PAPER NOTES

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Part I

urban economics

Chapter 1

THE ECONOMICS OF DENSITY: EVIDENCE FROM THE BERLIN WALL

1.1 THEORETICAL MODEL

The city consists of a set of discrete locations, index by $i = 1, \ldots, S$. Each block has an effective supply of floor space L_i. Floor space can be used commercially or residentially, and we denote the endogenous fractions of floor space allocated to commercial and residential use by θ_i and $1 - \theta_i$. City is populated by an endogenous measure of H workers, who are perfectly mobile within the city and the larger economy, which provides a reservation level of utility $\overline{U}$. Workers decide whether or not to move to the city before observing idiosyncratic utility shocks for each possible pair of residence and employment blocks within the city.

1.1.1 Workers

Workers are risk neutral and have preferences that are linear in a consumption index: $U_{ijo} = C_{ijo}$, where C_{ijo} denotes the consumption index for worker o residing in block i and working in block j. This consumption index depends on consumption of the single final good c_{ijo}; consumption of residential floor space (ℓ_{ijo}); residential amenities (B_i) that capture common characteristics that make a block a more or less attractive place to live; the disutility from commuting from residence block i to workplace block j ($d_{ij} \geq 1$); and an idiosyncratic shock that is specific to individual workers and varies with the worker's blocks of employment and residence (z_{ijo}). This idiosyncratic shock captures the idea that individual workers can have idiosyncratic reasons for living and working in different parts of the city. In particular, the aggregate consumption index is assumed to take the Cobb-Douglas form:

$$C_{ijo} = \frac{B_i z_{ijo}}{d_{ij}} (\frac{c_{ijo}}{\beta})^\beta (\frac{\ell_{ijo}}{1-\beta})^{1-\beta}, 0 < \beta < 1 \tag{1.1}$$

where the iceberg communiting cost $d_{ij} = e^{\kappa \tau_{ij}} \in [1, \infty)$ increases with the travel time (τ_{ij}) between blocks i and j. The parameter κ controls the size of commuting costs.

For each worker o living in block i and commuting to block j, the idiosyncratic component of utility (z_{ijo}) is drawn from an independent Frechet distribution:

$$F(z_{ijo}) = e^{-T_i E_j z_{ijo}^{-\varepsilon}}, T_i, E_j > 0, \varepsilon > 1 \tag{1.2}$$

where the scale parameter $T_i > 0$ determines the average utility derived from living in block i; the scale parameter E_j determines the average utility derived from working in block j; and the shape parameter $\varepsilon > 1$ controls the dispersion of idiosyncratic utility.

The indirect utility from residing in block i and working in block j can be expressed in terms of the wage paid at this workplace (w_j), commuting costs (d_{ij}), the residential floor price (Q_i), the common component of amenities (B_i), and the idiosyncratic shock (z_{ijo}):

$$u_{ijo} = \frac{z_{ijo} B_i w_j Q_i^{\beta-1}}{d_{ij}} \tag{1.3}$$

where we have used utility maximization and the choice of the final good as numeraire. Although we model commuting costs in terms of utility, there is an isomorphic formulation in terms of a reduction in effective units of labor, because the iceberg commuting cost $d_{ij} = e^{\kappa \tau_{ij}}$ enters the indirect utility function multiplicatively. As a result, commuting costs are proportional to wages, and this specification captures changes over time in the opportunity cost of travel time.

Since indirect utility is a monotonic function of the idiosyncratic shock (z_{ijo}), whch has a Frechet distribution, it follows that indirect utility for workers living in block i and working in block j also has a Frechet distribution. Each worker chooses the bilateral commute that offers her the maximum utility, where the maximum of Frechet distributed random variables is itself Frechet distributed. Using these distributions of utility, the probability that a worker choose to live in block i and work in block j is:

$$\pi_{ij} = \frac{T_i E_j (d_{ij} Q_i^{1-\beta})^{-\varepsilon} (B_i w_j)^\varepsilon}{\sum_{r=1}^{S} \sum_{s=1}^{S} T_r E_s (d_{rs} Q_r^{1-\beta})^{-\varepsilon} (B_r w_s)^\varepsilon} \equiv \frac{\Phi_{ij}}{\Phi}. \tag{1.4}$$

Summing these probabilities across workplaces for a given residence, we obtain the overall probability that a worker resides in block $i (\pi_{Ri})$, while summing these probabilities across residences for a given workplace, we obtain the overall probability that a worker works in block $j (\pi_{Mi})$:

$$\pi_{Ri} = \sum_{j=1}^{s} \pi_{ij} = \frac{\sum_{j=1}^{s} \Phi_{ij}}{\Phi}, \pi_{Mj} = \sum_{i=1}^{S} \pi_{ij} = \frac{\sum_{i=1}^{S} \Phi_{ij}}{\Phi} \tag{1.5}$$

These residential and workplace choice probabilities have an intuitive interpretation. The idiosyncratic shock to preferences z_{ijo} implies that individual workers choose different bilateral commutes when faced with the same prices $\{Q_i, w_j\}$, commuting costs $\{d_{ij}\}$ and location characteristics $\{B_i, T_i, E_j\}$. Other things equal, the more attractive its amenities B_i, the higher its average idiosyncratic utility determined by T_i, the lower its residential floor prices Q_i, and the lower its commuting costs d_{ij} to employment locations.

Conditional on living in block i, the probability that a worker commutes to block j is:

$$\pi_{ij|i} = \frac{E_j (w_j/d_{ij})^\varepsilon}{\sum_{s=1}^{S} E_s (w_s/d_{is})^\varepsilon} \tag{1.6}$$

where the terms in $\{Q_i, T_i, B_i\}$ have cancelled from the numerator and denominator. Therefore, the probability of commuting to block j conditional on living in block i depends on wage (w_j), average utility draw (E_j), and commuting costs (d_{ij}) of employment location j in the numerator as well as teh wage (w_s), average utility draw (E_s) and commuting costs (d_{is}) for all other possible employment locations s in the denominator.

Using the conditional commuting probabilities, we obtain the following commuting market clearing condition that equates the measure of worker employed in block $j (H_{M_j})$ with the measure of workers choosing to commute to block j:

$$H_{M_j} = \sum_{s=1}^{S} \frac{E_j (w_j/d_{ij})^\varepsilon}{\sum_{s=1}^{S} E_s (w_s/d_{is})^\varepsilon} H_{R_i} \tag{1.7}$$

where H_{R_i} is the measure of residents in block i. Since there is a continuous measure of workers residing in each location, there is no uncertainty in the supply of workers to each employment location.

Expected worker income conditional on living in block i is equal to the wages in all possible employment location weighted by the probabilities of commuting to choose those locations conditional on living in i:

$$E[w_j \mid i] = \sum_{j=1}^{S} \frac{E_j(w_j/d_{ij})^\varepsilon}{\sum_{s=1}^{S} E_s(w_s/d_{is})^\varepsilon} w_j \tag{1.8}$$

Finally, population mobility implies that the expected utility from moving to the city is equal to the reservation level of utility in the wider economy ($\tilde{U}$):

$$E[u] = \gamma [\sum_{r=1}^{S} \sum_{s=1}^{S} T_r E_s (d_{rs} Q_r^{1-\beta})^{-\varepsilon} (B_r w_s)^\varepsilon]^{1/\varepsilon} = \tilde{U} \tag{1.9}$$

where E is the expectation operator and expectation is taken over the distribution for the idiosyncratic component of utility: $\gamma = \Gamma(\frac{\varepsilon-1}{\varepsilon})$ and $\Gamma(\cdot)$ is the Gamma function.

1.1.2 Production

Production of the tradable final good occurs under conditions of perfectly competition and constant returns to scale. We can assume the production technology takes the CD-form

$$y_j = A_j H_{M_j}^\alpha L_{M_j}^{1-\alpha} \tag{1.10}$$

where A_j is final goods productivity and L_{M_j} is the measure of floor space used commercially. Firms choose their block of production and their inputs of workers and commercial floor space to maximize profits, taking as given final goods productivity A_j, the distribution of idiosyncratic utility, goods and factor prices, and the location decisions of other firms and workers. Profit maximization implies that equlibrium employment in block j is increasing in productivity (A_j), decreasing in wage (w_j), and increasing in commercial floor space (L_{M_j}).

$$H_{M_j} = (\frac{\alpha A_j}{w_j})^{1/(1-\alpha)} L_{M_j} \tag{1.11}$$

where the equilibrium wage is determined by the requirement that the demand for workers in each employment location equals the supply of workers to that location.

