Carrot and Stick Policies and the Affordability Puzzle:
Evidence from (Re)development in New York City*

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Abstract

Persistent housing affordability pressures remains a puzzle arising from tensions between public goals and private incentives. We develop a dynamic model in which density bonuses and property tax exemptions (*carrots*) and an affordability mandate (*stick*) enter developers' timing and density choices. Calibrated to New York City parcel-level data, the model shows that tax exemptions accelerate redevelopment on parcels near their investment threshold, while density bonuses expand project scale in high-value locations. Policy impacts are spatially heterogeneous: some neighborhoods see accelerated construction, others little response. Both incentives expand supply but fail to lower average rents because replacement of older units with new construction offsets supply effects. Mandates reallocate production toward subsidized housing and mitigate rent increases, but stringent requirements discourage redevelopment.

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Despite extensive policy intervention, housing affordability pressures persist across cities. The puzzle is driven in large part by tensions between private profitability and public affordability goals. Developers, guided by profitability, face rising land, construction, and regulatory costs that make below-market production unattractive (Glaeser and Gyourko, 2002; Quigley and Raphael, 2005). Governments, at both national and local levels, must balance tax revenues with affordability goals while confronting persistent demand pressures. The durability of real estate complicates policy design as redevelopment reshapes neighborhoods (Brueckner and Rosenthal, 2009; Diamond and McQuade, 2019), alters the urban environment (Glaeser and Gyourko, 2018), and generates broader macroeconomic effects (Duranton and Puga, 2023; Hsieh and Moretti, 2019). Because durability shifts the mix of market-rate and affordable housing in ways that make the overall impact uncertain, understanding affordability and evaluating policy effectiveness requires anticipating how developers choose the timing and intensity of (re)development. Neither policy efforts nor research on housing supply and regulation have resolved this affordability puzzle.

We address this puzzle with a forward-looking model that embeds a mix of incentives (*carrots*) and requirements (*sticks*) directly into developers' choices over when and how intensively to (re)develop. Policy effects operate through developers' optimization problem: interventions shift redevelopment thresholds, which in turn determine the scale and pace of new supply. Expected rents follow from these supply responses, reflecting both added units and the replacement of older stock with with newer, higher-rent construction. Because redevelopment thresholds depend on parcel characteristics and location, policy impacts are heterogeneous across the city. Existing studies have examined fiscal incentives and regulatory mandates separately, but no framework has jointly analyzed these tools while incorporating heterogeneity in parcels and thresholds together with the replacement mechanism.

To construct the framework, we build on classic models of irreversible investment under uncertainty (Capozza and Li, 1994; McDonald and Siegel, 1986; Paddock et al., 1988), which provide tractable decision rules approximating how developers behave in practice. In our setting, a real estate developer inherits a developed parcel that generates rental income based on its location and existing building attributes. Conditional on the maximum allowable density, developers initiate redevelopment at the time and intensity that maximize the present value of their property. Redevelopment requires demolition, non-instantaneous construction costs, and anticipation of future supply in the vicinity. The optimal decision rule depends on the regulatory environment. Governments may combine incentives (*Carrots*) such as property tax exemptions and density bonuses with obligations (*Sticks*) requiring in-kind provision of public goods. These goods may include infrastructure investment, environmental improvements,

or social housing provisions.[1] We develop and solve a model that yields closed-form expressions for parcel value, the probability of redevelopment at different horizons, optimal density, and expected rental income under alternative policy regimes. To illustrate the model's implications, we calibrate it to the New York City real estate market, with the affordable housing mandate serving as the central policy experiment.

The calibration integrates parcel-level data on density, building age, and location with rental data from the American Community Survey. Expected rent growth, and thus capitalization rate, incorporates current market conditions using statistics from Costar as well as neighborhood-level expected future supply captured from our model. Rental incomes following redevelopment are specified to increase with height (Ahlfeldt and Barr, 2022; Danton and Himbert, 2018; Liu et al., 2018), but construction costs are convex in height, too (Ahlfeldt et al., 2023; Ahlfeldt and McMillen, 2018; Eriksen and Orlando, 2022). We calibrate the elasticities associated with affordable housing shares to reduced-form estimates, and recover the implied rental volatility by matching the model's expected housing production with observed development patterns. To validate the model calibration, we compare predicted parcel values to transaction prices in Costar and find a strong positive correlation. Although benchmarked to New York City, our framework is not city-specific, as demand enters through the supply elasticity of rents, and the model accommodates both new construction and redevelopment.

Before analyzing policy counterfactuals, we evaluate how the baseline calibration predicts key development outcomes: the probability and intensity of redevelopment for each parcel, the expected number of housing units constructed in each neighborhood, and the expected rent level. The baseline projects 193,587 units over the next decade, closely matching observed construction. Development is concentrated in high-demand areas, particularly in Western Brooklyn and Queens, and on parcels with a high undeveloped capacity and time since last renovation. Spatial variation in (re)development affects rents through three channels: expected rental growth, the additional discount from another decade of depreciation on non-redeveloped properties, and the premium on new construction, which enters free of accumulated depreciation.[2] Because the replacement channel dominates, neighborhoods with more (re)development exhibit higher expected rents per unit.

[1] The ability of governments to recapture value increases resulting from public actions, often referred to as "land value capture" (Lincoln Institute of Land Policy, 2022), is central in current urban policy debates. In the United States, 41% of cities use some form of incentive zoning (Homsy and Kang, 2023). Canadian municipalities rely on development transfers to obtain privately provided public amenities (Moore, 2013). German federal law obligates developers to offset land development by protecting natural areas (Druckenbrod and Beckmann, 2018), and similar policies are expected across Europe under the "No Net Land Take by 2050" initiative.

[2] We assume that expected rental growth in the baseline already incorporates anticipated supply in the status quo, so rents are unaffected by additional supply. This assumption is relaxed in the counterfactual analysis.

We next examine how alternative policy combinations affect the built environment. Our analysis focuses on three instruments and their interactions: a 30% affordable housing mandate, a 25% density bonus through upzoning, and a 20-year property tax exemption. Both density bonuses and tax exemptions expand housing supply relative to the baseline, but operate through distinct mechanisms. Tax exemptions increase the probability of redevelopment, whereas density bonuses raise the optimal density of new projects without necessarily accelerating redevelopment timing. We also examine how the effects of these policies vary across the city. Blanket interventions produce uneven outcomes: parcels closer to their redevelopment thresholds respond more strongly to fiscal incentives, while high-quality locations benefit primarily from density bonuses.

