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Structural Estimations and Counterfactual Simulations for City Modelling: A Case Study on Traffic Exposure

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Introduction

Objectives

- This paper shows **how structural estimations**, computed with advanced statistical and econometrical techniques, **can be used in urban modeling to address diriment planning issues**.
- We use a **structural model for residential location choices** to estimate the **effect of traffic exposure changes on housing rental prices, population relocation, and income-based residential segregation**.
- Using the structurally estimated coefficients and a set of calibrated parameters, we build **counterfactual simulations** for two alternative traffic-management interventions, **forecasting changes in housing rental prices, residence choices according to the income level, and income-based residential segregation**.

What we have done

- We build a **residential location model** based on preferences for consumption, housing, and traffic exposure for the City of Lugano.
- The **structural estimation** is implemented through the **Classical Minimum Distance** (CMD) estimator, and the computations are based on the traffic variations induced by a **new road plan** (the PVP) introduced in Lugano in 2012.
- Thus, we perform **two counterfactual simulations** to investigate their potential effects on income classes' residence choices and the real estate market. The counterfactuals debated are the **Long-Lake closure to vehicular traffic** and an **ideal segregation-reductive traffic management policy**.

Structural Estimations

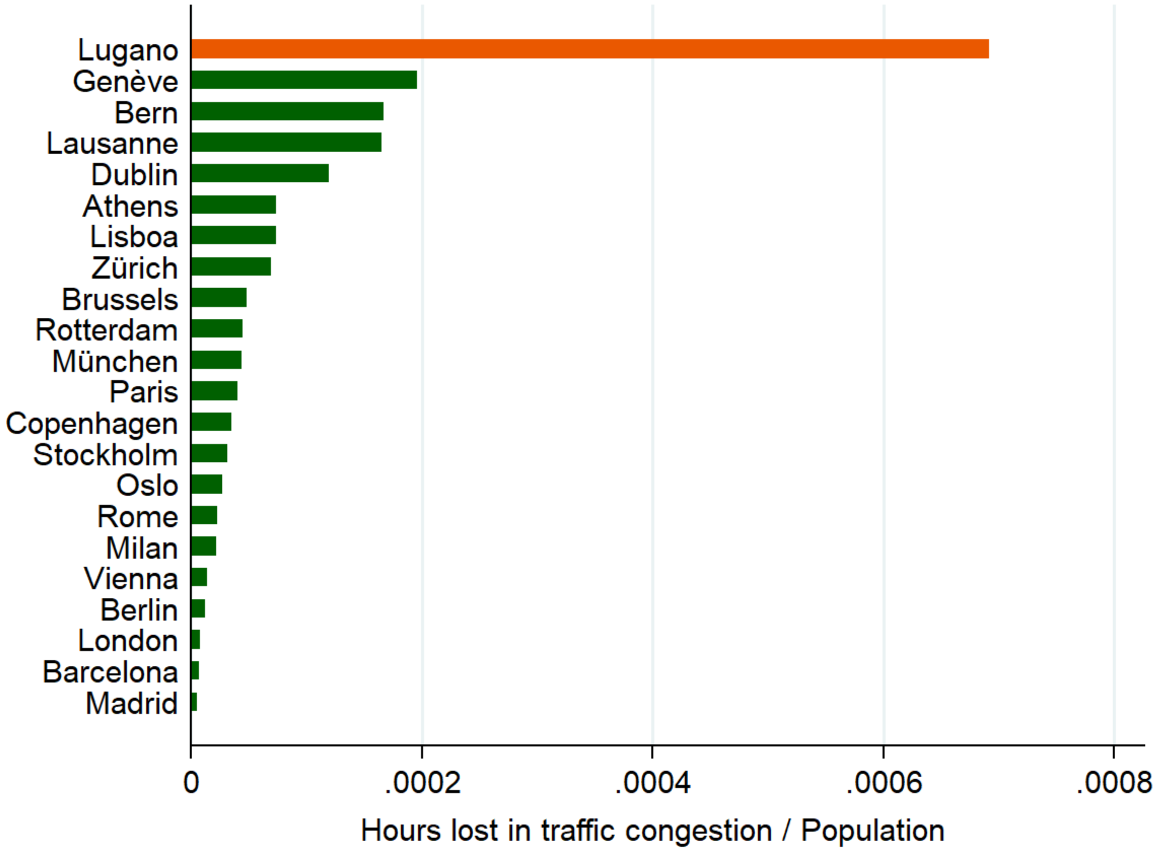
- Structural estimations are advanced statistical techniques based on the **association of a model to an empirical setting**, taken as an example. Based on the estimation of some parameters, it is possible to **simulate and foresee the effect of counterfactual interventions** on the objective variables of interest.

- Usually, they are implemented through the **Classical Minimum Distance** (CMD) estimator or the **Generalized Method of Moments** (GMM). Here we will see an application with the CMD.

- The structural estimations have **different fields of application**: economics (macroeconomics, monetary economics, labor economics, and urban economics), urbanism, policy evaluations, and others. According to the field, the model changes in accordance. We will see a **discrete residential location choice model** in this presentation.

