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Raian Kudashev, DEM, Université du Luxembourg, UL
Pierre M. Picard, DEM, Université du Luxembourg, UL

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For editorial correspondence, please contact: dem@uni.lu
University of Luxembourg
Faculty of Law, Economics and Finance
4, rue Alphonse Weicker
L-2721 Luxembourg

Floorspace price discontinuities and taxation in cross-border commuting areas *

R. Kudashev[†] P.M. Picard[‡]

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Abstract

Cross-border housing markets have become more prevalent in Europe since the establishment of the European Union. Using data from the functional urban area of Luxembourg, we document significant floorspace price discontinuities at the borders of Luxembourg with Belgium, France, and Germany. Employing a quantitative spatial urban model and spatial regression discontinuity techniques, we show that differences in tax rates and tax importation account for 9% and 17% of the observed price jump, respectively. The remaining price discrepancy is explained by differences in productivity and amenities.

Keywords: Tax, cross-border employment, land rents, quantitative urban economics.
JEL codes: H73, R13, R14, R23, and R31.

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[†]Department of Economics and Management, University of Luxembourg. 4, rue Alphonse Weicker L-2721 Luxembourg. Email: raian.kudashev@uni.lu

[‡]Department of Economics and Management, University of Luxembourg. 4, rue Alphonse Weicker L-2721 Luxembourg. Corresponding author: pierre.picard@uni.lu

1 Introduction

The emergence of the European Union and the free movement of workers have led to cross-border commuting and, consequently, to cross-border housing markets. Prominent examples include the Swiss-French housing market around Geneva, the Swiss-French-German housing market around Basel, and the Danish-Swedish housing market around Copenhagen and Malmö. In particular, floorspace prices exhibit significant changes at these borders. Although several researchers recognize the existence of a "border effect" in cross-border housing markets within the EU (e.g., Sielker *et al.* (2022)), to our knowledge, no attempts have been made to explain the underlying causes of these changes. Many observers attribute this land pattern to differing tax systems.

The objective of this paper is to discuss the factors that explain floorspace price discontinuities at the borders of small jurisdictions with significant tax differences and cross-border labor mobility. We aim to unravel the importance of taxes on labor, goods, and land, along with local productivity, amenities, and land use restrictions, in such price changes.

The paper focuses on the metropolitan area of Luxembourg City, which is a compelling case study for several reasons. First, its functional urban area spans three neighboring countries, France, Germany, and Belgium, each with distinct taxation rules for labor, goods, and land. Second, this metropolitan area is highly monocentric, with Luxembourg City serving as the main economic hub, attracting commuters from within the country and across borders. Third, since all the countries involved are EU members, workers and firms face no mobility restrictions. Finally, the Luxembourg commuting area provides a prominent example of *tax importation*, the cross-border phenomenon whereby workers pay labor taxes in the country of employment rather than in their country of residence, thereby allocating tax revenue across national borders.[1]

In this context, the paper empirically documents a sharp decrease in floorspace prices - by approximately 60% on the non-Luxembourgish side of the border. It also documents that commercial development is significantly more concentrated on the Luxembourgish side. These facts are associated with lower tax rates in that country.

It is, however, difficult to assert and quantify a causal relationship between the spatial structure of real estate and taxation. One primary challenge is the limited variation in tax policies within the country and across its three neighboring nations, which restricts the empirical identification of causal effects. Another challenge is that taxes are confounded with many other factors, including local productivity, amenities, land development policies, and agents' choices regarding residential and business locations. This confounding problem is further exacerbated by endogeneity issues arising from production and amenity spillovers that span neighborhoods and jurisdictions. In particular, the econometrics assumption of a "stable unit treatment value" is violated, since the characteristics of one country can affect foreign locations through the relocation of population, firms, and employment. This interference

[1] Labor income is taxed at the place of work. No official fiscal compensation is provided to the jurisdictions where cross-border workers reside. This setup contrasts with tax reciprocity arrangements (typically between US states) that oblige workers to pay their income taxes in their residence state.

between spatial units undermines the estimation of causal effects, which is particularly relevant in the context of cross-border labor and housing markets.[2] Consequently, it is necessary to explicitly account for spatial spillovers, which can be addressed using quantitative spatial models.

This paper therefore develops and estimates a quantitative model that captures the stylized facts described above and assesses the magnitude of the effects of local taxes, productivity, amenities, and government interventions. The structural approach explicitly accounts for the general equilibrium nature of the economic environment, and, therefore, for the endogeneity channels that cannot be properly addressed using reduced-form methods with available data.

We combine this framework with a spatial regression discontinuity design methodology to measure the importance of each factor. More precisely, we conduct a counterfactual exercise where the considered factor is equalized across countries and then perform a spatial regression discontinuity analysis on the simulated data to estimate its effect on the price jump. As a result, we show that taxes explain only 9% of the jump observed at the Luxembourg border. Our findings indicate that 17% of the price jump is due to tax importation, another 64% is attributable to productivity differences, and 10% is attributable to natural amenity differences. More intuitively, the price of an 80 m^2 apartment in Luxembourg (in 2022) would be reduced by €28,320 if all taxes had been equalized and €57,040 if tax importation was eliminated.

Our research is of primary interest for several reasons. First, housing is one of the most important assets in modern economies. Many growing metropolitan areas are subject to intense policy debates concerning real estate prices and housing affordability, which often play a central role in election campaigns and results (e.g. Choi *et al.* (2025)). In cross-border regions, these debates raise additional policy questions related to tax incentives and the mobility of labor and businesses, which are the central focus of this paper. Second, our study of cross-border housing markets demonstrates that national borders—even within economically integrated areas—continue to generate significant discontinuities in housing markets. This insight is essential for evaluating how effectively labor and housing markets function across borders. Our paper offers tools to quantify these effects and to interpret their underlying causes. Third, our findings on the role of cross-country differences in taxation illustrate how country's public policy influences residential and business location decisions and shapes the housing market. Finally, our use of a quantitative spatial model combined with a regression discontinuity design illustrates how theoretical urban economic models can be empirically validated and refined. The observed price jump at the Luxembourg border functions as a revealed-preference instrument: its magnitude assigns a direct monetary value to the institutional, fiscal, labor market, and public good characteristics of the Luxembourg side relative to its neighboring regions.

This work relates to several branches of urban economics literature. First, the paper relates to the small tax literature applied to urban structure. Close to this paper, Agrawal & Hoyt (2018) discuss the impact of tax differences on the structure of metropolitan areas that

[2] As a consequence, a simple regression discontinuity design based on the available data is unlikely to reliably identify causal effects.

overlap different US jurisdictions. Compared to this literature, we examine a novel setting by focusing on Luxembourg as a prime example of tax competition for mobile workers in a non-reciprocal tax context. Second, we build upon existing frameworks by incorporating realistic geography and commuting frictions. Third, we analyze the general equilibrium effects associated with changes in tax rates on housing prices, population and employment reallocation, and productivity. Finally, we integrate several sources of government tax revenue and demonstrate that the effects of different taxes may offset each other.

Second, Luxembourg is a small jurisdiction that sets attractive tax rates. In their study of tax competition, Kanbur & Keen (1993) explain the tendency of smaller jurisdictions to resort to tax dumping. Numerous studies discuss tax competition for capital (Baldwin & Krugman (2004), Pieretti & Zanaj (2011), Janeba & Osterloh (2013)), residents (Schmidheiny & Slotwinski (2015), Baselgia & Martínez (2023)), and labor (Kleven *et al.* (2020)). The present paper expands on this literature by highlighting the spatial effects of taxes and tax importation on urban land prices, population, and employment.

Third, traditional urban economics literature often relies on stylized geographic models—such as linear or circular cities—where city structures are either exogenously imposed (e.g., Alonso (1967)) or endogenously determined by agglomeration and congestion forces (e.g., Fujita & Ogawa (1982), Lucas & Rossi-Hansberg (2002)). In many of these models, land is fully specialized in either residential or commercial use, a simplification that lacks empirical realism. Moreover, under such assumptions—particularly with specialized land use and homogeneous residents—land market arbitrage eliminates land price discontinuities that might arise from differences in labor taxation. Specifically, when identical individuals reside along a strip straddling two jurisdictions, work in only one of them, and pay income taxes accordingly (as required by EU law), they place identical land bid rents on either side of the border. This symmetry prevents discontinuities in land prices. Therefore, to meaningfully explore the causal relationship between labor tax differentials and cross-border land price variation, it is relevant to study the geographies with mixed land use, as is done in the recent wave of quantitative urban models.

For a decade, the literature has proposed to study quantitative urban models that are based on observed geographical settings and allow for mixed land functions (Ahlfeldt *et al.* (2015), Delventhal *et al.* (2022), Tsivanidis (2019), etc.). Our paper is embedded in this literature and discusses the issues of geographical division in separate jurisdictions with distinct tax regimes. This approach requires highly granular data on prices, residential population, and employment data. Therefore, the paper relies heavily on various techniques for data disaggregation to obtain the low-level data needed to power these models. Some of the novel approaches are related to the work of Ahlfeldt (2011) and Ahlfeldt *et al.* (2021). Price data predictions utilize kriging methods, which account for spatial correlation structures (Wackernagel (2003) and Cressie (1988)). We construct high-resolution population data by combining administrative data and satellite data. Property price data are obtained through web scraping methods on the largest aggregator of property listings in Luxembourg and surrounding regions.

The paper is organized as follows: Section 2 presents some stylized facts about the residential and commercial floorspace markets, and tax discrepancies across the borders of the country of Luxembourg. Section 3 presents a quantitative urban economic model that includes tax collection and expenditure. Sections 4 and 5 discuss our data, parameter estimations, and model validation. Section 6 quantifies the effect of taxation on the model in the absence of geographic discrepancies. Section 7 uses counterfactual exercises to break down the factors explaining the price jump at the borders. Section 8 further discusses the effects of cross-border workers, and possible home bias. Finally, Section 9 concludes the paper. Methodological details and robustness exercises are relegated to the Appendices.

2 Stylized facts

This paper studies the commuting labor market around Luxembourg country. This market is part of the Greater Region of Luxembourg, which includes the whole country of Luxembourg, the French region of Lorraine, Belgian provinces of Luxembourg and Liege, and German federal lands of Saarland and Rhineland-Palatine. It is the most significant cross-border commuting area in the European Union. Cross-border commuting takes place on a daily basis and mainly in the direction of the city of Luxembourg, attracting up to 200,000 daily commuters, half of whom are from France. The functional urban area of Luxembourg expands beyond the border of the Grand Duchy, with more than 70% of the total workforce commuting to Luxembourg from abroad and residing in border municipalities of adjacent countries.

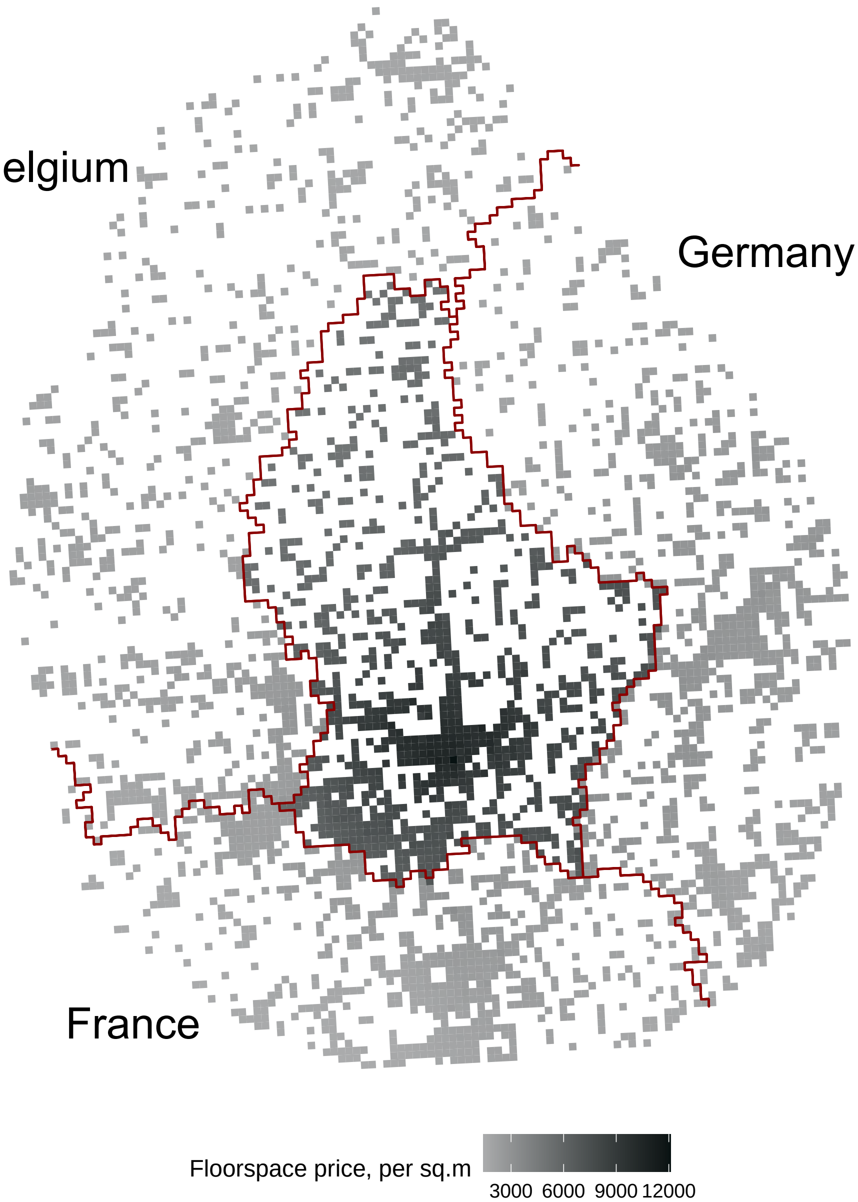
In this section, we present three stylized facts about the commuting labor market around Luxembourg. First, we highlight a significant discrepancy in floorspace prices at country borders, with prices per square meter being lower outside of Luxembourg. Second, we show that locations on the Luxembourgish side of the borders have more commercial development and less residential housing per person, compared to neighboring areas within a 5 km band from country borders. Finally, we show that taxes on goods, real property tax, and labor are significantly lower in Luxembourg than in any of its neighboring countries. Specifically, for labor tax, the marginal tax rate in Luxembourg is lower than in any neighboring country for any given level of gross monthly income.

2.1 Floorspace price jump at the border

We divide the geographical area into 1×1 km grid cells and derive the floorspace price indices using listings from `athome.lu`, the largest property price aggregator in Luxembourg. The price indices are adjusted for the hedonic characteristics of the housing. Figure 2 plots the floorspace price indices as a function of the distance between the cells and their closest borders. Those prices are, on average, 60% lower outside of Luxembourg than in nearby municipalities of Luxembourg. While earlier literature has identified differences in real estate wealth between these countries (e.g., Mathä *et al.* (2018)), our results highlight significant price discrepancies at the borders of these jurisdictions.

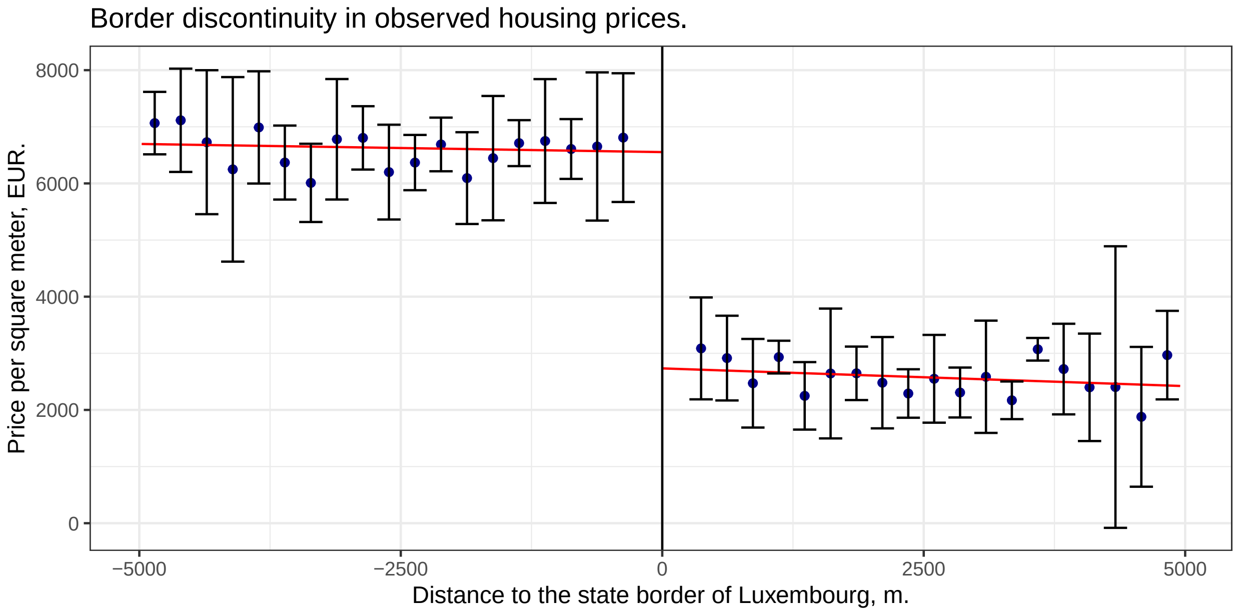
To demonstrate the distribution of housing prices across the whole region, we extrapolate the obtained indices using the kriging method to generate the price field (see Appendix B.5).

Those price indices are mapped in Figure 1, which shows strong discrepancies at the borders of Luxembourg.



Note: The state borders are shown in red. **Source:** athome.lu and own calculations.

Figure 1: Average house prices adjusted for hedonic characteristics of listed properties (€/m^2).



Note: The unit of observation is 1 × 1 kilometer cell. We use hedonics-adjusted cell-specific housing price indices obtained from the data. Negative values of the running variable correspond to cells in Luxembourg. The bars represent the 95% confidence interval. **Source:** `athome.lu` and own calculations.

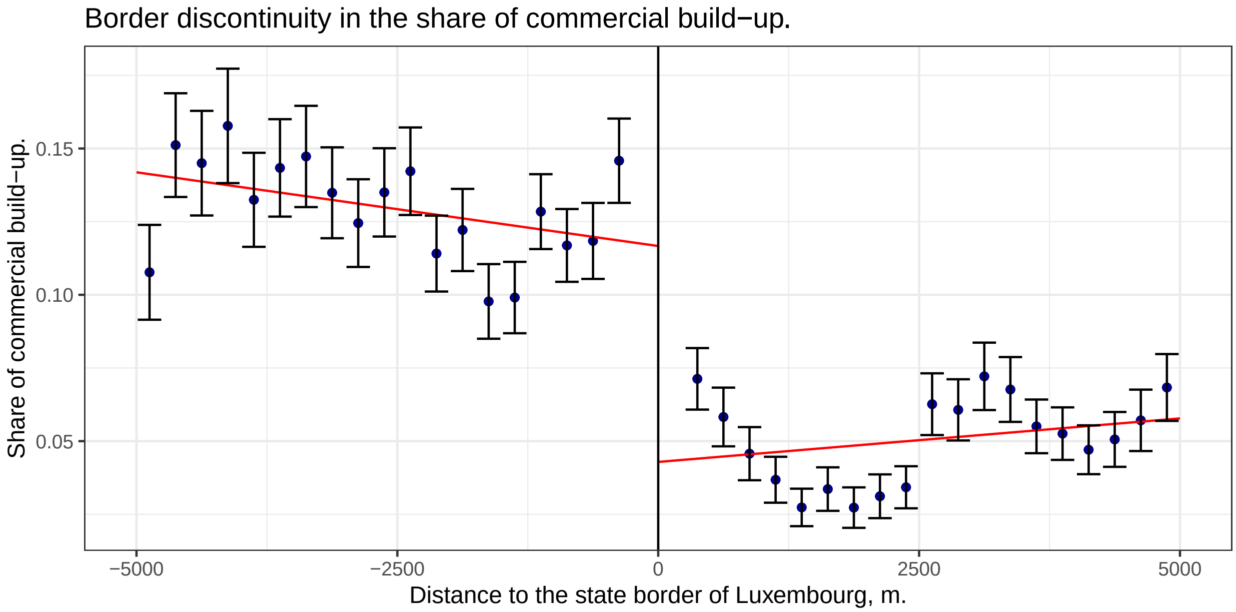
Figure 2: Price jump magnitude in hedonics-adjusted observed housing prices.

