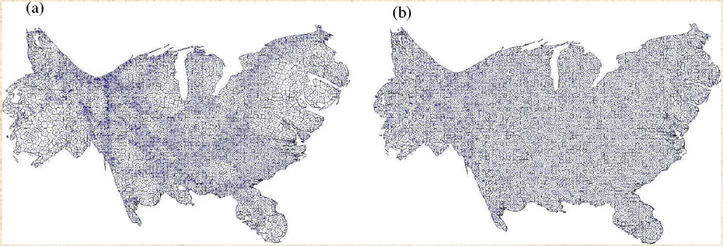
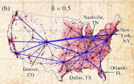


- Left: population density-equalized cartogram.
- Right: (population density)$^{2/3}$-equalized cartogram.

Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private

References



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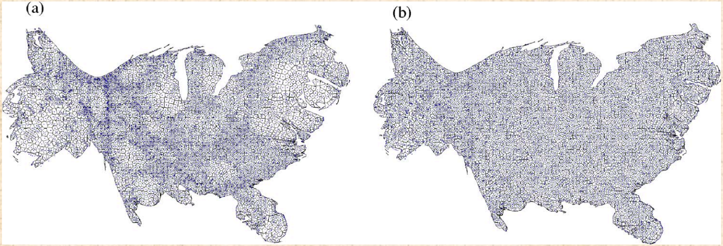
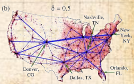


- Left: population density-equalized cartogram.
- Right: (population density)$^{2/3}$-equalized cartogram.
- Facility density is uniform for $\rho_{\text{pop}}^{2/3}$ cartogram.

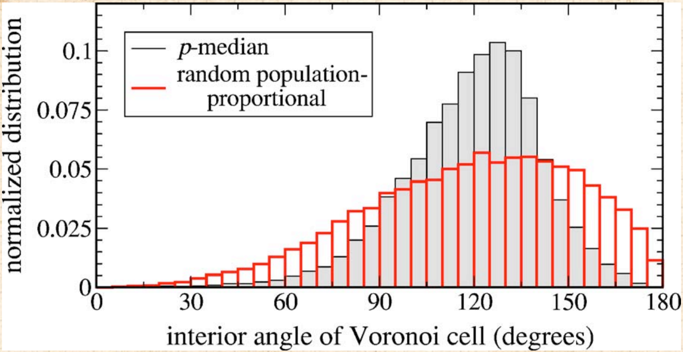
Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private

References



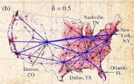
Size-density law

Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private
References



From Gastner and Newman (2006) [?]

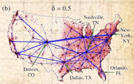
- Cartogram's Voronoi cells are somewhat hexagonal.



Outline

Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private

References

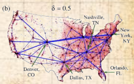


Size-density law

Deriving the optimal source distribution:

Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private

References



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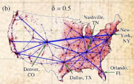
- Basic idea: Minimize the average distance from a random individual to the nearest facility. [?]

Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private
References



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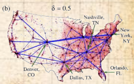
Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private

References



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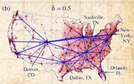
Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private
References



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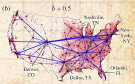
- Also known as the p-median problem.

Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private
References



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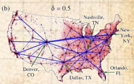
Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private
References



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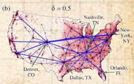
- Approximate solution originally due to Gusein-Zade [?].

Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private
References



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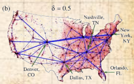
Approximations:

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



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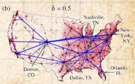
Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private
References



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

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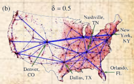
where c_i is a shape factor for the ith Voronoi cell.

Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private
References



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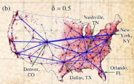
- Approximate c_i as a constant c.

Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private
References



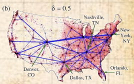
Size-density law

Carrying on:

- The cost function is now

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

Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private
References



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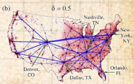
Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private
References



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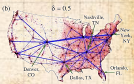
- Sneakily turn this into an integral constraint:

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

Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private
References



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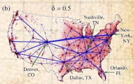
Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private
References



Size-density law

Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private

References

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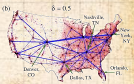
- Within each cell, $A(\vec{x})$ is constant.
- So ...integral over each of the n cells equals 1.