Introducing an affordability mandate to either of these policies reduces the number of market-rate units, although the substitution with affordable units partly offsets this effect. Mandates disproportionately affect parcels on the margin of redevelopment, where small requirement changes can delay projects that would otherwise proceed. The overall supply response is strongest when both incentives are combined. Yet these outcomes come with tradeoffs: exemptions reduce tax revenues, constraining public budgets, while upzoning raises density, requiring new infrastructure investment.[3]

We also evaluate how each policy counterfactual affects expected rents. The rent change can be decomposed into three components: (1) the discount associated with the share of affordable units in new buildings, (2) the premium from replacing depreciated units with new stock entering at higher quality, and (3) the downward effect of additional neighborhood-level supply. Across all plausible counterfactuals, expected citywide rents rise relative to the baseline. Although policies stimulate construction, they do not reduce average rents because the higher quality rent premium on new units outweighs the price-reducing effect of added supply. Increasing the affordable housing mandate lowers rents, but overly stringent mandates deter redevelopment and limit total housing production.

Taken together, our analysis shows that our model reproduces observed construction patterns in New York City and clarifies the channels through which different policy instruments operate. Tax exemptions increase redevelopment probabilities, density bonuses expand project size, and mandates reallocate supply between market-rate and affordable units. Policy effects, however, are heterogeneous: parcels close to redevelopment thresholds re-

[3]We assess these costs along two dimensions: the reduction in present value of taxes and the increase in density. Tax exemptions shrink the city's fiscal base and may constrain the provision of essential public services. Density bonuses raise expected density, requiring additional investment in transportation, utilities, and public amenities.

spond more strongly to fiscal incentives, while high-quality locations benefit disproportionately from density bonuses. Redevelopment policies also generate upward pressure on rents as new units enter without accumulated depreciation offsetting the price-reducing effect of added supply. Equally central are the policy trade-offs: tax exemptions erode fiscal revenues, density bonuses intensify infrastructure demands, and stringent mandates discourage (re)development. These findings explain why affordability pressures persist despite active zoning and fiscal interventions.

Our paper contributes to two strands of literature. The first concerns the determinants of real estate supply (Baum-Snow and Han, 2024; Glaeser and Gyourko, 2018). Prior research emphasizes the role of market structure and productivity in constraining housing growth (D'Amico et al., 2024; Goolsbee and Syverson, 2023), or the role of construction technology in enabling the rise of high-rise buildings (Ahlfeldt and Barr, 2022; Ahlfeldt et al., 2023; Ahlfeldt and McMillen, 2018). A parallel line of research highlights how physical and regulatory constraints generate spatial variation in supply elasticities (Albouy and Ehrlich, 2018; Brueckner and Singh, 2020; Büchler and v. Ehrlich, 2023; Gyourko et al., 2021; Saiz, 2010). Our study is more specifically related to work modeling forward-looking developers in dynamic settings (Cunningham, 2006; Hsiao, 2023; Murphy, 2018; Peng, 2023; Rollet, 2025), which emphasizes the option value embedded in land ownership.[4] We contribute by embedding realistic developer incentives and decision rules into a structural framework that incorporates public policy instruments, thereby offering new insights into policy design.

Second, our study contributes to the literature on the effects of urban regulatory and fiscal policies (Gyourko and Molloy, 2015; Quigley and Rosenthal, 2005).[5] Existing work examines the impact of supply-side policies such as tax incentives in opportunity zones (Chen et al., 2023; Corinth and Feldman, 2024), upzoning (Büchler and Lutz, 2024; Freemark, 2020, 2023; Greenaway-McGrevy and Phillips, 2023; Peng, 2023), affordable housing mandates (Favilukis et al., 2023), and inclusionary housing mandates coupled with density bonuses (Schuetz et al.,

[4]Theoretically, our models contribute to the long tradition of real options models (McDonald and Siegel, 1986; Myers, 1977) applied to real estate development (Arnott and Lewis, 1979; Capozza and Li, 1994; Grenadier, 1996; Quigg, 1993; Titman, 1985). These studies show that uncertainty delays development (Bulan et al., 2009), competition accelerates it (Grenadier, 2002), and the possibility of conversion to other uses creates additional value (Benmelech et al., 2005; Büchler et al., 2023). Building on the development framework of Lebret and Liu (2023), we extend this class of models to evaluate policy counterfactuals.

[5]It also relates to research on the origins of land-use restrictions (Clingermayer, 1993; Fischel, 2002; Helpman and Pines, 1977; Hilber and Robert-Nicoud, 2013; McMillen and McDonald, 2002; Stull, 1974), as our framework provides an ex-ante rationale for regulation by enabling subsequent *Carrot & Stick* negotiations with private stakeholders over public goods. Although this mechanism has been examined by urban planners and political scientists (Freemark, 2020; Homsy and Kang, 2023; Kim, 2020; Korngold, 2022; Moore, 2013), to our knowledge, no paper offers a formal economic analysis.

2009, 2011) or fiscal incentives (Baum-Snow and Marion, 2009; Eriksen and Rosenthal, 2010; Soltas, 2023, 2022). Krimmel and Wang (2023) further shows that attaching affordability constraints to upzoning in Seattle shifted development outside targeted areas, underscoring the tension between incentives and constraints. Our paper complements this work by providing a structural framework that unifies fiscal and regulatory tools and enables counterfactual policy evaluation.

The paper proceeds as follows. Section 1 presents the model, describing developers' decision rules and the city's policy instruments. Section 2 illustrates the mechanics of the model on a representative parcel. Section 3 outlines the empirical setting and calibration. Section 4 reports baseline results, and Section 5 analyzes policy counterfactuals. Section 6 concludes.

1 A Real Estate Development Model with Policy Instruments

In constructing our model, we explicitly account for the government's regulatory and fiscal authority over urban parcels. For each parcel, the government may shift from the current policy environment $\mathcal{P}_0$ to an alternative environment $\mathcal{P}$. This new environment $\mathcal{P}$ can vary in allowable density (ϕ), impose a mandate to include public goods on the site (α), or grant a tax exemption of τ years on completed buildings.[6] Because private developers factor each of these policy instruments into their decision about the timing and intensity of (re)development, we first describe the developers' optimal decision rules and then outline the mechanisms through which each policy instrument affects the built environment.

1.1 The Real Estate Developer Decision Rule

We take the residential net market rent per unit of newly built density, R_t, as the fundamental state variable. Under the risk-neutral measure $\mathbb{Q}$, rent evolves according to a geometric Brownian motion:

$$dR_t = \delta R_t \, dt + \sigma R_t \, dW_t$$

where δ is the risk-neutral expected growth rate of rent that adjusts for expected supply shocks, σ is the volatility, and $(W_t)_{t\geq 0}$ is a standard Brownian motion on the probability space $(\Omega, \mathcal{F}, \mathbb{Q})$.[7] This process is log-normal, implying that both expected growth and volatility scale proportionally with the current rent level.

