Topic 3
Urban general equilibrium & endogenous land use

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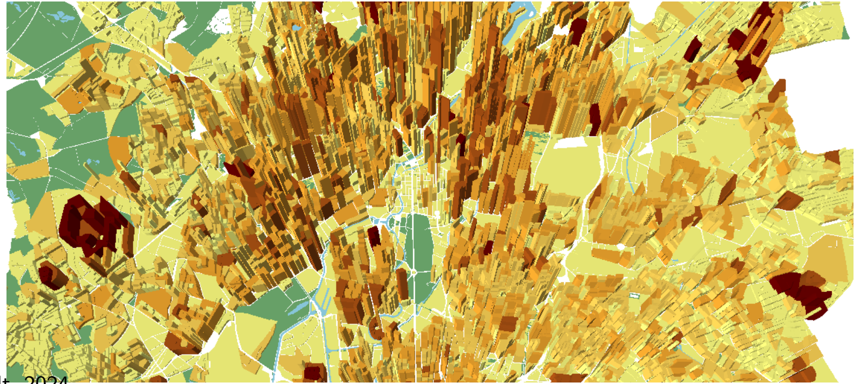
Introduction

Population density in central Berlin



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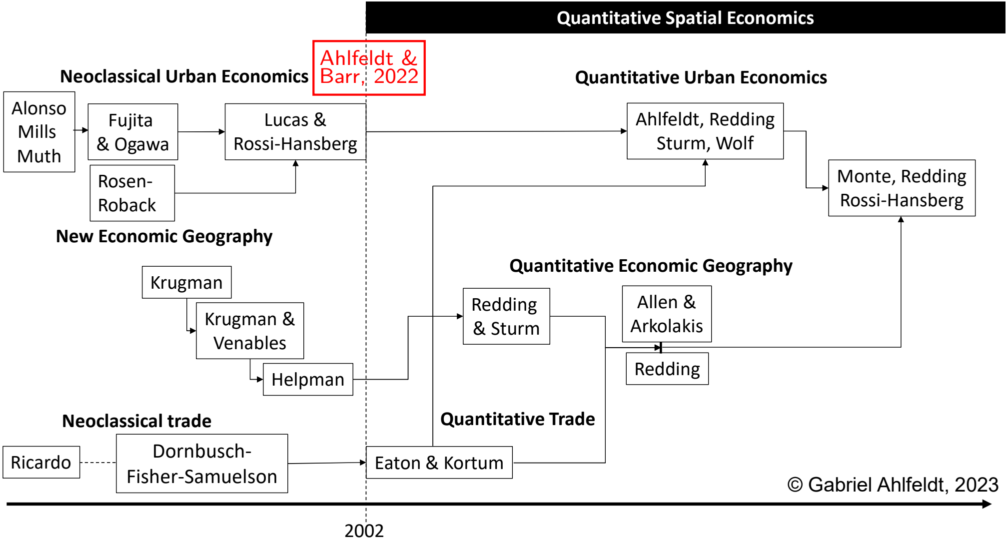
What is going on in the CBD(s)?

Roadmap

- Standard **MCM does not model labor market**
  - CBD does not take up space ⇒ inconsistent with reality
  - Wages do not adjust to clear the labour market ⇒ unlike in Rosen-Roback
- Urban **land use models** model allocate land to commercial and residential use
  - See Duranton & Puga (2015) for a review
- We discuss the **Ahlfeldt & Barr (2022)** model, which expands on MCM
  - Labour and land markets clear in general equilibrium
  - Productivity increases city population (agglomeration economies)
  - CBD endogenous
  - Vertical costs of and returns to height
  - **Can be taken to data and used for quantitative counterfactuals**

History of thought



Motivation

Motivation

- Recall the structure of a **quantitative model**
  - Consists of **exogenous objects** and **endogenous objects** (like any model)
  - Consists of **parameters** and **fundamentals**, inverted to **rationalize observed data**
  - Allows for **quantitative counterfactuals** to evaluate real-world shocks and policies
- **Ahlfeldt & Barr (2022) model bridges worlds**
  - **Intuitive** stylized vs. **tractable** quantitative models
  - Amenable to 'textbook' world' with **smooth gradients** & fully quantifiable
- **This week**
  - Cover building blocks and **intuition** with a **stylized city structure**
- Next week
  - **Quantification** and **computational implementation**

Ahlfeldt & Barr (2022)

- Use their model to guide a synthesis on the economics of tall buildings
  - Model is more broadly applicable
  - An **accessible & tractable standard urban model** with 'canonical' elements
- Simple **open-city GE model of *vertical* and *horizontal structure***
  - Incorporates vertical costs and benefit in horizontal land use model
  - Endogenous land use and prices and quantities on labour and land markets
- Use the model to conduct various counterfactuals
  - Changes in commuting cost, changes in housing productivity, labour productivity, height limit, agglomeration economies, agricultural rents, urban growth boundaries, etc.