2.2 Commercial build-up and residential build-up volume

The second empirical observation concerns the spatial pattern of commercial build-up across the border of Luxembourg. Toward this aim, we employ GHS-BUILT-S (2020) satellite imagery of fine resolution to calculate the proportions of commercial and residential build-up for 100×100 m cells located inside and outside the borders of Luxembourg.[3]

Figure 3 depicts the average share of commercial build-up within a 5 km radius of the Luxembourg border. It provides evidence of a discontinuity in the proportion of commercial build-up at the border, with a significantly higher proportion of commercial build-up within Luxembourgish borders. Hence, firms still prefer to establish their production within Luxembourg despite the considerably higher floorspace prices there.

[3]GHS-BUILT-S differentiates residential and commercial areas using image processing and machine learning on high-resolution satellite imagery (Sentinel-2, Landsat) and building data from sources like Facebook, Microsoft, and OpenStreetMap. Built-up types are identified through reflectance, textural, and morphological features. Large structures (e.g., commercial buildings) are detected via textural and connected component analysis. Objects are classified using symbolic machine learning based on training data patterns. The method provides an accuracy level largely above 90% for Western Europe (see Table 4, Pesaresi & Panagiotis (2023)). The main advantage of using GHS-BUILT-S is that it circumvents the issues of administrative data partitioning and compatibility between countries.



Note: Negative values of the running variable correspond to cells in Luxembourg. **Source:** GHS-BUILT-S (2020) satellite imagery by Copernicus Project.

Figure 3: Discontinuity in the share of commercial build-up at country borders.

2.3 Cross-border taxation

In the EU, countries are allowed to implement different taxation schemes, provided that they follow the EU tax directives on goods and OECD guidelines on labor taxation. For instance, the VAT Directive (2006/112/EC) ensures some level of commodity tax harmonization and implements the destination principle. By contrast, the EU does not have specific rules for taxing cross-border workers. Each Member State negotiates its own bilateral agreements with neighboring countries to handle the taxation of cross-border workers.

A cross-border commuter is defined as a person who is a resident of a state and commutes daily to work for an employer in another state. As EU Treaties prohibit any discrimination against EU workers employed in any other EU country, cross-borders in the Great Region of Luxembourg are entitled to the same tax benefits for work-related and personal expenses as residents, provided their situation is comparable. Importantly, cross-border workers employed in Luxembourg pay their labor taxes in Luxembourg on the income earned there. Any additional income earned in the country of residence is taxed according to the regulations of the state of residence. Double conventions currently limit cross-border workers to work from home or from a third country to less than 25 workdays without triggering taxation in the country of residence.

The Luxembourgish cross-border workers are entitled to social security benefits from the Luxembourgish state, such as pensions and health insurance. The pension remuneration only takes into account work experience obtained in Luxembourg. Medical bills of cross-border workers in their country of residence are reimbursed by the National Health Fund of

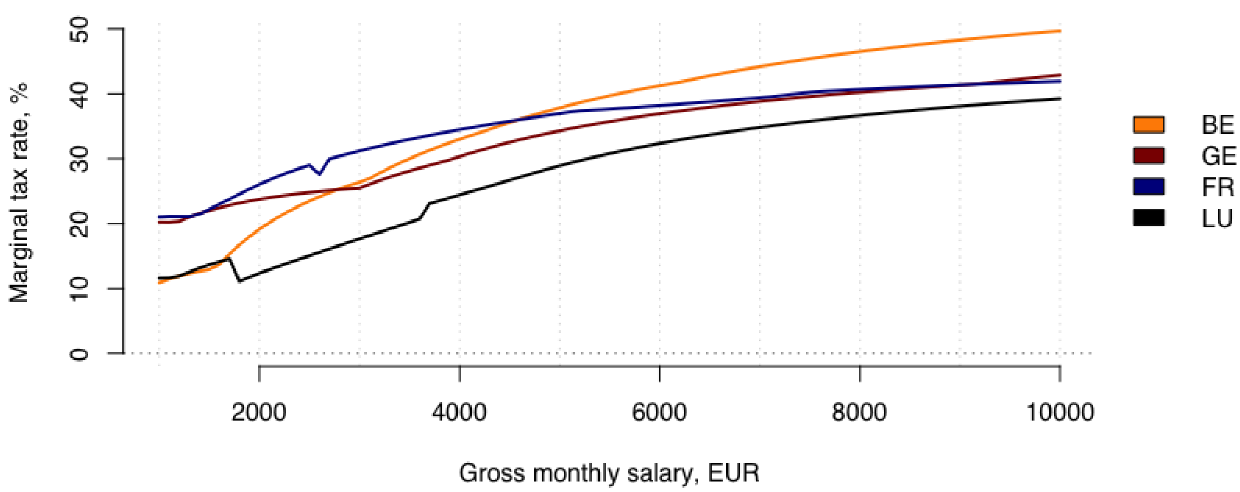
Luxembourg (CNS).

Each country has its unique combination of tax rates for corporate tax, labor tax, VAT, and land tax. Table 1 presents the average rates in the countries studied. It is apparent that Luxembourg has the lowest tax rates in all categories. Whereas the tax differences on goods are limited by the EU tax harmonization, labor taxes significantly differ across countries. In particular, labor taxes are roughly 10 percentage points lower in Luxembourg. Ceteris paribus, this allows Luxembourgish firms to offer higher net wages and therefore attract cross-border workers.

Tax:	Corporate	Labor	Goods (VAT)	Property
Luxembourg	0.260	0.382	0.17	0.0005
France	0.344	0.476	0.20	0.0125
Belgium	0.296	0.527	0.21	0.0055
Germany	0.298	0.495	0.19	0.0020

Note: The table shows effective tax rates. Labor tax is the tax wedge, i.e., the ratio between the taxes paid by an average single worker (a single person at 100% of average earnings, without children) and the total labor cost of the employer. Real property taxes are defined as property tax payments as a percent of the private capital stock. **Source:** OECD Tax Statistics (2017).

Table 1: Tax Rates in the Greater Region.



Note: Marginal tax rates are computed for a single worker without dependencies. **Source:** Eurostat Salary Calculator (2023) and own calculations.

Figure 4: Marginal tax rates.

The Luxembourg labor market is attractive for all levels of income. In fact, although labor taxes are progressive in all countries, marginal labor tax rates are consistently lower there, as shown in Figure 4.

3 Model

In this section, we present a general equilibrium model adapted to the Luxembourg metropolitan area that overlaps over the countries of Belgium, France, Germany and Luxembourg. The model is based on Ahlfeldt *et al.* (2015) and accounts for numerous cross-border workers and differing taxation on labor, goods, and property across countries. Consumers pay value-added taxes (VAT), while consumers and firms pay property taxes. In line with OECD and EU tax directives, firms pay labor taxes in the country of production, VAT is paid in the country of residence (destination principle), and property taxes are paid by firms and consumers in the country where houses and plants are located.

Furthermore, each country collects all local taxes and reinvests them in local public goods that enhance local amenities (e.g., schools, recreation areas, road infrastructure, security, etc.). The production of local amenities exhibits decreasing returns to scale and is allocated on a per-capita basis within each spatial unit. This formulation of government intervention ensures analytical tractability in the model (e.g., Fajgelbaum *et al.* (2019)) and aligns with the tax importation issues relevant to this metropolitan area (Kanbur & Keen (1993)).

The economy of the cross-national metropolitan area hosts H workers who live and work in several contiguous nations $n \in \mathcal{N}$. The geography consists of set of locations $i, j \in \mathcal{I}$ that cover these nations in subsets $\mathcal{I}_n$ with $\mathcal{I} = \cup_n \mathcal{I}_n$ and $\mathcal{I}_n \cap \mathcal{I}_{n'} = \{\varnothing\}$. In this text, unless stated otherwise, location indices refer to the whole geography $\mathcal{I}$ while summations $\sum_i$ are also taken over the whole geography $\mathcal{I}$.

We begin by discussing the consumption and location choices of workers and firms.

3.1 Consumers

As in Ahlfeldt *et al.* (2015), each worker, denoted by the subscript $_o$, takes residence in location $i \in \mathcal{I}$ and works in another location $j \in \mathcal{I}$. She consumes c_{ijo} units of a single final good and l_{ijo} units of floorspace. She incurs a commuting disutility $d_{ij} = e^{\kappa \tau_{ij}} \in [1, \infty)$ where τ_{ij} is a commuting time (minutes) from i to j and $\kappa > 0$ expresses (the log of) this disutility per time unit (minute). She furthermore benefits from an exogenous local residential amenity B_i and an endogenous local amenity G_i produced by the national government. She is endowed with a Cobb-Douglas utility function

$$U_{ijo} = \frac{z_{ijo} B_i G_i}{d_{ij}} \left(\frac{c_{ijo}}{\beta} \right)^{\beta} \left(\frac{l_{ijo}}{1-\beta} \right)^{1-\beta}, \tag{1}$$

where $\beta \in (0,1)$ denotes the share of goods in her expenditure. In this expression, z_{ijo} is an idiosyncratic preference shock over pairs of residential and workplace locations. As in (Eaton & Kortum (2002)), the latter is drawn from the Frèchet distribution with c.d.f. $F(z_{ijo}) = \exp\left(-z_{ijo}^{-\varepsilon}\right)$, where the shape parameter ε controls for the dispersion of preference shocks. The greater ε, the more homogeneous are preferences. This class of preference shocks generates an upward-sloping labor supply curve with Inada conditions in each location.

The worker's budget constraint is given by

$$w_j = t_i^c c_{ijo} + t_i^q Q_i l_{ijo},$$

where w_j denotes her net-of-tax wage earned at location j, Q_i the before-tax floorspace price, t_i^c and $t_i^q \in (1, \infty)$ the tax multipliers respectively on good and floorspace. The VAT and floorspace tax rates are given by $t_i^c - 1$ and $t_i^q - 1$. Taxes are the same across locations of the same country but different between countries. As mentioned above, goods and residential floorspace are consumed in the country of residence and are taxed there according to the destination principle.[4] Such a tax treatment constitutes a major departure from Ahlfeldt *et al.* (2015). Assuming that goods are freely traded and transported at no cost across locations, the (before-tax) price of the good is equal everywhere and can be normalized to one w.l.o.g.

The timeline is as follows: first, the worker moves into the area before the realization of her preference shock. She then observes her preferences shock realizations over all pairs of residential and workplace locations. She finally chooses her best locations to live and work and her consumption levels, taking prices as givens. We solve this sequence by backward induction.

After the realization of her preference shock, the worker chooses the consumption levels that maximize her utility subject to her budget constraint. Her optimal demands for goods and floorspace are given by

$$c_{ijo} = \frac{\beta w_j}{t_i^c} \quad \text{and} \quad l_{ijo} = \frac{(1-\beta) w_j}{t_i^q Q_i}, \tag{2}$$

while she obtains an indirect utility given by

$$u_{ijo} = \frac{z_{ijo} B_i G_i w_j}{d_{ij} (t_i^c)^\beta (t_i^q Q_i)^{1-\beta}}, \tag{3}$$

which has a same Frèchet distribution as z_{ijo}.

The worker then chooses the pair of residence i and workplace j that maximizes this indirect utility. Using the properties of the maximum operator on variables with Frèchet distributions, one establishes the following expression for the probability of commuting between i and j:

$$\pi_{ij} = \frac{\Phi_{ij}}{\Phi}, \tag{4}$$

where

$$\Phi_{ij} = \left[\frac{B_i G_i w_j}{d_{ij} (t_i^c)^\beta (t_i^q Q_i)^{1-\beta}} \right]^\varepsilon,$$

[4]This is the case for most commodities and services purchased by residents. For simplicity, we assume away the possibility of cross-border shopping.

and $\Phi = \sum_i \sum_j \Phi_{ij}$. Summing probabilities across workplaces for a given residence, we obtain the probability of residing in i,

$$\pi_{Ri} = \sum_j \Phi_{ij}/\Phi. \tag{5}$$

Similarly, the probability of working in j is given by

$$\pi_{Mj} = \sum_i \Phi_{ij}/\Phi. \tag{6}$$

Residential and employment populations are then given by $H_{Ri} = \pi_{Ri}H$ and $H_{Mj} = \pi_{Mj}H$. Conditional on residing in i, the probability of commuting to j is given by $\pi_{ij|i} = \pi_{ij}/\pi_{Ri} = \Phi_{ij}/\left(\sum_{j'} \Phi_{ij'}\right)$, which yields

$$\pi_{ij|i} = \frac{(w_j/d_{ij})^{\varepsilon}}{\sum_{j'}(w_{j'}/d_{ij'})^{\varepsilon}}. \tag{7}$$

Finally, before the realization of the preference shocks and choosing locations and consumptions, workers get an expected utility equal to $\mathbb{E}[u] = \Gamma_0 \Phi^{\frac{1}{\varepsilon}}$, where expectations apply on the preference shock distribution and where $\Gamma_0 = \Gamma(1 - 1/\varepsilon)$ and $\Gamma(.)$ is a Gamma function. Under free mobility, workers enter in the geographical area if their expected utility is greater than their reservation utility in the wider economy, $\bar{U}$. In an open city equilibrium, it must be that

$$\mathbb{E}[u] = \bar{U}. \tag{8}$$

3.2 Firms

Firms produce final goods under constant returns to scale and sell them under perfect competition in the global market at unit price. In each location j, they produce Y_j units of final goods by employing H_{Mj} units of labor and S_{Mj} units of floorspace according to the Cobb-Douglas production technology,

$$Y_j = A_j H_{Mj}^{\alpha} S_{Mj}^{1-\alpha}, \tag{9}$$

where A_j is a location-specific productivity and $\alpha \in (0, 1)$ denotes the share of labor in total cost. Production cost is given by $t_j^w w_j H_{Mj} + t_j^q q_j S_{Mj}$ where w_j is the net-of-tax wage, q_j the floorspace price and, t_j^w and $t_j^q > 1$ the labor and floorspace tax multipliers. The labor tax rate is given by $t_j^w - 1$.

Firms maximize their profits. Their optimal input is given by $H_{Mj} = \alpha Y_j/(w_j t_j^w)$ and $S_{Mj} = (1 - \alpha)Y_j/(q_j t_j^q)$. Under free entry, they make zero profits, which occurs if the following zero-profit condition holds:

$$A_j = \left[\frac{t_j^w w_j}{\alpha}\right]^{\alpha} \left[\frac{t_j^q q_j}{1-\alpha}\right]^{1-\alpha}. \tag{10}$$

Intuitively, too high wages or floorspace prices entice fewer firms to produce in the location, which pushes wages and floorspace prices downward. Similarly, higher local productivity pushes wages and floorspace prices upward. This establishes a negative relationship between local wages and floorspace prices à la Roback (1982).

3.3 Construction sector

Floorspace S_j is supplied by a competitive construction sector that uses capital K_j and land L_j as inputs and produces floorspace with a technology given by $S_i = K_i^{\mu} L_i^{1-\mu}$, where μ is a parameter. The capital price is set by the international capital market while the land price is endogenous. As in Ahlfeldt *et al.* (2015), the floorspace supply by this sector is given by

$$S_i = \phi_i L_i^{1-\mu}, \tag{11}$$

where $\phi_i \equiv K_i^{\mu}$ refers to *density of development*, which acts as an exogenous location-specific floorspace supply shifter.

3.4 Government

Each government collects national taxes and reinvests them in the form of local public investments that produce G_i units of local amenities in national locations. To fit the reality of the countries under study, we assume that the government treats its residents equally and invests the same amount g_i per resident (e.g. schools, infrastructure, ...). Local amenities are assumed to be given by the production function

$$G_i = (g_i)^{\zeta}, \tag{12}$$

where $\zeta \in (0,1)$ captures decreasing returns to scale. Note that expected consumptions in a location i are equal to $\mathbb{E}[c|i] = (\beta/t_i^c)\,\mathbb{E}[w|i]$ and $\mathbb{E}[l|i] = ((1-\beta)/t_i^w)\,\mathbb{E}[w|i]$, where $\mathbb{E}[w|i]$ is the expected wage conditional on residing in location i. As a result, the government budget constraint of country n takes the following form:

$$\begin{aligned}\sum_{i\in\mathcal{I}_n} g_i H_{Ri} &= \sum_{i\in\mathcal{I}_n}\left[\frac{t_i^c-1}{t_i^c}\beta + \frac{t_i^q-1}{t_i^q}(1-\beta)\right]\mathbb{E}[w|i]H_{Ri} \\ &\quad + \sum_{j\in\mathcal{I}_n}\left[(t_j^w-1)w_jH_{Mj} + (t_j^q-1)q_jS_{Mj}\right].\end{aligned}$$

where the LHS expresses the government spending and the RHS the taxes on national residents and firms. Since taxes and per-capita investments are equal within this country, we can index them by same country index n so that

$$\begin{aligned} g_n &= \frac{t_n^c-1}{t_n^c}\beta\frac{\sum_{i\in\mathcal{I}_n}\mathbb{E}[w|i]H_{Ri}}{\sum_{i\in\mathcal{I}_n}H_{Ri}} + \frac{t_n^q-1}{t_n^q}(1-\beta)\frac{\sum_{i\in\mathcal{I}_n}\mathbb{E}[w|i]H_{Ri}}{\sum_{i\in\mathcal{I}_n}H_{Ri}} \\ &\quad +(t_n^w-1)\frac{\sum_{j\in\mathcal{I}_n}w_jH_{Mj}}{\sum_{i\in\mathcal{I}_n}H_{Ri}} + (t_n^q-1)\frac{\sum_{j\in\mathcal{I}_n}q_jS_{Mj}}{\sum_{i\in\mathcal{I}_n}H_{Ri}}. \end{aligned} \tag{13}$$

At given prices and spatial distributions of firms and residents, higher taxes increase tax revenues and local government investments. Observe that the third term shows the effect of the labor tax component, which leads to labor tax importation. Ceteris paribus, a rise in location j's employment increases per-capita government investment by

$$\frac{\partial g_n}{\partial H_{Mj}} = \frac{(t_n^w - 1)w_j}{\sum_{i\in\mathcal{I}_n} H_{Ri}}. \tag{14}$$

A smaller residential population, therefore, increases the tax benefits of attracting more firms to the country. This factor is particularly important for Luxembourg, where many workers commute from neighboring countries.