[6] It follows that $\mathcal{P}_0 = \{\alpha = 0, \phi = 0, \tau = 0\}$ and $\mathcal{P} \neq \mathcal{P}_0$.

[7] The calibration of δ with respect to the supply effect can be found in section 3.2.1

Valuation relies on standard assumptions that ensure the existence of a risk-neutral measure. Under these conditions, the stochastic process for rents can serve as the fundamental state variable for arbitrage-free pricing, and redevelopment options can be valued as contingent claims on future rents.[8] Denoting R as the value at $t = 0$, we can rewrite the market rent of a new residential property per unit of density at $t \geq 0$ as $R_t = Re^{(\delta - \frac{\sigma^2}{2})t + \sigma W_t} = Re^{\sigma Z_t}$, where $Z_t = bt + W_t$, and $b = \frac{1}{\sigma}(\delta - \frac{\sigma^2}{2})$.

Before discussing options to redevelop, we introduce two adjustments needed to obtain the market value of a property with current density (F_B) and rental depreciation (z_B), denoted as $\pi(R, F_B, z_B)$.

- **Taxation:** We assume the government imposes a proportional tax on rental income of the developed properties, reducing the developer's effective payout by a factor of ψ.
- **Property scaling function:** We define $\Gamma(F, z, \alpha)$, as the function that scales the potential rent of a unit of density R_t, based on the characteristics of the built property, to yield the stochastic rental income of a developed property. In particular, the rent increases exponentially with the built density (F), decreases with the property depreciation rate (z), and decreases with the share of built space allocated to public goods (α). By construction, $\Gamma(1, 0, 0) = 1$ corresponds to a property with a density of 1 ($F_B = 1$), with no operational efficiency losses due to rental depreciation ($z_B = 0$), and no mandate to include public goods on the site ($\alpha = 0$). We revert to the full parametrization of $\Gamma(F, z, \alpha)$ in Section 3.

Consequently, the value of the developed property without its development option is

$$\pi(R, F_B, z_B; \Theta) = \mathbf{E}_{\mathbb{Q}} \left\{ \int_0^{\infty} e^{-ru} \left(1 - \psi\right) \Gamma(F_B, z_B, 0) R_u \mathrm{d}u \right\}$$

where Θ is the vector of parameters.

Baseline: Development Decision Under Current Regulatory Environment. Private developers have the option to replace the current building with a new property constructed at density $F \leq \bar{F}_0$ where $\bar{F}_0$ is the maximum density allowed under the regulatory environment $\mathcal{P}_0$. Exercising this option requires paying an instantaneous demolition cost $\gamma(F_B)$, in addition to an annual construction cost during the construction period of d years, denoted as $\kappa(F, \alpha)$.

[8] In practice, rents are not continuously traded and markets are incomplete. The assumption that rents are spanned by traded assets should be interpreted as an analytical convenience supported by the existence of correlated securities (e.g., REIT shares, lease-backed instruments) that allow developers to hedge rent risk partially. See discussion in Appendix C.1

Construction costs rise exponentially with the density of the new construction F, and might also depend on the share of built space dedicated to public goods (α).

Developers exercise the option to redevelop under $\mathcal{P}_0$ only when favorable market conditions prevail. We denote R^e, the predetermined level (i.e., expansion barrier) at which they initiate construction of a building of height F, and T_{R^e}, the time this barrier is reached for the first time. To complete (re)development at density F, rents must remain above the barrier for the full construction duration of d years. We denote H_{R^e}, the time at which the property is fully developed.[9]

As a result, we can express the value of the property under $\mathcal{P}_0$ inclusive of the development option as follows:

$$\pi_0(R, F_B, z_B, F; \mathcal{P}_0, \Theta) = \underbrace{\mathbf{E}_{\mathbb{Q}}\left\{ \int_0^{T_{R^e}} e^{-ru}\,(1-\psi)\;\Gamma(F_B, z_B, 0) R_u \,\mathrm{d}u \right\}}_{\text{Value before development}} - \underbrace{\mathbf{E}_{\mathbb{Q}}\left\{ e^{-rT_{R^e}} \gamma(F_B) \right\}}_{\text{Demolition costs}}$$
$$\underbrace{- \mathbf{E}_{\mathbb{Q}}\left\{ \int_{T_{R^e}}^{H_{R^e}} e^{-ru} \kappa(F, \alpha) \mathbf{1}_{R_u > R^e} \,\mathrm{d}u \right\}}_{\text{Development costs}} + \underbrace{\mathbf{E}_{\mathbb{Q}}\left\{ \int_{H_{R_0^e}}^{\infty} e^{-ru} (1-\psi)\,\Gamma(F, 0, \alpha) R_u \mathrm{d}u \right\}}_{\text{Value after development}} \quad (1)$$

Where $\mathbf{1}_x$ denotes the indicator function for event x. The model adjusts cash flows to reflect anticipated supply expansions in the surrounding market. Equation (1) consists of four discounted terms: net-of-taxes rents from the incumbent structure until redevelopment, demolition costs at the stopping time, expenditures during construction, and the payout stream from the completed asset.

Counterfactual: Adding Policy Instruments Into the Development Decision Rule. We model three distinct policy instruments that local governments can use independently or in combination. First, the government can mandate that the developer allocate a share α of the project to the public. Increasing α impacts the rental income of the property and the construction cost through $\Gamma(.)$ and $\kappa(.)$, respectively. Second, the government can grant additional density bonuses allowing an additional height ϕ, so that the developer chooses density F subject to $F \leq \bar{F}$ where $\bar{F} = \bar{F}_0(1+\phi)$. Third, the government can provide tax exemptions lasting τ years once construction is completed. The policy environment is thus summarized by the

[9] Formally the stopping times T_{R^e} and H_{R^e} are defined as $T_{R^e}(W) = \inf\{t \geq 0 : W_t = R^e\}$, and $H_{R^e}(W) = \inf\{t \geq 0 : (t - g_t^{R^e}(W)) \geq d, W_t \geq R^e\}$ with $g_t^{R^e}(W) = \sup\{s \leq t : W_s = R^e\}$ (Chesney et al., 1997).

vector $\mathcal{P} = \{\alpha, \phi, \tau\}$.