Height decisions are (mostly) rational

- Skyscrapers emerge when there are innovations in construction technology
  - Elevator and steel frame
  - Mainframe computing and buttressed core Record buildings
- Skyscrapers emerge where there is high demand Determinants Diffusion Count
  - Population, GDP per capita, GDP growth are determinants of vertical growth
  - Shift in gravity of vertical growth from North America to Asia
- Not much evidence for 'too tall' buildings #1, #2, #3 tallest ESB
  - #2 (#3) building (very) good predictor for #1 (#2) building height
  - ESB—led hight rankings longer than any other building—was profitable

Consistent with profit-maximization driving height decisions

Building blocks

Geography

- **Linear city**, similar to the MCM
  - Historic center located at $x = 0$, plus locations at $x < 0$ and $x > 0$
- City is embedded in a wider economy
  - Agricultural hinterland with **exogenous agricultural land rent** is r^A
  - Other cities and **spatial equilibrium** $\Rightarrow$ exogenous reservation utility $\bar{U}$
- Can write the model **as if space was continuous** $\Rightarrow$ so variables are $f(x)$
  - Assume $x = 0$ is the marketplace of ideas and spillovers decay in space
    - Production amenity falls in $|x| \Rightarrow$ **Downward-sloping commercial gradients**
  - Assume workers travel to $x = 0$ to shop and stop along the way for work
    - Residential amenity falls in $|x| \Rightarrow$ **Downward-sloping residential gradients**
- In practice, the model is solved numerically and locations are discrete
  - can index variables by i instead of expressing them as $f(x) \Rightarrow$ **like a QSM**

Workers

- Earn city specific wage y and use it to consume tradable goods g and floor space f

$$U(x,s) = A^R(x,s)\left(\frac{g}{\alpha^R}\right)^{\alpha^R}\left(\frac{f^R(x,s)}{1-\alpha^R}\right)^{1-\alpha^R},$$

- Cobb-Douglas utility function
  - Amenity depends on horizontal (x) and vertical location (floor) (s)
- A can be set arbitrarily, we choose

$$A^R(x,s) = \tilde{A}^R(x)s^{\omega^s}, \text{ where } \tilde{A}^R(x) = \bar{a}^R e^{-\tau^R|x|}, \quad \tilde{\omega} > 0$$

  - For now, we let $\tilde{A}^R$ fall in distance x at rate τ^R to generate standard urban form
  - F.O.C. and zero profits $\Rightarrow$ bid-rents fall in distance X

Which objects are endogenous, which objects are exogenous?

Firms

- Use labour l and floor space f to produce tradable good, g

$$g(x,s) = A^C(x,s)\left(\frac{l}{\alpha^C}\right)^{\alpha^C}\left(\frac{f^C(x,s)}{1-\alpha^C}\right)^{1-\alpha^C}$$

- Cobb-Douglas production function
  - Agglomeration benefits increase in total city employment N More on agglomeration
  - Amenity also depends on horizontal (x) and vertical (s) location
- A can be set arbitrarily, we choose $A^C(x,s) = \tilde{A}^C(x)s^{\omega^C}$, where $\tilde{A}^C(x) = \bar{a}^C N^\beta e^{-\tau^C|x|}$
  - For now, we let $\tilde{A}^C$ fall in distance X at rate τ^C to generate standard urban form
  - F.O.C. and zero profits $\Rightarrow$ bid-rents fall in distance X

Which objects are endogenous, which objects are exogenous?

Bid rents

- Workers
  - Use **first-order conditions** to compute indirect utility function
  - **Spatial equilibrium** implies that indirect utility is constant (assume $\bar{U} = 1$)
  - Solve for rent and integrate over vertical space to get horizontal bid rent
- Firms
  - Use **first-order conditions** in profit function
  - **Spatial equilibrium** implies zero economic profits
  - Solve for rent and integrate over vertical space to get horizontal bid rent
- Functional forms ensure **bid-rent functions** conveniently indexed by $U \in \{C, R\}$

  $\bar{p}^U(x) = \frac{1}{S^U(x)} \int_0^{S^U} p^U(x,s)ds = \frac{a^U(x)}{1+\omega^U(x)} \left(S^U(x)\right)^{\omega^U}$, where

  - $a^C(x) = \left(\bar{a}^C N^\beta \exp(-\tau^C x)\right)^{\frac{1}{1-\alpha^C}} (y)^{\frac{\alpha^C}{\alpha^C-1}}$

    $a^R(x) = \left(\bar{a}^R \exp(-\tau^R x)\right)^{\frac{1}{1-\alpha^R}} (y)^{\frac{1}{1-\alpha^R}}$

Developers

- Lease out floor space of use U at rent p^U; face unit cost that increase in height S, and land rent r^U, resulting in profit function:
  - $\pi^U(x, S^U(x)) = p^U(x)S^U(x) - \tilde{c}^U(S^U(x))S^U(x) - r^U(x)$,
    - where $\tilde{c}^U = c^U S^U(x)^{\theta^U}$ and θ is the height
- Profit-maximizing height (F.O.C.)
  - $S^{*U}(x) = \left(\frac{a^U}{c^U(1+\theta^U)}\right)^{\frac{1}{\theta^U - \omega^U}} \Rightarrow \tilde{S}^U(x) = \min(S^{*U}(x), \tilde{S}^U)$
- Zero profits gives land bid rent
  - $r^U(x) = \frac{a^U}{1+\omega^U}(\tilde{S}^U)^{1+\theta^U} - c^U(\tilde{S}^U)^{1+\theta^U}$

Which objects are endogenous, which objects are exogenous?