From the first order conditions for maximization and zero profit, equilibrium commercial floor prices (q_j) in each block with positive employment must satisfy:

$$q_j = (1-\alpha)(\frac{\alpha}{w_j})^{\alpha/(1-\alpha)} A_j^{1/(1-\alpha)} L_{M_j}^{-1/(1-\alpha)} \tag{1.12}$$

1.1.3 Land Market Cleaning

Land market equilibrium requires no-arbitrage conditions between the commercial and residential use of floor space after the tax equivalence of land use regulations. The share of floor space used commercially (θ_i) is:

$$\begin{aligned} \theta_i &= 1 \text{ if } q_i > \xi_i Q_i \\ \theta_i &\in [0,1] \text{ if } q_i = \xi_i Q_i \theta_i \quad = 0 \text{ if } q_i < \xi_i Q_i \end{aligned} \tag{1.13}$$

where $\xi_i \geq 1$ captures one plus the tax equivalent of land use regulations that restrict commercial land use relative to residential land use. We assume that the observed price of floor spaces in the data is the maximum of the commercial and residential price of floor space: $\mathbb{Q} = \max\{q_i, Q_i\}$. Hence the relationship between observed, commercial, and residential floor prices can be summarized as:

$$\mathbb{Q}_i = q_i, q_i > \xi_i Q_i, \theta_i = 1$$
$$\mathbb{Q}_i = q_i, q_i = \xi_i Q_i, \theta_i \in [0,1] \tag{1.14}$$
$$\mathbb{Q}_i = Q_i, q_i < \xi_i Q_i, \theta_i = 0$$

We follow the standard approach in the urban literature of assuming that floor space L is supplied by a competitive construction sector that uses land K and capital M a inputs. We assume that the production function takes the CD-form: $L_i = M_i^{\mu} K_i^{1-\mu}$. Therefore, the corresponding dual cost function for floor space is $\mathbb{Q}_i = \mu^{-\mu}(1-\mu)^{-(1-\mu)}\mathbb{P}^{\mu}\mathbb{R}_i^{1-\mu}$, where $\mathbb{Q}_i = \max\{q_i, Q_i\}$ is the price for floor space, $\mathbb{P}$ is the common price for capital across all blocks, and $\mathbb{R}_i$ is the price for land. Since the price for capital is the same across all locations, the relationship between the quantities and prices of floor space and land can be summarized as:

$$L_i = \phi_i K_i^{1-\mu} \tag{1.15}$$

$$\mathbb{Q}_i = \chi \mathbb{R}_i^{1-\mu} \tag{1.16}$$

where we refer to $\phi_i = M_i^{\mu}$ as the density of development and χ is a constant. Residential land market clearing implies that the demand for residential floor space equals the supply of floor space allocated to residential use in each location: $(1 - \theta_i)L_i$. Maximization for each worker and taking expectation over the distribution for idiosyncratic utility, the residential land market clearing condition can be expressed as:

$$\mathbb{E}[\ell_i]H_{R_i} = (1 - \beta)\frac{\mathbb{E}[w_s \mid i]H_{R_i}}{Q_i} = (1 - \theta_i)L_i. \tag{1.17}$$

Commercial land market cleaning requires that the demand for commercial floor space equals the supply of floor space allocated to commercial use in each location: $\theta_j L_j$. Using the FOC for profit maximization, the commercial land market clearing condition can be expressed as:

$$\left(\frac{(1-\alpha)A_j}{q_j}\right)^{1/\alpha}H_{M_j} = \theta_j L_j \tag{1.18}$$

We both residential and commercial land market clearing are satisfied, total demand for floor space equals the total supply of floor space:

$$(1 - \theta_i)L_i + \theta_i L_i = L_i = \phi_i K_i^{1-\mu} \tag{1.19}$$

1.1.4 General Equilibrium With Exogenous Location characteristics

Given the model's parameters $\{\alpha, \beta, \mu, \varepsilon, \kappa\}$, the reservation level of utility in the wider economy $\overline{U}$, and vectors of exogenous location characteristics $\{T, E, A, B, \phi, K, \xi, \tau\}$, the general equilibrium is referred with six vectors $\{\pi_M, \pi_R, Q, q, w, \theta\}$ and total city population H.

Proposition 1.1. *Assuming exogenous finite, and strictly location characteristics* $(T_i \in (0,\infty), E_i \in (0,\infty), \phi_i \in (0,\infty), K_i \in (0,\infty), \xi_i \in (0,\infty), \tau_{ij} \in (0,\infty) \times (0,\infty))$, *and exogenous, finite and nonnegative final goods productivity* $A_i \in [0,\infty)$ *and residential amnetities* $B_i \in [0,\infty)$, *there exists a unique general equilibrium vector* $\{\pi_M, \pi_R, Q, q, w, \theta\}$

Proof. The proof can be decomposed into two parts: firstly, we show that under the assumptions that all blocks have strictly positive, finite, and exogenous location and we allow some blocks to be more attractive than others in terms of these characteristics. But workers draw idiosyncratic preferences from a Frechet distribution for pairs of residence and workplace locations, and therefore, since teh Frechet distribution is unbounded from above, any block with strictly positive characteristics has a positive measure of workers that

prefer that location as a residence or workplace at a positive and finite price. Hence, all blocks with finite positive wages attract a positive measure of workers, and all blocks with finite positive floor prices attract a positive measure of residents.

Then We next show that blocks with strictly positive, finite, and exogenous location characteristics must have strictly positive and finite values of both wages and floor prices in equilibrium. □

1.1.5 Introducing Agglomenration Forces

We now introduce endogenous agglomenration forces. We allow final goods productivity to depend on production fundamentals (a_j) and production externalities (Y_j). Production fundamentals capture features of physical geography that make a location more or less productive independently of the surrounding density of economic activity. Production externalities impose structure on how the productivity of a given block is affected by the characteristics of other blocks. Specifically, we follow the standard approach in urban economics of modeling these externalities as depending on the travel-time weighted sum of workplace employment density in surrounding blocks:

$$A_j = a_j Y_j^\lambda, Y_j \equiv \sum_{s=1}^{S} e^{-\delta \tau_{js}} \left(\frac{H_{Ms}}{K_s} \right), \tag{1.20}$$

where H_{Ms}/K_s is workplace employment density per unit of land area; production externalities decline with travel time (τ_{js}) through the iceberg factor $e^{-\delta \tau_{js})} \in (0, 1]$; δ determines their rate of spatial decay, and λ controls their relative importance in determining overall productivity.

We model the externalities in workers' residential choices analygously to the externalities in firms' production choices. We allow residential amenities to depend on residential fundamentals (b_i) and residential externalities (Ω_i). Residential fundamentals capture features of physical geography that make a location a more or less attractive place to live independently of the surrounding density of economic activity. Residential externalities again impose structure on how the amenities in a given block are affected by the characteristics of other blocks. Specifically, we adopt a symmetric specification as for production externalities, and model residential externalities as depending on the travel time weighted sum of residential employment density in surrounding blocks:

$$B_i = b_i \Omega_i^\eta, \Omega_i \equiv \sum_{r=1}^{S} e^{-\rho \tau_{ir}} \left(\frac{H_{Rr}}{K_r} \right) \tag{1.21}$$

where H_{Rr}/K_r is residence employment density per unit of land area; residential externalities decline with travel time (τ_{ir}) through the iceberg factor $e^{-\rho \tau_{ir}} \in (0, 1]$; ρ determines their rate of spatial decay; and η controls their relative importance in overall residential amenities. The parameter η captures the net effect of residence employment density on amenities, including negative spillover such as air pollution and crime, and positive externalities through the availability of urban amenities. Although η captures the direct effect of higher residence employment density on utility through amenities, there are clearly other general equilibrium effects through floor prices, commuting times and wages.

1.1.6 Recovering Location Characteristics

We now show that there is a unique mapping from the observed variables to unobserved location characteristics. Since a number of these unobserved variables enter the model isomorphically, we define the following composites denoted bya tilde:

$$\tilde{A}_i = A_i E_i^{\alpha/\varepsilon}, \tilde{a}_i = a_i E_i^{\alpha/\varepsilon}$$
$$\tilde{B}_i = B_i T_i^{1/\varepsilon} \zeta_{Ri}^{1-\beta}, \tilde{b}_i = b_i T_i^{1/\varepsilon} \zeta_{Ri}^{1-\beta}$$
$$\tilde{w}_i = w_i E_i^{1/\varepsilon}$$
$$\tilde{\phi}_i = \tilde{\phi}_i(\phi_i, E_i^{1/\varepsilon}, \xi_i)$$

where we use i to index all blocks, and the function $\tilde{\phi}_i(\cdot)$ is a defined function; $\zeta_{Ri} = 1$ for completely specialized residential blocks; and $\zeta_{Ri} = \zeta_i$ for residential blocks with some commercial land use.

In the labor market, the adjusted wage for each employment location ($\tilde{w}_i$) captures the wage (w_i) and the Frechet scale parameter for the location ($E_i^{1/\varepsilon}$), because these both affect the relative attractiveness of an employment location to workers. On the production side, adjusted productivity for each employment location ($\tilde{A}_i$) captures productivity (A_i) and the Frechet scale parameter for the location ($E_i^{\alpha/\varepsilon}$) because these both affect the adjusted wage consistent with zero profits. Adjusted production fundamentals are defined analogously. On the consumption side, adjusted amenities for each residence location ($\tilde{B}_i$) capture amenities (B_i), the Frechet scale parameter for that location ($T_i^{1/\varepsilon}$) and the relationship between observed and residential floor prices ($\zeta_{Ri} \in \{1, \zeta_i\}$), because these all affect the relative attractiveness of a location consistent with population mobility. Adjusted residential fundamentals are defined analogously. Finally, in the land market, the adjusted density of development ($\tilde{\phi}_i$) includes the density of development (ϕ_i) and other production and residential parameters that affect land market clearing.

Proposition 1.2.   *1. Given known values for the parameters $\{\alpha, \beta, \mu, \varepsilon, \kappa\}$ and the observed data $\{\mathbb{Q}, \mathbf{H_M}, \mathbf{H_R}, \mathbf{K}, \tau\}$ there exists unique vectors of the unobserved location characteristics $\{\tilde{\mathbf{A}}^*, \tilde{\mathbf{B}}^*, \tilde{\phi}^*\}$ that are consistent with the data being an equilibrium of the model.*

2. Given known values for the parameters $\{\alpha, \beta, \mu, \varepsilon, \kappa, \lambda, \delta, \eta, \rho\}$ and the observed data $\{\mathbb{Q}, \mathbf{H_M}, \mathbf{H_R}, \mathbf{K}, \tau\}$ there exists a unique vectors of the unobserved location characteristics $\{\tilde{\mathbf{a}}^*, \tilde{\mathbf{b}}^*, \tilde{\phi}^*\}$ that are consistent with the data being an equilibrium of the model.

