Urbanization and Economies of Scale: Topics in Network Theory

Nicholas J. Linesch

Institute of Transportation Studies
University of California, Davis

May 12, 2009
Outline of Part I

1. Context for transportation networks
   - Motivation
   - Terms and Definitions
Outline of Part II

2 Urban Systems
   - The Modern City
   - Using software to simulate urbanization
Part I

Context Setting
Flow

- Goods
- People
- Information

Children in Jakarta

Thanks to Shaxun
Flow
Growth

Baltimore simulated forest land cover showing 200 years of urban growth in yellow.
biology.usgs.gov
Sustainability

- How do these modes interact?
- What other systems are impacted by movement and flow?
- How are land use and transportation plans sensitive to one another?
Defining a network

A set of nodes or vertices joined together in pairs by lines or edges
Spatial Distribution Network Design Problem

Given a set of things that ‘want’ to move between a set of spatial points $V$, what’s the cheapest way to get them there?

Gastner & Newman (2006) wants us to think about two specific parts of this question as applied to transportation networks:

- How do we determine the points $V$ anyway?
- What do we mean by ‘cheapest’? Does how we measure cost change the optimal structure?

(Wuellner on spacial distribution networks, 2009)
Network Properties

Cost

- Cost $= \sum_{edges(i,j)} d_{ij}$ where $d_{ij}$ is the Euclidean distance between nodes $i$ and $j$.
- Cost can be measured in travel time and can be influenced by traffic.
- Let $w_{ij}$ be the amount of traffic between $i$ and $j$.
- Total Travel Cost can be calculated as $Z = \sum_{i<j} w_{ij} d_{ij}$
### Network Properties

#### Distance
- Euclidean distance
- Legs of air travel
- Hops an Internet packet will make

#### Diameter
Largest graph distance between two points
Network Properties

**Vertex Degrees**

The degree of a vertex is the number of edges connected to it.

→ A distinguishing characteristic of a network
Interstate System

[Map of the Interstate System via Wikimedia Commons]

Nicholas J. Linesch

Urbanization and Economies of Scale: Topics in Network Theory
Interstate Rail System
Air Network

Gaster Slides from MAE 298, 2008
Information network: Internet

Gaster Slides from MAE 298, 2008

GOTO: http://www.akamai.com Content Delivery Networks
Counting Network Edges

Histograms of the lengths of edges in three networks (Gastner & Newman, 2006) Small worlds formed in airlines.
Zipf’s Law: 1949

**Figure:** Log Size versus Log Rank of the 135 largest U. S. Metropolitan Areas in 1991 Source: Statistical Abstract of the United States [1993]
Part II

Urban Systems Analysis
2 Urban Systems

- The Modern City
- Using software to simulate urbanization
Organisms as metabolic engines

Characterized by energy consumption rates, growth rates, body size, and behavioral times

Cities as organisms
Scaling and Biological Metaphors

- A metabolic engine is a consumer of resources
- Consider biological scaling
- Almost all physiological elements scale with body mass $= M$
Scaling and Biological Metaphors: Generalized Case

- Consider $M$ as a body mass.
- $M$ has a metabolic rate, $B$.
- $B$ is the energy required to sustain the organism.
- $B \propto M^{3/4}$, typically the exponent is a multiple of $1/4$ (or $1/(1+d)$ in d-dimensional space.

$y = x^{3/4}$

- The metabolic rate per unit mass: $\frac{B}{M} \propto M^{-1/4}$.
Scaling and Biological Metaphors: Examples

- $M^{1-\beta} \approx M^{1/4}$ can be used to scale physiological times (life spans, turnover time, etc.)
- $M^{1-\beta} \approx M^{-1/4}$ can be used to scale associated rates (heart rate, population growth)
Scaling and Biological Metaphors: Examples

- $M^{1-\beta} \approx M^{1/4}$ can be used to scale physiological times (life spans, turnover time, etc.)
- $M^{1-\beta} \approx M^{-1/4}$ can be used to scale associated rates (heart rate, population growth)
Scaling and Biological Metaphors: Generalizable Items

- Rates
- Times
- Internal structures
Bettencourt et. al (2007) go on further to describe urban growth and decay with a power law function

\[ Y(t) = Y_0 N(t)^\beta \]  

(1)