3.5 Urban externalities

In every location j, the local productivity, A_j, depends on production fundamentals, a_j, and production externalities, Υ_j. Production fundamentals capture factors that make a location more productive, independent of the surrounding density of economic activity. Production externalities relate the productivity in the location to that of its neighboring locations.The structure of productivity is as follows:

$$A_j = a_j \Upsilon_j^{\lambda}, \quad \text{and} \quad \Upsilon_j = \sum_i e^{-\delta\tau_{ij}} \left(\frac{H_{Mi}}{L_i}\right). \tag{15}$$

In this definition, externalities increase with employment densities H_{Mi}/L_i in surrounding locations i and decline with travel time to those locations, following a spatial decay parameter δ. The parameter λ controls the importance of externalities in overall productivity.

Similarly, the local amenity, B_j, depends on residential fundamentals, b_i, and residential externalities, Ω_i:

$$B_j = b_j \Omega_i^{\eta}, \quad \text{and} \quad \Omega_i = \sum_j e^{-\rho\tau_{ij}} \left(\frac{H_{Rj}}{L_j}\right), \tag{16}$$

where H_{Rj}/L_j is the residential density, ρ the spatial decay and η the importance of residential externalities in residential externalities. As Ahlfeldt *et al.* (2015), there exists a potential for multiple equilibria in the model if externalities are strong enough relative to the exogenous differences in characteristics across locations.

3.6 Market clearing and equilibrium

In equilibrium, markets clear in every location. As mentioned above, product and capital prices are fixed by the outside (international) markets. The prices of labor and floorspace are the result of the balances in local supply and demand. We discuss the clearing conditions for the labor and floorspace market.

On the one hand, the labor market in location j balances the demand for workers by firms H_{Mj} to the numbers of commuters who offer their working force there. This gives the labor market clearing condition: $H_{Mj} = \sum_i \pi_{ij|i} H_{Ri}$. Using the value of $\pi_{ij|i}$, this implies

$$H_{Mj} = \sum_i \frac{(w_j/d_{ij})^\varepsilon}{\sum_{j'} (w_{j'}/d_{ij'})^\varepsilon} H_{Ri}. \tag{17}$$

On the other hand, the floorspace market clears in every location if the floorspace supply by the construction sector, S_i expressed in (11), matches its demands by residents and firms. In equilibrium, floorspace is allocated to the highest bidder amongst firms and residents. To reflect the presence or absence of those two demand segments, we introduce the share of commercial floorspace over total floorspace, $\theta_j \in [0, 1]$. The market clearing condition in the commercial segment then writes as

$$\theta_j S_j = A_j^{\frac{1}{\alpha}} \left[\frac{1-\alpha}{t_j^q q_j} \right]^{\frac{1}{\alpha}} H_{Mj}, \tag{18}$$

while the one in the residential segment is

$$(1-\theta_i) S_i = (1-\beta) \frac{E[w_j|i] H_{Ri}}{t_i^q Q_i}. \tag{19}$$

Finally, in equilibrium, floorspace must be fully commercial if firms pay more than residents and fully residential if they cannot while floorspace must mix commercial and residential activities when firms and residents offer the same price. Let P_i be the equilibrium floorspace price. Then,

$$\begin{cases} P_i = q_i \text{ and } \theta_i = 0 & \text{if } q_i > Q_i, \\ P_i = q_i \text{ and } \theta_i \in [0,1] & \text{if } q_i = Q_i, \\ P_i = Q_i \text{ and } \theta_i = 1 & \text{if } q_i < Q_i. \end{cases} \tag{20}$$

To sum up, the economic geography is defined by a collection of preference and cost parameters $\{\alpha, \beta, \mu, \varepsilon, \kappa\}$ and urban externality parameters $\{\delta, \lambda, \eta, \rho\}$, vectors of national tax multipliers $\{t^c, t^q, t^w\}$, vectors of location characteristics $\{a, b, \varphi, L, \xi\}$, a commuting time matrix τ and a reservation utility $\bar{U}$. The equilibrium is defined by the population H and the vectors of prices $\{Q, q, w\}$, shares $\{\pi_M, \pi_R, g, \theta\}$ and local productivities and amenities $\{A, B, G\}$ that respectively solve the conditions for free mobility (8), commercial and residential floorspace market clearing (18) and (19), labor market clearing (17), residential and workplace choices (5) and (6), government budget balance (13), floorspace market arbitrage (20) and production of urban externalities and local public good (15), (16) and (12). (See details in Appendix A)

4 Data

In this section, we describe the datasets used for parameter estimation and model calibration. We explain our data sources and constructions for commuting times, population and employment densities, floorspace prices, and wages.

Our analysis focuses on the functional area around Luxembourg, which we define as the entire country of Luxembourg and a 50 km deep band within the adjacent areas of France, Belgium, and Germany. Furthermore, we apply the data on a grid of 1×1 km cells covering this geographic area, resulting in a grid with 11,800 cells, as shown in Figure 1. To concentrate on urban clusters and minimize computational intensity, we exclude cells with residential and employment densities below 100 individuals per km^2, resulting in 3,182 urbanized cells (non-blank cells in Figure 1).

4.1 Travel flows and times

To assess travel flows and time, we use the 2017 Luxembourgish "LuxMobil" survey (Ministry of Mobility and Public Works) and the 2017 "Population Census – Mobility Flow Database" (INSEE) for the French departments bordering Luxembourg (Meuse, Moselle, Meurthe-et-Moselle). The data includes domestic and cross-border commutes between Luxembourg and France. We restrict the sample to work commutes from and to municipalities located within the functional area defined above. The merged data yields 447 municipalities from which we construct our travel flow matrix. Pairs of municipalities with no observed commute are assigned a zero flow. Due to the granularity and anisotropic nature of commute travel, the travel flow matrix includes about 6 % non-zero values.

To encompass the entire geographical area, we calculate travel times using the existing road network using Open-StreetMap and Open Source Routing Machine (OSRM, Giraud (2022)). With this algorithm, we calculate the free-flow minimal travel times by car. A focus on car flows is justified by the LuxMobil survey, which reveals that more than 85% of commutes are made by car. Travel within 1 km is predominantly made on foot. Free-flow travel times do not account for congestion. We use this approach to calculate the travel times between the centroids of the municipalities of the LuxMobil survey and French census data, as well as between the centers of the grid cells of the commuting matrix. The travel time within a cell or municipality is calculated as the average travel time between a set of 50 randomly selected points along existing roads. Table 2 reports summary statistics for the number of commuters and commuting times between all municipalities and those with non-zero flows.

	Mean	SD	Min	Max	Observations
Number of commuters	1.6	34.8	0.0	12249	199764
Travel time (min)	53.6	23.9	1.9	139.0	199764
Number of commuters (non-zero flow)	27.5	144	1	12249	11277
Travel time (min, non-zero flow)	28	14.8	2.7	101.8	11277

Note: The data reports numbers of commuters and travel time for pairs of municipalities within and outside Luxembourg that are located within 50 km from the state border of Luxembourg. The numbers of commuters are extracted from the LuxMobil Survey and the French Population Census in 2017. Travel times are calculated with OSRM between the centroids of municipalities. Travel time within the same municipality is given by the minimum between the average travel time by car and by foot between 50 randomly drawn points within each municipality.

Table 2: Summary statistics for commuting data within 50 km from the border of Luxembourg.

4.2 Residential and employment populations

We take the residential population on every 1 × 1 km grid cell from the Global Human Settlement Layer Population Grid (GHS-POP-2023) issued by the European Commission's Joint Research Centre. Population counts are derived from official census and administrative records at the municipal level for 2020, harmonized and disaggregated using satellite-derived built-up area information.

We construct our employment data by mapping administrative employment records to every 1 ×1 km grid cell according to the municipality's footprint and the cell's total build-up information reported in the GHS-BUILT-S dataset issued by the above Centre. Administrative employment records capture the number of workers at their place of work in the municipalities of Luxembourg, Germany, France, and Belgium, including cross-border employment. A dasymetric mapping strategy is used to accurately allocate employment to grid cells (see details in Appendix B).

Restricting the dataset to the Luxembourg functional area results in 11,800 cells, as depicted in Figure 1. To ease numerical computations, we also exclude all cells with population or employment density less than 100 individuals per km^2. This results in 3182 active cells, which capture 91.5% of the total population and 97.5% of total employment. We finally equalize population and employment in the economy by scaling the employment in each cell by the ratio of total population to total employment. The summary statistics of the residential population and employment in the cells are presented in the first two rows of Table 3.

	Mean	SD	Min	Max	N
Population (individuals/cell)	512	828	5	13364	3182
Employment (individuals/cell)	512	2015	0	40108	3182
Prices (€/m^2)	3715.5	2440.4	1440.4	12083.4	3182

Note: Population and employment report the numbers of residents and workers per cell. Floorspace price gives the price index (€/m^2) attributed to each cell after hedonic price adjustment.

Table 3: Summary statistics on cell data.

4.3 Floorspace prices

We build floorspace price indices using information on property prices obtained from the largest property listings aggregator, `athome.lu`. This source jointly covers the Grand Duchy of Luxembourg and its adjacent regions of France, Belgium, and Germany, while it offers property listings for sale and rental properties with geocoded information and hedonic characteristics (from which we retain ten features, including surface). Data is collected from the website between March and September 2022. Because this data includes twice as many price observations as rental ones, we construct the index for the floorspace price. Housing prices and rents have, nevertheless, very close properties (Appendix B.4 and B.5). Outliers with the highest 5% and lowest 5% prices are removed in each country.

A floorspace price index is computed for each cell using a hedonic price regression model or a geostatistical interpolation. More precisely, for the cells with property listings, we run hedonic regressions of the logarithm of prices across the geographical area, including surface and other hedonic controls, and a fixed effect on each cell. The fixed effect yields the price index of the cell (Appendix B.4). For cells without property listings, we interpolate the price index between all available cells with more than 5 listings using a universal kriging procedure (Appendix B.5). The summary statistics of price indices are described in the third row of Table 3, which are consistent with those in Figure 1

4.4 Wages

Finally, to estimate the Fréchet parameter ε, we use the net hourly wage data at the municipality level. For Luxembourg, this data is approximated by adjusting official average gross yearly wages in 2020 from the Luxembourg statistical office (STATEC), using the 2017 tax brackets (single worker, Tax Class 1) and dividing by the average annual hours worked (OECD data). For France, the INSEE provides the nominal hourly wage data by French municipality communes (with populations over 2,000) for a single worker with no dependents.

5 Estimations

In this paper, we estimate four parameters specific to the functional area of Luxembourg using the above data. Those parameters include the commuting elasticity κ, the Frèchet scale parameter ε, the productivity spillover parameter λ, and the residential spillover parameter η. Other parameters will be sourced from the literature.

5.1 Semi-elasticity of commuting

The parameter bundle, $\varepsilon\kappa$, denoted here as ν, is estimated using the data on work travels by car in Luxembourg and surrounding countries provided by the Luxembourgish LuxMobil survey and French census. We use the equation for the unconditional commuting probability (4) and write it as

$$\log \pi_{ij} = -\nu\tau_{ij} + \xi_i + \zeta_j + \epsilon_{ij} \tag{21}$$

Here, ξ_i represents origin-specific fixed effects, such as amenities and floorspace prices, while ζ_j captures destination-specific fixed effects. The origin-specific and destination-specific variables are absorbed by fixed effects.

	log, Flows		
	(1)	(2)	(3)
OSRM Travel Time, min	-0.110***	-0.129***	-0.116***
	(0.006)	(0.005)	(0.004)
Origin FE	Yes	Yes	Yes
Destination FE	Yes	Yes	Yes
Data	LuxMobil	INSEE	INSEE + LuxMobil
Origin	LU	FR	LU+FR
Destination	LU	FR	LU+FR
R^2	0.810	0.842	0.840
Observations	13689	52649	116827

Note: Departure communes are within 50 km from the state border of Luxembourg. Standard errors in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 4: Commuting elasticity estimation.

To estimate this regression model, we associate the work travels by car provided by the Luxembourgish LuxMobil survey and the French census with the above-computed travel times. To balance municipality sizes in Luxembourg and France, we consider French municipalities with more than 2000 residents. Results are presented in Table 4. We use the Poisson Pseudo-Maximum-Likelihood (PPML) regression model to account for the count nature and the zeroes in commuting flows.

Columns 1 to 3 present PPML estimates for the baseline regression based on different subsamples. Column 1 uses LuxMobil Survey data only. Column 2 uses data from the INSEE commuting survey only. Column 3 uses a combined commuting survey. Estimates are robust to the choice of datasets and countries of travel origins and destinations (see Appendix C.1). In the subsequent analysis, we use the results in Column 3 with the estimate $\nu = 0.116$.

5.2 Residence and workplace preferences

We choose the Fréchet parameter ε that produces the wage dispersion closest to the observed one (Ahlfeldt *et al.* (2015)). More formally, we minimize the absolute difference between the variances of the logarithm of the observed wages and the wages simulated by the model, $|\text{var}(\log w_m^{data}) - \text{var}(\log w_m^{sim}(\varepsilon))|$. The net wage w_m^{data} is observed at the municipal level, and the simulated wages $w_m^{sim}(\varepsilon)$ are computed for each cell from the labor market conditions (17) and then aggregated for each municipality. We find the minimizer $\varepsilon = 4.2$, which yields the value of κ equal to 0.027 (see details in Appendix C.2).

5.3 Local characteristics

We recover the local productivities A_j, amenities B_i, and density of development ϕ_i by inverting the model using our data on floorspace prices, population and employment densities, and the parameter values estimated above, as well as parameter values imported from the literature (see Table 6 below). Toward this aim, we invert the model using our data on floorspace prices, population, and employment densities, the values of the parameters estimated above. Namely, the conditions of the labor market (17) yield the wages given the observed residential populations and travel times. Zero-profit conditions (10) yield the local productivities given these wages and observed floorspace prices. This allows us to establish the government budget and local public good production in (14). Finally, local amenities are recovered from the identities of residential density (5). Density of development is obtained from (11). (See details in Appendix D)

5.4 Urban externalities

We finally estimate the importance of externalities in local productivity and amenities. The local productivity and amenities for each location i are defined in (15) and (16). We estimate the parameters λ and η and borrow the decay parameters ρ and δ from (Ahlfeldt *et al.* (2015)). Both equations are estimated using the available data on residential and employed densities.

However, we need to consider the endogeneity issue whereby local productivity and amenity are determined by the employment and population densities of surrounding residential and employment areas, which are, in turn, influenced by those productivities and amenities. To address the issue, we instrument production and amenity externalities Υ_i and Ω_i, with the spatial distribution of commercial and residential floor area in 1975. More specifically, we compute those externalities from the employment and population imputed from the residential and non-residential build-up area GHS-BUILT-S dataset for 1975 (see details in Appendix C.3). The exclusion restriction is based on the sharp deindustrialization that followed the steel market collapse of 1974-1975. Past manufacturing operations, which once fueled commercial activity (in particular, the steel industry), are unlikely to correlate with the current productivity of Luxembourg's service industries. In 1975, manufacturing accounted for more than 45% of total employment in Luxembourg. By 2021, its share had decreased to below 10%.

Table 5 presents our regression results. Following Combes *et al.* (2010) and Combes & Gobillon (2015), the regression models include geographic controls to account for first-nature determinants that may affect current productivity and amenity at the same time as past population and employment patterns. These geographic controls are furthermore interacted with country indicator variables to allow for country-specific heterogeneity.

The first-stage regression results displayed in Panel A report a strong correlation between current and instrumented externalities and confirm the relevance of the instruments. The second-stage regression results presented in Panel B report significant agglomeration effects and small corrections for endogeneity, which are consistent with the literature, as in Combes & Gobillon (2015). Our estimate for the agglomeration elasticity, 0.07, lies on the upper end of the estimates in the literature (between 0.04 and 0.06), which can be attributed to the current specialization of Luxembourg in banking and services. [5] Finally, our estimate of the elasticity of residential amenity with respect to residential density, 0.028, is significant. This low value is explained by our geography, with a medium-sized city with 150 thousand people surrounded by relatively sparsely populated areas.

	$\log \Upsilon$	$\log \Omega$	log A		log B	
			OLS	IV	OLS	IV
Panel A: First Stage						
$\log \hat{\Upsilon}$	0.949***					
	(0.008)					
$\log \hat{\Omega}$		1.039***				
		(0.004)				
Geographic Controls	Yes	Yes				
Observations	2658	3182				
R^2	0.911	0.967				
F-Statistics	1593.69	5460.05				
Panel B: Second Stage						
$\log \Upsilon$			0.084***	0.070***		
			(0.005)	(0.006)		
$\log \Omega$					0.032***	0.028***
					(0.003)	(0.003)
Geographic Controls			Yes	Yes	Yes	Yes
R^2			0.431	0.429	0.194	0.193
Wu-Hausman				44.18***		54.74***
Observations			2658	2658	3182	3182

Note: Geographic controls include log of distance to forests and water, mean elevation, and terrain ruggedness (absolute difference in elevation per cell). All geographic controls are interacted with country fixed effects. Country fixed effects are not included as a separate control. Standard errors in parentheses.
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 5: Instrumental variable regression results.

5.5 Summary

Table 6 summarizes the values and sources of the parameters we use in our analysis. The first four rows report the parameters estimated above with our data. The other rows present the parameters we import from the literature. The latter parameters are used in the above model inversion.

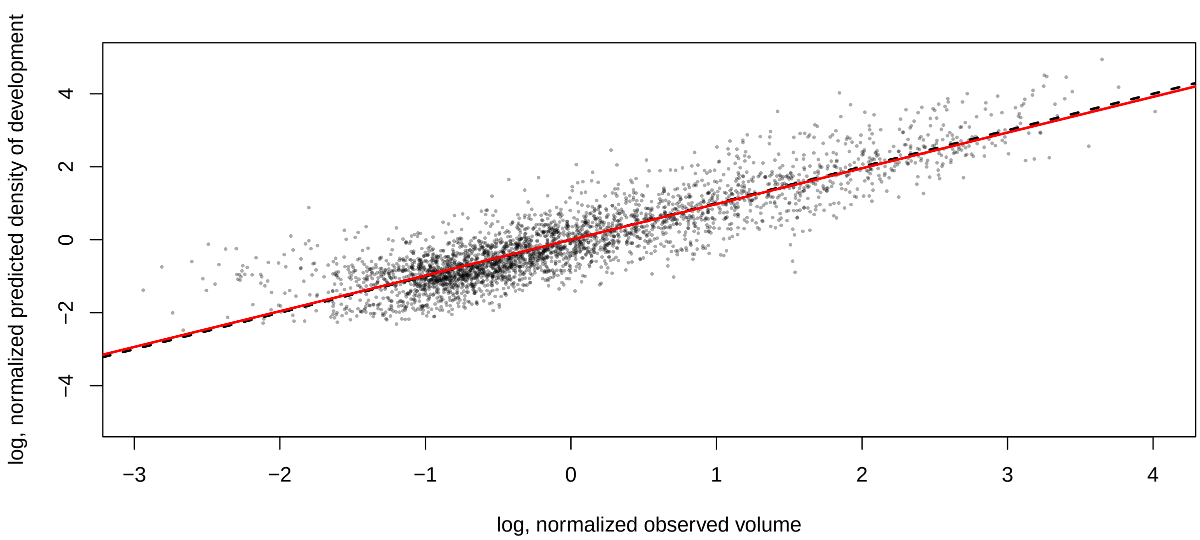
[5] Graham & Gibbons (2019) find agglomeration elasticities of about 0.08 for UK business services. Hörcher & Graham (2024) find agglomeration elasticities up to 0.15 for London city.