The value of a property under the new regulatory environment is:

$$\pi(R, F_B, z_B, F; \mathcal{P}, \Theta) = \underbrace{\mathbf{E}_{\mathbb{Q}}\left\{ \int_0^{T_{R^e}} e^{-ru} \left(1-\psi\right) \Gamma(F_B, z_B, 0) R_u \, \mathrm{d}u \right\}}_{\text{Value before completed development}}$$
$$- \underbrace{\mathbf{E}_{\mathbb{Q}}\left\{ e^{-rT_{R^e}} \gamma(F_B) \right\}}_{\text{Demolition costs}} - \underbrace{\mathbf{E}_{\mathbb{Q}}\left\{ \int_{T_{R_e}}^{H_{R^e}} e^{-ru} \kappa(F, \alpha) \, \mathbf{1}_{R_u > R^e} \, \mathrm{d}u \right\}}_{\text{Development costs}}$$
$$+ \underbrace{\mathbf{E}_{\mathbb{Q}}\left\{ \int_{H_{R^e}}^{\infty} e^{-ru} \, \Gamma(F, 0, \alpha) R_u \, \mathrm{d}u \right\}}_{\text{Value after development gross of tax}} - \underbrace{\mathbf{E}_{\mathbb{Q}}\left\{ \int_{H_{R^e}+\tau}^{\infty} e^{-ru} \, \psi \, \Gamma(F, 0, \alpha) R_u \, \mathrm{d}u \right\}}_{\text{Property taxes after } \tau \text{ years of exemption}} \quad (2)$$

Similar to Equation (1), the property value in $\mathcal{P}$ consists of the sum of present values with an additional final term that captures the impact of postponing property taxes for τ years after the development has been completed.

1.2 Analytical Solutions

Parcel value.

Proposition 1 *In the presence of the expansion threshold R^e, the property value $\pi(.)$ satisfies*

$$\pi(R, R^e, F_B, z_B, F, \alpha, \phi, \tau; \Theta) = \underbrace{\Gamma(F_B, z_B, 0) \frac{1-\psi}{r-\delta} \left[R - R^e \left(\frac{R^e}{R} \right)^{\xi} \right]}_{\textit{Value before completed development}} - \underbrace{\gamma(F_B) \left(\frac{R^e}{R} \right)^{\xi}}_{\textit{Demolition costs}}$$
$$- \underbrace{\frac{\kappa(F, \alpha)}{r} \Big(B(d) - A(d) \Big) \left(\frac{R^e}{R} \right)^{\xi}}_{\textit{Development costs}} + \underbrace{\frac{1}{r-\delta} \Gamma(F, 0, \alpha) R^e C(d) \left(\frac{R^e}{R} \right)^{\xi}}_{\textit{Value after development}}$$
$$- \underbrace{\frac{\psi h}{r-\delta} \Gamma(F, 0, \alpha) R^e C(d) \left(\frac{R^e}{R} \right)^{\xi}}_{\textit{Property taxes after } \tau \textit{ years of tax credits}} \quad (3)$$

with $b = (1/\sigma)(\delta - \sigma^2/2)$, $\lambda = \sqrt{2r + b^2}$, $h = e^{\left[(b+\sigma)^2 - \lambda^2\right]\frac{\tau}{2}}$ *and* $\xi = (1/\sigma)(b - \lambda)$ *and where also*

$$A(d) = \frac{\Phi(b\sqrt{d})}{\Phi(\lambda\sqrt{d})},\ B(d) = \frac{b+\lambda}{2\lambda} - \frac{b-\lambda}{2\lambda}\frac{\Phi(-\lambda\sqrt{d})}{\Phi(\lambda\sqrt{d})},\ \textit{and} \quad C(d) = \frac{\Phi((\sigma+b)\sqrt{d})}{\Phi(\lambda\sqrt{d})}$$

with $\Phi(x) = \int_0^{+\infty} z e^{zx - \frac{z^2}{2}}\,\mathrm{d}z = 1 + x\sqrt{2\pi}e^{\frac{x^2}{2}}\mathcal{N}(x)$, $\mathcal{N}(.)$ *being the standard normal cumulative distribution function.*[10]

The proof is in Appendix C.2.

Probability of development. Although developers formally control the timing of redevelopment, it is endogenous to the policy environment $\mathcal{P}$. Conditional on the current market and policy conditions, developers initiate construction only when rents cross a critical threshold R^{e*}. This threshold reflects the point at which the expected value of redevelopment exceeds the continuation value of the existing property, making construction the optimal choice.

Proposition 2 *When developers select the optimal timing for development under the regulatory regime* $\mathcal{P}$*, the expansion threshold is given by*

$$R^{e*} = \frac{\xi}{1+\xi}\frac{1}{\vartheta}\left[\gamma(F_B) + \frac{\kappa(F,\alpha)}{r}\Big(B(d) - A(d)\Big)\right] \tag{4}$$

with $\vartheta = \Gamma(F, 0, \alpha)\frac{1-\psi h}{r-\delta}C(d) - \Gamma(F_B, z_B, 0)\frac{1-\psi}{r-\delta}$.

The proof is in Appendix C.3.

From Proposition 2, we note that as the expansion barrier increases with construction and demolition costs: developers delay (re)development when costs are higher. Recall that $T^{R^{e*}}(R) = \inf\{t \geq 0 | R_t = R^{e*}\}$ represents the first time the new residential net market rent per unit of built density reaches the expansion threshold. Using this stopping time, we can derive the probability that (re)development begins before time t.

Proposition 3 *Given the expansion threshold* R^{e*}*, the probability that development starts before time* t *under regulatory regime* $\mathcal{P}$ *satisfies*

$$\mathbf{P}\left(T^{R^{e*}} \leq t; \mathcal{P}, \Theta\right) \quad = \quad \int_0^t \textit{Prob}\left(T^{R^{e*}} \in \mathrm{d}s\right)$$

[10] Operationally, we calibrate δ from observed capitalization rates c_{obs} (rent-to-price ratio) via $\delta = r - c_{\text{obs}}$. This treats δ as a reduced-form representation of rent risk premia.

$$= \int_0^t \frac{a}{\sqrt{2\pi s^3}} \exp\left(-\frac{a^2}{2s}\right) \mathrm{d}s \tag{5}$$

where $a = \ln(R^{e*}/R)/\sigma$ *and* $\mathbf{P}(.)$ *is the probability under the new measure* $\mathbb{P}$*, such that* $(Z_t)_{t\geq 0}$[11] *becomes a Brownian motion under* $\mathbb{P}$*.*

The proof is in Appendix C.4.