Where \( N \) is the population,
\( Y \) is material resources (such as energy or infrastructure),
\( Y_0 \) is a normalization constant
Data collected to understand scaling of the urban metabolism
Data is grouped by metropolitan statistical areas (MSAs), and larger urban zones (LUZs)
The data set is applied to the scaling equation described in the previous slide
Scaling and Biological Metaphors

a) Total wages per MSA vs. metropolitan population
b) Supercreative employment per MSA vs. metropolitan population
Scaling and Biological Metaphors

a) Scaling of walking speed vs. population for cities around the world.
b) Heart rate vs. the size (mass) of organisms
Scaling exponents for urban indicators vs. city size

<table>
<thead>
<tr>
<th>Indicator</th>
<th>$\beta$</th>
<th>95% CI</th>
<th>Adj-$R^2$</th>
<th>Observations</th>
<th>Country-year</th>
</tr>
</thead>
<tbody>
<tr>
<td>New patents</td>
<td>1.27</td>
<td>[1.25,1.29]</td>
<td>0.72</td>
<td>331</td>
<td>U.S. 2001</td>
</tr>
<tr>
<td>Inventors</td>
<td>1.25</td>
<td>[1.22,1.27]</td>
<td>0.76</td>
<td>331</td>
<td>U.S. 2001</td>
</tr>
<tr>
<td>Private R&amp;D employment</td>
<td>1.34</td>
<td>[1.29,1.39]</td>
<td>0.92</td>
<td>266</td>
<td>U.S. 2002</td>
</tr>
<tr>
<td>“Supercreative” employment</td>
<td>1.15</td>
<td>[1.11,1.18]</td>
<td>0.89</td>
<td>287</td>
<td>U.S. 2003</td>
</tr>
<tr>
<td>R&amp;D establishments</td>
<td>1.19</td>
<td>[1.14,1.22]</td>
<td>0.77</td>
<td>287</td>
<td>U.S. 1997</td>
</tr>
<tr>
<td>R&amp;D employment</td>
<td>1.26</td>
<td>[1.18,1.43]</td>
<td>0.93</td>
<td>295</td>
<td>China 2002</td>
</tr>
<tr>
<td>Total wages</td>
<td>1.12</td>
<td>[1.09,1.13]</td>
<td>0.96</td>
<td>361</td>
<td>U.S. 2002</td>
</tr>
<tr>
<td>Total bank deposits</td>
<td>1.08</td>
<td>[1.03,1.11]</td>
<td>0.91</td>
<td>267</td>
<td>U.S. 1996</td>
</tr>
<tr>
<td>GDP</td>
<td>1.15</td>
<td>[1.06,1.23]</td>
<td>0.96</td>
<td>295</td>
<td>China 2002</td>
</tr>
<tr>
<td>GDP</td>
<td>1.26</td>
<td>[1.09,1.46]</td>
<td>0.64</td>
<td>196</td>
<td>EU 1999–2003</td>
</tr>
<tr>
<td>GDP</td>
<td>1.13</td>
<td>[1.03,1.23]</td>
<td>0.94</td>
<td>37</td>
<td>Germany 2003</td>
</tr>
<tr>
<td>Total electrical consumption</td>
<td>1.07</td>
<td>[1.03,1.11]</td>
<td>0.88</td>
<td>392</td>
<td>Germany 2002</td>
</tr>
<tr>
<td>New AIDS cases</td>
<td>1.23</td>
<td>[1.18,1.29]</td>
<td>0.76</td>
<td>93</td>
<td>U.S. 2002–2003</td>
</tr>
<tr>
<td>Serious crimes</td>
<td>1.16</td>
<td>[1.11,1.18]</td>
<td>0.89</td>
<td>287</td>
<td>U.S. 2003</td>
</tr>
<tr>
<td>Total housing</td>
<td>1.00</td>
<td>[0.99,1.01]</td>
<td>0.99</td>
<td>316</td>
<td>U.S. 1990</td>
</tr>
<tr>
<td>Total employment</td>
<td>1.01</td>
<td>[0.99,1.02]</td>
<td>0.98</td>
<td>331</td>
<td>U.S. 2001</td>
</tr>
<tr>
<td>Household electrical consumption</td>
<td>1.00</td>
<td>[0.94,1.06]</td>
<td>0.88</td>
<td>377</td>
<td>Germany 2002</td>
</tr>
<tr>
<td>Household electrical consumption</td>
<td>1.05</td>
<td>[0.89,1.22]</td>
<td>0.91</td>
<td>295</td>
<td>China 2002</td>
</tr>
<tr>
<td>Household water consumption</td>
<td>1.01</td>
<td>[0.89,1.11]</td>
<td>0.96</td>
<td>295</td>
<td>China 2002</td>
</tr>
<tr>
<td>Gasoline stations</td>
<td>0.77</td>
<td>[0.74,0.81]</td>
<td>0.93</td>
<td>318</td>
<td>U.S. 2001</td>
</tr>
<tr>
<td>Gasoline sales</td>
<td>0.79</td>
<td>[0.73,0.80]</td>
<td>0.94</td>
<td>318</td>
<td>U.S. 2001</td>
</tr>
<tr>
<td>Length of electrical cables</td>
<td>0.87</td>
<td>[0.82,0.92]</td>
<td>0.75</td>
<td>380</td>
<td>Germany 2002</td>
</tr>
<tr>
<td>Road surface</td>
<td>0.83</td>
<td>[0.74,0.92]</td>
<td>0.87</td>
<td>29</td>
<td>Germany 2002</td>
</tr>
</tbody>
</table>