Chapter 2

THE MAKING OF THE MODERN METROPO-LIS: EVIDENCE FROM LONDON

2.1 Theoretical Framework

We consider a city embedded in a wider economy (Great Britain). The economy as a whole consists of a discrete set of locations $\mathbb{M}$. Greater London is a subset of these locations $\mathbb{N} \subset \mathbb{M}$, Time is discrete and is indexed by t. The economy as a whole is populated by an exogenous continuous measure $L_{\mathbb{M}t}$ of workers, who are geographically mobile and wndowed with one unit of labor that is supplied inelastically. Workers simultaneously choose their preferred residence n and workplace i given their idiosyncratic draws. We denote the endogenous measure of workers who choose a residence-workplace pair in Greater London by $L_{\mathbb{N}t}$. We allow locations to differ from one another in terms of their attractiveness for production and residence, as determined by productivity, amenities, the supply of floor space, and transport connections, where each of these location characteristics can evolve over time.

2.1.1 Preferences

We assume that preferences take the CD-form, such that the indirect utility for a worker ω residing in n and working in i is:

$$U_{ni}(\omega) = \frac{B_{ni}b_{ni}(\omega)w_i}{\kappa_{ni}P_n^\alpha Q_n^{1-\alpha}}, 0 < \alpha < 1 \tag{2.1}$$

where we suppress the time subscript from now on; P_n is the price index for consumption goods, which may include both tradeable and nontradeable consumption goods; Q_n is the price of residential floor space; w_i is the wage, κ_{ni} is an iceberg commuting cost; B_{ni} captures amenities from the bilateral commute from residence n to workplace i that are common across all workers; and $b_{ni}(\omega)$ is an idiosyncratic amenity draw that captures all the idiosyncratic factors that can cause an individual to live and work in particular locations in the city.

We assume that idiosyncratic amenities $(b_{ni}(\omega))$ are drawn from an independent extreme value (Frechet) distribution for each residence-workplace pair and each worker:

$$G(b) = e^{-b^{-\varepsilon}}, \varepsilon > 1 \tag{2.2}$$

where we normalize the Frechet scale parameter in Equation (2.2) to 1 because it enters worker choice probabilities isomorphically to common bilateral amenities B_{ni}. The Frechet shape parameter ε regulates the dispersion of idiosyncratic amenities, which controls the sensitivity of worker location decisions to economic variables. The smaller the shape parameter ε, the greater the heterogeneity in idiosyncratic amenities, and the less sensitive are worker location decisions to economic variables.

We decompose the bilateral common amenities parameter (B_{ni}) into a residence component common across all workplaces $(B_n^{\mathcal{R}})$, a workplace component common across all residences (B_i^L), and an idiosyncratic component (B_{ni}^I) specific to an individual residence-workplace pair:

$$B_{ni} = B_n^{\mathcal{R}} B_i^L B_{ni}^I, \quad B_n^{\mathcal{R}}, B_i^L, B_{ni}^I > 0 \tag{2.3}$$

We allow the levels of $B_n^{\mathcal{R}}, B_i^I$ and B_{ni}^I to differ across residences n and workplace i, although when we examine the impact of the construction of railway network, we assume that B_i^L and B_{ni}^I are time-invariant. In contrast, we allow $B_n^{\mathcal{R}}$ to change over time, and for those changes to be potentially endogenous to the evolution of the surrounding concentration of economic activity through agglomeration forces.

Conditional on choosing a residence-workplace pair in Greater London, we know that the probability a worker chooses to reside in location $n \in \mathbb{N}$ and work in location $i \in \mathbb{N}$ is given by:

$$\begin{aligned}
\lambda_{ni} &= \frac{L_{ni}}{L_{\mathbb{M}}} \frac{L_{\mathbb{M}}}{L_{\mathbb{N}}} = \frac{L_{ni}}{L_{\mathbb{N}}} \\
&= \frac{(B_{ni} w_i)^\varepsilon (\kappa_{ni} P_n^\alpha Q_n^{1-\alpha})^{-\varepsilon}}{\sum_{k \in \mathbb{N}} \sum_{\ell \in \mathbb{N}} (B_{k\ell} w_\ell)^\varepsilon (\kappa_{k\ell} P_k^\alpha Q_k^{1-\alpha})^{-\varepsilon}}, n, i \in \mathbb{N}
\end{aligned} \tag{2.4}$$

where L_{ni} is the measure of commuters from n to i.

The probability of commuting between residence n and workplace i depends on the characteristics of that residence n, the attributes of that workplace i and bilateral commuting costs and amenities. Summing across workplaces $i \in \mathbb{N}$, we obtain the probability that a worker lives in residence $n \in \mathbb{N}$, conditional on choosing a residence-workplace pair in Greater London $(\lambda_n^R = \frac{R_n}{L_{\mathbb{N}}})$. Similarly, summing across residences $n \in \mathbb{N}$, we obtain the probability that a worker is employed in workplace $i \in \mathbb{N}$, conditional on choosing a residence-workplace pair in Greater London $(\lambda_i^L = \frac{L_i}{L_{\mathbb{N}}})$

$$\begin{aligned}
\lambda_n^R &= \frac{\sum_{i \in \mathbb{N}} (B_{ni} w_i)^\varepsilon (\kappa_{ni} P_n^\alpha Q_n^{1-\alpha})^{-\varepsilon}}{\sum_{k \in \mathbb{N}} \sum_{\ell \in \mathbb{N}} (B_{k\ell} w_\ell)^\varepsilon (\kappa_{k\ell} P_k^\alpha Q_k^{1-\alpha})^{-\varepsilon}} \\
\lambda_i^L &= \frac{\sum_{n \in \mathbb{N}} (B_{ni} w_i)^\varepsilon (\kappa_{ni} P_n^\alpha Q_n^{1-\alpha})^{-\varepsilon}}{\sum_{k \in \mathbb{N}} \sum_{\ell \in \mathbb{N}} (B_{k\ell} w_\ell)^\varepsilon (\kappa_{k\ell} P_k^\alpha Q_k^{1-\alpha})^{-\varepsilon}}
\end{aligned} \tag{2.5}$$

where R_n denotes employment by residence in location n and L_i denotes employment by workplace in location i. A second implication of our extreme value specification is that expected utility conditional on choosing a residence workplace pair $(\overline{U})$ is the same across all residence-workplace pairs in the economy:

$$\overline{U} = v \left[\sum_{k \in \mathbb{M}} \sum_{\ell \in \mathbb{M}} (B_{k\ell} w_{k\ell})^\varepsilon (\kappa_{k\ell} P_k^\alpha Q_k^{1-\alpha})^{-\varepsilon} \right]^{\frac{1}{\varepsilon}} \tag{2.6}$$

where the expectation is taken over the distribution for idiosyncratic amenities; $v \equiv \Gamma(\frac{\varepsilon-1}{\varepsilon})$; $\Gamma(\cdot)$ is the gamma function. Using the probability that a worker chooses a residence-workplace pair in Greater London $(\frac{L_{\mathbb{N}}}{L_{\mathbb{M}}})$, we can rewrite this probability mobility condition as:

$$\overline{U} (\frac{L_{\mathbb{N}}}{L_{\mathbb{M}}})^{\frac{1}{\varepsilon}} = v \left[\sum_{k \in \mathbb{N}} \sum_{\ell \in \mathbb{N}} (B_{k\ell} w_{k\ell})^\varepsilon (\kappa_{k\ell} P_k^\alpha Q_k^{1-\alpha})^{-\varepsilon} \right]^{\frac{1}{\varepsilon}} \tag{2.7}$$

where only the limits of the summations differ on the right hand sides of the equations.

Intuitively, for a given common level of expected utility in the economy $(\overline{U})$, locations in Greater London must offer higher real wages adjusted for common amenities (B_{ni}) and commuting costs (κ_{ni}) to attract workers with lower idiosyncratic draws with an elasticity determined by the parameter ε.

2.1.2 Production

We assume that consumption goods are produced according to a Cobb-Douglas technology using labor, machinery capital, and commercial floor space, where commercial floor space includes both building capital and land. Cost minimization and zero profits imply that payments for labor, commercial floor space, and machinery are constant shares of revenue (X_i):

$$w_i L_i = \beta^L X_i, q_i H_i^L = \beta^H X_i, r M_i = \beta^M X_i, \beta^L + \beta^H + \beta^M = 1 \tag{2.8}$$

where q_i is the price of commercial floor space; H_i^L is commercial floor space use; M_i is machinery use; and machinery is assumed to be perfectly mobile across locations with a common price r determined in the wider economy. We allow the price of commercial floor space (q_i) to potentially depart from the price of residential floor space (Q_i) in each location i through a location-specific wedge (ξ_i):

$$q_i = \xi_i Q_i. \tag{2.9}$$

From the relationship between factor payments and revenue in equation, payments for commercial floor space are proportional to workplace income ($w_i L_i$):

$$q_i H_i^L = \frac{\beta^H}{\beta^L} w_i L_i \tag{2.10}$$

2.1.3 Commuter Market Clearing

commuter market clearing implies that the measure of workers employed in each location (L_i) equals the measure of workers chooosing to commute to that location:

$$L_i = \sum_{n \in \mathbb{N}} \lambda_{ni|n}^R R_n \tag{2.11}$$

where $\lambda_{ni|n}^R$ is the probability of commuting to workplace i conditional on living in residence n:

$$\lambda_{ni|n}^R = \frac{\left(\frac{B_{ni} w_i}{\kappa_{ni}}\right)^\varepsilon}{\sum_{\ell \in \mathbb{N}} \left(\frac{B_{n\ell} w_\ell}{\kappa_{n\ell}}\right)^\varepsilon} \tag{2.12}$$

where all characteristics of residence n have canceled from the above equation because they do not vary across workplaces for a given residence.