Parameter	Value	Description	Source
ε	4.2	Residence-workplace heterogeneity	Own estimation
λ	0.07	Productivity externalities	Own estimation
η	0.03	Amenity externalities	Own estimation
κ	0.028	Commuting disutility	Own estimation
α	0.7	Firms' labor expenditure share	Valentinyi & Herrendorf (2008)
$1-\beta$	0.33	Consumers' housing expenditure share	Combes *et al.* (2019)
μ	0.65	Housing capital expenditure share	Combes *et al.* (2021)
δ	0.36	Productivity spatial decay	Ahlfeldt *et al.* (2015)
ρ	0.76	Amenity spatial decay	Ahlfeldt *et al.* (2015)
ζ	0.25	Public good production	Fajgelbaum *et al.* (2019)

Table 6: Parameters.

5.6 Overidentification checks

In this section, we validate the model inversion using additional empirical data. First, we show that the observed density of development aligns with the model predictions. Second, after controlling for geographic terrain features, we show that neither production nor residential fundamentals exhibit a discontinuity at the border.



Note: The black dashed line represents the diagonal, while the solid red line indicates the OLS best-fit line. We consider cells with residential and employment density higher than 100 people per km^2. Each axis is normalized by the geometric mean of its respective values. **Source:** GHS-BUILT-V (2020) satellite imagery, Copernicus Project.

Figure 5: Predicted density of development against observed build-up volume.

On the one hand, we check whether the density of development predicted by the model is greater in locations where there is more observed build-up volume. Satellite data allows us to observe the build-up volume in each grid cell. Figure 5 shows the predicted development density plotted against the observed build-up volume. The figure confirms a strong correlation between those two variables ($R^2 = 0.787$) and a slope coefficient close to one. A similar conclusion holds for the correlation with building height and space (see Appendix D.3).

On the other hand, we show that, controlling for observable first-nature land characteristics, neither production nor residential fundamentals exhibit a discontinuity at the border. To verify this, we focus on a 5 km wide band across the state border of Luxembourg, and run a regression discontinuity specification with location in the country of Luxembourg as the treatment indicator and proximity to the state border of Luxembourg as a running variable. Fundamental productivities a_j, amenities b_i, and density of development ϕ_i are corrected for geographical features, accessibility, and building structure to eliminate first-nature advantages and increase the comparability between land plots. Table 7 indicates that fundamental productivity, amenity and density of development are not significantly affected by being located in Luxembourg. Cells with similar characteristics inside and outside of Luxembourg have, therefore, very similar fundamental characteristics.

	Calibrated values			Residualized values		
	$\log a$	$\log b$	$\log \phi$	$\log a$	$\log b$	$\log \phi$
Luxembourg	0.321***	0.072*	-0.042	0.046	-0.001	0.076
	(0.064)	(0.038)	(0.197)	(0.093)	(0.045)	(0.046)
Distance to border, km	0.014	-0.009	-0.055	0.011	0.012	-0.016**
	(0.012)	(0.007)	(0.037)	(0.017)	(0.008)	(0.007)
Residualized values	No	No	No	Yes	Yes	Yes
Observations	516	567	567	516	567	567
R^2	0.249	0.007	0.019	0.010	0.016	0.010

Note: The table shows regression discontinuity estimates for residualized residential and production fundamentals, and density of development. We restrict the sample to cells located within 5 km of the Luxembourg state border that report non-zero fundamental productivities or amenities. Luxembourg is a dummy variable that is equal to 1 if the cell lies within the country of Luxembourg. To balance cell characteristics across the cutoff, the fourth, fifth, and sixth columns use residualized values of production fundamentals, residential fundamentals, and density of development. Residualized values are defined as residuals of the OLS regression of the latter on the geographic controls used in Table 17, the number of observed buildings for the whole sample of locations, and accessibility, defined as the sum of the inverse of travel times to all cells in the economy. Robust standard errors in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 7: Effect of Luxembourg on production and residential fundamentals, and density of development.

In Appendix D.3, we further check that the Luxembourg country's administrative border does not affect the workers' expected income, commuting market access, productivity, and residential spillover predicted by the model, while it affects floorspace prices and commercial build-up shares. This suggests that the model replicates the commercial build-up jump and its magnitude. Finally, we also show that fundamental productivities and residential amenities correlate with observable first-nature features.

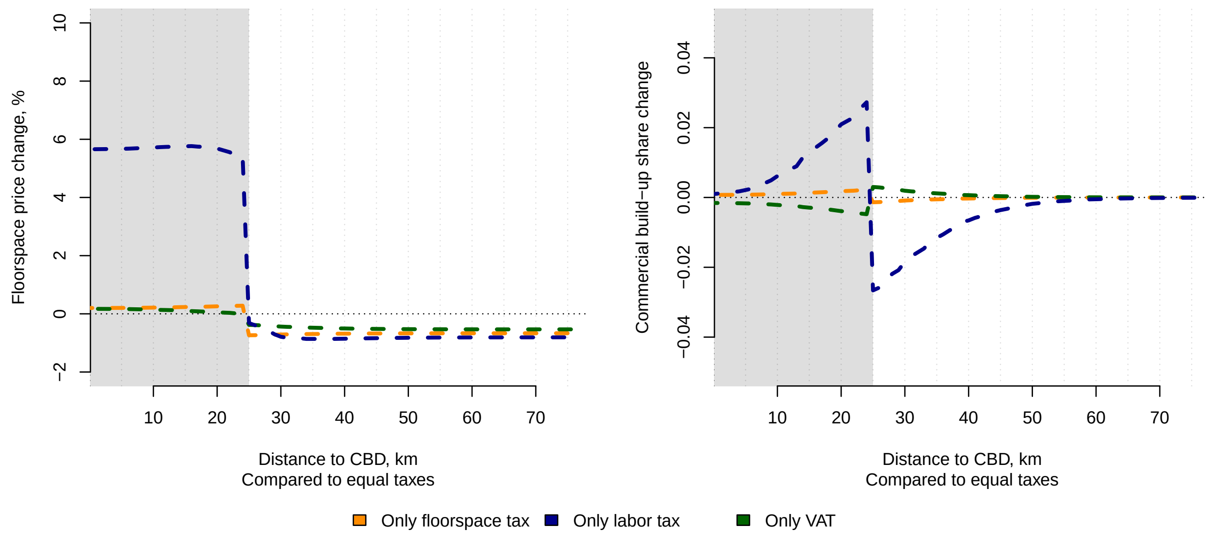
6 Effects of taxation

As stated in the stylized facts, discrepancies in country taxes are essential factors of the economic activity in the Luxembourg metropolitan area. In this section, we discuss the general equilibrium effects of taxes in a stylized geography. Such geography allows us to disentangle the impact of taxes on economic variables from the effects of location characteristics.

Toward this aim, we consider a circular and featureless geographical area with a 75 km radius, covered by 1×1 km grid cells and including two jurisdictions. The first one occupies the area within 25 km of the central point, while the second one is larger and covers the remaining area. The central jurisdiction, therefore, has a smaller land area. The geography is featureless in the sense that the residential fundamentals, the production fundamentals, and the density of development are set equal to one in every cell. The travel distances between cells are determined by Euclidean distances. The only differences between locations are the VAT, land, and labor tax regimes. The area mimics Luxembourg's actual commuting market to account for similar commuting times and urban externalities. Model parameters are set to those reported in Table 6, which will allow comparison with the next sections.

We present four different scenarios. In the baseline scenario, both countries set identical tax rates, equal to the average observed in Belgium, France, Germany, and Luxembourg. In each of the alternative scenarios, the central jurisdiction reduces its taxes — on goods, floorspace, or labor, respectively — to the levels observed in Luxembourg, while the other jurisdiction keeps the baseline tax level. We consider an open city where workers arrive from or exit to the outside economy. Numerical simulation results are presented in Figures **??** to **??**.[6]

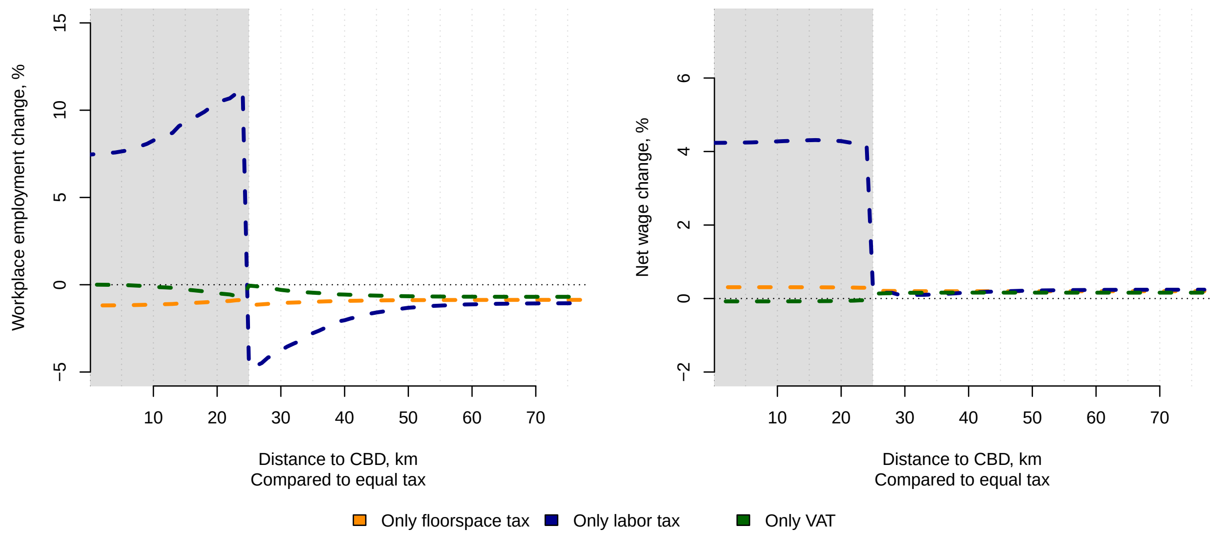
[6]Because of computing time and memory constraints, we restrict the number of grid cells by keeping one cell out of every four cells.



Note: This figure illustrates the impact of floorspace, labor, and value-added taxes on floorspace prices and commercial build-up shares in the context of a circular, featureless geography. The curves show the effect of introducing the Luxembourg tax regimes in the center (gray area), compared to a situation with uniform taxes set to country averages. The circular and featureless geography consists of a central jurisdiction with a 25 km radius and a surrounding peripheral zone 50 km wide. Residential and production fundamentals, as well as development density, are uniform across all cells. Model parameters are set according to those reported in Table 6.

Figure 6: Changes in floorspace prices and in share of commercial buildup.

Figure **??** shows that the labor tax discrepancy causes a 7% jump in floorspace price and a drop of about four percentage points in the share of commercial build-up at the jurisdiction border, which is consistent with our stylized facts. The labor tax difference generates the main spatial differences. Nevertheless, whereas relative changes in floorspace prices are stable within each jurisdiction, commercial buildup drops at the center and steadily rises when one moves to the border. At this point, it dramatically falls and then recovers to the level with uniform taxation.



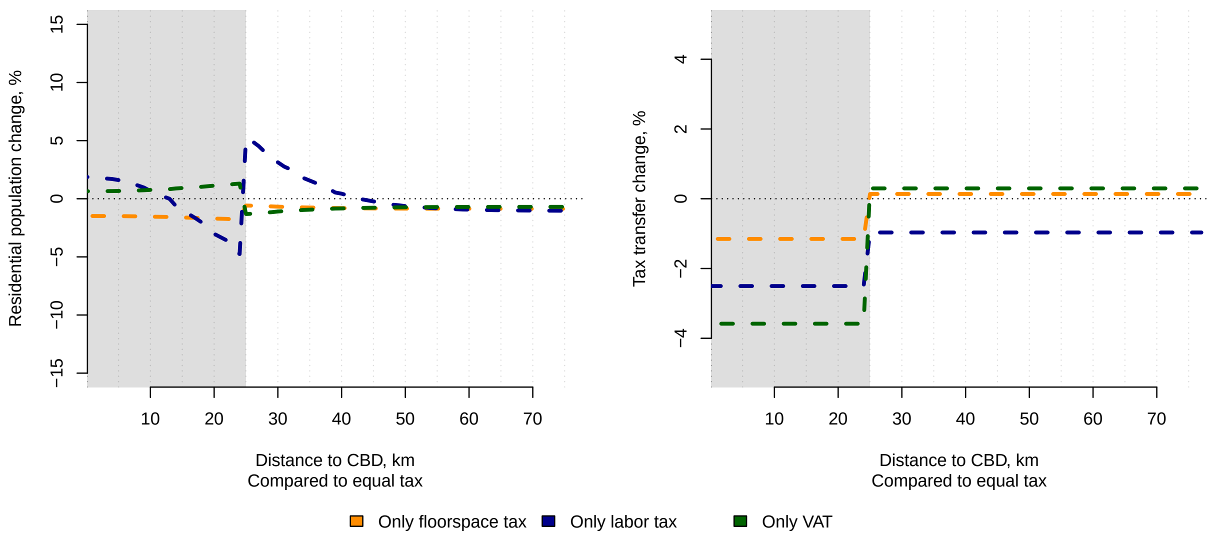
Note: This figure illustrates the impact of floorspace, labor, and value-added taxes on workplace employment and net wages in the context of a circular, featureless geography. The curves show the effect of introducing the Luxembourg tax regimes in the center (gray area), compared to a situation with uniform taxes set to country averages. Same definition of geography as in Figure **??**.

Figure 7: Changes in workplace employment and net local wages.

Figure 7 shows that a lower labor tax in the central jurisdiction raises net wages and attracts more employment there, while it decreases employment without significantly affecting wages in the outer and larger jurisdiction. Employment rapidly falls by 15 % across the border. This is because workers in the border neighborhoods are attracted by large wage differences and incur small travel times to jobs there. The employment difference is largely attributed to the 4% discrepancy in net wages. However, note that only half of the 9 p.p. labor tax difference is passed onto workers' wages because of imperfect spatial mobility. Again, the effects of VAT and real property taxes on workplace employment are negligible compared to the effect of the labor tax change.

The left panel of Figure **??** shows that the labor tax difference entices the residential population to live close to the border of the outside jurisdiction, where floorspace prices are lower and high-paid jobs are still accessible. By contrast, residents avoid the proximity of the border of the central jurisdiction, where they must compete for floorspace with more firms at higher prices.

Changes in public investment in local amenities are depicted in the right panel of Figure **??**. From this exercise, the 9 p.p. fall of labor tax in the central jurisdiction decreases per-resident tax revenues and local public amenities by only 2.5% in this area and by 1 % in the outer jurisdiction. This supports the idea of a tax importation mechanism, by which the outer jurisdiction loses a share of workers and labor tax contributions. The mechanism is, nevertheless, too weak to generate an increase in per-resident tax revenues in the central jurisdiction. In a sense, tax importation is less related to tax differentials than to the job attractiveness of the central place. The differences in VAT and floorspace taxes here also significantly reduce the central jurisdiction's tax revenues and local public investment.



Note: This figure illustrates the impact of floorspace, labor, and value-added taxes on residential population and local public good investment (summarized by the per-capita tax transfer in the cell) in the context of a circular, featureless geography. The curves show the effect of introducing the Luxembourg tax regimes in the center (gray area), compared to a situation with uniform taxes set to country averages. Same definition of geography as in Figure **??**.

Figure 8: Changes in residential employment and public good investment in local amenities.

To sum up, the main effect on the spatial economic structure of the geography lies in the discrepancies in labor tax regimes. They generate strong differences in floorspace prices and commercial build-up as well as employment, net wages, residential population density, and local public investment, across the border and particularly in its neighborhoods. Second, while employment and commercial activity increase on the interior side of the border and decrease on the exterior side, the population follows the opposite pattern. These features reflect the key stylized facts outlined in Section 2.

7 Main results

In this section, we discuss the main results of the paper. The objective is to disentangle the effect of the tax setting from land use restrictions, productivity, and amenities specific to the country of Luxembourg.

Towards this aim, we decompose the observed floorspace price jump and assess the relative impact of its components. First, we perform a series of nested counterfactual exercises where we sequentially remove border discontinuities in tax rates, the tax importation mechanism, and discontinuities in fundamental productivities and amenities. By altering only one parameter at a time in each counterfactual, we attribute changes in the price jump to each specific factor.

In Table 8, we present the results of our nested counterfactual exercises, showing how different factors contribute to the observed floorspace price jump. Column 1 reports the actual observed floorspace price jump across the border. The subsequent regression estimates reflect the simulated price jump under various counterfactual scenarios. Column 2 shows the floorspace price jump when we eliminate the tax importation mechanism. To do this, we assume that all tax revenues collected in the metropolitan area of Luxembourg are collected by a (supranational) central administration, which redistributes its revenue on a per-capita basis in local public goods across the entire geography. Tax rates are maintained at their actual levels. Column 3 shows the floorspace price jump when we equalize all taxes to their average values across the commuting area. Columns 4 and 5 further eliminate cross-border discontinuities in productivity and residential amenity fundamentals.

	Floorspace price (€/m^2)				
	(1)	(2)	(3)	(4)	(5)
Luxembourg	3219.266***	2357.100***	1988.742***	29.076	-154.898
	(163.329)	(170.512)	(163.650)	(136.544)	(132.991)
Distance to border, km	126.211***	121.205***	112.964***	67.449***	65.425***
	(30.529)	(31.871)	(30.589)	(25.522)	(24.858)
No tax importation	No	Yes	Yes	Yes	Yes
Equal taxes	No	No	Yes	Yes	Yes
No jump in a	No	No	No	Yes	Yes
No jump in b	No	No	No	No	Yes
Observations	568	568	568	568	568
R^2	0.791	0.673	0.623	0.053	0.020

Note: Luxembourg is a dummy variable that is equal to 1 if the cell lies in the country of Luxembourg. Column 1 shows the observed price jump at the border. Column 2 shows the price jump after eliminating the tax importation mechanism. Column 3 shows the price jump after equalizing all taxes across all countries. We equalize taxes to the average across the four countries. Column 4 additionally eliminates cross-border productivity differences. Finally, Column 5 additionally eliminates residential fundamentals discontinuities. Robust standard errors in parentheses. To adjust fundamental amenity and productivity differences, we use shifters reported in the first two columns of Table 7. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 8: Nested counterfactual floorspace price discontinuities.

The first row of Table 8 shows that the effect of the Luxembourg location dummy vanishes as we eliminate the tax importation, differences in taxes, fundamental productivities, and fundamental residential amenities. When all local tax and geographical features are eliminated (last column), the spatial economy converges to a monocentric city similar to the actual one (see Appendix E). The diminishing R^2 suggests the explanatory power of each factor. From the first row, it can be established that the tax importation mechanism explains 27%

(= 1 − 2357.1/3219.2) of the observed price jump. Differences in tax rates account for an additional 11% (= (2357.1 − 1988.7)/3219.2), while differences in production fundamentals contribute a further 62% (= 1988.7/3219.2). Residential fundamental amenities do not contribute to this. The fact that the Luxembourg coefficient in Column 5 is not significantly different from zero confirms that only the above factors contribute to the price jump.