Data sources are shown in SI Text. CI, confidence interval; Adj-$R^2$, adjusted $R^2$; GDP, gross domestic product.
Introduction to Land Use Modeling Software

- Software package
- Built by team at University of Washington
- Open source software used for simulating growth of metropolitan regions
- Series of discrete choice models is run to determine the final land use outputs
UrbanSim: Land Use Modeling Package

UrbanSim Model Components and Data Flow
Key Features of the System

- Simulates key decision makers and choices that impact urban development
- Accounts for land, structures, and occupants
- Urban development simulated as dynamic process over time and space
- Incorporates governmental policy assumptions
- Returns disaggregate information by parcel
- Simulates development and redevelopment
Key Features of Implementation

- Linux, Mac OS, and Windows compatible
- Code predominantly implemented in Python
- Open source and downloadable
- User interface focuses on model configuration, data management, and scenario evaluation
- Object-oriented programming
- Results are GIS compatible
- Binary files used for reading and writing, can be converted to shapefile, database, etc.
Discrete Choice Equations

Utility Function

\[ U_i = V_i + \epsilon_i \]

\( V_i = \beta x_i \) is a linear-in-parameters function and \( \beta \) is a vector of \( k \) estimator coefficients.

Probability Function

\[ P_i = \frac{e^{V_i}}{\sum_j e^{V_j}} \]

\( j \) is an index over all possible alternatives.
Sub-model routines

- Real estate price model
- Building transition model
- Household transition model creates and removes households and updates the set of persons accordingly. It is based on random sampling and is driven by macroeconomic predictions.
- Business transition model
- Household relocation choice model determines households for moving, using a logit model.
- Household location choice model
- Business relocation model
- Business location choice model
Business Growth in San Francisco

Business Loc Model
Growth by 2010
Business Growth in San Francisco

Business Loc Model
Growth by 2020
Business Growth in San Francisco

Business Loc Model
Growth by 2030
A Quick Video Presentation of UrbanSim

Goto: http://www.youtube.com/watch?v=nmBnRAde5Xw
Population Growth in San Francisco

Figure: Year 2001
Population Growth in San Francisco

Figure: Year 2010
Population Growth in San Francisco

Figure: Year 2020
Population Growth in San Francisco

Figure: Year 2030
Employment Growth in San Francisco

Figure: Year 2001
Employment Growth in San Francisco

Figure: Year 2010
Employment Growth in San Francisco

Figure: Year 2020
Employment Growth in San Francisco

Figure: Year 2030

Nicholas J. Linesch

Urbanization and Economies of Scale: Topics in Network Theory
Jobs by Sector in San Francisco

Year 2001

- Ag_Nat_Res
- Manuf Transportation, Wholesale
- Retail
- Finance, Professional Services
- Health Education and Recreational Services
- Other
Jobs by Sector in San Francisco

Year 2010

- Ag_Nat_Res
- Manuf. Transportation, Wholesale
- Retail
- Finance, Professional Services
- Health, Education and Recreational Services
- Other

Urbanization and Economies of Scale: Topics in Network Theory
Jobs by Sector in San Francisco

Year 2020

- Ag_Nat_Res
- Manuf Transportation, Wholesale
- Retail
- Finance, Professional Services
- Health, Education and Recreational Services
- Other
Jobs by Sector in San Francisco

Year 2030
Activity Based Modeling Scenario: Auto Networks
Activity Based Modeling Scenario: Transit Networks
What to do with land use forecasts?

Urbanization and Economies of Scale: Topics in Network Theory
What to do with land use forecasts?

Nicholas J. Linesch
Next Steps

- Land use model validation
- Solidify key links between network theory and urban modeling
- Further quantify the urban metabolism for long term planning
- Generalize for generic metropolitan implementation