Commuter market clearing also implies that per capita income by residence (v_n) is a weighted average of the wages in all locations, where the weights are these conditional commuting probabilities by residences ($\lambda_{ni|n}^R$):

$$v_n = \sum_{i \in \mathbb{N}} \lambda_{ni|n}^R w_i. \tag{2.13}$$

2.1.4 Land Market Clearing

We assume that floor space is owned by landlords, who receive payments from the residential and commercial use of floor space and consume only consumption goods. Land market clearing implies that total income from the ownership of floor space equals the sum of payments for residential and commercial floor space use:

$$\mathbb{Q}_n = Q_n H_n^R q_n H_n^L = (1 - \alpha) \left[\sum_{i \in \mathbb{N}} \lambda_{ni|n}^R w_i\right] R_n + \frac{\beta^H}{\beta^L} w_n L_n \tag{2.14}$$

where H_n^R is residential floor space use; rateable values ($\mathbb{Q}_n$) equals the sum of prices times quantities for residential floor space ($Q_n H_n^R$) and commercial floor space ($q_n H_n^L$); and we have used the expression for per capita income by residence (v_n) from commuter market clearing.

From the combined land and commuter market-clearing condition, payments for residential floor space are a constant multiple of residence income ($v_n R_n$), and payments for commercial floor space are a constant multiple of workplace income ($w_n L_n$). Importantly, we allow the supplies of residential floor space (H_n^R) and commercial floor space (H_n^L) to be endogenous, and we allow the prices of residential and commercial floor space to potentially differ from one another through the location-specific wedge $\xi_i (q_i = \xi_i Q_i)$. In our baseline quantitative analysis below, we are not required to make assumptions about these supplies of residential and commercial floor space or this wedge between commercial and residential floor prices. The reason is that we condition on the observed rateable values in the data ($\mathbb{Q}_n$) and the supplies and prices for residential and commercial floor space (H_n^R, H_n^L, Q_n, q_n) only after the land market-clearing condition.

2.2 Quantitative Analysis

2.2.1 Combined Land and Commuter Market Clearing

We evaluate the effect of changes in the transport network by using an "exact hat algebra" approach. In particular, we rewrite our combined land and commuter market clearing condition for another year $\tau \neq t$ in terms of the values of variables in a baseline year t and the relative changes of variables between years τ and t:

$$\hat{\mathbb{Q}}_{nt} \mathbb{Q}_{nt} = (1 - \alpha) \hat{v}_{nt} v_{nt} \hat{R}_{nt} R_{nt} + \frac{\beta^H}{\beta^L} \hat{w}_{nt} w_{nt} \hat{L}_{nt} L_{nt} \tag{2.15}$$

where $\hat{x}_{nt} = \frac{x_{n\tau}}{x_{nt}}$ for the variable x_{nt} and we now make explicit the time subscripts. The relative change in employment ($\hat{L}_{it}$) and the relative change in average per capita income by residence ($\hat{v}_{nt}$) for year τ can be expressed as:

$$\hat{L}_{it} L_{it} = \sum_{n \in \mathbb{N}} \frac{\lambda_{nit|n}^R \hat{w}_{it}^\varepsilon \hat{\kappa}_{nit}^{-\varepsilon}}{\sum_{\ell \in \mathbb{N}} \lambda_{n\ell t|n}^R \hat{w}_{\ell t}^\varepsilon \hat{\kappa}_{n\ell t}^{-\varepsilon}} \hat{R}_{nt} R_{nt} \tag{2.16}$$

$$\hat{v}_{nt} v_{nt} = \sum_{i \in \mathbb{N}} \frac{\lambda_{nit|n}^R \hat{w}_{it}}{\sum_{\ell \in \mathbb{N}} \lambda_{n\ell t|n}^R \hat{w}_{\ell t}^\varepsilon \hat{\kappa}_{n\ell t}^{-\varepsilon}} \hat{w}_{it} w_{it} \tag{2.17}$$

where these equations include terms in change in wages ($\hat{w}_n$) and commuting costs ($\hat{\kappa}_{ni}$) but not in amenities, because we assume that the workplace and bilateral components of amenities are constant ($\hat{B}_{it}^L = 1$ and $\hat{B}_{nit}^I = 1$), and changes in the residential component of amenities ($\hat{B}_{nt}^R \neq 1$) cancel from the numerator and denominator of the fractions.

substituting the expressions to the market clearing conditions for year τ we can get the result.

Lemma 2.1. *Suppose that* $(\hat{\mathbb{Q}}_{nt}, \hat{R}_{nt}, L_{nit}, \lambda_{nit|n}^R, \mathbb{Q}_{nt}, v_{nt}, R_{nt}, w_{nt}, L_{nt})$ *are known. Given known values for model parameters* $\{\alpha, \beta^L, \beta^H, \varepsilon\}$ *and the change in bilateral commuting costs* $(\hat{\kappa}_{nit}^{-\varepsilon})$, *the combined land and commuter market clearing condition determines a unique vector of relative changes in wages* $(\hat{w}_{it})$ *in each location.*

Chapter 3

Urban Diversity, Process Innovation, and the Life Cycle of Products

3.1 The model

There are N cities in the economy, where N is endogenous, and a continuum L of infinitely lived workers, each of which has one of m possible discrete aptitudes. There are equal proportion of workers with each aptitude in the economy, but their distribution across cities is endogenously determined through migration. Let us index cities by i and worker aptitudes by subscript j so that l_i^j denotes the supply of labor with aptitude j in city i. Time is discrete and indexed by t.

3.1.1 Technology

The ideal production process is firm specific and randomly drawn from a set of m possible discrete processes, with equal probability for each. Each of the m possible processes for each firm requires process specific intermediate inputs from a local sector employing workers of a specific aptitude. We say that two production processes for different firms are of the same type if they require intermediates produced using workers with the same aptitude.

 A newly created firm does not know its ideal production process, but it can find this by trying, one at a time, different processes in the production of prototypes. After producing a prototype with a certain process, the firm knows whether this process is its ideal one or not. Thus in order to switch from prototype to mass production a firm needs to have produced a prototype with its ideal process first, or to have tried all of its m possible processes except one. Furthermore, we allow for the possibility that a firm decides to stop searching before learning its ideal process. Firms have an exogenous probability δ of closing down each period. Firms also lose one period of production whenever they relocate from one city to another. Thus, the cost of firm relocation increases with the exogenous probability of closure δ.

 THe intermediates specific to each type of process are produced by a monopolistically competitive intermediate sector, each such intermediate sector hires workers of aptitude j and sells process-specific nontradable intermediate services to final-good firms using a process of type j. These differentiated services enter the production function of final good producers with the same constant elasticity of substitution $\frac{\varepsilon+1}{\varepsilon}$. The production is:

$$\overset{?\,j}{C_i}(h) = Q_i^j \overset{?\,j}{x_i}(h) \tag{3.1}$$

$$\text{where } Q_i^j = (l_i^j)^{-\varepsilon} w_i^j, \varepsilon > 0 \tag{3.2}$$

We distinguish variables corresponding to prototypes from those corresponding to mass-produced goods by an accent in the form of a question mark, ?. INdexing the differentiated varieties of goods by h, we denote ouput of prototype h made with a process of type j in city i by $\overset{?}{x}{}_i^{\,j}(h)$. Q_i^j is the unit cost for firms producing prototypes using a process of type j in city i and w_i^j is the wage per unit of labor for the corresponding workers. Note that Q_i^j decreases as l_i^j increases: there are localization economies that reduce unit costs when there is a larger supply of labor with the relevant aptitude in the same city.

When a firm finds its ideal production process, it can engage in mass production at a fraction ρ of the cost of producing a prototype, where $0 < \rho < 1$. Thus the cost function for a firm engaged in mass production is:

$$C_i^j(h) = \rho Q_i^j x_i^j(h) \tag{3.3}$$

where $x_i^j(h)$ denotes the ouput of mass produced good h, made with a process of type j, in city i.

With respect to the internal structure of cities, there are congestion costs in each city incurred in labor time and parameterized by $\tau(>0)$. Labor supply, l_i^j, and production, L_i^j, with aptitude j in city i are related by the following expression:

$$l_i^j = L_i^j\left(1 - \tau \sum_{j=1}^{m} L_i^j\right). \tag{3.4}$$

THe expected wage income of a worker with aptitude j in city i is then $(1 - \tau \sum_{j=1}^{m} L_i^j)w_i^j$, where the higher land rents pair by those living closer to the city center are offset by lower commuting costs.

3.1.2 Preferences

Each period consumers allocate a fraction μ of their expenditure to prototypes and a fraction of $1 - \mu$ to mass-produced goods. The instantaneous indirect utility of a consumer in city i is:

$$V_i = \overset{?}{P}{}^{-\mu} P^{-(1-\mu)} e_i^j \tag{3.5}$$

where e_i denotes individual expenditure.

$$\overset{?}{P} = \left\{ \sum_{j=1}^{m} \int \int [\overset{?}{P}{}_i^{\,j}(h)]^{1-\sigma} dh di \right\}^{1/(1-\sigma)} \tag{3.6}$$

$$P = \left\{ \sum_{j=1}^{m} \int \int [p_i^j(h)]^{1-\sigma} dh di \right\}^{1/(1-\sigma)} \tag{3.7}$$

and the appropriate price indices of prototypes and mass-produced goods respectively, and $\overset{?}{P}{}_i^{\,j}(h)$ and $p_i^j(h)$ denote the price of individual varieties of prototypes and mass-produced goods respectively. All prototypes enter consumer preferences with the same elasticity of substitution $\sigma(>2)$, and so do all mass produced goods.