The implications of non-instantaneous construction costs are not trivial. We discuss the importance of modeling non-instantaneous construction durations in comparison to the previous literature, and its implications for investment dynamics in Appendix B.

Optimal Density. In the analytical solutions presented above, developers chose the optimal timing of construction conditional on a chosen construction density $F \leq \bar{F}$. To numerically derive the optimal density F^*, we maximize the value of the property subject to the maximum allowable density and optimal expansion barrier R^{e*}:

$$\begin{aligned} F^* = \arg\max_F \quad & \pi(R, R^{e*}, F_B, F, \alpha, \phi, \tau; \Theta) \\ \text{s.t.} \quad & 0 \leq F \leq \bar{F} \end{aligned} \tag{6}$$

This numerical optimization allows us to derive the property value $\pi^*(.)$, the optimal barrier R^{e**}, and the development probability $\mathbf{P}^*$ that corresponds to the developer's decision rule. Together, these characterize the developer's decision rule, incorporating both the optimal timing and intensity of redevelopment. Intuitively, higher density raises the potential value of redevelopment but also increases construction costs, so the optimal choice of F^* balances these competing forces.

Expected rental incomes. Using Proposition 3 and the optimal density F^*, we derive the expected parcel-level rental income at time t inclusive of the development option. Adoption of a new regulatory regime is voluntary: developers choose $\mathcal{P}$ only if $\pi_i(\mathcal{P}) \geq \pi_i(\mathcal{P}_0)$. This participation condition makes policy take-up endogenous, since the decision to adopt depends on whether the relative payoff from redevelopment under the new rules exceeds the value under the baseline environment.

Proposition 4 *Given the probability that development starts* $\mathbf{P}^*$*, and the optimal density* F^**, the*

[11] $Z_t = bt + W_t$

expected parcel-level rental income at time t satisfies:

$$\begin{aligned}\mathbf{Rent}_i(\mathcal{P};\Theta|t) = &\underbrace{[1-\mathbf{P}^*\left(T^{R^{e**}}\leq t;\mathcal{P},\Theta\right)]}_{\textit{Prob No Development}}\times\underbrace{\Gamma(F_B,z_B(t),0)\times\mathbf{E}_{\mathbb{P}}\{R_{it}\}}_{\textit{Rent without Development}}\\ &+\underbrace{\mathbf{P}^*\left(T^{R^{e**}}\leq t;\mathcal{P},\Theta\right)}_{\textit{Prob Development}}\times\underbrace{\Gamma(F^*,0,\alpha)\times\mathbf{E}_{\mathbb{P}}\{R_{it}\}}_{\textit{Rent with Development under }\mathcal{P}}\end{aligned} \tag{7}$$

with $\mathbf{P}\left(T^{R^{e*}}\leq t;\mathcal{P},\Theta\right)$ *defined in (5),* F^* *in (6), and* $\mathbf{E}_{\mathbb{P}}\{R_t\} = R\,e^{\frac{\sigma^2}{2}t}$.

The derivation $\mathbf{E}_{\mathbb{P}}\{R_T\}$ is in appendix C.5.

The expected rent can be seen as a weighted average that depends on the expansion barrier R^{e*}, the potential rent at time t that include expectation of future supply $E[R_{it}]$, and the optimal density F^*, that all, under the status quo $\mathcal{P}_0$ do not coincide with the counterparts in a new regime $\mathcal{P}$. We provide a decomposition of expected rent changes in Section 5.2.

The general solutions in Equations (3), (5), (6), and (7) provide expressions for the property value, the probability of development, the optimal density, and the expected rent under a flexible policy framework. This setup allows us to evaluate policy outcomes across a wide range of regulatory environments. For example, we can derive the property value and development probability under several commonly used regulatory environments such as (1) current zoning $\mathcal{P}_0 = \{\alpha = 0, \phi = 0, \tau = 0\}$, (2) upzoning $\mathcal{P} = \{\alpha = 0, \phi > 0, \tau = 0\}$, or (3) mandatory inclusionary programs with density bonuses $\mathcal{P} = \{\alpha > 0, \phi > 0, \tau = 0\}$, or with tax incentives $\mathcal{P} = \{\alpha > 0, \phi = 0, \tau > 0\}$.

2 Impact of Public Policies in Simple Numerical Frameworks

Before analyzing policies citywide policy analysis, we first demonstrate that our model captures the trade-off between carrots (ϕ and τ) and sticks (α) at the parcel level, both in terms of valuation and development probability. To illustrate, we examine a representative parcel close to redevelopment and compute comparative statics; heterogeneity across parcels are introduced later. We use the parametrization and calibration described in Section 3. This calibration incorporates not only returns and costs of density but also the impact of mandate α which simultaneously reduces rental income and construction cost.

Figure 1 shows the effect of each policy instrument on property values (left panels) and on the probability of development within 10 years (right panels). The figure also illustrates how these effects vary with initial demand, by shifting the rent potential R_i above or below

the baseline. Figure A1 decomposes the effects of each policy instrument on property value, distinguishing between the developed property and the redevelopment option. The latter is computed as the difference between the current value and the predicted parcel value if construction costs go to infinity. Table 1 reports the sensitivity of these results to key elasticity assumptions. Figure A2 illustrates marginal effects with respect to additional parameters. Together, these figures establish the mechanisms through which carrots and sticks affect redevelopment incentives before extending the analysis to citywide heterogeneity.

Affordable Housing Mandates (α)**:** Panel (a) of Figure 1 shows that raising the affordable unit requirement (α) consistently lowers both property values and development probabilities. For example, Table 1 indicates that a 20% mandate reduces property values by 0.83% and development probabilities by 0.98 percentage points. Figure A1 further demonstrates that this decline in property value comes primarily from a reduction in the redevelopment option value, rather than from the value of the developed property.

The affordable housing mandates have a stronger impact in high-demand areas. Under the same 20% mandate in Table 1, a parcel with higher demand (R up by 100%) experiences a 2.1% decline in property values and a 4.8 percentage-point reduction in redevelopment probability. Effects are also larger on parcels already close to redevelopment, confirming that mandates mainly bind where redevelopment is most imminent.

Sensitivity tests highlight the role of parameter variation. If the rental discount on affordable units doubles (ϵ_α), a 20% mandate reduces property values by 1.73% and 10-year development probabilities by 2.26 percentage points. In contrast, if affordable housing development costs are 100% higher, the 20% mandate reduces property values by 0.6% with smaller effects on (re)development probabilities, suggesting that lower construction costs can partially offset the mandate's negative impact.