Empirical Setting

- **Lugano** is considered the **most congested city in Switzerland** and the 47th worldwide (INRIX Global Traffic Scorecard, 2020).



- Implementing as a quasi-natural experiment the **introduction of a new road plan in 2012**, called PVP, we test how the real estate market reacts and how residents relocate to changes in traffic exposure.

- The plan aimed to **reduce traffic congestion in the city center** and the residential areas by deviating traffic flows to the suburban neighborhoods.

- For such a purpose, the PVP implemented several **changes in traffic direction** and different **road-management interventions**.

- Moreover, the PVP consisted also of the construction of the **Vedeggio-Cassarate gallery**, which allows drivers to directly reach the highways from the city-center reducing traffic congestion in residential districts.

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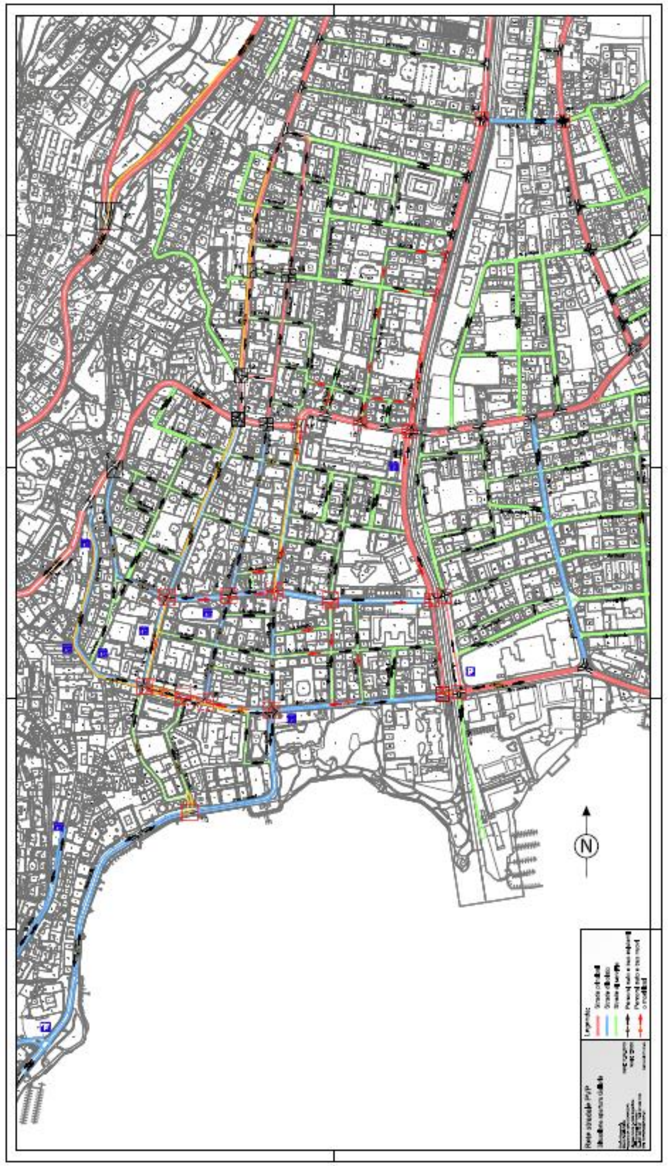
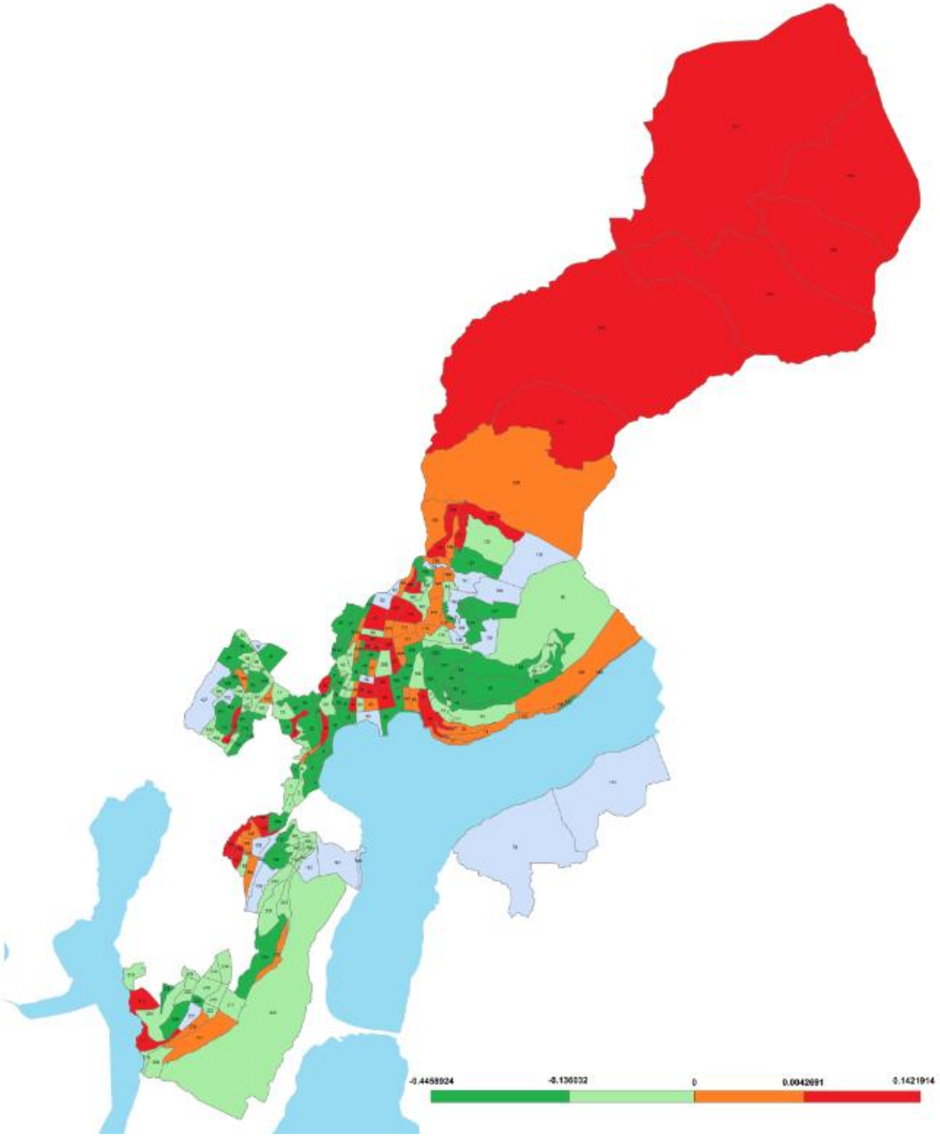
Structural Estimations and Counterfactual Simulations for City Modelling