3.1.3 Income and Migration

National income, Y, is the sum of expenditure and investment:

$$Y = \sum_{j=1}^{m} \int L_i^j e_i^j di + \overset{?}{P}{}^{\mu} P^{1-\mu} F \overset{\circ}{n} \tag{3.8}$$

L_i^j denotes population with aptitude j in city i. Investment $\overset{?}{P}{}^{\mu} P^{1-\mu} F \overset{\circ}{n}$ comes from aggregation of the start-up costs incurred by newly created firms. To come up with a new product, the firm must spend F on market research, purchasing the same combination of goods bought by the representative consumer. Finally, $\overset{\circ}{n}$ denotes the total number of new firms.

Definition 3.1 (Specialized City). A city is said to be fully specialzied if all its workers have the same aptitude, so that all local firms use the same type of production process.

Definition 3.2 (Diversified City). A city is said to be (fully) diversified if it has the same proportion of workers with each of the m aptitudes, so that there are equal proportions of firms using each of the m types of production process.

3.1.4   City Formation

Each potential site for a city is controlled by a different land development company or land developer, not all of which will be active in equilibrium. Developers have the ability to tax local land rents and to make transfers to local workers. When active, each land developer commits to a contract with any potential worker in its city that specifies the size of the city, whether it has a dominant sector and if so which, and any transfers.

3.1.5   Equilibrium Definition

Finally, a steady state equilibrium in this model is a configuration such that all of the following are true. Each developer offers a contract designed so as to maximize its profits. Each firm chooses a location/production strategy and prices so as to maximize its expected lifetime profits. All profit opportunities are exploited and then urban structure is constant over time.

3.2   Equilibrium City Sizes

Lemma 3.1 (Output per Worker). *In equilibrium, output per worker by firms using processes of type j in city i in a given period is:*

$$\frac{\overset{?}{n}_i^j \overset{?}{x}_i^j + \rho n_i^j x_i^j}{L_i^j} = (L_i^j)^\varepsilon (1 - \tau \sum_{j=1}^{m} L_i^j)^{\varepsilon+1}.$$

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Chapter 4

Spatial Sorting and Inequality

4.1 Change in SKill Sourting: Framework

4.1.1 Setup

On the production side, rather than modelling imperfect trade between locations, we consider an economy that is more stylized spatially, with two types of goods: (a) a homogeneous manufactured good that is freely traded across space and (b) housing, a local nontraded good.

Preferences

Consider a spatial equilibrium framework with two skill groups $\theta = U, S$, who choose where to live among locations $i \in [1, \ldots, N]$. Aggregate skill supply for each group, L^θ, is exogenously given, and each worker supplies one unit of labor for wage w_i^θ in location i. The utility of worker w, who is type θ and lives in location i, is:

$$u_i^\theta(w) = \max_{c,b} \log U^\theta(A_i, c, b) + \varepsilon_i^\theta(w), \text{ such that } c + r_i b = w_i^\theta \tag{4.1}$$

Here $\log U^\theta(\cdot)$ is the representative utility of a worker of type θ; c is the consumption of the freely traded good and is taken as the numeraire; b denote housing, with price r_i in location i; and A_i is a vector of amenities in location i. Finally, $\varepsilon_i^\theta(w)$ is a worker-specific preference shock for living in location i.

First, we make assumption of CD type preferences over traded and nontraded goods. Second, we assume that amenities are separable from consumption. We allow amenities in location i to be valued differently by the two groups, as caputured by a group-specific amenity level A_i^θ. Third, preference shocks are typically chosen to be extreme value (EV) distributed. Papers in the tradition of urban and labor economics or industrial organization tend to use logit shocks, with normalized variance $\frac{\pi^2}{6}$ shifted by a factor $\frac{1}{\kappa^\theta)}$, which together with CD utility lead to the following indirect utility of worker θ in location i:

$$v_i^\theta(w) = \log A_i^\theta + \log w_i^\theta - \alpha^\theta \log r_i + \frac{1}{\kappa^\theta} \varepsilon_i^\theta(w)$$

Equivalently, papers in the tradition of trade and economic geography typically choose Frechet shocks for $\varepsilon_i^\theta(w)$ with scale parameter $\kappa^\theta > 1$ that enter utility in a multiplicatively separable way. In that case, the indirect utility of worker θ in location i is:

$$v_i^\theta(w) = \frac{A_i^\theta w_i^\theta}{r_i^{\alpha^\theta}} \varepsilon_i^\theta(w).$$

In either case, location choices in group θ can be summarized with λ_i^θ, the share of θ workers who choose location i:

$$\lambda_i^\theta = \frac{(\frac{A_i^\theta w_i^\theta}{r_i^{\alpha^\theta}})^{\kappa^\theta}}{\sum_{j=1}^N (\frac{A_j^\theta w_j^\theta}{r_j^{\alpha^\theta}})^{\kappa^\theta}} \tag{4.2}$$

The parameter κ^θ captures the elasticity of population shares with respect to amenity-adjusted real wages and is therefore a measure of mobility of group θ, which we allow to be group specific. Expected utility for a worker in group θ across locations is:

$$W^\theta = \delta^\theta \left[\sum_{k=1}^N (\frac{A_i^\theta w_i^\theta}{r_i^{\alpha^\theta}})^{\kappa^\theta} \right]^{\frac{1}{\kappa^\theta}} \tag{4.3}$$

where $\delta^\theta = \Gamma(\frac{\kappa^\theta-1}{\kappa^\theta})$ and $\Gamma(\cdot)$ is the gamma function in the Frechet case.

Supply of goods, amenities, and housing

We first write down the labor demand side of the economy. In location i, output is produced by perfectly competitive firms. They combine skilled and unskilled labor, who are imperfect substitutes in production:

$$Y_i = \left[(z_i^U)^{\frac{1}{\rho}} (L_i^U)^{\frac{\rho-1}{\rho}} + (z_i^S)^{\frac{1}{\rho}} (L_i^S)^{\frac{\rho-1}{\rho}} \right]^{\frac{\rho}{\rho-1}} \tag{4.4}$$

In the CES production function, $\rho \geq 1$ is the elasticity of substitution between skills and z_i^θ are location- and skill specific productivity shifters. The shifters can be in part exogenous and in part endogenous, reflecting externalities. We assume that, for $\theta = \{U, S\}$ and $\forall i$,

$$z_i^\theta = z^\theta(\overline{Z}_i, L_i^U, L_i^S) \tag{4.5}$$

where $\overline{Z}_i$ is the exogenous productivity component in city i. Local productivity spillovers are allowed here to depend not just on city size or density but also on its composition (L_i^U, L_i^S). Given equation, relative labor demand in location i is:

$$\log\left(\frac{L_i^S}{L_i^U}\right) = \log\left(\frac{z_i^S}{z_i^U}\right) - \rho \log\left(\frac{w_i^S}{w_i^U}\right) \tag{4.6}$$

Furthermore, competition across cities ensures that the unit cost of production in all cities is 1, the common price of the freely traded good:

$$\sum_\theta z_i^\theta (w_i^\theta)^{1-\rho} = 1, \forall i$$

Similar to productivity, amenities A_i^θ are assumed to be driven by both exogenous differences, and endogenous differences between cities, that is,

$$A_i^\theta = A^\theta(\overline{A}_i, L_i^U, L_i^S) \tag{4.7}$$

where A_i is the exogenous amenity component of city i. Endogenous amenities capture elements of quality of life that change when the size or composition of cities changes.

Finally, we assume that housing is supplied by atomistic absentee landowners and the aggregate housing supply function in city i is:

$$H_i = \overline{H}_i r_i^{\eta_i} \tag{4.8}$$

The housing supply elasticity η_i is allowed to be city specific.

A spatial equilibrium of this economy is a set of location choices $\{\lambda_i^\theta\}_{i,\theta}$ prices $\{w_i^\theta, r_i\}_{i,\theta}$ and amenities and productivity shifters $\{z_i^\theta, A_i^\theta\}_{i,\theta}$ such that workers and firms optimize, traded good firms make no profits, and markets clear. Since amenities and productivity shifters $\{z_i^\theta, A_i^\theta\}_{i,\theta}$ typically depend on the equilibrium distribution of economic activity, these local spillovers act as feedback loops that may amplify or dampen concentration and sorting.

We now discuss conditions under which sorting arises in the equilibrium. In using the term spatial sorting, we mean the fact that the skilled and unskilled groups make different location choices, i.e., there exist locations i and j such that, denoting $\Delta X = X_i - X_j$ for any variable X,

$$\Delta \log\left(\frac{L^S}{L^U}\right) \neq 0$$

Then relative spatial supply is combined with location choices, combining labor supply and labor demand:

$$\Delta \log\left(\frac{L^S}{L^U}\right) = \underbrace{\frac{\tilde{\kappa}^S}{\rho}\Delta \log\left(\frac{z^S}{z^U}\right)}_{} \equiv \Delta z + \underbrace{\tilde{\kappa}^S \Delta \log\left(\frac{A^S}{A^U}\right)}_{} \equiv \Delta A + \underbrace{\tilde{\kappa}^S(\alpha^U - \alpha^S)\Delta \log r}_{} \equiv \Delta \alpha + \underbrace{\frac{\tilde{\kappa}^S}{\kappa^U}(1 - \frac{\kappa^U}{\kappa^S})\Delta \log L^U}_{} \equiv \Delta \tag{4.9}$$

where we denote $\tilde{\kappa}^S = \frac{\kappa^S \rho}{\kappa^S + \rho}$. Conceptually, one can therefore distinguish four sources of sourcing in this framework: We say that soring is shaped by comparative advantage in production when $\Delta \log\left(\frac{z^S}{z^U}\right) \neq 0$, by amenities when $\Delta \log\left(\frac{A^S}{A^U}\right) \neq 0$ by housing price when $\alpha^S \neq \alpha^U$, and by heterogeneous across groups when $\kappa^U \neq \kappa^S$.