The preceding analysis considers a specific sequence for eliminating differences among the four identified factors, although fifteen other sequences are possible. At the same time, interactions and nonlinearities may influence the effect associated with eliminating each factor. To assess the impact of each factor for all possible sequences, we compute the effect of the Luxembourg jurisdiction on floorspace prices across all sixteen possible sequences and then estimate a linear regression model with the coefficient of the Luxembourg dummy variable as the dependent variable and these factors as independent variables. The results are reported in Table 9. The high R^2 value and low RMSE indicate that the relationship is well approximated by a linear specification. The coefficients in the table indicate the average value of eliminating each factor difference. According to the table, on average, tax importation explains 17% of the price jump. Tax differences explain 9% of the floorspace price jump. Spatial differences in fundamental productivities and residential amenities explain 64% and 10% of the effect.[7]

From a policy perspective, tax rates and the tax redistribution policy can be adjusted by policymakers. The above results therefore suggest that the average price for an 80 m^2 apartment in Luxembourg could be reduced by €51,040 if the tax revenue was redistributed to all residents of the Greater Region by the centralized supranational authority. Similarly, a Luxembourgish resident would pay €28,320 less if tax rates were equalized to the averages among the four countries.

	Impact on floorspace price, €/m^2
No tax importation	-638.8
Equal taxes	-354.7
No jump in a	-2413.7
No jump in b	-372.3
Observations	16
R^2	0.990
RMSE	256.6

Note: We report the estimation of the meta regression of the Luxembourg dummy coefficient in Table 8 on the dummies for equal taxes, no tax importation, and no jumps in a, and b. We report two measures of non-linearity of the effects: R^2 and residual mean square error (RMSE).

Table 9: Meta-regression.

[7] The share of the effect attributed to each factor is computed as its coefficient estimate divided by the sum of all coefficient estimates in Table 9.

8 Discussion

In this section, we conclude our investigation by discussing the effects of cross-border work and home bias.

8.1 Cross border commuting

Under the EU's fundamental right to free movement of workers, individuals are entitled to seek and accept employment in a country where they do not reside. In the cross-border region examined in this paper, workers are expected to optimize their choice of residence based on local amenities, income prospects, and degree of spatial mobility. By arbitraging between locations across the border, workers are expected to smooth the spatial structure of floorspace prices. We assess how cross-border mobility mitigates spatial differences in floorspace prices.

Towards this aim, we build a counterfactual scenario with no cross-border commuting by assigning infinite travel time to cross-border commutes. Travel times within countries remain unchanged. Workers and firms freely set up their plants and residences across countries. Since workers are paid and consume in their countries of residence, tax importation does not occur. The impact of Luxembourg's jurisdiction on the floorspace price around the border is reported in Table 10[8]. Column 2 shows a decrease of floorspace price per m^2 by €216.2 in Luxembourg in the absence of cross-border commuting (first row). This effect offsets the decrease in floorspace prices on the Luxembourgish side, due to the loss of tax importation, with the decline in floorspace prices in neighboring countries resulting from their loss of access to the Luxembourgish labor market. However, the former mechanism dominates.

The equalization of local taxes, productivity, and residential amenities mainly explains the remaining discrepancy in floorspace prices. When differences in local factors across countries are controlled for, Luxembourg exhibits no floorspace price premium (Column 5). Note finally that the effect of the distance to the border weakens (second row, second column). While commuting directions differ on each side of the border, the coefficient mainly reflects the commuting cost from the border to Luxembourg City.

[8]See Supplementary Appendix A.6 for description of the evolution of endogenous outcomes.

	Floorspace price (€/m^2)				
	(1)	(2)	(3)	(4)	(5)
Luxembourg	3219.266***	3003.058***	2682.147***	228.064	80.387
	(200.343)	(186.757)	(180.385)	(155.188)	(154.866)
Distance to border, km	126.211***	95.098***	91.330***	55.722**	53.269*
	(32.786)	(31.188)	(30.021)	(27.188)	(27.304)
No cross-border	No	Yes	Yes	Yes	Yes
Equal taxes	No	No	Yes	Yes	Yes
No jump in a	No	No	No	Yes	Yes
No jump in b	No	No	No	No	Yes
Observations	568	568	568	568	568
R^2	0.791	0.766	0.744	0.096	0.050

Note: Luxembourg is a dummy variable that is equal to 1 if the cell lies in the country of Luxembourg. Column 1 shows the observed price jump at the border. Column 2 shows the price jump after eliminating cross-border commuting. Column 3 additionally shows the price jump after equalizing all taxes across all countries. We equalize taxes to the average across 4 countries. Column 5 additionally eliminates cross-border productivity differences. Finally, Column 6 additionally eliminates residential fundamentals discontinuities. Robust standard errors in parentheses. To adjust fundamental amenity and productivity differences, we use shifters reported in the first two columns of Table 7. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 10: Counterfactuals with no cross-border commuting.

8.2 Home bias

In cross-border regions, individuals may hold preferences for local goods and legal systems. For example, access to and compensation for ancillary rights such as child education, pension, or healthcare may differ across borders and may be subject to restrictions or uncertainty. As a result, individuals may exhibit a home bias in their residential or employment choices.

In this subsection, we examine the impact of home bias on the floorspace price differences. To this end, we assume that individuals incur an additional disutility shock when working in a country different from their country of residence. That is, we postulate $d_{ij} = e^{\kappa \tau_{ij} + T_{ij}}$ where T_{ij} measures the utility discount when i and j lie in different jurisdictions. Intuitively, such a home bias generates an effect that is similar to, but weaker than, the closing-border scenario described above. The point is to assess the actual magnitude of such a disutility shock. To measure the latter, we extend the approach discussed in Section 5.1 to account for a potential discount associated with crossing a border (see Appendix F). We then run the same sequence of counterfactual scenarios as in Table 8 with the measured home bias.

Results are shown in Table 11. Column 2 shows that the presence of a home bias decreases the floorspace price jump at the border by 9% (= (2935.4 − 3219.2)/3219.2). This is because home-biased residents of neighboring countries perceive their access to the Luxembourg labor market as less favorable, which lowers their expected incomes and, consequently, reduces floorspace prices in those areas. Nevertheless, the elimination of tax importation reduces the floorspace price difference by 15% (= (2935.4 − 2452.8)/3219.2), and the equalization of taxes reduces it further by 13% (= (2452.8 − 2027.1)/3219.2), which is similar to the effect found in the absence of home bias. Differences in fundamental productivity explain 63% of the floorspace price fall at the border (=2027.1/3848.4)). As in Section 8.1, home bias mitigates the arbitrage intensity of floorspace prices across the border.

	Floorspace price (€/m^2)					
	(1)	(2)	(3)	(4)	(5)	(6)
Luxembourg	3219.266***	2935.385***	2452.877***	2027.139***	-21.042	-179.938
	(200.343)	(185.553)	(180.858)	(178.983)	(166.848)	(164.445)
Distance to border, km	126.211***	118.089***	114.216***	107.497***	67.495**	64.655**
	(32.786)	(30.373)	(29.377)	(28.867)	(28.170)	(28.023)
Home bias	No	Yes	Yes	Yes	Yes	Yes
No tax importation	No	No	Yes	Yes	Yes	Yes
Equal taxes	No	No	No	Yes	Yes	Yes
No jump in a	No	No	No	No	Yes	Yes
No jump in b	No	No	No	No	No	Yes
Observations	568	568	568	568	568	568
R^2	0.791	0.785	0.745	0.690	0.044	0.018

Note: Luxembourg is a dummy variable that is equal to 1 if the cell lies in the country of Luxembourg. Column 1 shows the observed price jump at the border. Column 2 shows the price jump after introducing home bias. Column 4 additionally shows the price jump after equalizing all taxes across all countries. We equalize taxes to the average across 4 countries. Column 5 additionally eliminates cross-border productivity differences. Finally, Column 6 additionally eliminates residential fundamentals discontinuities. Robust standard errors in parentheses. To adjust fundamental amenity and productivity differences, we use shifters reported in the first two columns of Table 7. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 11: Counterfactuals with home bias.

9 Conclusion

In this paper, we highlight the existence of a jump in floorspace prices and the share of commercial buildings at the borders of Luxembourg and its neighboring countries. We discuss the drivers behind this observation by combining a quantitative urban economic model with spatial regression discontinuity techniques to decompose the relative contributions of taxes, productivity, and amenities. Our analysis underscores the critical role of geography and commuting frictions in shaping labor competition. It considers the full range of taxes on labor, land, and goods to account for possible offsetting effects. It also incorporates the labor tax importation mechanism, through which the labor taxes of cross-border workers are spent on local public goods for Luxembourgish residents.

Our theoretical discussion suggests that international differences in labor taxation contribute more to explaining the border gap in floorspace prices and the share of commercial buildings than do differences in property or goods taxation. However, our quantitative model indicates that tax differences are not the predominant drivers of these disparities. Indeed, we estimate that tax differences account for up to 9% of the observed price jump, with the remaining gap largely driven by tax importation (17 %) and local productivity differences (64%). Equalizing tax regimes across borders would reduce the price of an 80 m^2 apartment by €28,320. Eliminating tax importation leads to a larger reduction of €51,040. This finding sheds light on the relative importance of international taxes and tax importation in shaping the spatial structure of economic activities and values. While restrictions on cross-border mobility and/or home bias preferences can magnify the observed price differentials, they do not substantially increase the relative importance of tax effects.

This paper focuses on the key economic mechanisms underlying cross-border housing and labor markets, which can be disentangled using our data. However, it leaves aside several important questions that are reserved for future research. Notably, the paper abstracts from an important discussion of fiscal compensation. As shown in the paper, tax importation is associated with public good under-provision in countries bordering Luxembourg, which raises the question of whether cross-border workers or the affected territories should be compensated for these losses. The extent of compensation, its allocation across jurisdictions, and the design of an optimal compensation scheme are subject to ongoing political debate in the region. These issues are of considerable interest but lie beyond the scope of this paper. Furthermore, the roles of transport infrastructure development and congestion merit further investigation, particularly within a fiscal federalism framework where neighboring jurisdictions differ in their resource endowments, political institutions, and policy incentives.

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Online Appendices

A Appendix Theoretical model

Here, we provide a detailed definition of spatial general equilibrium.

Given parameters $\{\alpha, \beta, \mu, \varepsilon, \kappa, \lambda, \delta, \eta, \rho\}$, location characteristics $\{\varphi, L, \xi, \tau\}$, productivity and amenities $\{a, b\}$, reservation utility $\bar{U}$, and tax multipliers $\{t^c, t^q, t^w\}$, the spatial general equilibrium is given by the scalar H and the vectors $\{\pi_M, \pi_R, Q, q, w, \theta, g\}$ that solve the following system of equations:

$$\bar{U} = \Gamma_0 \left[\sum_{i \in \mathcal{I}} \sum_{j \in \mathcal{I}} (d_{ij} (t_i^q Q_i)^{1-\beta} (t_i^c)^{\beta})^{-\varepsilon} (B_i G_i w_j)^{\varepsilon} \right]^{\frac{1}{\varepsilon}},$$

$$\pi_{Ri} = \frac{\sum_{s \in \mathcal{I}} (d_{is} (t_i^q Q_i)^{1-\beta} (t_i^c)^{\beta})^{-\varepsilon} (B_i G_i w_s)^{\varepsilon}}{\sum_{r \in \mathcal{I}} \sum_{s \in \mathcal{I}} (d_{rs} (t_r^q Q_r)^{1-\beta} (t_r^c)^{\beta})^{-\varepsilon} (B_r G_r w_s)^{\varepsilon}}, \quad \forall i \in \mathcal{I}.$$

$$\pi_{Mj} = \frac{\sum_{r \in \mathcal{I}} (d_{rj} (t_r^q Q_r)^{1-\beta} (t_r^c)^{\beta})^{-\varepsilon} (B_r G_r w_j)^{\varepsilon}}{\sum_{r \in \mathcal{I}} \sum_{s \in \mathcal{I}} (d_{rs} (t_r^q Q_r)^{1-\beta} (t_r^c)^{\beta})^{-\varepsilon} (B_r G_r w_s)^{\varepsilon}}, \quad \forall j \in \mathcal{I}.$$

$$q_j = \frac{(1-\alpha) A_j^{\frac{1}{1-\alpha}}}{t_j^q} \left(\frac{\alpha}{w_j t_j^w} \right), \quad \forall j \in \mathcal{I}.$$

$$\begin{cases} P_i = q_i \text{ and } \theta_i = 0 & \text{if } q_i > Q_i, \\ P_i = q_i \text{ and } \theta_i \in [0,1] & \text{if } q_i = Q_i, \\ P_i = Q_i \text{ and } \theta_i = 1 & \text{if } q_i < Q_i. \end{cases}$$

$$\theta_j \phi_j L_j^{1-\mu} = A_j^{\frac{1}{\alpha}} \left(\frac{1-\alpha}{q_j t_j^q} \right)^{\frac{1}{\alpha}} H \pi_{Mj}, \quad \forall j \in \mathcal{I}.$$

$$(1-\theta_i) \phi_i L_i^{1-\mu} = (1-\beta) \left(\sum_{s \in \mathcal{I}} \frac{(w_s/d_{is})^{\varepsilon}}{\sum_{r}^{S} (w_r/d_{ir})^{\varepsilon}} w_s \right) \frac{H \pi_{Ri}}{t_i^q Q_i}, \quad \forall i \in \mathcal{I}.$$

$$
\begin{aligned}
g_i &= \frac{t_n^c - 1}{t_n^c}\beta\frac{\sum_{i\in\mathcal{I}_n}\mathbb{E}[w|i]H_{Ri}}{\sum_{i\in\mathcal{I}_n}H_{Ri}} + \frac{t_n^q - 1}{t_n^q}(1-\beta)\frac{\sum_{i\in\mathcal{I}_n}\mathbb{E}[w|i]H_{Ri}}{\sum_{i\in\mathcal{I}_n}H_{Ri}} \\
&\quad + (t_n^w - 1)\frac{\sum_{j\in\mathcal{I}_n}w_j H_{Mj}}{\sum_{i\in\mathcal{I}_n}H_{Ri}} + (t_n^q - 1)\frac{\sum_{j\in\mathcal{I}_n}q_j S_{Mj}}{\sum_{i\in\mathcal{I}_n}H_{Ri}}, \quad \forall i \in \mathcal{I}_n. \\
G_i &= g_i^{\zeta}, \quad \forall i \in \mathcal{I}_n.
\end{aligned}
$$

B Appendix Data

B.1 Commuting times

We impute travel time within each cell or municipality using the average travel time between 50 randomly selected points along the existing road network of the spatial unit. Travel time is defined as the minimum of the travel times by car and on foot. Car travel times are obtained from OSRM. Since OSRM assumes that pedestrians follow the same road network as vehicles, we instead proxy pedestrian travel time by dividing the Euclidean distance between the selected points by an assumed pedestrian speed of 5 km/h, to better reflect pedestrian flexibility.

B.2 Population data

Population measurement is extracted from the GHS-POP-2023 dataset, produced by the European Commission's Joint Research Centre as part of the Global Human Settlement Layer (GHSL) initiative. It provides 1×1 gridded residential population estimates for 2020. The GHS-POP-2023 dataset sources its population data from official census counts and administrative records provided by national statistical offices. These official figures are harmonized and disaggregated into grid cells using satellite-derived built-up area information. Population counts from these official sources are disaggregated into grid cells using a dasymetric mapping strategy that employs built-up area information from the GHS-BUILT product derived from satellite imagery.

B.3 Employment data

We construct our employment data by mapping municipal-level records to our grid of 1×1 km cells as a function of municipalities' footprint and commercial volumes.

The data on employment (at the place of work) is obtained at the municipal level from national statistical agencies. Employment in Luxembourg is obtained from the IGSS (Inspection générale de la sécurité sociale) employment data from 2020, recording the number of workers per municipality based on the place of work, including both residents and cross-border workers. Employment in Germany is obtained from the Regionaldatenbank Deutschland supplies data from the Registry of Employees subject to Social Security Contributions at the place of work at the municipal level for 2020. Employment in France is sourced from the INSEE Municipal Data Registry, covering the employed population at the place of work. Workers are assigned to their municipality of residence when their activities cross municipalities (e.g., truck drivers, taxi drivers, VRP representatives, itinerant traders, or fishermen). We consider three French departments adjacent to Luxembourg, with census information available for 2021. Employment in Belgian municipalities bordering Luxembourg are provided by the Walloon Statistical Agency (IWEPS) for 2020, using methods consistent with those applied in France.

We further use the built-up volume information from the GHS-BUILT-V dataset, produced by the European Commission's Joint Research Centre. Built-up volumes are identified from Landsat satellite imagery using automated classification techniques. We use the volume allocated to dominant non-residential and residential at a 1×1 km spatial resolution. The dataset has global geographical coverage and is available for 2020.

We allocate employment across the grid cells as follows. We allocate the observed municipal employment according to the share of the municipal building volume attributed to municipal land. That is, the employment in cell j is given by $H_{Mj} = \sum_m H^m_{Mj}$ where H^m_{Mj} is the employment of municipality m allocated in cell j, which is given by $H^m_{Mj} = H^m_M L^m_j V_j / (\sum_k L^m_k V_k)$ where H^m_M is the observed administrative employment in municipality m, L^m_j is the observed area of municipality m in cell j and V_j is the volume of build-up observed in cell j. Finally, because our simulations require attributing a single country to each cell, we assign each cell j to the country with the largest area in the cell. Consistently, we erase the land surface of the other country. That is, we set $L^{m'}_j = 0$ if $L^m_j > L^{m'}_j$ where m and m' are municipalities of two different countries.

Our employment data turns out to be more accurate than existing high-resolution employment databases, in particular the daytime population densities reported in the ENACT 2011 Population Grids of the European Commission. See discussion in supplementary section A.1.

B.4 Floorspace Prices

Rental and sale property listing data is obtained from March to September 2022 from the at-home.lu website, which jointly covers Luxembourg, Germany, France, and Belgium. Listings with valid geographical coordinates and housing characteristics (longitude, latitude, prices/rents, hedonics) are selected, resulting in 11,319 property listings and 5,366 rental listings. We remove the top 5% and bottom 5% of listings based on prices and rents, respectively for Luxembourg and countries outside Luxembourg. This yields 4,819 rentals (4,362 in Luxembourg) and 10,183 property purchase listings (6,740 in Luxembourg).

We assign each cell to a single country. A cell is assigned a country if and only if more than half of its area lies within the country's border. The rest of the area and the listing located in it are discarded. This leaves 4,790 rentals (4,352 in Luxembourg) and 10,137 property purchase listings (6,716 in Luxembourg).

Finally, the data is filtered by property type to include houses, apartments, offices, studios, bedrooms, detached and semi-detached houses, and duplexes. This step results in a final dataset of 8,916 property purchase listings (6,016 in Luxembourg) and 4,149 rental listings (3,807 in Luxembourg) used for computing cell fixed effects. Since the sale property listings are twice as numerous and spread over more cells, they are naturally preferred for estimating the floorspace price index.

The cell i's price index is computed as the fixed effect η_i in the hedonic price regression model $\log Q_{ni} = \mathbb{H}_n' \beta + \eta_i + \epsilon_{ni}$, where Q_{ni} denotes the price per m^2 for housing unit n in grid cell i, $\mathbb{H}_n$ is a vector of hedonic characteristics, and ϵ_{ni} is the error term.

The regression results for prices per square meter are presented in Table 12. The first column includes only house characteristics, while the second column adds the cells' fixed effects. The latter controls for neighborhood amenities and productivity, transport infrastructure, access to employment, etc. The high explanatory power is noticeable in the second column. Fixed effects are balanced between countries. In our specification, we get 973 price indices, of which 496 are in Luxembourg.