Empirical Setting





	2SLS	3SLS		
	(1)	(2)	(3)	(4)
	ΔHousing rental prices	ΔLow-income taxpayers	ΔMiddle-income taxpayers	ΔHigh-income taxpayers
Elasticity ΔT_s	0.309** (0.154)	-0.063 (0.044)	-0.143*** (0.051)	0.299*** (0.106)
Controls	Yes	Yes	Yes	Yes
Observations	117	216	216	216

Elasticities are computed at the mean of traffic variation (where the [illegible] traffic change is equal to -3870.04): they represent the percentage change in the outcome variable's variati[illegible]% decrease in the traffic level. Robust standard errors in parentheses: *** p<0.01, ** p<0.05, * p<0.1

Amenity effect prevails

Housing price effect prevails

Residential Location Model

Setting

- In the economy there are **renters, absentee landlords**, and the **local government**.
- The city is composed of **discrete locations**, the sub-districts $s = 1, \dots, r, \dots S$, and is embedded within a wider economy.
- The city is populated by a **fixed measure of N individuals**, divided in income classes $g \in G$, in relationship to their exogenous income level y_g.
- Sub-districts are characterized by **amenities** B_s, **traffic** level T_s, and average **housing rental price** p_s.
- Individuals have a **location-specific idiosyncratic shock** z_{gs}, which captures idiosyncratic reasons to live in different parts of the city. We assume that this is Fréchet distributed:

$$F(z_{gs}) = e^{-A_s z_{gs}^{-\epsilon}}, \qquad A_s > 0 \qquad \epsilon > 1$$

- **Individuals consume** a numeraire **basket of goods** c_{gs} and **housing** h_{gs} according to the place of residence:

$$c_{gs} + p_s h_{gs} = y_g$$

- Individuals have a **Stone-Geary utility function** of the form:

$$U_{gs} = T_s^{\theta} B_s z_{gs} \left(\frac{c_{gs}}{\alpha}\right)^{\alpha} \left(\frac{h_{gs} - \bar{h}}{1 - \alpha}\right)^{1-\alpha}$$

- From the utility maximization process, we derive the **consumption demand, housing demand, and indirect utility function** for the renter:

$$h_{gs}^{*} = \bar{h} + \frac{(1-\alpha)\left(y_g - p_s \bar{h}\right)}{p_s} \qquad c_{gs}^{*} = \alpha\left(y_g - p_s \bar{h}\right)$$

$$V_{gs} = \frac{T_s^{\theta} B_s z_{gs}\left(y_g - p_s \bar{h}\right)}{p_s^{1-\alpha}}$$

Residence Choice and housing market

- Combining the indirect utility function with a discrete choice framework, we get the three main elements of the model:

1) **Indifference condition**:

$$\mathbb{E}[u] = \gamma \left\{ \sum_{s=1}^{S} A_s \left(T_s^{-\theta} p_s^{1-\alpha}\right)^{-\epsilon} \left[B_s\left(y_g - p_s \bar{h}\right)\right]^{\epsilon} \right\}^{1/\epsilon} = \bar{U}$$