Land use

- **Land is allocated** to the use associated with the **highest land bid rent**:
  - Commercial use if
$$S^C(x) = \tilde{S}^C(x), S^R(x) = 0, \text{ if } r^C(x) \geq r^R(x), r^C \geq r^A$$
  - Residential use if
$$S^R(x) = \tilde{S}^R(x), S^C(x) = 0, \text{ if } r^R(x) > r^C(x), r^R \geq r^A$$
  - Else (if $r > r^{U \in \{C,R\}}$) agricultural use
- Under plausible restrictions $r^C(x=0) > r^R(x=0), \frac{\partial r^U}{\partial D} < \frac{\partial r^C}{\partial D} < \frac{\partial r^R}{\partial D}$
  - two points $\{-x_0, x_0\}$ at which the commercial and residential land rents equate $\Rightarrow$ **boundaries of the CBD**
  - two points $\{-x_1, x_1\}$ where the residential and agricultural land rents intersect $\Rightarrow$ **boundaries of urban area**

Land market clearing

- Real estate markets clear at the **local level**

$$F^C(x) = S^C(x), x \in (-x_0, x_0)$$

$$F^R(x) = S^R(x), \quad x \in (-x_1, -x_0) \cup (x_0, x_1)$$

- Commercial floor space demand (from the MRS) is $F^C(x) = \frac{y^C}{\bar{p}^C} \frac{1-\alpha^C}{\alpha^C} L(x)$
  - where $L(x)$ is number of workers working at x (workplace employment)
- Residential floor space (Marshallian) demand $F^R(x) = \frac{(1-\alpha^R)y}{\bar{p}^R} n(x)$
  - where $n(x)$ is the number of workers living at x (residence employment)

Labour market clearing

- Use commercial land market clearing to get **workplace employment** as

$$L(x) = \frac{\alpha^C \bar{p}^C(x)}{(1-\alpha^C)y^C} S^C(x)$$

- Use residential land market clearing and to get **residence employment**

$$n(x) = \frac{S^R(x)\bar{p}^R(x)}{y^R\,(1-\alpha^R)}$$

- Labour markets clear at the **city level**

$$\int_{-x_0}^{x_0} L(x)\,dx = \int_{-x_1}^{x_0} n(x)\,dx + \int_{x_0}^{x_1} n(x)\,dx = N$$

Equilibrium

Mapping

- We have the following **primitives**: $\{\alpha^U, \beta^U, \omega^U, \theta^U, \tau^U, \tilde{a}^U, \tilde{c}^U, S^U, r^A\}$
- We have the following **endogenous objects**
  - Variables: $\{L(x), n(x), p^U(x), r^U(x), S^U(x)\}$
  - Scalars: $\{y, N\}$
- How do we get from the primitives to the values of the endogenous objects?
  - Which equations can we use?
    - Generally need as many equations as unknowns
  - Is there an analytical solution?

Always include an accessible summary of what the primitives and the endogenous objects are. Then discuss the mapping.

Solving for the equilibrium: Analytical solution

- Direct **mapping** from exogenous to endogenous objects
  - Need **as many equations as unknowns** (and a bit of patience)
  - Express endogenous objects as functions of exogenous objects, exclusively
- Recall Glaeser-Gottlieb (2009)
  - **Three** endogenous objects $\{L_c, P_c, W_c\}$, **three** equations:
    - Inverse demand, housing market clearing, indifference condition
  - Rearranging those equations, we obtained the **mapping**
    - **from parameters** $\{\alpha, \beta, \delta, \sigma, d\}$ **and fundamentals** $\{A_c, B_c, M_c\}$
    - **to the endogenous objects** $\{L_c, P_c, W_c\}$

Can run counterfactuals without any solver

Solving for the equilibrium: Numerical solution

- Since in QSMs there is **usually no analytical solution**, we need to think about
  - the **endogenous objects that reference the equilibrium**
    - set of N objects that need to be solved simultaneously
    - there is a corresponding set of N equations we can use for that
  - the subset of **target objects** that we need to solve numerically
    - in a procedure that involves **all referencing endogenous objects**
- Then we use a **recursive structure** to get
  - from **target objects** to the **referencing objects**
  - from the **referencing objects** to all other endogenous objects

Understanding what objects reference the equilibrium and what target variables need to be solved numerically is key to writing your solver

Referencing objects I

- **Course codebook**:
  - "Given the model's exogenous parameters $\{\alpha^U, \beta, \omega^U, \theta^U, \tau^U, \tilde{c}^U, r^a, \bar{U}\}$ and the exogenous fundamentals $\{\bar{a}^U, \bar{S}^U\}$, the general equilibrium of the model is referenced by $\{a^U, \tilde{S}^U, r^U, S^U, \bar{p}^U, n(x), L(x), y\}$, where $U \in C, R$ indexes commercial (C) and residential (R). These **13** components of the equilibrium are determined by the following **13** equations":

1. Production amenity: $a^C(x,N) = \tilde{A}^C(x,N)^{\frac{1}{1-\alpha^C}} (y^C)^{\frac{\alpha^C}{1-\alpha^C}}$
2. Residential amenity: $a^R(x) = \tilde{A}^R(x)^{\frac{1}{1-\alpha^R}} (y^R)^{\frac{1-\alpha^R}{\alpha^R}}$
3. Constrained commercial height: $\tilde{S}^C(x) = \min\left(\left(\frac{a^C}{c^C(1+\theta^C)}\right)^{\frac{\theta^C}{\theta^C-\omega^C}}, \bar{S}^C\right)$
4. Constrained residential height: $\tilde{S}^R(x) = \min\left(\left(\frac{a^R}{c^R(1+\theta^R)}\right)^{\frac{\theta^R}{\theta^R-\omega^R}}, \bar{S}^R\right)$
5. Commercial land rent: $r^C(x) = \frac{a^C}{1+\omega^C}(\tilde{S}^C)^{1+\omega^C} - c^C(\tilde{S}^C)^{1+\theta^C}$