Density Bonuses (ϕ)**:** Panel (b) of Figure 1 shows that increasing allowable density (ϕ) raises property values but can lower the probability of development when ϕ is large. Property values and development probabilities thus need not move together. Higher ϕ increases construction costs through $\kappa(\cdot)$ while also boosting income from added density. Because developers retain the option to build at higher density, property value always rises. Yet for sufficiently high ϕ, developers may postpone construction, reducing the observed development probability. In this case, as Figure 1 shows, the increase in property value reflects a larger redevelopment option.

Table 1 quantifies these effects. A 50% increase in allowable density (setting $\phi = 0.5$) increases property values by 8.55% and development probabilities by 3.58 percentage points. In high demand areas, the same density bonus raises property values by 14.3% and development probabilities by 14.6 percentage points. For parcels already near the redevelopment threshold, property values increase but development probabilities remain unchanged, since additional density rationally postpones redevelopment. Increasing the marginal benefit of height (ϵ_F) with $\phi = 0.5$ increases property values by 10.5% and development probabilities by 4.7 percentage points. Because the height elasticity of construction cost depends on bedrock depth and can vary by a factor of ten (Ahlfeldt et al., 2023), higher elasticities sharply weaken the effect of density bonuses. For example, if the elasticity of construction costs is 50% higher, property values increase by only 3.3% and development probabilities show no significant change. These results highlight that the impact of density policy depends critically on construction technology.

Tax Exemptions (τ)**:** Panel (c) of Figure 1 shows that offering tax exemptions unambiguously increases property values and accelerates (re)development. The gain in property value comes entirely from the redevelopment option, since the exemption applies only to newly developed buildings (Panel C of Figure A1). For example, offering a 20-year tax credit increases property values by 4.1% and development probabilities by 6.3 percentage points. These effects are amplified on parcels already close to redevelopment, where development probabilities rise by 11.2 percentage points. On high-demand parcels (with rents doubled), the same exemption increases property values by 13.5% and development probabilities by 23.7 percentage points. As expected, the impact of exemptions is amplified when property tax rates are higher. Doubling the property tax rate magnifies the effect of a 20-year tax credit, further raising property values and (re)development probabilities.

3 Model Quantification

We calibrate the model to New York City's affordable housing mandate, which serves as our central case study. The calibration proceeds in three steps. First, we describe the parcel-level dataset used to establish the baseline. Second, we specify the functional forms of the three key functions—$\Gamma(\cdot)$, $\gamma(\cdot)$, and $\kappa(\cdot)$—and their elasticities, drawing on micro evidence and established values from the literature. Third, we calibrate the levels of demolition costs, construction costs, and the volatility of rents by matching the model's predicted construction activity to observed development patterns. Table 2 summarizes the parameter definitions and sources, while Table 3 reports parcel-level statistics.

3.1 Data

Each parcel i is characterized by its current density F_i, maximum allowable density $\bar{F}_i$, rental depreciation z_i, and location. Location determines both the expected return and the volatility of rental income, as well as the potential rent per unit of density R_i. We restrict the sample to parcels zoned or partially zoned for residential use, excluding parcels designated exclusively for public or other non-residential purposes.[12] In total, the dataset comprises 781,226 parcels.

Potential Rent per unit of density (R_i). To calibrate R_i, we use the 2022 American Community Survey 5-year (ACS) data on median gross rent at the census block group level. To address missing values and smooth discontinuities across census boundaries, we implement an inverse distance weighting (IDW) interpolation with a decay parameter of two to obtain $Rent_i$ for each parcel. Because census-reported rent reflects the rent of a typical unit that may vary in size, we normalize by the average number of rooms (also from ACS). In our sample, the average normalized annual rent is \$24,119. Since R_i in our model represents the potential rent for the first non-depreciated housing unit, we adjust observed rents to remove the effects of depreciation (Age) and density (F_i), defining

$$R_i = \frac{Rent_i}{\Gamma(\overline{F}_{i(j)}, \overline{z}_{i(j)}, \overline{\alpha}_{i(j)})},$$

where $\overline{F}_{i(j)}$ is the average built density, $\overline{z}_{i(j)}$ the average estimated rental depreciation, and $\overline{\alpha}_{i(j)}$ the average share of the building allocated to affordable housing within neighborhood j. After this adjustment, the average annual potential rent in our sample is \$31,700. Panel A of Figure 2 illustrates its spatial distribution, highlighting the substantial premium associated with proximity to Manhattan.

Built and Maximum Allowed Density (F_i and $\bar{F}_i$). We calibrate F_i and $\bar{F}_i$ using the existing built Floor-Area-Ratio (FAR) and the maximum allowable FAR, which serve as the core density measures. We normalize these values based on the observed relationship between FAR and the number of residential units per unit of land area. This normalization expresses F_i in terms of residential units per standardized parcel of 2,500 square feet.[13] In our baseline calibration, the average built density F_i is 2.66 while the average maximum allowable density $\bar{F}_i$

[12] To retain parcels eligible for residential use, we keep those with an "R-x" zoning classification in the first through fourth zoning categories. We also retain parcels with observed residential units regardless of zoning classification.

[13] For example, in the Chelsea–Hudson Yards neighborhood of Manhattan, a built FAR of one corresponds to 3.46 residential units on a 2,500-square-foot parcel, whereas in Queens the comparable figure is 2.53 units.

is 3.66. Notably, 36.8% of parcels are already built to their maximum allowable density.

Rental depreciation (z_i). To account for rental depreciation, we assume that the current asset yields lower rental income as it ages. We model this effect with the functional form $z_i = Age_i^{\epsilon_z}$, where Age_i is the number of years since the last recorded renovation or construction and ϵ_z is the age elasticity of rental income. To estimate ϵ_z, we follow Rosenthal (2014) and run a hedonic pricing regression on residential building transactions from CoStar. The results, reported in Table A1, show an age elasticity of per-unit price ranging from -0.145 to -0.068, depending on the controls. We set $\epsilon_z = -0.08$ in the baseline.[14] This specification implies an annual rental depreciation pattern that is steeper in the early years (averaging -2.4% over the first 5 years), consistent with the findings of Lopez and Yoshida (2022) on condominium rental depreciation. In the baseline calibration, z_i has a mean of 0.72 and a standard deviation of 0.63.

Return and rental growth (δ_i). We collect capitalization rates (the net rent-to-price ratio) and annual rental growth rates (g_i) directly from CoStar market data, manually geocoding parcels to their corresponding submarkets. Capitalization rates vary systematically across boroughs: they average 4.6% in Manhattan and 6.0% in the Bronx, reflecting lower expected rental growth in the Bronx (0.1%). The sum of the capitalization rate and rental growth defines the total return ($\tilde{\delta}_i$), shown in Panel C of Figure 2. Following the mapping between physical and risk-neutral measures, we compute the risk-neutral discount rate used in the model as $\delta_i = r - \tilde{\delta}_i + g_i$.