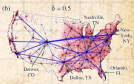


Now a Lagrange multiplier story:

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

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

Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private
References



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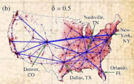
Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private
References



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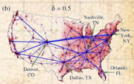
Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private

References



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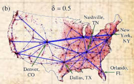

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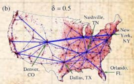
Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private
References



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Now a Lagrange multiplier story:

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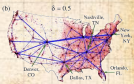
Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private

References



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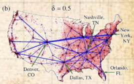
Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private
References



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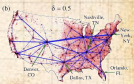
Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private
References



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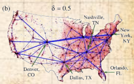
- Normalizing (or solving for λ):

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

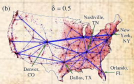
Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private
References



Outline

Distributed Sources
- Size-density law
- Cartograms
- A reasonable derivation
- Global redistribution
- Public versus Private

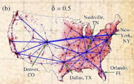
References



Global redistribution networks

One more thing:

- How do we supply these facilities?



Global redistribution networks

Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private
References

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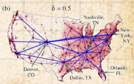

Global redistribution networks

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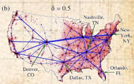
Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private

References



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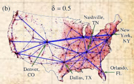
Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private
References



Global redistribution networks

Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private

References

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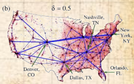
$$C_{\text{maint}} + \gamma C_{\text{travel}}.$$

- 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:

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



Global redistribution networks

Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private
References

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:

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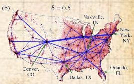
- When $\delta = 1$, only number of hops matters.



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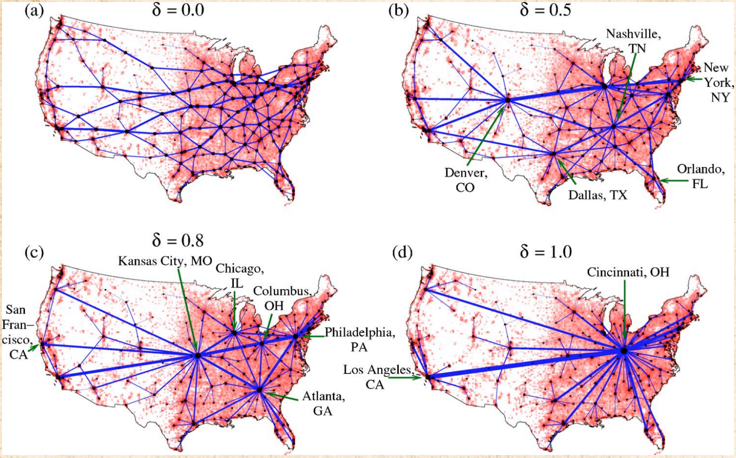
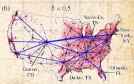
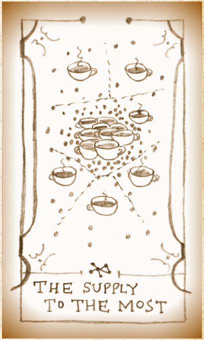
Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private
References



From Gastner and Newman (2006) [?]

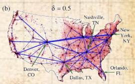



THE SUPPLY
TO THE MOST

Outline

Distributed Sources
- Size-density law
- Cartograms
- A reasonable derivation
- Global redistribution
- Public versus Private

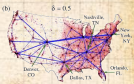
References



Public versus private facilities

Beyond minimizing distances:

Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private
References



Public versus private facilities

Distributed
Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private

References

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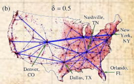


Public versus private facilities

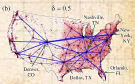
Beyond minimizing distances:

- "Scaling laws between population and facility densities" by Um *et al.*, Proc. Natl. Acad. Sci., 2009. [?]
- 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 $\alpha = 2/3$.

Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private
References



Public versus private facilities

Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private

References

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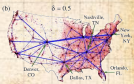
- Two idealized limiting classes:
  1. For-profit, commercial facilities: $\alpha = 1$;



Public versus private facilities

Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private
References

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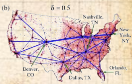
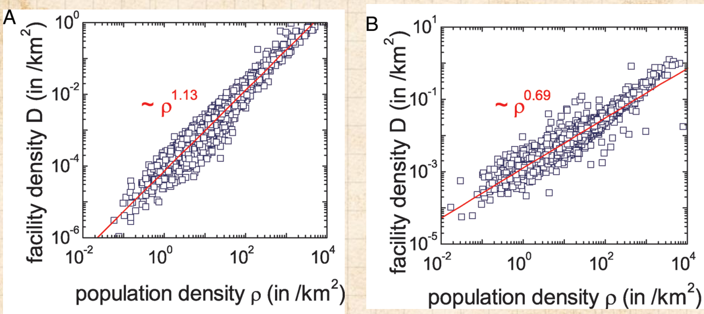
$$\rho_{\text{fac}} \propto \rho_{\text{pop}}^{\alpha}$$

  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.



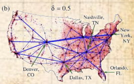
Public versus private facilities: evidence



- Left plot: ambulatory hospitals in the U.S.
- Right plot: public schools in the U.S.

Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private

References



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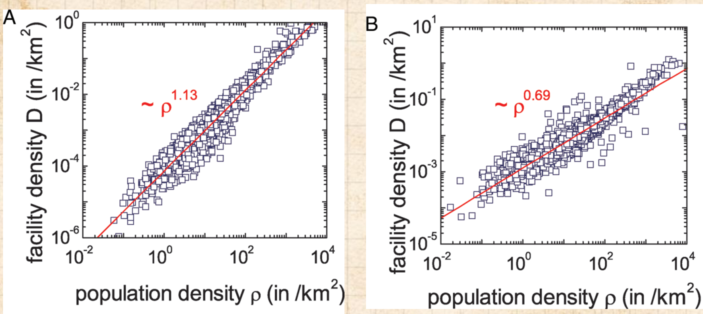
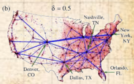
Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private

References



- 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

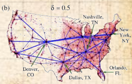
US facility	α (SE)	R^2
Ambulatory hospital	1.13(1)	0.93
Beauty care	1.08(1)	0.86
Laundry	1.05(1)	0.90
Automotive repair	0.99(1)	0.92
Private school	0.95(1)	0.82
Restaurant	0.93(1)	0.89
Accommodation	0.89(1)	0.70
Bank	0.88(1)	0.89
Gas station	0.86(1)	0.94
Death care	0.79(1)	0.80
* Fire station	0.78(3)	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 $\alpha \simeq 0.8$.

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

Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private
References



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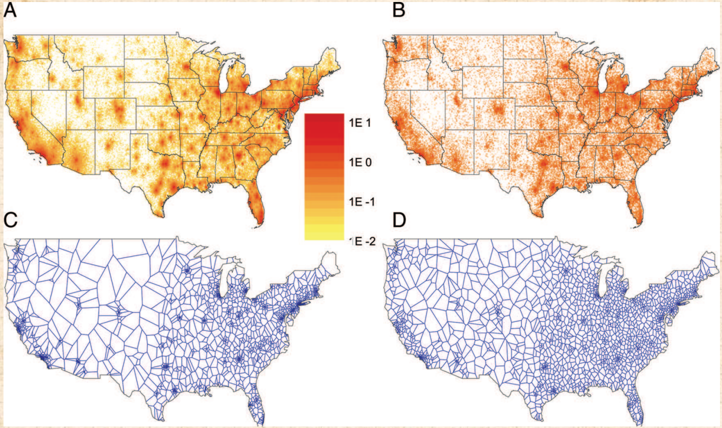
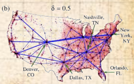


A, C: ambulatory hospitals in the U.S.; B, D: public schools in the U.S.; A, B: data; C, D: Voronoi diagram from model simulation.

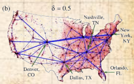


Public versus private facilities: the story

So what's going on?

- Social institutions seek to minimize distance of travel.

Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private
References



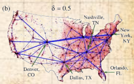
Public versus private facilities: the story

So what's going on?

- Social institutions seek to minimize distance of travel.
- Commercial institutions seek to maximize the number of visitors.

Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private

References



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- Social institutions seek to minimize distance of travel.
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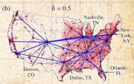
- Defns: For the ith facility and its Voronoi cell V_i, define
  - n_i = population of the ith cell;
  - $\langle r_i \rangle$ = the average travel distance to the ith facility.
  - A_i = area of ith cell (s_i in Um *et al.* [?])

Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private
References



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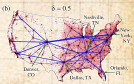
- Objective function to maximize for a facility (highly constructed):

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

Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private
References



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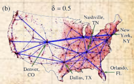
- Objective function to maximize for a facility (highly constructed):

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

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

Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private
References

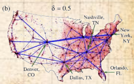


Public versus private facilities: the story

- 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:

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

Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private
References



Public versus private facilities: the story

Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private
References

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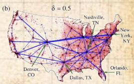
- For $\beta = 0$, $\alpha = 1$: commercial scaling is linear.



Public versus private facilities: the story

Distributed
Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private
References

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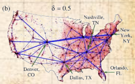
- For $\beta = 0$, $\alpha = 1$: commercial scaling is linear.
- For $\beta = 1$, $\alpha = 2/3$: social scaling is sublinear.



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Distributed Sources
Size-density law
Cartograms
A reasonable derivation
Global redistribution
Public versus Private
References

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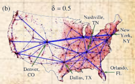
- For $\beta = 0$, $\alpha = 1$: commercial scaling is linear.
- For $\beta = 1$, $\alpha = 2/3$: social scaling is sublinear.
- You can try this too:
  Insert question from assignment 4



References I