Referencing objects II

6. Residential land rent: $r^R(x) = \frac{a^R}{1+\omega^R}(\tilde{S}^R)^{1+\omega^R} - c^R(\tilde{S}^R)^{1+\theta^R}$
7. Realized commercial height: $S^C(x) = \tilde{S}^C(x),\ S^R(x) = 0,$ if $r^C(x) \geq r^R(x),\ r^C \geq r^A$
8. Realized residential height: $S^R(x) = \tilde{S}^R(x),\ S^C(x) = 0,$ if $r^R(x) > r^C(x),\ r^R \geq r^A$
9. Horizontal commercial rent: $\bar{p}^C(x) = \frac{a^C(x)}{1+\omega^C} S^C(x)^{\omega^C}$
10. Horizontal residential rent: $\bar{p}^R(x) = \frac{a^R(x)}{1+\omega^R} S^R(x)^{\omega^R}$
11. Workplace employment: $L(x) = \frac{\alpha^C}{1-\alpha^C} \frac{\bar{p}^{-C}(x)}{y^C} S^C(x)$
12. Residence employment: $n(x) = \frac{S^R(x)}{y^R} \frac{\bar{p}^{-R}(x)}{1-\alpha^R}$
13. Labour market clearing: $\int_{-x_0}^{x_0} L(x)dx = \int_{-x_1}^{x_0} n(x)dx + \int_{x_0}^{x_1} n(x)dx = N$

What does this actually mean? Let's walk through...

Recursive structure

- Assume we have values for wage, y, and total employment, N (and all primitives)
  - We can use $\{y, N\}$ in 1. and 2. to get $\{a^C, a^R\}$
  - We can use $\{a^C, a^R\}$ in 3. and 4. to get $\{\tilde{S}^C, \tilde{S}^R\}$
  - We can use $\{\tilde{S}^C, \tilde{S}^R\}$ in 5. and 6. to get $\{r^C, r^R\}$
  - We can use $\{\tilde{S}^C, \tilde{S}^R\}$ and $\{S^C, S^R\}$ in 7. and 8. to get $\{S^C, S^R\}$
  - We can use $\{a^C, a^R\}$ and $\{S^C, S^R\}$ in 9. and 10. to get $\{\bar{p}^C, \bar{p}^R\}$
  - We can use $\{y, N\}$, $\{\bar{p}^C, \bar{p}^R\}$ and $\{S^C, S^R\}$ in 11. and 12. to get $\{n(x), L(x)\}$
  - We can use $\{n(x), L(x)\}$ in 13. to compute N

How we reference the equilibrium

- There is just one combination of values for $\{y, N\}$ that ensures that 13. holds
  - we predict the aggregate labour demand we have assumed
  - we predict the aggregate labour supply we have assumed
- We 'just' need to find $\{y, N\}$ numerically
  - $\{y, N\}$ are our **target variables**
  - Since we cannot do that without solving for all $\{a^U, \tilde{S}^U, r^U, S^U, \bar{p}^U, n(x), L(x), y\}$, these objects **reference the equilibrium**
- Once we have $\{y, N\}$ we can use the recursive structure to solve for $\{a^U, \tilde{S}^U, r^U, S^U, \bar{p}^U, n(x), L(x)\}$
  - And any other endogenous object within the model

Programming task is to write solver to find $\{y, N\}$ (next week)
Spoiler alert: We will exploit the recursive structure

Uniqueness

- Is the equilibrium **unique**?
  - Is there just one combination of $\{y, N\}$ that satisfy all equilibrium conditions?
  - Relevant when there is no direct **mapping** from primitives to endogenous objects
  - Can be violated in multi-location models with agglomeration economies
- Intuition
  - Increasing total employment monotonically reduces utility (rents increase)
    - Unless agglomeration economies are too strong
  - For any total employment, monotonic labour demand and supply curves imply that there is only one market-clearing wage
- Formal proofs are always welcome
  - But not always feasible
- Can also do Monte Carlos (next week)

Comparative statics

Parameter values

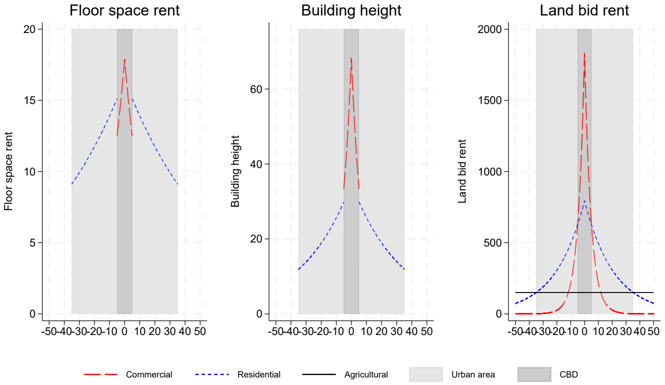
	Parameter	Value	Further reading
$1-\alpha^C$	Share of floor space at inputs	0.15	Lucas & Rossi-Hansberg (2002)
$1-\alpha^R$	Share of floor space at consumption	0.33	Combes et al. (2019)
β	Agglomeration elasticity of production amenity	0.03	Combes & Gobillon (2015)
θ^C	Commercial height elasticity of construction cost	0.5	Ahlfeldt & McMillen (2018)
θ^R	Residential height elasticity of construction cost	0.55	Ahlfeldt & McMillen (2018)
ω^C	Commercial height elasticity of rent	0.03	Liu et al. (2018)
ω^R	Residential height elasticity of rent	0.07	Danton & Himbert (2018)
τ^C	Production amenity decay	0.01	Ahlfeldt et al. (2015)
τ^R	Residential amenity decay	0.005	Ahlfeldt et al. (2015)

- 'Canonical' parameter values
  - Baseline in Ahlfeldt & Barr (2022) toolkit, but can be changed ▸ Open AB2022-toolkit

Equilibrium & gradients

1. Developers take floor space prices as given
2. Choose height to maximize profits
3. Perfect competition ensures that profit capitalizes in land rent
4. Land bid-rent curves determine land use pattern
5. In equilibrium, land-use allocation needs to facilitate labor market clearing

- If not, need to update $\{y, N\}$ and return to 1.