A first takeaway is that, when productivity is separable between a location shifter Z_i and nationwide group productivity z^θ so that $z_i^\theta = Z_i z^\theta$, the productivity advantage of a location is skill neutral and hence does not drive sorting directly. We now assume, in contrast, that some skill group has comparative advantage in production in some location over another so that $\Delta \log\left(\frac{z^S}{z^U}\right) \neq 0$. For simplicity, we assume that local productivity depends on population, which is the most classic way to parameterize agglomeration effects, but with a different intensity γ_P^θ for different skill groups, that is,

$$z_i^\theta = \overline{z}_i^\theta (L_i^U + L_i^S)^{\gamma_P^\theta} \tag{4.10}$$

In this expression, $\overline{z}_i^\theta$ are exogenous location-group productivity shifters. Equilibrium sorting is then pinned down by:

$$\Delta \log\left(\frac{L^S}{L^U}\right) = \frac{\tilde{\kappa}^S}{\rho}\Delta \log\left(\frac{\overline{z}^S}{\overline{z}^U}\right) + \frac{\tilde{\kappa}^S}{\rho}(\gamma_P^S - \gamma_P^U)\Delta \log L + \Delta_A + \Delta_\alpha + \Delta_\kappa$$

Changes in sorting due to productivity correspond to the first two terms on the right hand side of the above equation. First, such changes may occur because of changes in exogenous comparative advantage $\Delta \log\left(\frac{\overline{z}^S}{\overline{z}^U}\right)$. Second, changes in sorting may occur because of changes in relative city sizes $\Delta \log L$ or because of changes in relative agglomeration forces $\gamma_P^S - \gamma_P^U$.

We parameterize utility derived from amenities as a CD aggregator of a vectorof amenities $\{A_{ki}\}_k$ in location i, with skill group-specific preference parameters γ_{kA}^θ. This allow both skill groups to have different preferences over each city's amenity bundle:

$$A_i^\theta = \Pi_k (A_{ki})^{\gamma_{kA}^\theta} \tag{4.11}$$

We allow a component of each amenity in the amenity bundle to be endogenous. We model the endogenous component of amenity as responding to the skill ratio $\frac{L_i^S}{L_i^U}$ of that city; that is,

$$A_{ki} = \tilde{A}_{ki}(\frac{L_i^S}{L_i^U})^{\beta_k} \tag{4.12}$$

where $\tilde{A}_{ki}$ is the exogenous component of amenity k and β_k measures how elasticity the supply of amenity k is to the skill ratio. With these formulations, equilibrium sorting is:

$$\Delta \log\left(\frac{L^S}{L^U}\right) = \frac{\tilde{\kappa}^S}{1 - \tilde{\kappa}^S(\tilde{\gamma}_A^S - \tilde{\gamma}_A^U)} \Delta \log\left(\frac{\tilde{A}^S}{\tilde{A}^U}\right) + \frac{1}{1 - \tilde{\kappa}^S(\tilde{\gamma}_A^S - \tilde{\gamma}_A^U)}[\Delta_z + \Delta_\alpha + \Delta_\kappa]$$

where we denote $\tilde{\gamma}_A^\theta = \sum_k[\beta_k(\gamma_{kA}^\theta)]$ and $\frac{\tilde{A}_i^S}{\tilde{A}_i^U} = \Pi_k(\tilde{A}_{ki})^{\gamma_{kA}^S - \gamma_{kA}^U}$. First, amenities are a source of sorting in themselves only to the extent that the first term is nonzero. Second, the endogenous provision of amenities ($\beta_k \neq 0$) together with their heterogeneous valuation across skills ($\gamma_{kA}^S - \gamma_{kA}^U \neq 0$) serve only as an amplifier of other sorting forces.

To make clear the specific mechanisms at play here, we shut down the other sources of sorting by making the following assumptions:

Assumption 4.1. $\Delta \log\left(\frac{z^S}{z^U}\right) = 0, \Delta \log\left(\frac{A^S}{A^U}\right) = 0$ and $\kappa^U = \kappa^S$.

Under assumption 1, some cities may still be more productive or have hiigher amenities than others, but in a way that is skill neutral: there exist citywide shifters Z_i and A_i and nationwide group-specific shifters z^θ, A^θ such that $z_i^\theta = Z_i z^\theta$ and $A_i^\theta = A_i A^\theta$ for all location i. If housing is a necessary, then $\alpha^U - \alpha^S > 0$ and skilled workers are overrepresented in expensive cities. Given the housing supply equation, equilibrium housing prices are implicit solution to:

$$\frac{Z_i^{\frac{1+\kappa}{\rho-1}} A_i^\kappa}{\overline{H}_i} = r_i^{\eta_i} \left[\sum_\theta w^\theta f_i(r_i) r_i^{\kappa\alpha^\theta \frac{1-\rho}{\kappa+\rho} - 1}\right]^{-1} \tag{4.13}$$

where $f_i(r_i)$ captures that, in equilibrium, wages depend on rents. This function can be shown to be equal to 1 when skills are perfect substitutes, and it is a decreasing function of r_i otherwise. Given that equation, rents r_i increase with $\frac{Z_i^{\frac{1+\kappa}{\rho-1}} A_i^\kappa}{\overline{H}_i}$: More productive cities and cities with higher amenities are more expensive in equilibrium. We denote $\mathcal{R}_i(\cdot)$ as the corresponding solution to that equation. Turning to the implication of housing rents for skill sorting, we obtain:

$$\Delta \log\left(\frac{L^S}{L^U}\right) = (\alpha^U - \alpha^S)\Delta \log \mathcal{R}(\frac{Z^{\frac{1+\kappa}{\rho-1}} A^\kappa}{\overline{H}}) \tag{4.14}$$

and high skill sorting into more productive and/or more attractive locations. First, when housing expenditure shares different across groups, Hicks-neutral city advantage is enough to drive sorting through its impact on housing prices. Second, the role of housing in mediating spatial sorting forces is stronger, all else equal, in locations with more inelastic housing supply (lower η). Inelastic supply directly leads to steeper $\mathcal{R}(\cdot)$, hence to a steeper response of housing price to productivity and amenities, and in turn to a steeper response of the skill ratio.

Heterogeneous migration elasticity

Finally, a last possible driver of sorting arises when $\kappa^U \neq \kappa^S$. Empirical findings find that higher-skill workers are more mobile than lower-skill workers, so, $\kappa^S > \kappa^U$.

Assumption 4.2. $\Delta \log\left(\frac{z^S}{z^U}\right) = 0, \Delta \log\left(\frac{A^S}{A^U}\right) = 0,$ *and* $\alpha^U = \alpha^S$.

It is easy to see that:

$$\Delta \log\left(L^S\right) = \left[\underbrace{1 + \frac{\rho}{\kappa^S + \rho}(\frac{\kappa^S}{\kappa^U} - 1) > 0}\right] \Delta \log L^U \tag{4.15}$$

Under Assumption 2, there is no skill-biased amenity or productivity advantage of places. Still, the high-skill population increases faster than the low-skill population in attractive cities because members of the former group are more sensitive to city characteristics.

Urban skill premium and sorting

We now turn to considering how they shape the distribution of the skill wage premium in the cross section of cities, in equilibrium. Solving out for the equilibrium skill premium and its variation over space leads to

$$\Delta \log\left(\frac{w^S}{w^U}\right) = \frac{1}{\kappa^S}\Delta_z - \frac{1}{\rho}\Delta_A - \frac{1}{\rho}\Delta_\alpha - \frac{1}{\rho}\Delta_\kappa \tag{4.16}$$

Comparing this expression with the one that summarizes skill sorting we have:

$$\Delta \log\left(\frac{L^S}{L^U}\right) = \Delta_z + \Delta_A + \Delta_\alpha + \Delta_\kappa$$

Chapter 5

Urban Accounting and Welfare

5.1 The Model

5.1.1 Technology

Consider a model of a system of cities in an economy with N_t workers. Goods are produced in I monocentric circular cities. Cities have a local level of productivity. Production in city i in period t is given by:

$$Y_{it} = A_{it} K_{it}^{\theta} H_{it}^{1-\theta}$$

where A_{it} denotes city productivity, K_{it} denotes total capital, and H_{it} denotes total hours worked in the city. We denote the population size of city i by N_{it}. The standard first-order conditions of this problem are:

$$w_{it} = (1-\theta)\frac{Y_{it}}{H_{it}} = (1-\theta)\frac{y_{it}}{h_{it}} \text{ and } r_t = \theta\frac{Y_{it}}{K_{it}} = \theta\frac{y_{it}}{k_{it}} \tag{5.1}$$

where lowercase letters denote per capita variables. Note that capital is freely mobile across locations so there is a national interest rate r_t. Mobility patterns will not be determined solely by the wage, w_{it}, so there may be equilibrium differences in wages across cities at any point in time. We can then write down the "efficiency wedge", which is identical to the level of productivity, A_{it}, as:

$$A_{it} = \frac{Y_{it}}{K_{it}^{\theta} H_{it}^{1-\theta}} = \frac{y_{it}}{k_{it}^{\theta} h_{it}^{1-\theta}} \tag{5.2}$$