2) **Residential choice probability equation**:

$$\pi_{gs} = \mathbb{P}\left[u_{gs} \leq \max\left(V_{gr}\right); \forall r\right] = \frac{A_s \left(T_s^{-\theta} p_s^{1-\alpha}\right)^{-\epsilon} \left[B_s\left(y_g - p_s \bar{h}\right)\right]^{\epsilon}}{\sum_{r=1}^{S} A_r \left(T_r^{-\theta} p_r^{1-\alpha}\right)^{-\epsilon} \left[B_r\left(y_g - p_r \bar{h}\right)\right]^{\epsilon}} = \frac{N_{gs}}{N_g}$$

3) **Housing market equilibrium equation**:

$$H_s^D = \sum_g h_{gs}^* N_{gs} = H_s^S = \beta p_s^{\eta_s^{S,p}}$$

The structural estimation

- Log-differentiating and rearranging the residential choice probability equation and the housing market equilibrium equation, we obtain the so-called "**mapping equation**":

$$\left[\frac{\varpi_{gs}S_{gs}}{(1-\bar{S}_{gs})\left(\eta_s^{S,p}-\eta_s^{D,p}\right)}+\frac{1}{\epsilon}\right]\dot{N}_{gs}+\frac{S_{gs}}{(1-\bar{S}_{gs})\left(\eta_s^{S,p}-\eta_s^{D,p}\right)}\sum_{g'\neq g}\varpi_{g's}\dot{N}_{g's}=\theta\dot{T}_s$$

which can be rewritten in matrix notation: $\mathrm{A_s}\dot{\mathrm{N}}_\mathrm{s}=\theta\dot{T}_s$

$$\boldsymbol{\theta}=\theta l=\theta\begin{bmatrix}1\\ \vdots\\ 1\end{bmatrix}\qquad \dot{\mathbf{N}}_s=\begin{bmatrix}\dot{N}_{1s}\\ \dot{N}_{2s}\\ \vdots\\ \dot{N}_{Gs}\end{bmatrix}\qquad \mathbf{A}_s=\begin{bmatrix}\frac{\varpi_{1s}S_{1s}}{(1-\bar{S}_{1s})(\eta_s^{S,p}-\eta_s^{D,p})}+\frac{1}{\epsilon} & \frac{\varpi_{2s}S_{1s}}{(1-\bar{S}_{1s})(\eta_s^{S,p}-\eta_s^{D,p})} & \cdots & \frac{\varpi_{Gs}S_{1s}}{(1-\bar{S}_{1s})(\eta_s^{S,p}-\eta_s^{D,p})}\\ \frac{\varpi_{1s}S_{2s}}{(1-\bar{S}_{2s})(\eta_s^{S,p}-\eta_s^{D,p})} & \frac{\varpi_{2s}S_{2s}}{(1-\bar{S}_{2s})(\eta_s^{S,p}-\eta_s^{D,p})}+\frac{1}{\epsilon} & \vdots & \vdots\\ \vdots & \cdots & \ddots & \vdots\\ \frac{\varpi_{1s}S_{Gs}}{(1-\bar{S}_{Gs})(\eta_s^{S,p}-\eta_s^{D,p})} & \cdots & \cdots & \frac{\varpi_{Gs}S_{Gs}}{(1-\bar{S}_{Gs})(\eta_s^{S,p}-\eta_s^{D,p})}+\frac{1}{\epsilon}\end{bmatrix}$$

- The **empirical analogue** of the equilibrium equation is:

$$\widehat{\mathrm{N}}_\mathrm{s}=\underbrace{\mathrm{A}_\mathrm{s}^{-1}\theta\;\dot{T}_s}_{\eta=\mathrm{m}(\vartheta)}+\mathrm{A}_\mathrm{s}^{-1}\mathrm{e}_\mathrm{s}\qquad \Rightarrow_{\mathrm{CMD}}\qquad \boxed{\hat{\vartheta}=\begin{bmatrix}\epsilon\\ \theta\end{bmatrix}=\mathrm{argmin}\,[\hat{\eta}-\mathrm{m}(\vartheta)]'\widehat{\mathrm{V}}^{-1}[\hat{\eta}-\mathrm{m}(\vartheta)]}$$

Parameter	Description	Estimation
$\eta_s^{D,p}$	Housing demand elasticity	Calibration
$\eta_s^{S,p}$	Housing supply elasticity	
$1-\alpha$	Housing tastes	
S_g	Housing expenditure share	
$p_s\bar{h}$	Minimum housing expenditure	
y_g	Average gross income	
ϖ_g	Aggregate housing share	
θ	Marginal disutility of traffic	Structural Estimations
ϵ	Fréchet shape parameter	

Calibration

Parameters' Calibration	Low-income households	Middle-income households	High-income households
Swiss Households Panel			
$(1-\alpha)$	0.19	0.19	0.19
y_g	34'173 CHF	93'407 CHF	331'827 CHF
$p_s\bar{h}$	1'764 CHF	1'764 CHF	1'764 CHF
S_g	0.46	0.21	0.10
ϖ_g	0.043	0.93	0.024
$\eta^{D,p}$	-0.90	-0.90	-0.90
Implied Housing Supply Elasticity (IV Estimates in Table 8)			
$\eta^{S,p}$	0.85	0.85	0.85

Structural Estimation

Structural Estimations	
Parameters Estimation	
Marginal disutility of traffic exposure	
θ	-0.0051
Fréchet parameter	
ε	31.68

We will call them: θ^* and ϵ^*

Counterfactual Simulations

- We can compute **counterfactual simulations** to show the effect of **potential changes in traffic exposure on housing prices and income-based population composition**.