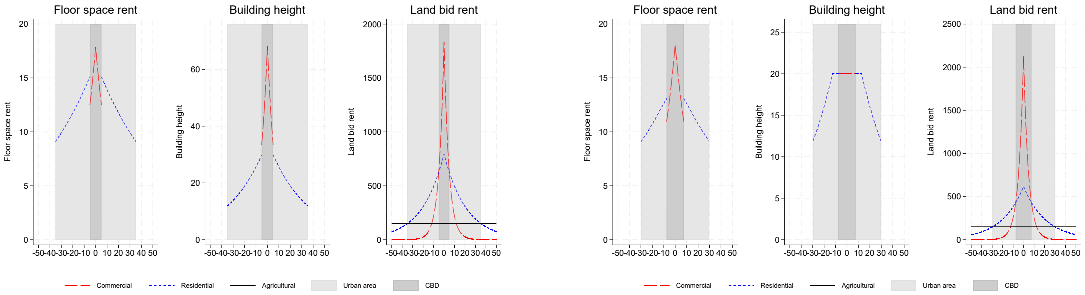


Q: Why is there a discontinuity in the height gradient?

Empirical support

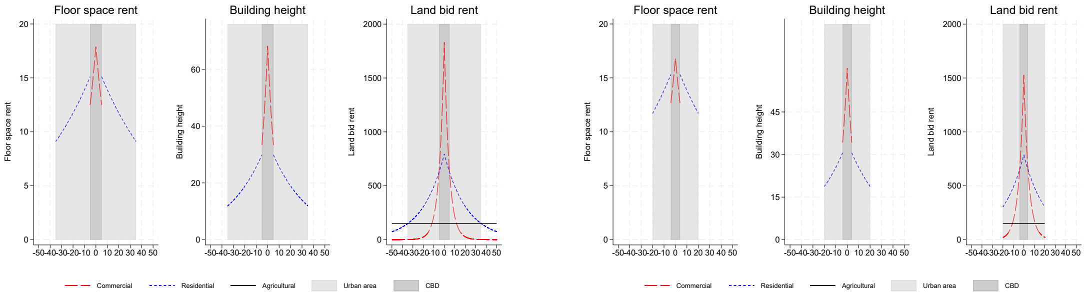
- Slope of height gradient across *global cities* **constant over time**
  - Distance elasticity about -0.29 in 1900 and 2000
- **Commercial height gradient steeper** than residential gradient
  - Driven by substitution in use an construction (in model)
- North American height gradients steeper than European or Asian gradients
  - Role for regulation?
- Evidence for **height discontinuity** at land use border
  - Discontinuous change of 0.2 log points at CBD boundaries of North Am. cities

Height limit



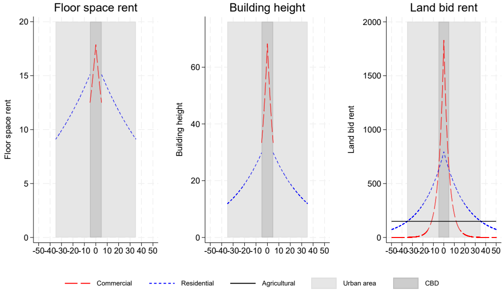
- Vertical contraction of CBD ⇒ horizontal expansion, higher commericial land rent
  - Firms cannot concentrate in most productive locations ⇒ productivity and wages fall
  - Wages fall ⇒ city less attractive ⇒ loses workers ⇒ urban area shrinks

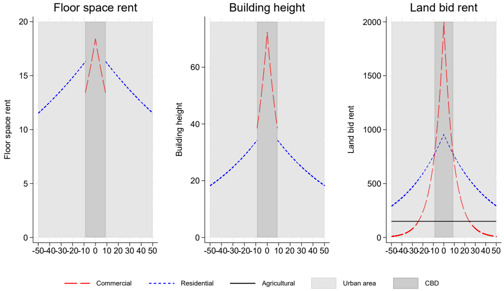
Urban growth boundary



- Horizontal contraction of city $\Rightarrow$ less housing supply
  - Pressure on housing markets $\Rightarrow$ city loses worker
  - Firms require less space $\Rightarrow$ Commercial heights fall
  - Amplified by reduction in agglomeration economies