5.1.2 Preferences

Agents order consumption and hour sequenecs according to the following utility function:

$$\sum_{t=0}^{\infty} \beta^t \left[\log c_{it} + \psi \log(1 - h_{it}) + \gamma_i\right],$$

where γ_i is a city-specific amenity and ψ is a parameter that governs the relative preference for leisure. Each agent lives on one unit of land and commutes from his home to work. Commuting is costly in terms of goods. The problem of an agent in city i_0 with cpaital k_0 is therefore,

$$\max_{\{c_{i_t,t}, h_{i_t,t}, k_{i_t,t}, i_t\}_{t=0}^{\infty}} \sum_{t=0}^{\infty} \beta^t \left[\log c_{it} + \psi \log(1 - h_{it}) + \gamma_i\right]$$

subject to the budget constraint:

$$c_{it} + x_{it} = r_t k_{it} + w_{it} h_{it} (1 - \tau_{it}) - R_{it} - T_{it}$$
$$k_{it+1} = (1 - \delta) k_{it} + x_{it}$$

where x_{it} is investment, τ_{it} is a labor tax or friction associated with the cost of building the commuting infrastructure, R_{it} are land rents, and T_{it} are commuting costs.

We assume that we are in steady state so $k_{it+1} = k_{it}$ and $x_{it} = \delta k_{it}$. Furthermore, we assume k_{it} is such that $r_t = \delta$. The simplified budget constraint of the agent becomes:

$$c_{it} = w_{it} h_{it} (1 - \tau_{it}) - R_{it} - T_{it}. \tag{5.3}$$

The first-order conditions of this problem imply $\psi \frac{c_{it}}{1 - h_{it}} = (1 - \tau_{it}) w_{it}$. Combining the expression with the first equation, we obtain:

$$(1 - \tau_{it}) = \frac{\psi_{it}}{(1 - \theta)} \frac{c_{it}}{1 - h_{it}} \frac{h_{it}}{y_{it}} \tag{5.4}$$

We refer to τ_{it} as the "labor wedge". Although τ_{it} is modeled as a labor tax, it should be interpreted more broadly as anything that distorts an agent's optimal labor supply decision. Agents can move freely across cities so utility in each period has to be determined by:

$$\overline{u} = \log c_{it} + \psi \log(1 - h_{it}) + \gamma_i \tag{5.5}$$

for all cities with $N_{it} > 0$, where $\overline{u}$ is the economy-wide per period utility of living in a city.

5.1.3 Commuting Cost, Land Rents, and City Equilibrium

Cities are monocentric, all production happens at the center, and people live in surrounding areas characterized by their distance to the center, d. Cities are surroundedby a vast amount of agricultural land that can be freely converted into urban land. We normalize the price of agricultural land to zero. Since land rents are continuous in equilibrium, this implies that at the boundary of a city, $\overline{d}_{it}$, land rents should be zero as well, namely, $R(\overline{d}_{id}) = 0$. Since, all agents in a city are identical, in equilibrium they must be indifferent between they live in a city, which implies that the total cost of rent plus commuting costs should be identical in all areas of a city. So,

$$R_{it}(d) + T(d) = T(\overline{d}_{it}) = \kappa \overline{d}_{it}, \forall d \in [0, \overline{d}_{it}]$$

since $T(d) = \kappa d$ where κ denotes commuting costs per mile.

Everyone lives on one unit of land, $N_{it} = \overline{d}_{it}^2 \pi$, and so $\overline{d}_{it} = (N_{it}/\pi)^{\frac{1}{2}}$. Thus $R_{it} + T(d) = \kappa(N_{it}/\pi)^{\frac{1}{2}}$. This implies that $R_{it}(d) = \kappa(\overline{d}_{it} - d)$ and so total land rents in a city of size N_{it} are given by $TR_{it} = \int_0^{\overline{d}_{it}} (\kappa(\overline{d}_{it} - d) d2\pi) dd = \frac{\kappa}{3} \pi^{-\frac{1}{2}} N_{it}^{\frac{3}{2}}$. Hence, arrange land rents are equal to $AR_{it} = \frac{2\kappa}{3} (\frac{N_{it}}{\pi})^{\frac{1}{2}}$. Taking logs and rearranging terms, we obtain that:

$$\log(N_{it}) = o_1 + 2 \log AR_{it}. \tag{5.6}$$

where o_1 is a constant. We can also compute the total miles traveled by commuters in the city, which is given by:

$$TC_{it} = \int_0^{\overline{d}_{it}} (d^2 2\pi) dd = \frac{2}{3} \pi^{-\frac{1}{2}} N_{it}^{\frac{3}{2}} \tag{5.7}$$

5.1.4 Government Budget Constraint

The government levies a labor tax, τ_{it}, to pay for the transportation infrastructure. Let government expenditure be a function of total commuting costs and wages such that:

$$G(h_{it}w_{it}, TC_{it}) = g_{it}h_{it}w_{it}\kappa TC_{it} = g_{it}h_{it}w_{it}\kappa\frac{2}{3}\pi^{-\frac{1}{2}}N_{it}^{\frac{3}{2}}$$

where g_{it} is a measure of government inefficiency. That is, the government requires κg_{it} workers per mile commuted to build and maintain urban infrastructure. The government budget constraint is then given by:

$$\tau_{it}h_{it}N_{it}w_{it} = g_{it}h_{it}w_{it}\kappa\frac{2}{3}\pi^{-\frac{1}{2}}N_{it}^{\frac{3}{2}} \tag{5.8}$$

which implies that the labor wedge can be written as:

$$\tau_{it} = g_{it}\kappa\frac{2}{3}\left(\frac{N_{it}}{\pi}\right)^{\frac{1}{2}} \tag{5.9}$$

or

$$\log\tau_{it} = o_2 + \frac{1}{2}\log N_{it} + \log g_{it} \tag{5.10}$$

5.1.5 Equilibrium

The consumer budget constraint is given by:

$$c_{it} = w_{it}h_{it}(1 - \tau_{it}) - R_{it} - T_{it} = (1 - \theta)(1 - \tau_{it})y_{it} - \kappa\left(\frac{N_{it}}{\pi}\right)^{\frac{1}{2}}$$

To determine output we know that the proudction function is given by $y_{it} = A_{it}k_{it}^{\theta}h_{it}^{1-\theta}$ and the decision of firms to rent capital implies that $r_t k_{it} = \theta y_{it}$. Hence,

$$y_{it} = A_{it}\left(\frac{\theta y_{it}}{r_t}\right)^{\theta}h_{it}^{1-\theta} = A_{it}^{\frac{1}{1-\theta}}\left(\frac{\theta}{r_t}\right)^{\frac{\theta}{1-\theta}}h_{it}.$$

Using the above result, we can derive

$$h_{it} = \frac{1}{1+\psi}\left(1 + \frac{\psi(R_{it} + T_{it})}{(1-\theta)(1-\tau_{it})}\frac{\left(\frac{r_t}{\theta}\right)^{\frac{\theta}{1-\theta}}}{A_{it}^{\frac{1}{1-\theta}}}\right)$$

and

$$c_{it} = \frac{1}{1+\psi}\left[(1-\theta)(1-\tau_{it})\left(\frac{\theta}{r_t}\right)^{\frac{\theta}{1-\theta}}A_{it}^{\frac{1}{1-\theta}} - (R_{it} + T_{it})\right]$$

The free mobility assumption in the result implies that $\bar{u}_t = \log c_{it} + \psi\log(1 - h_{it}) + \gamma_{it}$ for some $\bar{u}_t$ determined in general equilibrium so:

$$\bar{u}_{it} + (1+\psi)\log(1+\psi) - \psi\log\psi$$

$$= \log\left((1-\theta)\left(1 - \kappa g_{it}\frac{2}{3}\left(\frac{N_{it}}{\pi}\right)^{\frac{1}{2}}\right)\frac{A_{it}^{\frac{1}{1-\theta}}}{\left(\frac{r_t}{\theta}\right)^{\frac{\theta}{1-\theta}}} - \kappa\left(\frac{N_{it}}{\pi}\right)^{\frac{1}{2}}\right)$$

$$+ \psi\log\left(1 - \frac{\kappa\left(\frac{N_{it}}{\pi}\right)^{\frac{1}{2}}}{(1-\theta)\left(1 - \kappa g_{it}\frac{2}{3}\left(\frac{N_{it}}{\pi}\right)^{\frac{1}{2}}\right)}\frac{\left(\frac{r_t}{\theta}\right)^{\frac{\theta}{1-\theta}}}{A_{it}^{\frac{1}{1-\theta}}}\right) + \gamma_{it}. \tag{5.11}$$

The last equation determines the size of the city N_{it} as implicit function of city productivity A_{it}, city amenities, γ_i, government inefficiency, g_{it}, and economy wide variables like r_t and $\overline{u}_{it}$. In the above euqation, the LHS is decreasing in N_{it}. THe LHS is also increasing in A_{it} and γ_i and decreasing in g_{it}. Hence, we can prove immediately that:

$$\frac{\partial N_{it}}{\partial A_{it}} > 0, \frac{\partial N_{it}}{\partial \gamma_i} > 0, \frac{\partial N_{it}}{\partial g_{it}} < 0 \tag{5.12}$$

The economy wide utility level $\overline{u}_t$ is determined by the labor market clearing conditions

$$\sum_{i=1}^{I} N_{it} = N_t \tag{5.13}$$

This last equation clarifies that our urban system is closed; we do not consider urban-rural migration.