	Price per m^2	
	No cell fixed effects	With cell fixed effects
log, Surface	-0.049***	-0.239***
	(0.015)	(0.007)
Number of Rooms	-0.110***	-0.016***
	(0.004)	(0.002)
Number of Bedrooms	0.001	-0.001
	(0.002)	(0.001)
Number of Bathrooms	0.007*	-0.002
	(0.004)	(0.002)
Furnished	0.009	-0.008
	(0.012)	(0.006)
Age, decade	0.008***	0.004***
	(0.001)	(0.000)
Age^2, decade 10^{-3}	-0.004***	-0.002***
	(0.001)	(0.000)
Balcony surface	0.009***	0.002***
	(0.001)	(0.001)
Age not defined	0.015	-0.035***
	(0.012)	(0.005)
Type FE	Yes	Yes
Type FE × Number of Rooms	Yes	Yes
Thermal Insulation FE	Yes	Yes
Cell FE	No	Yes
R^2	0.488	0.926
Observations	8916	8916

Note: "Type of FE" refers to the types of properties: apartments, bedrooms, detached houses, duplexes, houses, offices, semi-detached houses, studios. Thermal insulation refers to the grade of the house's thermal certificate. Standard errors in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 12: Hedonic regressions for purchase prices.

B.5 Universal kriging

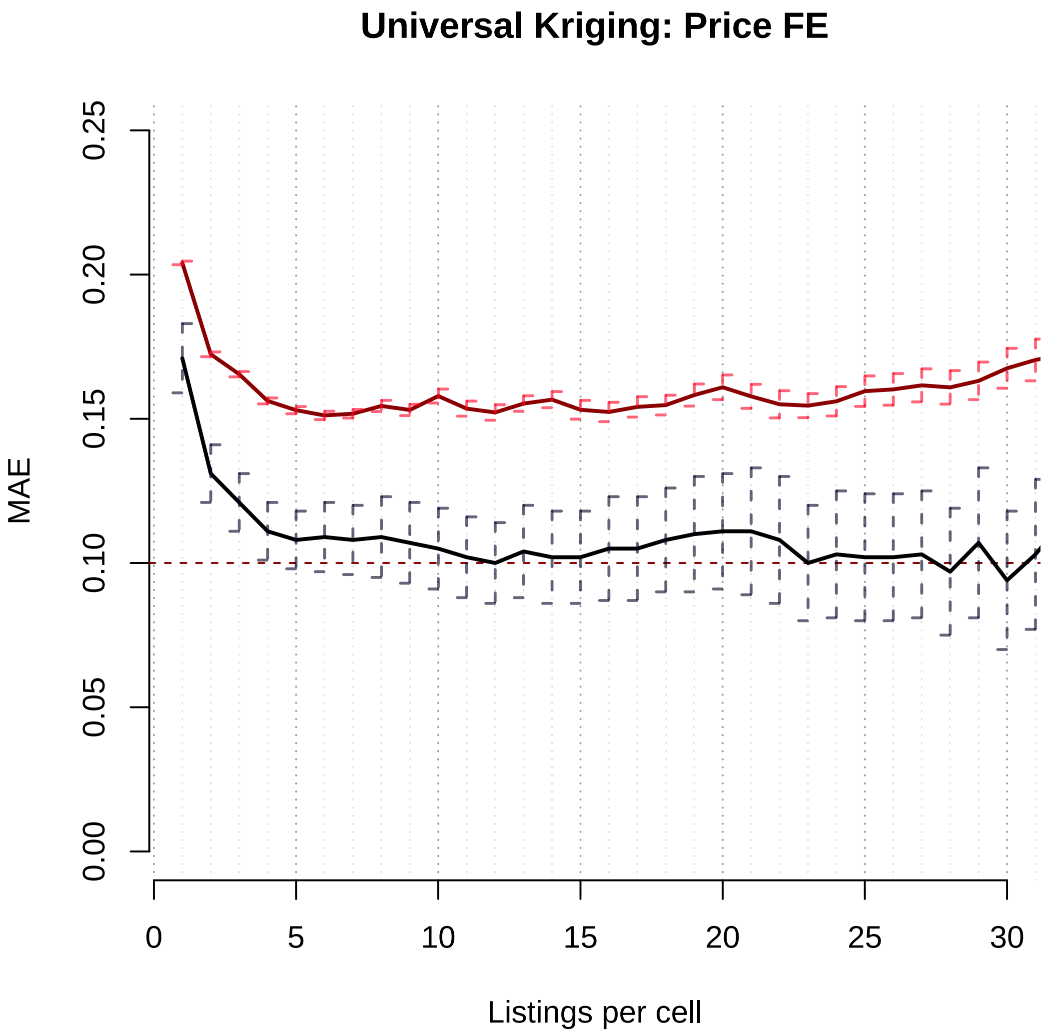
Universal kriging is a geostatistical method for predicting values at unsampled locations by combining a deterministic trend with spatially correlated errors (Matheron (1963)). The trend is modeled as a linear function of known covariates (e.g., a constant, spatial coordinates, or other predictors). The spatial dependence is captured through a variogram, which describes how the variance of the differences between observations increases with distance between them.

In our context, the universal kriging approach assumes that the price index is given by $\eta_i = \mathbb{H}_i'.\beta + \epsilon_i$, $i = 1, ..., N$ where $\mathbb{G}_i$ are characteristics of cell, ϵ_i is an error with $E[\epsilon_i] = 0$ and variance $E[(\epsilon_i - \epsilon_j)^2] = 2\gamma(d_{ij})$ where d_{ij} is the distance between two cells i and j. The main assumption is that the function $\gamma(d)$ is a function of distance d given by the variogram fitted with the dataset. The unbiased predictor of the price index of an outside cell n with characteristics $\mathbb{G}_n$ is then given by $\widehat{\eta}_n \equiv \sum_{i=1}^{N} \omega_i \eta_i$ where the weights ω_i and coefficients β are chosen to minimize the variance of the prediction error $E\left[(\eta_n - \widehat{\eta}_n)^2\right]$. Unbiasedness requires $\sum_{i=1}^{N} \omega_i = 1$ and $\sum_{i=1}^{N} \omega_i \mathbb{G}_i = 1$. The minimization is repeated for every cell prediction.

In this paper, the vector of cell's characteristics $\mathbb{G}_i$ includes the logarithms of local population $\log(1 + H_{Ri})$, local employment $\log(1 + H_{Mi})$, travel time to central business district for Luxembourg cells $\log(1 + d_i^{CBD}) \times LUX_i$. The variogram $\gamma(d)$ is estimated from the data by averaging squared differences between nearby points, and then fitted with an exponential function.

To enhance precision, we restrict data to the cells with more than five listing observations. This is because the price indices estimated for cells with very few listing observations are expected to include significant error components. Figure 9 shows the mean absolute errors (MAEs) of the prediction of the price index as a function of the minimum number of listings per cell. The bars reflect standard errors. The reader can see that MAEs drop significantly until we keep the cells with more than five listings. Figure 9 also shows the MAEs of the prediction using the OLS regression, $\eta_i = \mathbb{G}_i' \beta + \epsilon_i$. One can see that kriging predictions are systematically more precise than OLS predictions, because they capture the spatial correlation between neighboring price indices.

The supplementary material A.3 further quantifies the advantage of the kriging approach and compares the results with price and rental listings.



Note: The table reports the mean absolute error (MAE) for cell-specific price fixed-effect prediction using universal kriging (black) and compares it to OLS prediction (red). The out-of-sample prediction quality is assessed with a 5-fold cross-validation. "Listings per cell" denotes the minimum number of listings in the cells of the sample that is used for prediction. Standard errors of MAE are shown by brackets.

Figure 9: Precision of kriging and OLS predictions.

C Estimations

C.1 Robustness checks on semi-elasticity of commuting

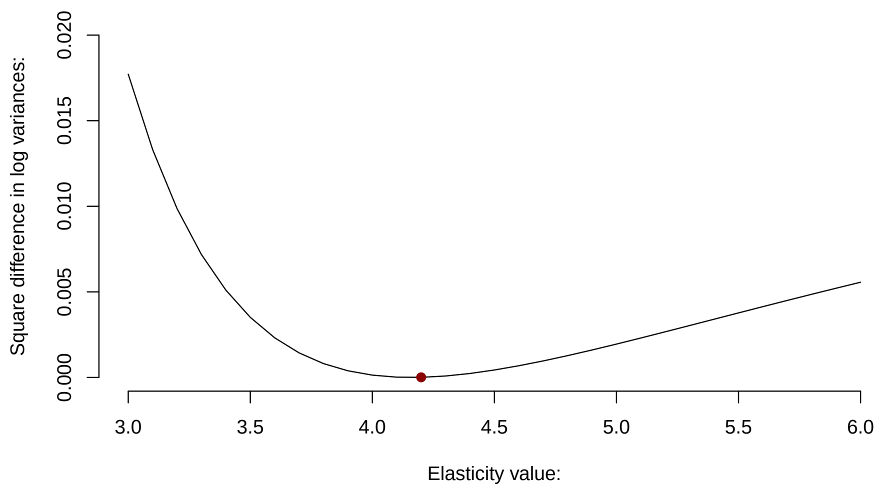
The semi-elasticity commuting parameter κ is estimated from the regression equation (21), where we use the travel flow data from the LuxMobil survey and the INSEE census data. Table 13 allows for comparison of the estimations with various combinations of databases and pairs of origin and destination countries. Column 1 reproduces column 1 of Table 4 with only travels in the country Luxembourg reported by the LuxMobil survey. Column 2 shows almost the same coefficient using LuxMobil travels from the country of Luxembourg to the whole Luxembourg functional area. Column 3 reports a slightly lower coefficient within the whole functional area using LuxMobil travels. This is potentially explained by a selection bias in LuxMobil survey that mainly focuses on individuals working in the country of Luxembourg. Column 4 reports a slightly higher coefficient for travels of INSEE census data within the French municipalities, which have a slightly different communication infrastructure. Column 5 gives a similar coefficient for travel from France to Luxembourg and France. Column 6 reproduces column 3 of Table 4 with travels within Luxembourg and France using both datasets. Overall, estimates are similar in all settings.

	log, Flows					
	(1)	(2)	(3)	(4)	(5)	(6)
OSRM Travel Time, min	-0.110***	-0.109***	-0.100***	-0.122***	-0.111***	-0.116***
	(0.006)	(0.006)	(0.004)	(0.005)	(0.003)	(0.004)
Survey	LuxMobil	LuxMobil	LuxMobil	INSEE	INSEE	Both
Country of Origin	LU	LU	All	FR	FR	LU + FR
Country of Destination	LU	All	All	FR	LU + FR	LU + FR
Origin FE	Yes	Yes	Yes	Yes	Yes	Yes
Destination FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	13689	16263	25308	86114	191367	214468
R^2	0.810	0.815	0.821	0.835	0.831	0.850

Table 13: Commuting flows elasticity with respect to the travel time.

C.2 Fréchet scale parameter

We choose the Fréchet parameter ε that produces the wage dispersion closest to the observed one (Ahlfeldt *et al.* (2015)). Toward this aim, we minimize the absolute difference between the variances of the logarithm of the observed wages and the wages simulated by the model, $|\mathrm{var}(\log w_m^{data}) - \mathrm{var}(\log w_m^{sim}(\varepsilon))|$ where $|.|$ is the absolute value operator. In this expression, variances are taken over the municipalities m. w_m^{data} denotes the net wage reported at the municipal level, while $w_m^{sim}(\varepsilon)$ is the employment-weighted average of simulated wages across the cells in the municipality. That is, denoting the set of cells in the municipality by $j \in \mathcal{I}_m$, we set $w_m^{sim}(\varepsilon) = \sum_{j\in\mathcal{I}_m} w_j^{sim}(\varepsilon)(H_{Mj}/\sum_{j'\in\mathcal{I}_m} H_{Mj'})$ where $w_j^{sim}(\varepsilon)$ denotes the simulated wage in cell j while H_{Mj} is given by the observed employment in the cell j. The vector of simulated wages $w_j^{sim}(\varepsilon)$ is obtained by numerically solving the labor market conditions (17) for w_j at each value of ε, using the observed residential populations H_{Ri}, observed travel time τ_{ij} and the above-estimated semi-elasticity of commuting ν. Figure 10 shows the plot of this difference between observed and simulated wage variances. It has a minimizer at $\varepsilon = 4.2$.



Note: The wages are the hourly net wages in Luxembourgish municipalities and French municipalities in the departments bordering Luxembourg.

Figure 10: Difference between variances of observed and simulated (log) wages as a function of ε.

C.3 Urban externalities

Instruments for the productivity and amenity regressions are derived from the spatial distribution of commercial and residential floor area in 1975.

First, we estimate employment-to-buildup conversion coefficients $(\hat{\alpha}_M, \hat{\beta}_M)$ and $(\hat{\alpha}_R, \hat{\beta}_R)$, by regressing 2020 the logarithm of employment and log-population on the logarithm of 2020 commercial and residential buildup areas. Results are reported in Table 14.

	Employment (log, 2020)	Population (log,2020)
Residential build-up (log, 2020) (β_R)	1.107***	
	(0.008)	
Commercial build-up (log, 2020) (β_M)		1.175***
		(0.009)
Intercept (α_M, α_R)	0.375***	-1.358***
	(0.030)	(0.052)
Observations	3182	3182
R^2	0.855	0.854

Table 14: Population and employment and build-up areas.

Second, we apply those coefficients to commercial build-up data for 1975, using the variables $SNRES_s^{1975}$ and $SRES_s^{1975}$ in the GHS-BUILT-S database. This yields the 1975 predicted employment: $\hat{H}_{Mj} = e^{\hat{\alpha}_M} \left(SNRES_j^{1975}\right)^{\hat{\beta}_M}$ and $\hat{H}_{Ri} = e^{\hat{\alpha}_R} \left(SRES_i^{1975}\right)^{\hat{\beta}_R}$.

Finally, we impute the instrumental variables for urban externalities for 1975 using the following expressions: $\hat{\Upsilon}_j = \sum\limits_{i \in \mathcal{I}} e^{-\delta \tau_{ij}} \hat{H}_{Mi}/L_i$ and $\hat{\Omega}_i = \sum\limits_{j \in \mathcal{I}} e^{-\rho \tau_{ij}} \hat{H}_{Rj}/L_j$.

To visualize instrumental variables, Figure 11 shows the changes in residential and productivity spillover estimates between 1975 and 2010. Productivity spillovers experience declines in areas of former industrial production in France (Thionville, Metz), Saarland, and south of Luxembourg (Esch, Differdange, Dudelange).

Figure 11: Changes between residential and productivity spillover estimates between 1975 and 2010.

Table 5 reports the first- and second-stage regression results for the constructed spillover instrument. Following Combes *et al.* (2010) and Combes & Gobillon (2015), geographic controls are incorporated to account for first-nature determinants that may affect both present-day productivity and past population and employment patterns. Since these variables plausibly influence both historical and current employment distributions, the exclusion restriction is assumed to hold only conditional on geographic controls. These geographic control variables are interacted with country indicator variables to allow for country-specific slope heterogeneity. Nevertheless, no separate country fixed effects are introduced, thus cross-country differences are represented exclusively through the observed covariates and their interactions.

A robustness check with alternative instruments is available in the Supplementary Appendix A.4.

D Model inversion, calibration and validation

In this appendix, we detail the procedure used to invert the model, the resulting benchmark model, and an additional validity check.

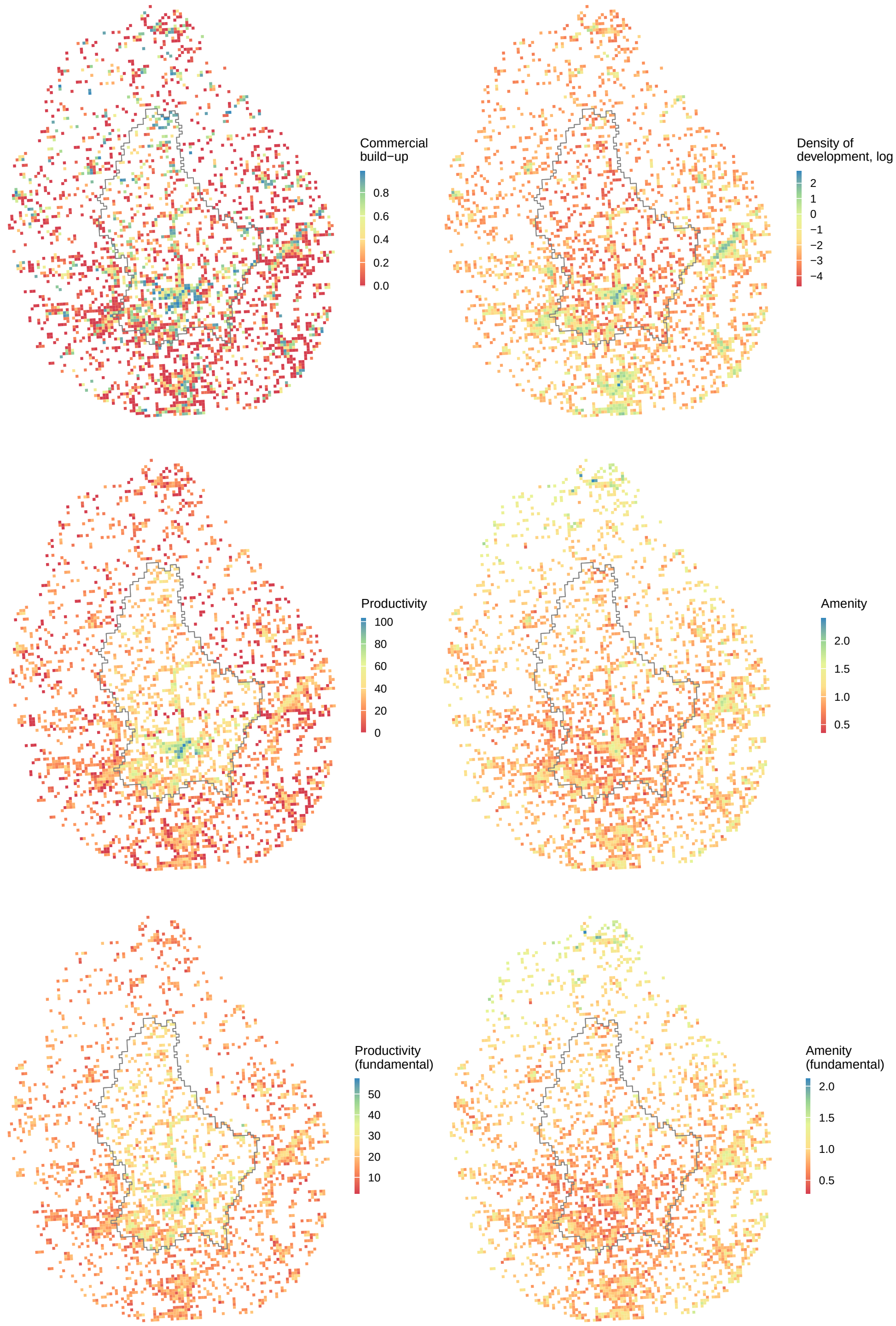
D.1 Model inversion

The inversion of the model recovers the vectors of the characteristics of the unobserved location A, B, a, b, and φ using the values of the parameters $\alpha, \beta, \mu, \varepsilon, \kappa, \lambda, \delta, \eta$, and ρ as well as our data vectors on the residential population, H_R, employment at work, H_M, commuting time, τ, floorspace rents, Q, and tax multipliers, t^c, t^q, and t^w. (Vectors and matrices are denoted by deleting references to i and j.) We apply the following steps:

1. Given $\{\varepsilon, \kappa\}$ and the observed data $\{H_M, H_R, \tau\}$, we determine the equilibrium wage vector w from the labor market clearing condition (17).
2. Given $\{\varepsilon, \kappa, \alpha, \beta, \mu\}$, the observed data $\{\mathbb{Q}, H_M, H_R, \tau, t^c, t^q, t^w\}$ and the wage vector w, we determine the public investment in local amenities g from the government budget constraint 14.
3. Given $\{\varepsilon, \kappa, \alpha, \beta, \mu\}$, the observed data $\{\mathbb{Q}, H_M, H_R, \tau\}$, wages w and public investment in local amenities g, we determine the residential amenities, B, from residential choice probabilities (5) and local productivity, A, from zero-profit condition (10).
4. Given $\{\lambda, \eta, \rho, \nu\}$, the observed data $\{H_M, H_R, \tau\}$, local productivities A and amenities B, we determine the fundamental residential amenities, b, from (16) and fundamental productivities, a, from (15).
5. Given $\{\varepsilon, \kappa, \alpha, \beta, \mu\}$, the observed data $\{\mathbb{Q}, H_M, H_R, \tau\}$, wages w and productivity A, we determine the density of development φ and a share of commercial buildup θ from land market clearing condition 11, commercial (18) and residential (19) floorspace demand and floorspace market clearing condition 20.