Reduction in transport cost I



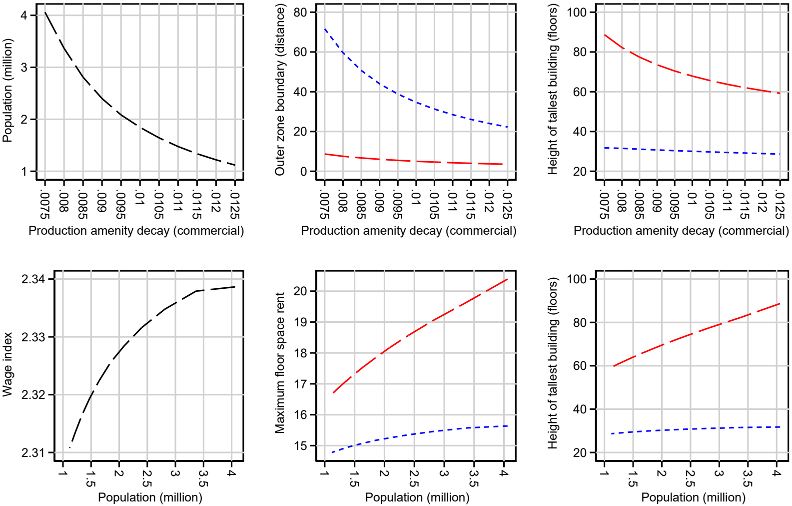


- Lower transport cost parameter $\tau^U \Rightarrow$ Gradients flatten
  - City more attractive $\Rightarrow$ city attracts workers
  - Rents increase in suburbs *and* in center

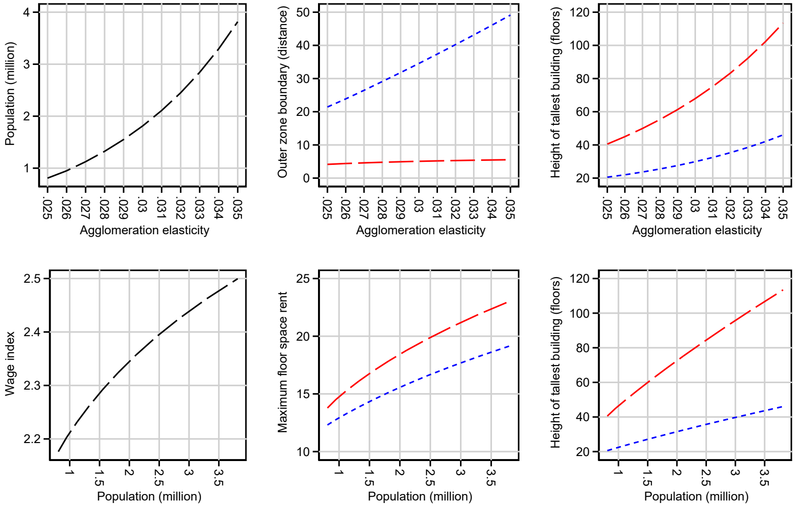
Counterfactuals

- Solve for endogenous objects given primitives
  - Exogenous parameters: $\{\alpha^U, \beta, \omega^U, \theta^U, \tau^U, \bar{a}^U, \tilde{c}^U, \bar{S}^U, \bar{U}, r^a\}$
  - Location-specific endogenous objects $\{L(x), n(x), \bar{p}^U(x), r^U(x), \tilde{S}^U(x)\}$
  - City-specific endogenous objects $\{y, N\}$
- Pick one exogenous parameter and consider a **series of alternative values**
  - Change all use-specific values at a time, maintaining relative size
  - Generate a vector of equilibrium values for each endogenous outcome
- Explore vector of equilibrium values of endogenous outcomes
  - Outcomes vs. "forcing" parameter
  - Endogenous outcome vs. other endogenous outcomes (e.g. population)

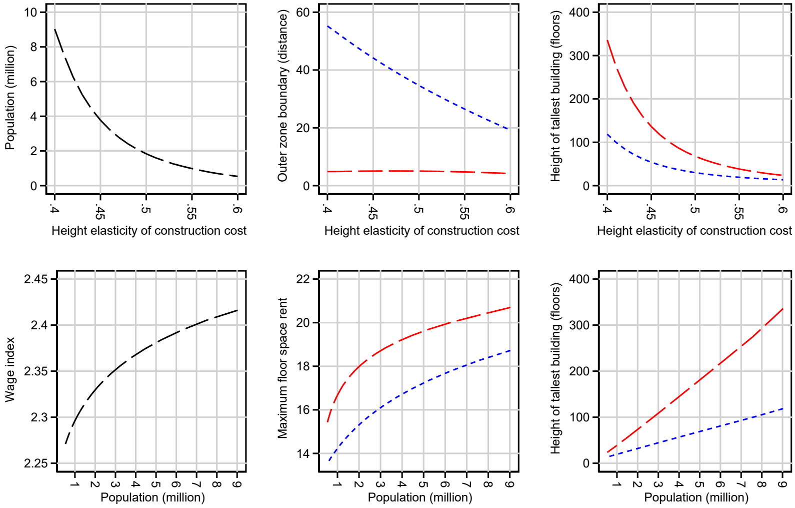
GE effects of variation in transport cost



GE effects of variation in agglomeration elasticity



GE effects of variation in cost of height



Summary

- Height positively correlated with various outcomes
  - Rent, productivity, wage, population
- Skyscrapers are cause and effect of urbanization
  - **Demand channels**, e.g. agglomeration gains, reduction in transport cost
    - Urbanization causes skyscraper development
  - **Supply channel**, reduction in cost of height
    - Skyscrapers cause urbanization, deserves more attention in literature
- Model generates **empirically relevant elasticities** that **vary by channel**
  - Population elasticity of rent: 0.1-0.3 (in line with Ahlfeldt & Pietrostefani, 2019)
  - Population density elasticity of height: 0.1-1