5.2 Evidence of Efficiency, Amenities, and Frictions

5.2.1 Empirical Approach

We start by estimating the following equation:

$$\log N_{it} = \alpha_1 + \beta_1 \log A_{it} + \varepsilon_{it} \tag{5.14}$$

THe value of β_1 yields the effect of the "efficiency wedge" on city population. According to the model, $\beta_1 > 0$ by the Equation (5.12). Furthermore, $\log N_{it}(A_{it}) = \beta_1 \log A_{it}$ is the population size explained by the size of the "efficiency wedge". In contrast, ε_{1it} is the part of the observed population in the city that is unrelated to the productivity; according to the model it is related to both g_{it} and γ_i. We can then estimate the following equation: $\tilde{\varepsilon}_1(g_{it}, \gamma_{it}) \equiv \varepsilon_{1it}$.

Since the "efficiency wedge" increases population size, total commuting increases, which affects the "labor wedge". This is the standard urban trade-off between productivity and agglomeration. We can estimate the effect of producitvity on the labor wedge and the decomposition of $\log N_{it}$ into $\log \tilde{N}_{it}(A_{it})$ and ε_{1it}. Hence, we estiamte:

$$\log \tau_{it} = \alpha_2 + \beta_2 \log \tilde{N}_{it}(A_{it}) + \varepsilon_{2it} \tag{5.15}$$

We denote the effect of efficiency on distortions by $\log \tilde{\tau}_{it} = \beta_2 \log \tilde{N}_{it}(A_{it})$. We can then estimate the following equation: $\tilde{\varepsilon}_{2it} \equiv \varepsilon_{2it}$. The equation also implies that the error term ε_{2it} is related to g_{it} and to $\tilde{\varepsilon}_1(g_{it}, \gamma_{it})$. Hence, we define $\tilde{\varepsilon}_2(g_{it}, \tilde{\varepsilon}_1(g_{it}, \gamma_{it})) \equiv \varepsilon_{2it}$.

We now can decompose the effect from all three elements of $(A_{it}, \gamma_{it}, g_{it})$. To do so, we estimate:

$$\log(AR_{it}) = \alpha_3 + \beta_3 \log \tilde{\tau}_{it} + \beta_4 + \varepsilon_{1it} + \beta_5 \varepsilon_{2it} + \varepsilon_{3it} \tag{5.16}$$

using median rents for AR_{it}. The effect of γ_{it} and g_{it} are determined by the estimates of β_4 and β_5. Note that ε_{1it} and ε_{2it} depend on both γ_{it} and g_{it}. However, since $\varepsilon_{2it} = \tilde{\varepsilon}_2(g_{it}, \tilde{\varepsilon}_1(g_{it}, \gamma_{it}))$ depend only on γ_{it} through ε_{1it} and we are including ε_{1it} directly in the regression, β_5 capture only the effect of changes in g_{it} on land rents.

Note that we can then use the equation to relate average rents and population sizes. So we can estiamte the model using

$$\log(N_{it}) = \alpha_4 + \beta_6 \log(AR_{it}) + \varepsilon_{4it} \tag{5.17}$$

In a circular city $\beta_6 = 2 > 0$.

5.2.2   Effects of Efficiency, Amenities, and Frictions on City Size

We can decompose the labor wedge into taxes and other distortions such that

$$(1 - \tau_{it}) = (1 - \tau'_{it})(\frac{1 - \tau_{ith}}{1 + \tau_{ith}}) \tag{5.18}$$

where τ_{it} is our measure of the labor wedge, τ_{ith} is the labor tax rate, τ_{itc} is the consumption tax rate, and τ'_{it} are other distortions. Thus expect our measure of the total labor wedge, $(1 - \tau_{it})$, to be correlated with $(1 - \tau_{ith})/(1 + \tau_{itc})$.

Chapter 6

Interacting Agents, Spatial Externalities and the Evolution of residential land use patterns

6.1 Optimal Timing of Development

Define $A(i,t)$ as the returns to the original, unsubdivided parcel (denoted i) in the undeveloped use in time period t. We will refer to this as agriculture, broadly defined to include any uses of the land in an undeveloped state. Conversion of parcel i at time T will require the agent to incur costs to reap expected one-time gross returns. Costs include the provision of subdivision infrastructure, as well as permitting and other administrative fees. We denote δ as the discount factor, defined as $\frac{1}{1+r}$ where r is the interest rate, and the one-time returns from development minus costs of conversion in time T as $V(i,T)$. Then the net returns from developing parcel i in time T equals the one time net returns minus the present value of foregone agricultural returns and is given by:

$$V(i,T) - \sum_{t=0}^{\infty} A(i,T+t)\delta^t \tag{6.1}$$

The net returns from keeping parcel i in an agricultural use in period T and developing in time period $T+1$, discounted to time T, are:

$$A(i,T) + \delta V(i,T+1) - \sum_{t=0}^{\infty} A(i,T+1)\delta^t \tag{6.2}$$

The optimal development time will occur in period T only if the Equation (6.1) is positive and if Equation (6.1) is greater than Equation (6.2). The optimal development time is the time period T if:

$$V(i,T) - \sum_{t=0}^{\infty} A(i,T+t)\delta^{T+t} > 0 \tag{6.3}$$

and

$$V(i,T) - A(i,T) \geq \delta V(i,T+1) \tag{6.4}$$

The agent develops in periop T only if (a) the net value of conversion is positive and (b)

$$\frac{V(i,T+1) - \{V(i,T) - A(i,T)\}}{V(i,T) - A(i,T)} < r$$

where r is the interest rate. Here we are interested in explaining the scattered pattern of exurban development. Such a pattern would result if net negative interactions were present, e.g., due to congestion externalities, and if these effects were sufficiently strong as to create a 'repelling' effect among residential development.

Let $\delta_s I_s(i,t)$ represent this spillover effect, where $I_s(i,t)$ is the proportion of neighboring parcels that are in a developed state at time the development decision is made, δ_s is the interaction parameter, and s indexes the order of the spaital lag, which increases with increasing distance from parcel i. Because neighboring developed lands could conceivably have positive and/or negative spillover effects, the parameter λ_s, which represents the net effect of these spillovers, could be either positive or negative at any given distance s.

Rewritting the Equation (6.1) to incorporate the effect of interactions, the net returns from developing parcel i in time period T equals:

$$V(i,T) + \sum_s \lambda_s I_s(i,T) - \sum_{t=0}^{\infty} A(i,T+t)\delta^{T+t} \tag{6.5}$$

Rewritting the conversion rule in Equation (6.4), development now occurs in the first period in which:

$$V(i,T) - \delta V(i,T+1) - A(i,T) + \sum_s (1-\delta)\lambda_s I_s(i,T) \geq 0 \tag{6.6}$$

where the value of $I(i,T)$ is assumed to be constant between periods T and $T+1$.

6.2 The Empirical Model

6.2.1 Hazard model of development

To take account of these differences across agents, define ε_i as these unobservable factors associated with the owner of parcel i. Given that ε is viewed by the research as a stochastic variable, the following gives the probability that parcel i, with surrounding land use pattern $\sum_s I_s(i,T)$ will be converted by period T:

$$\text{Prob}\{\varepsilon_i < \frac{1}{1-\delta}(V(i,T) - \delta V(i,T+1) - A(i,T)) + \sum_s \lambda_s I(i,T)\} \tag{6.7}$$

This implies that agents with large ε's, such as those who are particularly good farmers or those that place a particular high value on their undeveloped land as a source of direct utility, will convert later than agents with the same type of parcel but smalle values of ε.

The probability that a parcel with a given set of characteristics will be converted in period T is its hazard rate for period T, which is given by:

$$h(T) = \frac{F[\varepsilon^*(T+1)] - F[\varepsilon^*(T)]}{1 - F[\varepsilon^*(T)]} \tag{6.8}$$

where F is the cumulative distribution function for ε and define ε^* as the ε that makes the equation an equality. In this analysis, we choose Cox's partial likelihood method because it can accomodate time-varying covariates. Assuming that $V(i,t)$ is separable in these factors that are time varying, but spatially constant, we can apply Cox's model to our problem by defining a baseline hazard rate that is a function of time only. Let $\omega(T)$ represent the exponential of this baseline hazard rate and assume that the log of the hazard rate it linear in other arguments. Then the hazard rate for parcel i is given by:

$$h(i,T) = \omega(T) \times \exp(Z\beta). \tag{6.9}$$

where Z is a vector of parcel i's attributes, including $I_s(i,T)$, and β is a corresponding parameter vector. Cox's method is a semiparametric approach that relies on formulating the likelihood in such a way that the

baseline hazard, $\omega(T)$, drops out and therefore specification of an error distribution is unnecessary. It is the product of N contributions to the likelihood function, where N is the number of developable parcels, and the form of the nth contribution is given by:

$$L_n = \frac{h(n, T_n)}{\sum_{j=1}^{J_n} h(j, T_n)} \tag{6.10}$$

By definition, T_n is the time at which the nth parcel is converted. In the above equation, $h(n, T_n)$ is the hazard rate for the nth parcel, $h(j, T_n)$ is the hazard rate for the jth parcel, but evaluated at time T_n, and J_n is the set of parcels that have 'survived' in the undeveloped state until time T_n.

6.2.2   The identification Problem

The vector of $Z(i)$ contains all attributes associated with parcel i and the stochastic term ε_i captures the existence of idiosyncratic factors associated with agent i.