D.2 Local fundamental characteristics

Figure 12 presents the results of the model inversion. The top left panel displays the spatial distribution of the density of development, which is higher in urban areas with high residential and workplace employment. The figure shows the existence of a fall at the Luxembourgish jurisdiction border. The top right panel shows the distribution of the share of commercial build-up. Regions with a greater share of commercial build-up align with large urban areas. The middle panels show the spatial distribution of local productivity, A, and residential amenities, B. The middle left panel indicates the presence of a high-productivity cluster located in and around the city of Luxembourg. Surrounding towns, such as Arlon, Echt, Metz, and Trier, exhibit much smaller productivity hikes. The middle right panel shows the spatial distribution of the local amenities. Residential amenities are more pronounced in the city of Luxembourg and Trier than in other urban areas. Finally, the bottom panels show the spatial distribution of fundamental productivities, a, and fundamental residential amenities, b. Production fundamentals peak in the city of Luxembourg, while residential fundamentals are more dispersed and show no significant peaks.



Note: Only cells with workplace employment or residential employment density above 100 people per km^2 are shown.

Figure 12: Calibration results for density of development (top left), commercial land use (top right), local productivity (middle left), local amenities (middle right), production fundamentals (bottom left), and residential amenity fundamentals (bottom right). Update: 02.09.2025

D.3 Over-identification

Table 15 shows the result of the OLS regression of the density of development predicted by the model on the average height, volume, and space of buildings observed from satellite data.

	$\log \phi$		
	(1)	(2)	(3)
log, average building height	2.217***		
	(0.047)		
log, build-up volume		0.979***	
		(0.011)	
log, build-up area			1.314***
			(0.020)
Observations	3182	3182	3182
R^2	0.574	0.787	0.716

Note: Robust standard errors in parentheses.
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 15: OLS regression of predicted density of development and observed average building height, volume, and space. Heteroskedasticity-robust standard errors are reported in parentheses.

To further check the validity of the model, Table 16 shows the effect of Luxembourg's administrative border effect for six endogenous variables predicted by the model: workers' expected income, commuting market access, productivity and residential spillover, floorspace rents, and commercial build-up share. We only use cells with both residential and commercial floorspace. The first four columns suggest no significant effect in expected worker income, commuting market access, and residential spillovers. The last two columns show significant discontinuities in floorspace price and commercial build-up share, which are consistent with the one observed in the stylized facts. This suggests that the model replicates the commercial build-up jump and its magnitude.

Dependent variable:	Expected income	Commuting access	Productivity spillover	Residential spillover	Floorspace prices	Commercial build-up
Luxembourg	-0.020	0.047	5.418	173.631	3221.181***	0.127**
	(0.047)	(0.141)	(81.385)	(547.599)	(209.798)	(0.055)
Distance to border, km	0.013	0.052*	30.499*	316.709***	122.284***	0.004
	(0.010)	(0.029)	(16.544)	(120.930)	(34.652)	(0.010)
Observations	517	517	517	517	517	517
R^2	0.008	0.032	0.025	0.062	0.782	0.053

Note: We consider cells located within 5 km from the state border of Luxembourg and we consider only cells with mixed floorspace use. Luxembourg is a dummy variable that is equal to 1 if the cell lies in the country of Luxembourg. Robust standard errors in parentheses.
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 16: Parametric regression discontinuity estimates for total workers' income, commuting market access, productivity, and residential spillover, floorspace prices, and share of commercial build-up.

We propose a final validity check for production and residential amenity fundamentals by examining their correlation with observable first-nature characteristics. Both production and residential fundamentals reflect environmental characteristics, such as proximity to water sources, forests, pastures, vineyards, and former industrial sites. Following Ahlfeldt *et al.* (2015), we regress these fundamentals on distances to extraction sites, water, forests, roads, vineyards, pastures, and green urban areas, as well as on noise levels. The regression results are shown in Table 17. Fundamental amenities increase with lower noise levels and with proximity to water bodies, and decrease with proximity to extraction sites, roads, pastures, and vineyards. The opposite is true for production fundamentals—their value increases as one gets closer to roads and green urban areas. The fact that production fundamentals decrease with proximity to water bodies can be partly explained by the nature of modern production, where proximity to water bodies no longer offers a productivity advantage. We use all available calibrated fundamentals to run this regression.

Dependent variable:	a	b
Distance to extraction sites (log)	-0.320*	0.018***
	(0.190)	(0.004)
Distance to water (log)	0.792***	-0.009**
	(0.172)	(0.004)
Distance to forests (log)	0.278***	0.006***
	(0.072)	(0.002)
Distance to roads (log)	-0.913***	0.033***
	(0.160)	(0.005)
Distance to vineyards (log)	-0.539***	0.014***
	(0.139)	(0.003)
Distance to pastures (log)	0.463***	0.004***
	(0.056)	(0.001)
Distance to green urban areas (log)	-2.320***	0.004
	(0.254)	(0.005)
Noise level	-10.152	-2.207***
	(9.854)	(0.202)
Num.Obs.	3178	3178
R2	0.122	0.067

Notes: Columns 1 and 2 report regression results for the fundamental productivity and amenity. The quietness index takes values from 0 to 100, where 0 denotes the location with the least noise. We use CORINE Land Cover data from the Copernicus Project to measure the distance to different amenities. Robust standard errors are in parentheses.
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 17: Regression of calibrated production fundamentals, a, and residential fundamentals, b, on observed geographical characteristics.

E Featureless geography

The last column of Table 8 shows the (insignificant) effect of the Luxembourgish area in the absence of tax differences and geographical features. In this case, residential and commercial choices are driven solely by commuting distances. In the presence of spatial externalities, it is important to assess whether the featureless equilibrium deviates significantly from the benchmark model, which mainly maps to a monocentric city surrounded by a subset of secondary cities.

Figure 13 shows the main economic variables in the featureless geography. It can be seen that wages, floorspace prices, employment, and population follow the characteristics of a monocentric city centered around the city of Luxembourg, with sub-centers in the areas of Arlon, Esch, and Metz. The wages are lower in the center, reflecting the average preference for the center discussed in Thisse *et al.* (2024). Floorspace rents fall with distance from the urban center. This gives reassurance about the applicability of the model in the absence of first-nature characteristics.

Note: Only cells with workplace employment or residential employment density above 50 people per km^2 are shown.

Figure 13: Spatial distribution of economic variables in the featureless geography.

F Home bias

We estimate the following specification:

$$\log \pi_{ij} = -\nu\tau_{ij} - \nu'\tau'_{ij} + \xi_i + \zeta_j + \epsilon_{ij}, \tag{22}$$

where τ_{ij} denotes the commuting time between residence location i and job-place location j; τ'_{ij} is a cross-border dummy equal to 1 if the residence and job-place are located in different countries, and 0 otherwise; ξ_i captures residence-specific fixed effects (such as amenities and floorspace prices); ζ_j captures job-place-specific fixed effects (e.g., productivity); and ϵ_{ij} is an error term. Estimation results are reported in Table 18. We pick the value for home bias discount from Column 2 as the baseline for the subsequent simulations.

	Flows, log	
	(1)	(2)
OSRM Travel Time, min	-0.116***	-0.110***
	(0.004)	(0.004)
Crossing Border		-1.513***
		(0.222)
Origin FE	Yes	Yes
Destination FE	Yes	Yes
Observations	116827	116827
R^2	0.840	0.845

Table 18: Estimation of home bias and commuting elasticity. Data from LuxMobil Survey and INSEE Commuting Survey. Departure communes are within 50 km of the state border of Luxembourg.

A Supplementary Material

A.1 Comparison between our employment data and ENACT data

Our employment data turns out to be more accurate than existing high-resolution databases, in particular the daytime population densities reported in the ENACT 2011 Population Grids of the European Commission. This grid cell information combines satellite imagery and administrative data from Eurostat for the entire EU at a 1×1 km resolution (Schiavina et al. (2020)). The daytime population is derived from workplace population data obtained from employment statistics and travel surveys, with spatial allocation informed by CORINE land use data. However, ENACT 2011 disaggregates population information from NUTS3 regions according to build-up volumes. This is an issue for the country of Luxembourg, which constitutes a single NUTS-3 region. This discrepancy is shown in Figure 14, which plots the administrative municipal employment data as a function of the ENACT 2021 values aggregated at the municipal level. By contrast, our approach reports employment levels and provides better precision because it disaggregates information from the municipal level. Figure 15 plots our employment data and the ENACT employment data and shows the strong correlation between the two datasets.

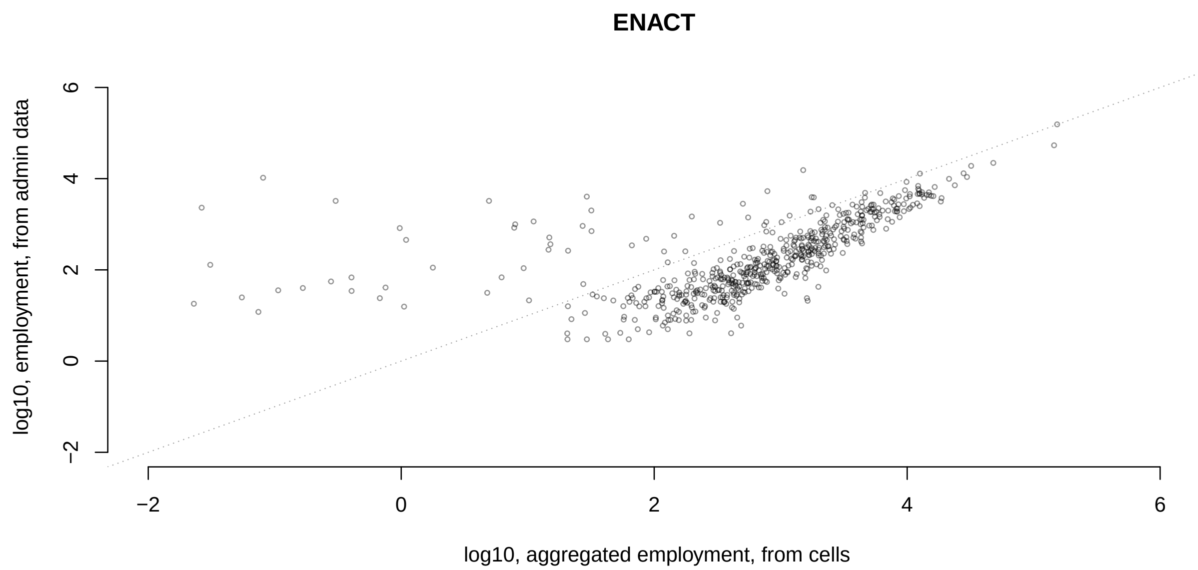


Figure 14: Comparison between administrative employment records and aggregated ENACT daytime data, by municipality.

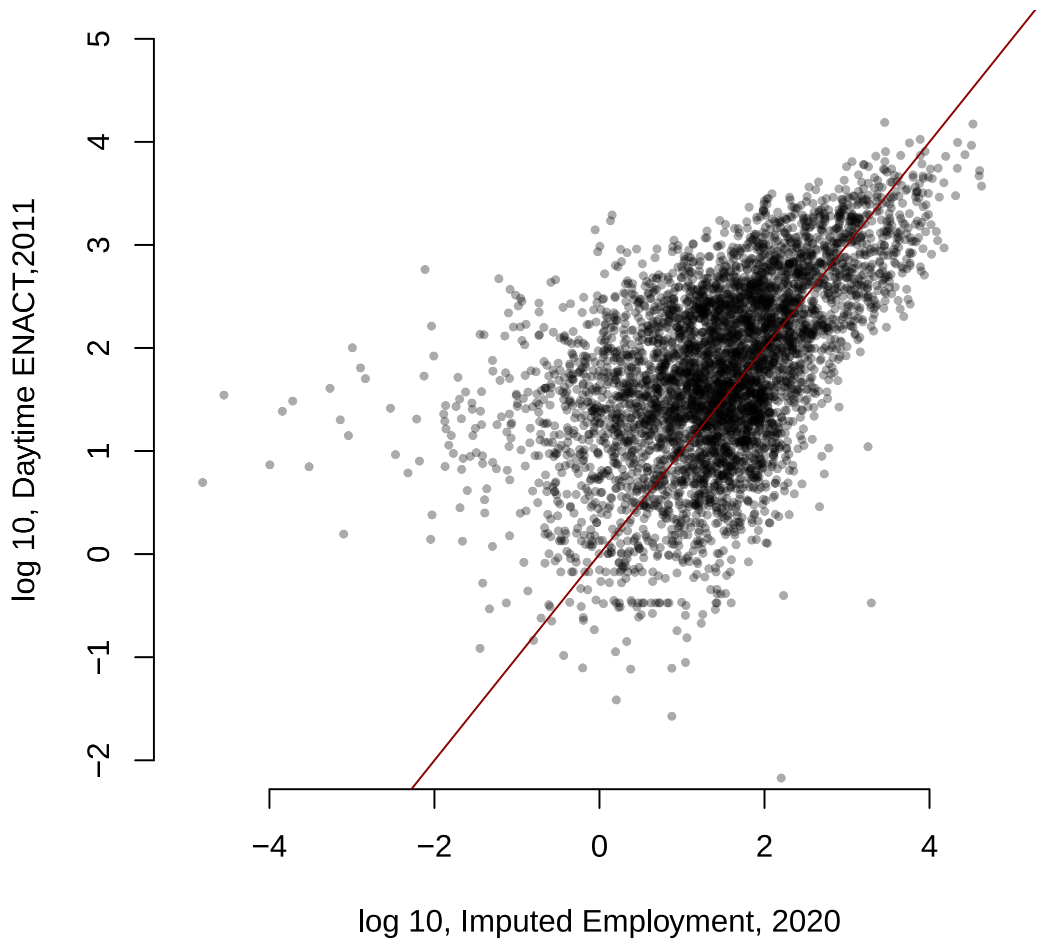


Figure 15: Comparison between our 2020 imputed values for employment and daytime ENACT population data.

A.2 Robustness on hedonic price regression

Table 19 gives information about the number of cells that include more than 1, 2, 3, 5 and 10 observations of price and rent listings. Restricting to a minimum number of 5 listings reduces the number of cells by about half.

FE Type	Country	All	≥ 2	≥ 3	≥ 5	≥ 10
Price FEs	Luxembourg	496	297	296	216	116
	Not Luxembourg	478	367	223	150	77
Rent FEs	Luxembourg	295	193	142	104	69
	Not Luxembourg	149	60	27	15	6

Note: The table depicts the number of cells with 0 or more, 2 or more, 3 or more, 5 or more and 10 or more listings per cell for both rental and purchase prices.

Table 19: Count of cells according to the number of listings per cell for rents and purchase prices.

Table 20 compares the hedonic price regressions for rental prices (columns 1 and 5) and purchase prices (columns 2 and 6) without and with cell fixed effects. It also displays the results with the merger of rental and price listings with dummy control for a purchase in Luxembourg (columns 3 and 7) and dummy control for a purchase (versus rental) (columns 4 and 8).

	log, Rent	log, Buy	log, Rent	log, Rent	log, Rent	log, Buy	log, Rent	log, Rent
log, Surface	-0.112***	-0.049***	-0.130***	-0.093***	-0.156***	-0.239***	-0.165***	-0.165***
	(0.005)	(0.015)	(0.004)	(0.006)	(0.004)	(0.007)	(0.003)	(0.003)
Number of Rooms	-0.079***	-0.110***	-0.045***	-0.108***	-0.004	-0.016***	-0.018***	-0.018***
	(0.006)	(0.004)	(0.002)	(0.003)	(0.006)	(0.002)	(0.002)	(0.002)
Number of Bedrooms	0.003	0.001	-0.002*	0.003*	0.000	-0.001	-0.001*	-0.001*
	(0.003)	(0.002)	(0.001)	(0.002)	(0.002)	(0.001)	(0.001)	(0.001)
Number of Bathooms	0.008	0.007*	0.003	0.010***	0.004	-0.002	-0.001	-0.001
	(0.005)	(0.004)	(0.002)	(0.003)	(0.004)	(0.002)	(0.002)	(0.002)
Furnished	0.085***	0.009	0.024***	0.021**	0.039***	-0.008	0.006	0.002
	(0.013)	(0.012)	(0.007)	(0.009)	(0.010)	(0.006)	(0.005)	(0.005)
Age, decade	0.016***	0.008***	0.004***	0.007***	0.007**	0.004***	0.004***	0.004***
	(0.005)	(0.001)	(0.001)	(0.001)	(0.004)	(0.000)	(0.000)	(0.000)
Age^2, decade 10^{-3}	0.092***	-0.004***	-0.002***	-0.004***	0.059**	-0.002***	-0.002***	-0.002***
	(0.034)	(0.001)	(0.000)	(0.001)	(0.027)	(0.000)	(0.000)	(0.000)
Balcony surface	0.003	0.009***	0.005***	0.009***	-0.003	0.002***	0.002***	0.002***
	(0.003)	(0.001)	(0.001)	(0.001)	(0.003)	(0.001)	(0.001)	(0.001)
Year not defined	-0.028	0.015	-0.011	0.020**	-0.019	-0.035***	-0.026***	-0.022***
	(0.019)	(0.012)	(0.007)	(0.010)	(0.016)	(0.005)	(0.006)	(0.006)
Purchase: Lux			6.035***				5.919***	
			(0.010)				(0.009)	
Purchase: Not Lux			4.862***				5.516***	
			(0.012)				(0.017)	
Purchase				5.685***				5.837***
				(0.014)				(0.008)
Type FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Type FE × Rooms	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Insulation FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Buy FE	No	No	No	Yes	No	No	No	Yes
Buy FE × Lux	No	No	Yes	No	No	No	Yes	No
Cell FE	No	No	No	No	Yes	Yes	Yes	Yes
R^2	0.590	0.488	0.983	0.965	0.820	0.926	0.992	0.992
Observations	4149	8916	13065	13065	4149	8916	13065	13065

Table 20: Hedonic regression outcomes for purchase prices and rents. Types of properties used: Apartments (reference), bedrooms, detached houses, duplexes, houses, offices, semi-detached houses, studios. .