Summary

- Model consist of exogenous objects and endogenous objects
  - With analytical solutions, there is a direct mapping from the former to the latter
  - Numerical solutions are often required due to due to non-linear systems of equations
- Equilibrium
  - Referencing variables are all variables that need to be solved simultaneously
  - Target variables is the subset for which we need to solve numerically
  - Obtain the other endogenous objects via a recursive structure

Next week: **Quantification and solvers**

Literature I

Core readings

- **Ahlfeldt, G., J. Barr (2022): The economics of skyscrapers: A synthesis. Journal of Urban Economics. 129.**
- **Duranton, G., D. Puga (2015). Urban Land Use. Handbook of Regional and Urban Economics, Volume 5.**

Other readings

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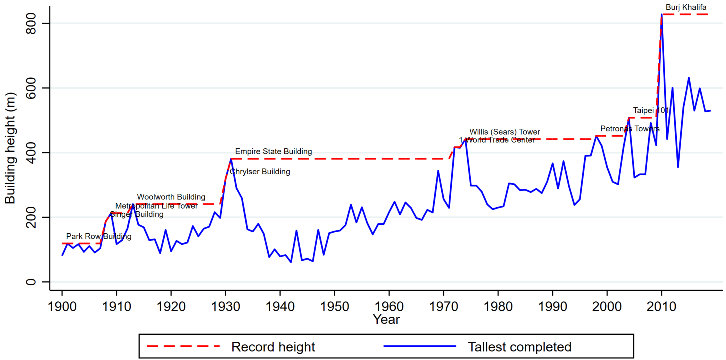
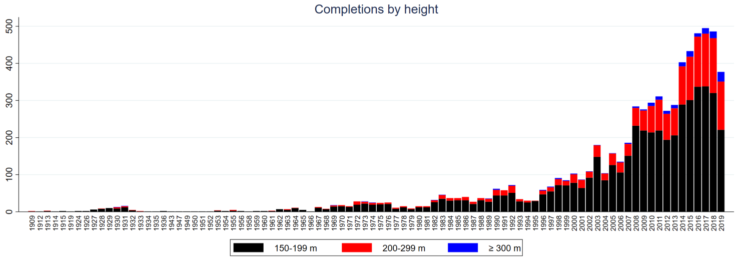
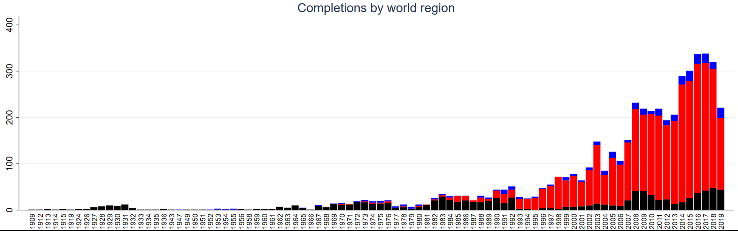
Tallest buildings in history