- To do so, we **iteratively solve** for each sub-district $s \in S$ **the following system of mapping equations**, using the estimated parameters θ^* and ϵ^* and solving for the income-based population $\dot{\mathrm{N}}_s = \left[\dot{N}_{1s} \quad \dots \quad \dot{N}_{Gs}\right], \forall\, s \in S$:

$$\begin{cases} \left[\frac{\varpi_{1s}S_{1s}}{(1-\bar{S}_{1s})(\eta^{S,p}-\eta_1^{D,p})} + \frac{1}{\epsilon}\right]\dot{N}_{1s} + \frac{S_{1s}\sum_{g'\neq 1}\varpi_{g's}\dot{N}_{g's}}{(1-\bar{S}_{1s})(\eta^{S,p}-\eta_1^{D,p})} = \theta\dot{T}_s \\ \vdots \\ \left[\frac{\varpi_{gs}S_{gs}}{(1-\bar{S}_{gs})(\eta^{S,p}-\eta_1^{D,p})} + \frac{1}{\epsilon}\right]\dot{N}_{gs} + \frac{S_{gs}\sum_{g'\neq g}\varpi_{g's}\dot{N}_{g's}}{(1-\bar{S}_{gs})(\eta^{S,p}-\eta_1^{D,p})} = \theta\dot{T}_s \\ \vdots \\ \left[\frac{\varpi_{Gs}S_{Gs}}{(1-\bar{S}_{Gs})(\eta^{S,p}-\eta_1^{D,p})} + \frac{1}{\epsilon}\right]\dot{N}_{Gs} + \frac{S_{Gs}\sum_{g'\neq G}\varpi_{g's}\dot{N}_{g's}}{(1-\bar{S}_{Gs})(\eta^{S,p}-\eta_1^{D,p})} = \theta\dot{T}_s \end{cases}$$

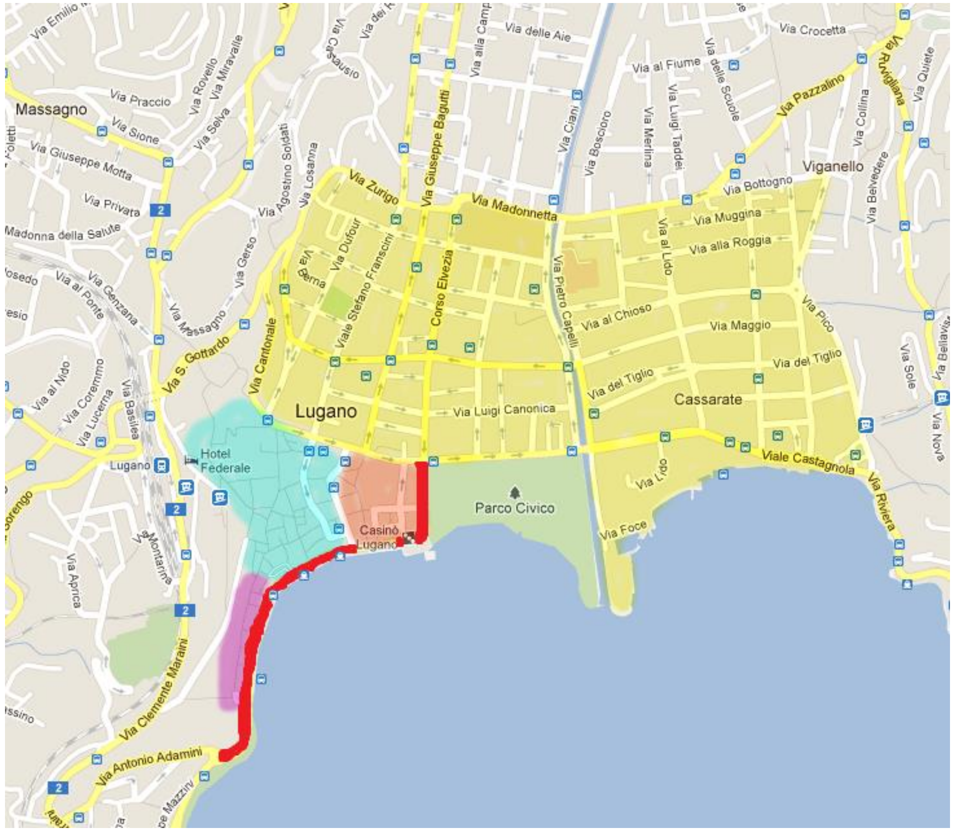
- Thus, we can compute the **counterfactual change rate in housing prices** for the given change rate in traffic exposure:

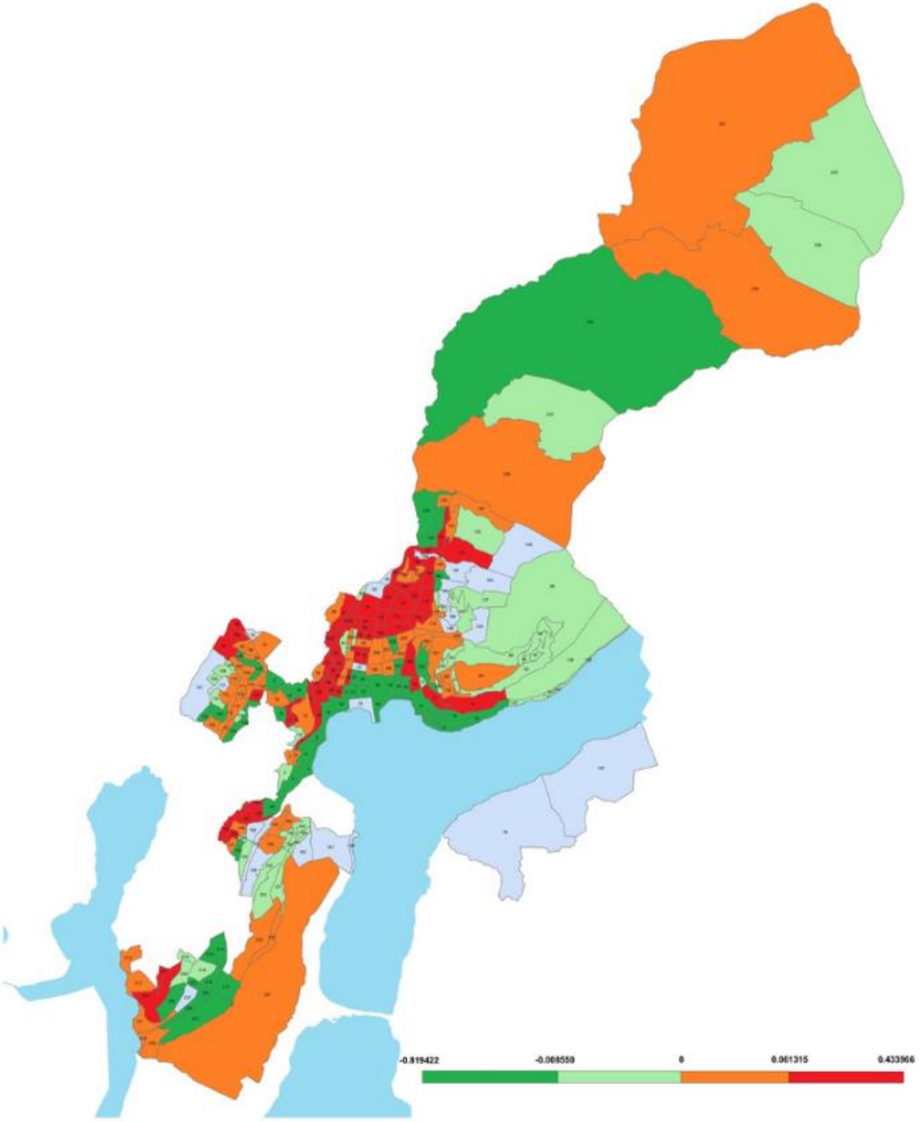
$$\dot{p}_s = \eta^*_{p,T} \cdot T_s$$

where:

$$\eta^*_{p,T} = \frac{\epsilon^*\theta^*\sum_g \varpi_{gs}}{\left(\eta_s^{S,p} - \eta_s^{D,p}\right) + \epsilon\sum_g \varpi_{gs}\zeta_{gs}} < 0$$

The Long-Lake Closure to Vehicular Traffic

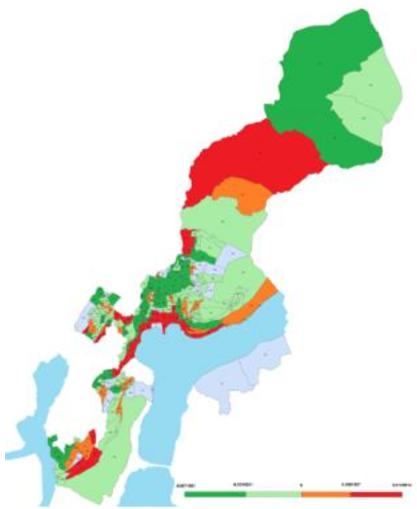




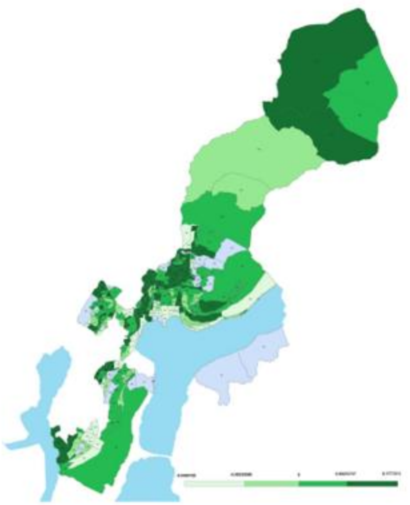
Structural Estimations and Counterfactual Simulations for City Modelling