A.3 Robustness on kriging regression and rental values

In the universal kriging approach, the deterministic trend of the cell's price index is given by $\eta_i = \mathbb{G}_i'.\beta + \epsilon_i$, or

$$\eta_i = \beta_1 \log(1 + d_i^{CBD}) \times LUX_i + \beta_2 \log(1 + POP_i) + \beta_3 \log(1 + EMP_i) + \epsilon_i \qquad (23)$$

where d_i^{CBD} denotes the distance to the central business district, LUX_i is an indicator for being in Luxembourg, and POP_i and EMP_i represent local population and employment figures, respectively.

This expression can also be used in an OLS regression model, the results of which are shown in Table 21. This table includes specifications with rent listings, price listings, and pooled transaction listings. Price listings are more numerous and, therefore, have stronger explanatory power. The combination of rental and price listing further increases the explanatory power. The table includes specifications with all cells or only those with more than five listings. The explanatory power is higher with the latter, as it removes error components of price/rent indices.

	FE^{Rent}	FE^{Rent}	FE^{Price}	FE^{Price}	FE^{Rent}	FE^{Rent}	FE^{Rent}	FE^{Rent}
log, d(CBD)	-0.420***	-0.276**	-0.339***	-0.298***	-0.362***	-0.321***	-0.377***	-0.321***
	(0.072)	(0.124)	(0.043)	(0.052)	(0.041)	(0.047)	(0.043)	(0.048)
Luxembourg	0.091	0.489	0.880***	0.998***	0.400**	0.462***	0.641***	0.764***
	(0.262)	(0.438)	(0.165)	(0.203)	(0.156)	(0.178)	(0.161)	(0.180)
log, Population	-0.016	-0.004	-0.013	-0.011	-0.013	-0.008	-0.016	-0.010
	(0.021)	(0.021)	(0.014)	(0.021)	(0.013)	(0.016)	(0.012)	(0.016)
log, Employment	-0.001	-0.010	0.004	-0.008	0.002	-0.007	0.006	-0.004
	(0.018)	(0.027)	(0.013)	(0.020)	(0.012)	(0.015)	(0.012)	(0.016)
log, d(CBD) × Lux	0.127*	0.048	0.048	0.012	0.064	0.044	0.088*	0.056
	(0.073)	(0.127)	(0.046)	(0.060)	(0.044)	(0.052)	(0.045)	(0.053)
Observations	444	119	973	366	1073	419	1073	419
Sample	All	5+	All	5+	All	5+	All	5+
Pooled transactions	No	No	No	No	Yes	Yes	Yes	Yes
R^2	0.745	0.812	0.844	0.912	0.724	0.846	0.819	0.911
Transaction FE	No	No	No	No	No	No	Yes	Yes
Transaction-country FE	No	No	No	No	Yes	Yes	No	No

Table 21: OLS predictions for values of hedonics-adjusted cell fixed effects.

Table 16 compares the prediction errors of kriging and OLS methods for various minimum numbers of listings in the cells used to make a prediction. The figure shows that the OLS predictions yield higher mean absolute errors. This is because they do not consider spatial correlation. The top panels show that kriging regression errors are smaller for price listings than for rent listings, which justifies our choice of using the dataset with prices. The top-left panels show that price prediction errors diminish with the number of listings per cell and become stable for cells with more than five listings. The bottom panels show the prediction errors with pooled listings. Although they increase the number of cells with many listings, pooled listings do not bring significantly more accuracy.

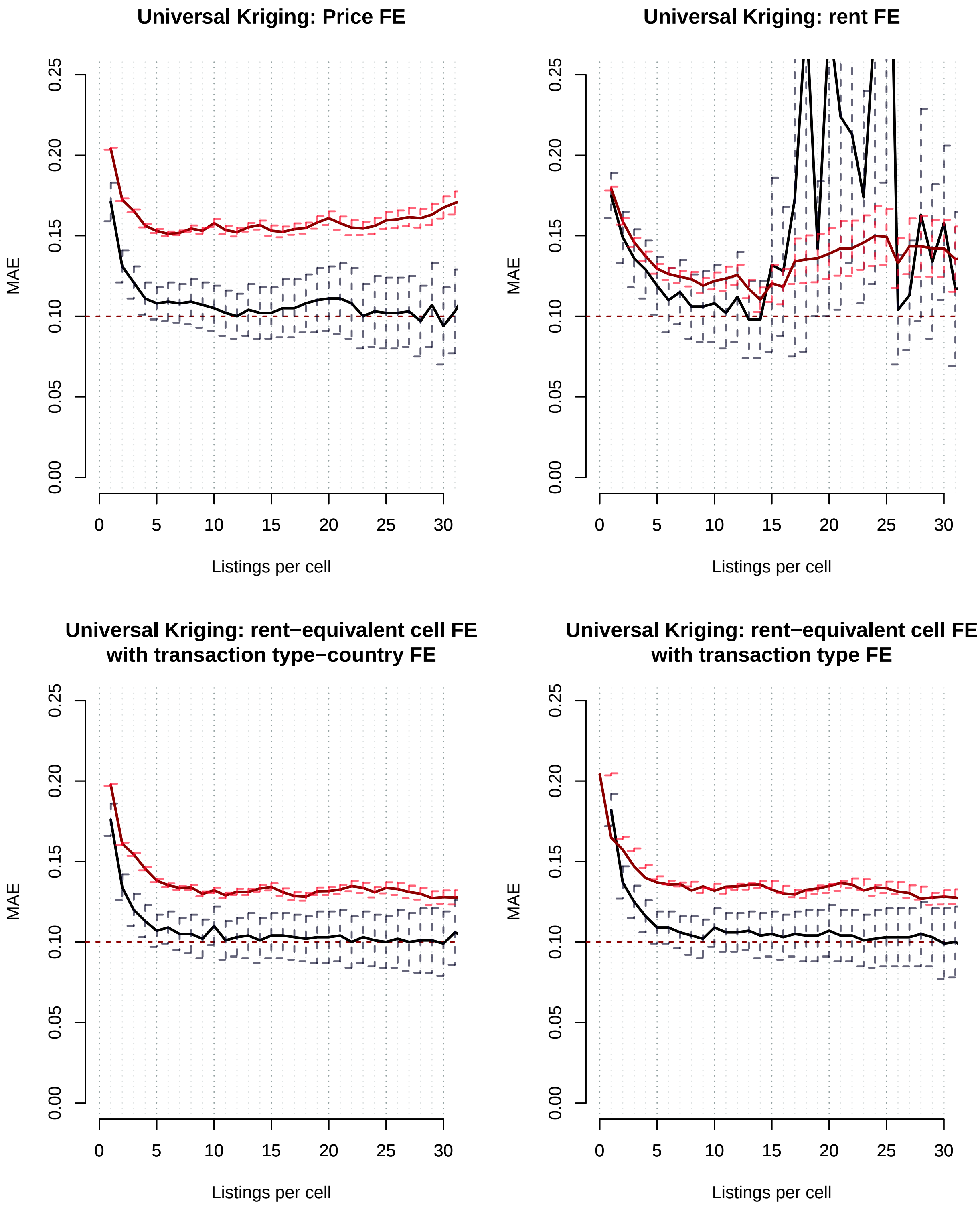


Figure 16: Mean absolute errors for universal kriging (black) and OLS (red) preductions based on purchase prices (top left), rents (top right), rent equivalent housing prices with transaction type and country fixed effects (bottom left), rent equivalent with transaction type fixed effects (bottom right). Standard errors of MAE are reported.

Table 22 reports the same information and yields the same conclusion for cells with all listings and with more than five listings.

Model	Variable	Listings per cell	N	MAE	RMSE	R^2
OLS	FE^{Rent}	All	444	0.179	0.228	0.740
		More than 5	119	0.130	0.165	0.787
	FE^{Price}	All	973	0.204	0.273	0.843
		More than 5	366	0.153	0.194	0.910
Kriging	FE^{Rent}	All	444	0.175	0.226	0.741
		More than 5	119	0.121	0.155	0.811
	FE^{Price}	All	973	0.172	0.244	0.874
		More than 5	366	0.108	0.147	0.948

Note: Both universal kriging and OLS use the deterministic specification (Equation 23). Values in the "Listings per cell" column denote the minimum listing threshold for cell fixed effects used for prediction. Out-of-sample prediction quality is assessed using 5-fold cross-validation. For universal kriging, optimal semivariogram models may vary.

Table 22: Out-of-sample prediction quality metrics for different model specifications for the natural logarithm of prices and rents.

A.4 Urban externalities

As a robustness check, Table 23 reproduces the empirical analysis of urban externalities with an instrument based on the proximity to ancient Roman cities and vicus settlements in ancient times for population, and another instrument based on distance to locations of Gaul Gold hoards and Roman coins for current employment. Table 23 presents the main results of our IV estimations with previous and current instruments. Columns (1) and (4) use the above 1975 build-up instrument, columns (2) and (5) the ancient times instruments, and columns (3) and (6) include both instruments. Results include the F-statistics from the first-stage regression, which confirm the relevance of our instruments. Wu-Haussman test statistics signal the presence of endogeneity in most situations. The small Sargan statistics in columns (3) and (6) suggest that the overidentifying restrictions are not violated for production and amenity externalities. Production externalities (columns 1 to 3) are mildly affected by the instruments. For amenity externalities (columns 4 to 6), the instrument of ancient city proximity seems too weak to conclude about a significant externality effect of residential amenity.

	log A (1)	log A (2)	log A (3)	log B (4)	log B (5)	log B (6)
$\log \Upsilon$	0.070***	0.098***	0.070***			
	(0.006)	(0.034)	(0.006)			
$\log \Omega$				0.028***	-0.003	0.027***
				(0.003)	(0.020)	(0.003)
Geographic Controls	Yes	Yes	Yes	Yes	Yes	Yes
Instrument: 1975 build-up	Yes	No	Yes	Yes	No	Yes
Roman	No	Yes	Yes	No	Yes	Yes
First stage F-Statistics	16792.89***	61.32***	8395.37***	73161.07***	82.20***	38011.62***
Sargan Statistics			0.671			2.292
Sargan p-value			0.413			0.130
Wu-Hausman	44.18***	0.175	44.01***	54.74***	3.118*	61.691***
Observations	2658	2658	2658	3182	3182	3182
R^2	0.429	0.429	0.429	0.193	0.163	0.193

Table 23: Instrumental variable regressions with old and new instruments.

A.5 Tax importation

We eliminate tax importation by assuming that all tax revenues collected in the metropolitan area of Luxembourg are collected by a (supranational) central administration, which reinvests its revenue on a per-capita basis in local public goods across the entire geography. Tax rates are maintained at their actual levels. Changes in endogenous variables of the model are reported in Table 24.

Country	Belgium	France	Germany	Luxembourg
Change in population, %	24.57	28.61	14.01	-24.31
Change in employment, %	7.81	6.75	7.58	3.19
Change in per capita tax transfer, %	52.31	64.00	28.71	-36.03
Change in total tax revenue, %	89.72	110.93	46.74	-51.58
Change in expected income, %	1.12	1.55	-0.15	0.61
Change in floorspace prices, %	13.64	16.92	7.97	-7.77
Change in wages at workplace, %	-3.55	-3.20	-2.17	-0.13
Total population change: 4.89 %				

Note: We report changes in total population and employment by country, changes in population-weighted averages for tax transfer, changes in total tax revenue, expected income, and average floorspace price, and changes in employment-weighted average for wages at workplace.

Table 24: Changes in endogenous variables of the model in a counterfactual with no tax importation.

A.6 Cross border commuting

In Table 25, we report changes in the endogenous outcomes of the model after the prohibition of cross-border commuting. The reported values correspond to the difference between the baseline and the counterfactual analyzed in Column 2 of Table 10. We observe a decrease in total population of the economy by 13.68%, which roughly corresponds to the number of cross-border workers commuting to Luxembourg. We observe a decrease in expected income for Belgium, France and Germany, and a decrease in floorspace prices for all four countries. Per capita tax transfer decreases in Luxembourg and increases elsewhere, which is indicative of the mechanical elimination of the tax importation effect in the couterfactual with closed borders.

Country	Belgium	France	Germany	Luxembourg
Change in population, %	-23.17	-24.43	-15.67	-1.73
Change in employment, %	16.58	39.37	13.92	-38.89
Change in per capita tax transfer, %	30.01	43.41	23.24	-25.55
Change in total tax revenue, %	-0.12	8.38	3.92	-26.83
Change in expected income, %	-18.26	-21.77	-9.92	11.70
Change in floorspace prices, %	-11.07	-14.81	-8.49	-15.35
Change in wages at workplace, %	-1.57	-3.19	-0.99	10.46
Total population change: -13.68 %				

Note: We report changes in total population and employment by country, changes in population-weighted averages for tax transfer, changes in total tax revenue, expected income, and average floorspace price, and changes in employment-weighted average for wages at workplace.

Table 25: Changes in endogenous variables of the model in a counterfactual with no cross-border commuting.

A.7 Multiple equilibria

In Section 6, we examine the effect of taxation in a seamless geography where firms and residents are located on a disk matching the dimensions of our empirical area. In such a setting, fundamental local productivities, amenities, and development densities are equalized across space. The aim is to compare the observed and predicted impacts of taxes on floorspace prices and the share of commercial buildings, using the parameter estimates from our empirical analysis. We find and discuss a spatial equilibrium in which employment is more concentrated at the center of the disk—that is, a configuration with monocentric properties. This naturally raises the question of equilibrium multiplicity.

We here adopt a heuristic approach to test for the existence of equilibria other than the benchmark discussed in the seamless geography on the 75 km-ray disk with 1×1 km grid cells. The benchmark case is computed with initial wages set to one, $w_i^0 = 1$. The outcome of the simulation yields a model-consistent distribution of wages, w_i^*. We then substantially alter the initial conditions for wages and verify whether our fixed-point algorithm still converges to the benchmark solution. We choose the initial wage of each cell w_i^0 to the values either

$\underline{w}^0 = 0.2 \min\{w_i^*\}$ and $\overline{w}^0 = 5 \max\{w_i^*\}$. Initial conditions on floorspace prices, share of commercial build-up, population, and employment densities are set as functions of the initial wage vector under uniform taxation, applying equations (4), (5), (6), (10), and (18). We assume uniform productivity A_j and uniform G_i for the initial guess. These exercises are computationally intensive. Because of computing time and memory constraints, we restrict the number of grid cells by keeping one cell out of every four cells. [9] We repeat this exercise with the tax differences defined in the paper.

Four types of initial wage vectors are tested. Initial conditions (1) to (5) randomize wages between $\underline{w}^0$ and $\overline{w}^0$ with a probability equal to 1/2. Initial condition (6) sets wages to $\overline{w}^0$ in potential subcenters and to $\underline{w}^0$ elsewhere. We chose two symmetric subcenters located 40 km away from the geographical center of the economy. The radius of each of the subcenters is equal to 30 km. Initial conditions (7) to (9) set wages to $\overline{w}^0$ in a ring-shaped donuts located at distances from 20 to 40, from 40 to 60, and from 60 to 75 km respectively from the center and at the boundary of the disk, and $\underline{w}^1$ elsewhere.

Tables 26 and 27 report the number of iterations K, the uniform norm (sup-norm) convergence indicator, $\|w_i^K - w_i^{K-1}\|_\infty$, the statistics of wages and floorspace prices in the last iteration K. It can be verified that none of the initial conditions converges to a solution different from the benchmark, and that all deviations in numbers are within the machine precision.

[9] This restriction furthermore parallels the properties of our calibrated model on the set of active cells.

	Benchmark	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Iterations K		202	202	202	224	202	205	207	231	254
$\|w_i^K - w_i^{K-1}\|_\infty$	2.16711×10^{-9}	1.76633×10^{-9}	1.2006×10^{-9}	1.25203×10^{-9}	6.8858×10^{-10}	1.43566×10^{-9}	1.0778×10^{-9}	3.97786×10^{-9}	1.53106×10^{-9}	1.31334×10^{-10}
$\|q_i^K - q_i^{K-1}\|_\infty$	9.45025×10^{-6}	1.5281×10^{-6}	2.7461×10^{-6}	2.55959×10^{-6}	3.32929×10^{-6}	1.97565×10^{-6}	1.34852×10^{-6}	8.6301×10^{-6}	2.84053×10^{-6}	7.74735×10^{-7}
$\min_i w_i^K$	0.104135158	0.104135112	0.104135112	0.104135112	0.104135147	0.104135112	0.10413512	0.104135121	0.104135152	0.10413514
mean w_i^K	0.099970625	0.099970596	0.099970596	0.099970596	0.09997063	0.099970596	0.099970604	0.099970605	0.099970635	0.099970624
$\max_i w_i^K$	0.098900733	0.098900704	0.098900704	0.098900704	0.098900738	0.098900704	0.098900712	0.098900713	0.098900743	0.098900732
$\min_i q_i^K$	101.8057697	101.8058651	101.8058649	101.8058647	101.8057531	101.8058650	101.8058394	101.8058356	101.8057371	101.8057751
mean q_i^K	96.88661374	96.88670487	96.88670476	96.88670453	96.88659827	96.88670482	96.88668042	96.88667683	96.88658307	96.88661928
$\max_i q_i^K$	74.90646373	74.90655001	74.90654994	74.90654976	74.90646620	74.90654998	74.90653079	74.90652787	74.90645432	74.90648275

Table 26: Robustness check w.r.t. initial conditions - seamless geography, equal taxes.

	Benchmark	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Iterations K		217	217	217	253	217	220	230	245	239
$\|w_i^K - w_i^{K-1}\|_\infty$	3.0095×10^{-9}	8.47174×10^{-10}	6.37057×10^{-10}	6.43142×10^{-10}	4.01282×10^{-10}	7.39164×10^{-10}	2.40723×10^{-10}	1.26539×10^{-9}	4.453×10^{-11}	4.23955×10^{-10}
$\|q_i^K - q_i^{K-1}\|_\infty$	1.31982×10^{-5}	1.0172×10^{-6}	5.24669×10^{-7}	5.4134×10^{-7}	1.5353×10^{-6}	7.63913×10^{-7}	8.56382×10^{-7}	3.74044×10^{-6}	9.58894×10^{-7}	3.85421×10^{-7}
$\min_i w_i^K$	0.104135158	0.104135148	0.104135148	0.104135148	0.104135158	0.104135148	0.104135151	0.104135161	0.104135161	0.104135151
mean w_i^K	0.100743831	0.100743821	0.100743821	0.100743821	0.100743831	0.100743821	0.100743824	0.100743834	0.100743834	0.100743825
$\max_i w_i^K$	0.099139493	0.099139483	0.099139483	0.099139483	0.099139493	0.099139483	0.099139486	0.099139496	0.099139496	0.099139487
$\min_i q_i^K$	112.6815803	112.681617	112.6816169	112.6816169	112.6815805	112.681617	112.6816056	112.6815699	112.6815702	112.681604
mean q_i^K	97.31370871	97.31373934	97.31373929	97.31373921	97.3137078	97.31373931	97.31372946	97.31369866	97.31369886	97.31372809
$\max_i q_i^K$	74.29305848	74.29310291	74.29310288	74.29310282	74.29307845	74.29310290	74.29309527	74.29307141	74.29307153	74.29309420

Table 27: Robustness check w.r.t. initial conditions - seamless geography, unequal taxes.