3.2 Parametrization

3.2.1 Rental Discount Linked to Excess Supply

In our framework, the potential rent R_{it} depends on the rent growth rate for parcel i. Under the baseline policy vector $\mathcal{P}_0$, this rent growth is calibrated using CoStar market-level rent growth g_i, which we interpret as embedding developers' expectations of future supply under the status quo. In counterfactuals, however, this rent growth is affected by additional supply beyond the supply expected under the status quo. To capture this change in rent growth expectations, we allow additional supply to place downward pressure on potential rents, such that rents decline by ς percent for every one percent increase in units, where ς is

[14] Although the estimation relies on transaction prices rather than rents, the estimated price discount ϵ_z can be applied directly to rents because of the year and location fixed effects account for variations in capitalization rates.

the supply elasticity of rent.[15] Defining $\Delta S_i(t)/S_i$ as the percentage change in supply in the vicinity of parcel i at horizon t, we define rental growth *inclusive of supply effects* g_i^S as:

$$g_i^S(g_i, \Delta S_i, t) = g_i + \frac{1}{t} \ln\left(1 + \frac{\Delta S_i(t)}{S_i}\varsigma\right). \tag{8}$$

We assume that rent responses to supply shocks occur at the local level (Asquith et al., 2023; Li, 2022), and therefore compute $\Delta S_{i(j)}(t)$ for the NYC's 188 neighborhoods. We calibrate $\varsigma = -0.10$ following Li (2022), who estimate the impact of unanticipated supply shocks on NYC rents. This relatively small elasticity reflects the offsetting balance between positive amenity spillovers from nearby market-rate construction and the negative price effects of additional units. As an alternative, one could separate these channels by geography and calibrate distinct elasticities: an amenity elasticity $\varsigma_A > 0$ linked to expected market-rate construction in the immediate vicinity of parcel i, with the possibility of $\varsigma_A < 0$ in settings where local opposition to densification generates negative amenity effects (NIMBY), and a supply elasticity $\varsigma_S < 0$ linked to aggregate citywide supply growth, so that R_{it} would rise with local construction while falling with citywide additions.

In this framework, expected future supply in excess of baseline $\Delta S_i(t)$ impacts expected rental growth g_i^S. Expected rental growth in turn affects developers' redevelopment decisions (see Panel B of Figure A2), generating a fixed-point problem. We resolve this endogeneity by iterating the model until citywide supply paths stabilize within a small tolerance.[16] The results of the first iteration correspond to a scenario in which developers are myopic in the sense that they do not anticipate others' actions when forming rent-growth expectations. At convergence, decision rules reflect full internalization of anticipated neighborhood supply responses to the policy at time 0.

[15] Housing demand is implicitly incorporated into the model through this elasticity, which makes the model generalizable across cities. In low-elasticity, high-demand markets, rents continue to rise even as supply expands. In contrast, in more elastic markets (often smaller cities) rent growth dissipates quickly and production halts after modest expansion.

[16] Algorithm. Initialize $g_i^{S,(0)} \equiv g_i$. For iteration $k \geq 1$: (i) simulate the counterfactual using $g_i^{S(k-1)}$ to obtain $\Delta S_j^{(k)}(t)$; (ii) update $g_i^{S(k)} = g_i + \frac{1}{t}\ln\left(1 + \frac{\Delta S_{i(j)}^{(k)}(t)}{S_{i(j)}}\varsigma\right)$; (iii) repeat until $|\sum_j \Delta S_j^{(k)}(t) - \sum_j \Delta S_j^{(k-1)}(t)| <$ tol. We define convergence as the stability of citywide supply paths $\sum_j \Delta S_j$. In practice, the procedure converges rapidly under this criterion. We also verified that convergence measured on rent-growth expectations g_i^S yields indistinguishable results.

3.2.2 The Rent Scaling Function, $\Gamma(F, z, \alpha)$.

In our model, the underlying rent of an unlevered unit of density R is scaled by the function $\Gamma(\cdot)$, which incorporates the characteristics of the built property and determines the annual rental income of the parcel. We parametrize this scaling function as

$$\Gamma(F, z, \alpha) = F^{(1+\epsilon_F)} z(1 - \alpha\epsilon_\alpha), \tag{9}$$

where F is current density, $z \in (0, 1)$ is the discount associated with depreciation, and α is the share of affordable units in the building. The parameter $\epsilon_F > 0$ denotes the density elasticity of rent, while $\epsilon_\alpha > 0$ captures the rental discount associated to the non-market-unit share. We calibrate ϵ_F at 0.07 using estimates from the skyscraper literature (Ahlfeldt and Barr, 2022; Ahlfeldt et al., 2023; Danton and Himbert, 2018).[17] The positive ϵ_F reflects the amenity value of height, including better views and reduced street-level noise, that raise market rents on upper floors.

The rental discount associated with affordable housing ϵ_α could, in principle, be a policy parameter in $\mathcal{P}$. To limit the counterfactual space, we focus on mandates that vary only the share of affordable units α but fix the rental discount ϵ_α. We follow Favilukis et al. (2023) to calibrate ϵ_α. Specifically, they find that rent-stabilized units in NYC rent at an average 26.6% discount relative to market-rate units, and rent-controlled units rent at an average 77.7%. To span this range, we report results for $\epsilon_\alpha \in \{0.25, 0.50, 0.75\}$. Our main counterfactuals adopt a 50% discount, while Section 5 evaluates how results change when this discount is altered, focusing in particular on voluntary adoption of policy $\mathcal{P}$ from the developers' perspective.

3.2.3 The Demolition Cost Function

We parametrize demolition costs as

$$\gamma(F) = k_d F^{\eta_D}, \tag{10}$$

where $0 < \eta_D < 1$ is the density elasticity of demolition costs and k_d is a cost shifter for demolishing one unit of density. We calibrate these parameters using information from developer interviews. Practitioners reported that fixed costs typically account for 50–60% of demolition expenses, with the remainder varying with structure size. They also noted that demolition costs typically represent about 13–20% of total redevelopment costs. The first statistic is

[17] We abstract from ground-floor rent premia (Danton and Himbert, 2018; Liu et al., 2018), since the model focuses on additional floor space ϕ, which refers to construction above ground level.

matched to the mean fixed cost share implied by our model, yielding an elasticity of $\eta_D = 0.77$. The second statistic determines the relation between k_d and the construction cost parameter k_c, as discussed in Section 3.3.