Counterfactual Simulations

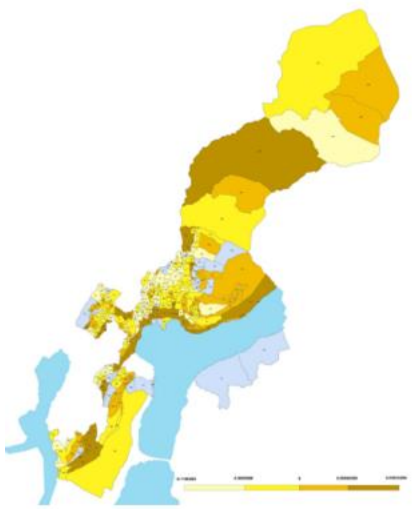
Change Rate in Housing Rental Prices



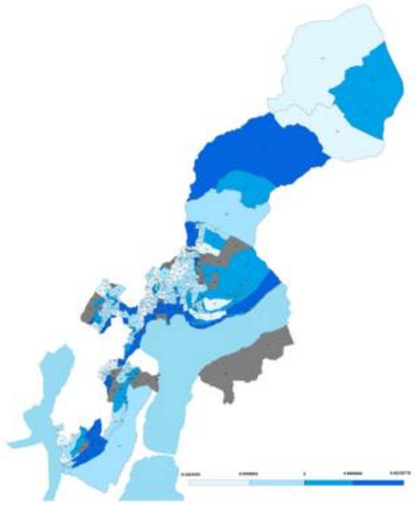
Change Rate in Low-income Taxpayers



Change Rate in Middle-income Taxpayers

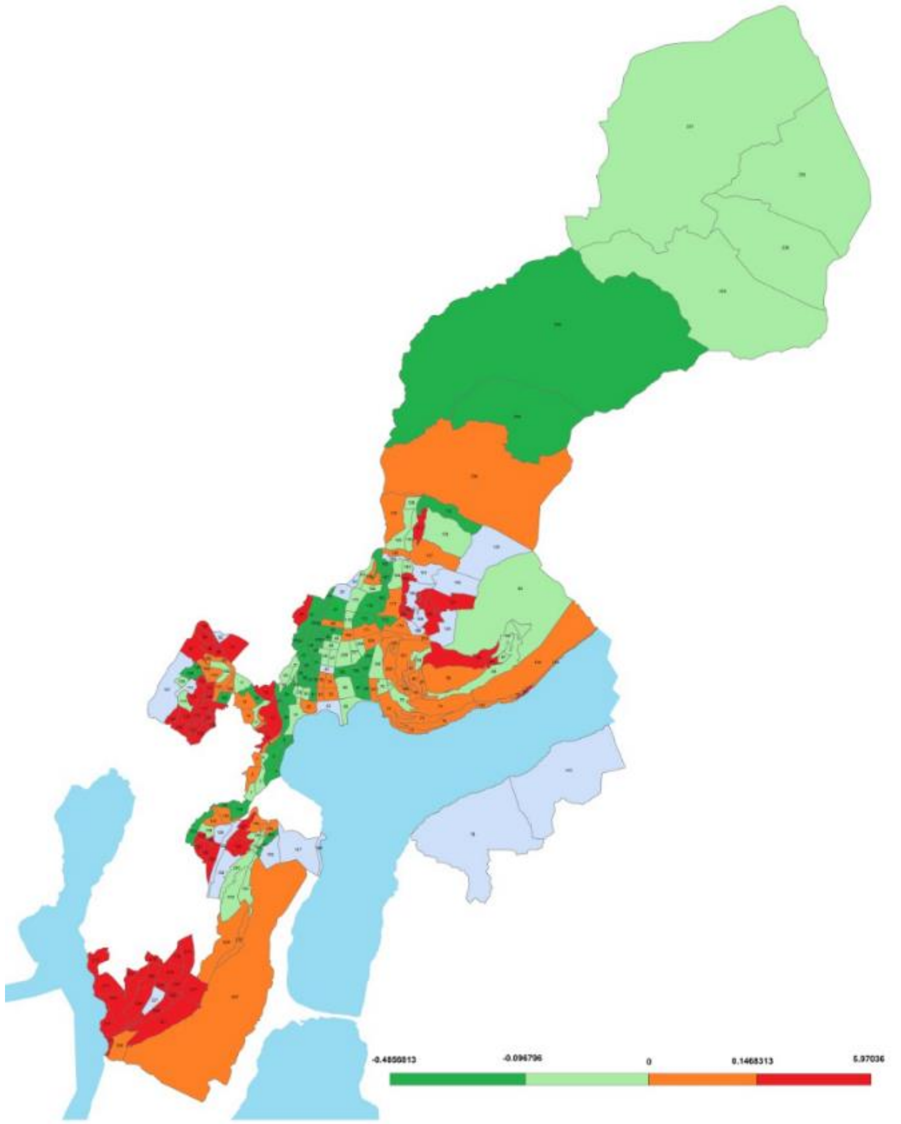


Change Rate in High-income Taxpayers



	(1)	(2)	(3)
Residential Segregation Effect of the Long-lake Closure	Pre-Closure of the Long-lake	Post-Closure of the Long-lake	Effect (%)
Panel A: Entropy Index			
Entropy Index	23.51%	23.53%	0.057%
Panel B: Dissimilarity Index			
Low-income taxpayers	16.69%	16.70%	0.026%
High-income taxpayers	52.07%	52.05%	-0.038%

Ideal Segregation-Reductive Traffic Management Policy



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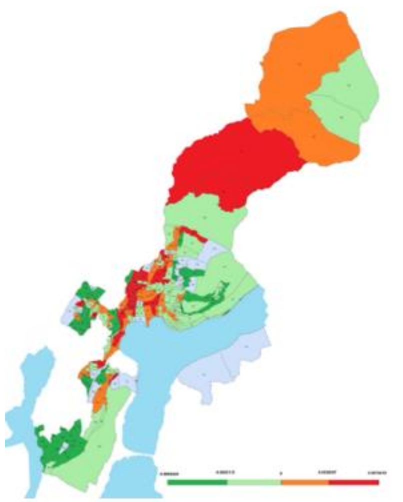
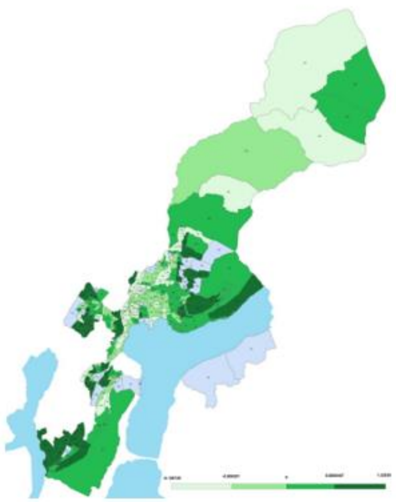
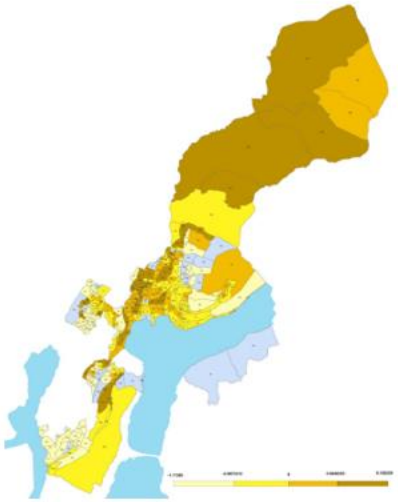
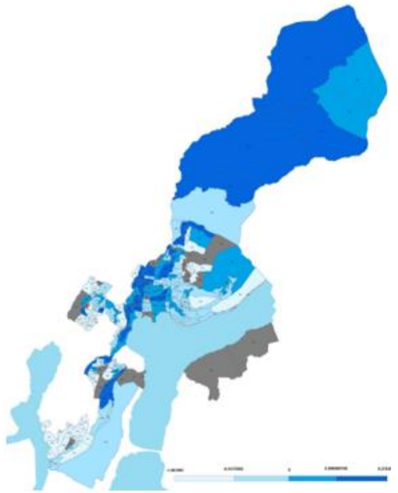
Counterfactual Simulations









Residential Segregation Effect of the 2030 Road Network	(1) Current Road Network	(2) 2030 Road Network (no long-lake closure)	(3) Effect (%)
Panel A: Entropy Index			
Entropy Index	23.51%	23.48%	-0.17%
Panel B: Dissimilarity Index			
Low-income taxpayers	16.69%	16.50%	-1.20%
High-income taxpayers	52.07%	51.88%	-0.36%

Conclusions

- This study shows how to **implement advanced statistical and econometrical techniques for city modeling** to optimize the political decision process and solve urban issues.
- We have seen how to **construct a simple structural model for location choices** at the city level and how to **compute counterfactual simulations** to estimate the effect of potential policies and interventions.
- Practically, considering that **traffic exposure** decreases housing prices and the number of high-income renters and rises the number of low-income ones, we have seen how the **long-lake closure** will increase the housing prices in the long-lake slightly enhancing the segregation of the poor while decreasing the one of the rich. On the other hand, the **local government can reduce income-based residential segregation by implementing traffic changes in contrast with the "desired" variation of each income category**.

For further information:

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Thanks for the attention.

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