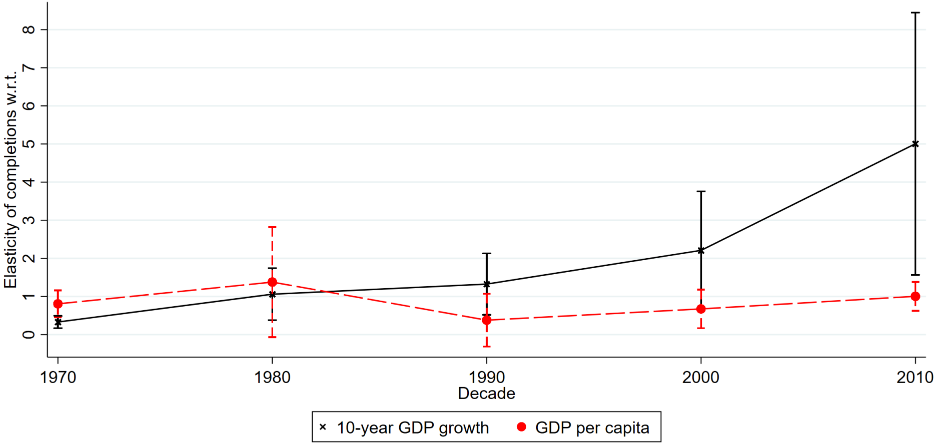
Height decisions

Vertical growth



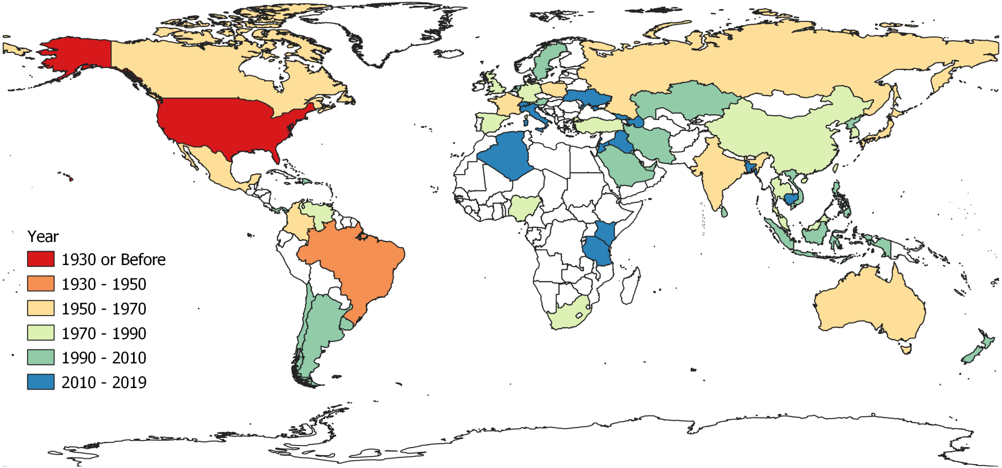


Determinants

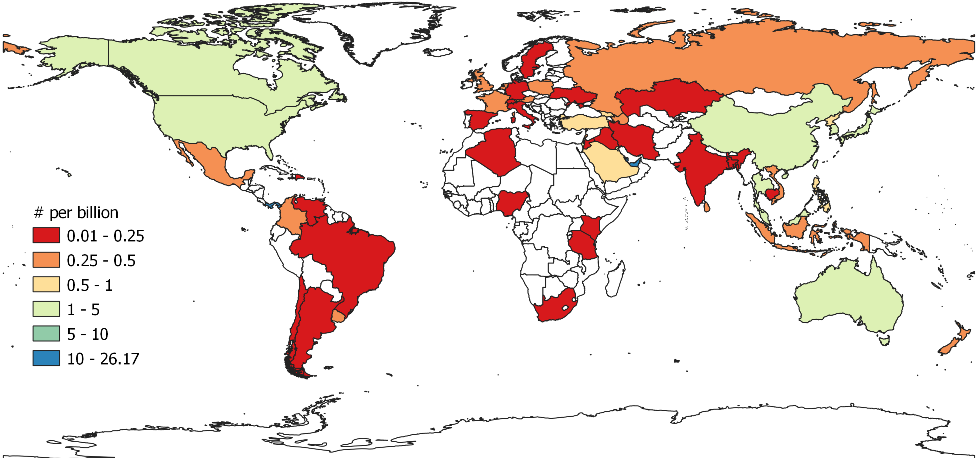


Height decisions

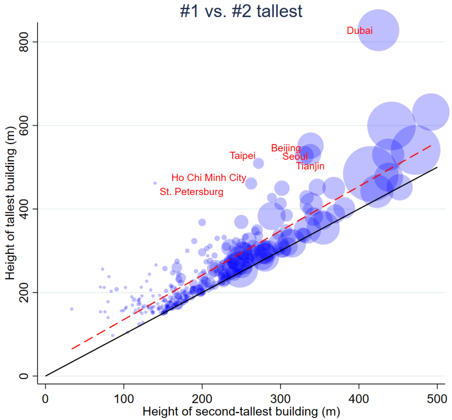
Diffusion

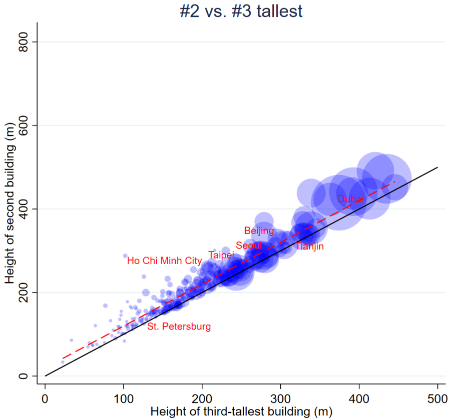

Year
1930 or Before
1930 - 1950
1950 - 1970
1970 - 1990
1990 - 2010
2010 - 2019

Skyscraperization



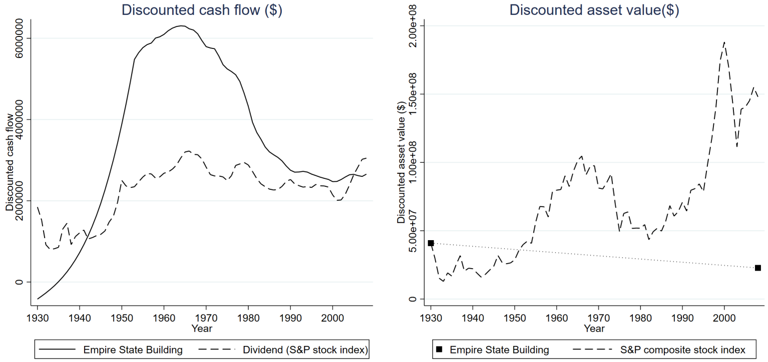
Tallest buildings in cities





Height decisions

Empire State Building



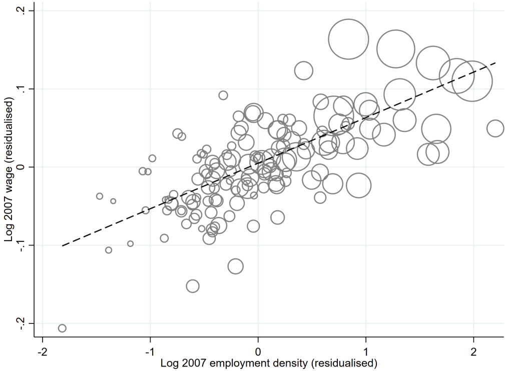
Height decisions

ESB beats stock market over its (first lifetime)

Agglomeration economies

- Productivity increase in density (city size) due to agglomeration economies
  - Arises from sharing, learning, and matching (Duranton & Puga, 2004)
  - Arise within (localisation) and between (urbanization) industry sectors
- Density elasticity of productivity
  - about 5% in cross-section
  - about haves when estimated from movers conditional on worker fixed effects (Combes & Gobillon, 2015, Ahlfeldt & Pietrostefani, 2019)

Back



Notes: Wages adjusted for worker characteristics (100% sample of German employees)