3.2.4 The Construction Cost Function

We parametrize construction costs as

$$\kappa(F, \alpha, d) = \frac{1}{d} k_c F^{(1+\eta_F)}(1 - \alpha\eta_\alpha), \tag{11}$$

where k_c is the baseline cost of constructing one unit of density, $\eta_F > 1$ is the density elasticity of construction cost, and η_α captures the cost adjustment for space dedicated to the public good α. Intuitively, η_F captures the engineering challenges and convex cost escalation of building taller structures, while η_α reflects the quality trade-off in affordable construction, where lower-cost finishes and materials reduce per-unit expenditures. We calibrate η_F using evidence from the skyscraper literature. Ahlfeldt and McMillen (2018) estimate a 0.61 elasticity for residential buildings above five floors, Ahlfeldt et al. (2023) calibrate their residential elasticity at 0.55, and Ahlfeldt and Barr (2022) estimate 0.56 for tall residential buildings. We set $\eta_F = 0.60$ to reflect this convex increase in construction costs with height.

The second elasticity, η_α, reflects the cost reduction from lower-quality fixtures and finishes in non-market units. To calibrate η_α, we use data from the National Apartment Association's Income and Expenses Report, cited in the RCLO report on The Affordable Housing Asset Class. This report documents capital expenditures per square foot for market-rate and subsidized units from 2012 to 2021. On average, subsidized units receive 19.9% lower capital expenditure per square foot than market-rate units. Although capital expenditures are not identical to construction costs, we assume they are a reasonable proxy for the differential and set $\eta_\alpha = 0.20$.

3.3 Matching

3.3.1 Baseline Construction and Demolition Costs

The levels of the model are governed by three parameters: the market rent for a unit of non-depreciated density R_i, the demolition cost k_d, and the construction cost k_c, all expressed per unit of density.[18] We calibrate k_d and k_c using the method of moments, assuming they are

[18]Because the probability of development and property value are homogeneous of degree zero and one, respectively, in R, k_d, and k_c, their relations can therefore be expressed in relative terms without affecting the

constant across New York City neighborhoods since labor, material, and regulatory costs are broadly similar within the city (Glaeser and Gyourko, 2018).

To identify k_c, we use PLUTO data on the ratio of land value to property value. The citywide average is 23.7%, which we match to the model's average land-value ratio across all built parcels. To obtain this land-value ratio, we solve for the parcel value π_i assuming it has no built space: $E[\pi(F_i = 0; \Theta)/\pi_i(F_i = F_i; \Theta)] = 0.237$. To identify k_d, we draw on evidence that demolition costs range from 13–20% of total development costs. We replicate this statistic in the model by calibrating k_d given the demolition elasticity $\eta_D = 0.77$. These calibrations yield $k_c = 113.04$ and $k_d = 15.20$. For comparison, the mean value of R_i in the model is \$31.7, implying that the cost of constructing one unit of density is about 3.5 times the annual rental income.

3.3.2 Calibration of σ_i: Rent Implied Volatility

With cost levels established, we next calibrate the volatility of rents. Conditional on the baseline elasticities and parameters, we determine the rent volatility σ_i that aligns the model's predictions with observed housing production across markets. Specifically, we match the model's predicted number of housing units to the actual number constructed in each community district between 2010 and 2023, using data from NYC Planning to calibrate σ_j, the rent volatility in community district j. We fix parcel characteristics at their 2013 values and estimate σ_j by minimizing the difference between predicted and observed construction activity in each market j:

$$\arg\min_{\sigma_j} \left[\sum_{i \in j} \underbrace{\mathbf{E}_{2013}\left[\mathbf{P}_i(..., \sigma_j, \Theta | t = 10) F_i^*(..., \sigma_j, \Theta)\right]}_{\text{Model: expected units within 13 years}} - \underbrace{UnitsConstructed_j^{2013-2022}}_{\text{Data: observed units}} \right]. \tag{12}$$

We calibrate σ_j using the volatility implied by the model, analogous to the method introduced by Black and Scholes (1973) for option pricing and extended in (Dumas et al., 1998) to corporate securities. The resulting average implied volatility across community districts is 20.7%, with cross-market variation displayed in Panel D of Figure 2.

3.4 Calibration of Other Parameters

Construction Length (d) We calibrate the construction period using data from the DCP Housing Database Project-Level Files, measuring duration as the time from permit issuance

validity of counterfactuals.

to building completion. The sample is restricted to multi-family buildings developed by private for-profit firms, excluding outliers completed in less than three months or more than ten years. Our baseline calibration sets $d = 3.08$ years, the average duration between permit issuance and completion, capturing the interval during which developers incur costs but receive no positive cash flows.[19]

Risk-free Rate (r) We calibrate r using the average three-month yield on U.S. Treasury securities reported by the Board of Governors of the Federal Reserve System (FRED). Over the period from September 1981 to December 2023, the average yield is 3.79%, which we use as the model's risk-free rate.

Property Tax Rate (ψ) We compute the effective property tax rate on residential properties by combining multiple datasets. First, we link assessment data for multi-family properties from the Primary Land Use Tax Lot Output (PLUTO) with statutory tax rates (NYC Department of Finance) to calculate parcel-level tax bills since 2000. We then merge these tax bills with 36,000 transactions of multi-family properties from CoStar and derive effective tax rates by dividing tax bills by corresponding sale prices. Since 2000, the effective asset-based tax rate has averaged 1.34%, with an interquartile range of 0.56–1.80%. Because the model requires a tax rate on rental flows, we convert this asset-based rate into an income-based rate by dividing by the sample's average discount rate, yielding an effective tax on rental incomes of 16.30%. This conversion highlights how even modest asset-based property taxes translate into substantially higher effective tax burdens on rental income, with direct implications for development incentives.

4 Baseline Model Outcomes and Model Fit

Using the parameterization from the previous section, we compute key outcomes under the baseline scenario $\mathcal{P}_0 = \{\alpha = 0, \phi = 0, \tau = 0\}$, which serves as the benchmark for counterfactual policies. The baseline outcomes are:

1. $\mathbf{P}_i(\mathcal{P}_0; \Theta|t)$, the probability that parcel i is redeveloped within a t-year horizon;
2. $\pi_i(\mathcal{P}_0; \Theta)$, the parcel value including both current use and redevelopment option value;
3. $F_i^*(\mathcal{P}_0; \Theta)$, the optimal redevelopment density;
4. $\mathbf{Rent}_i(\mathcal{P}_0; \Theta|t)$, the expected rental income at horizon t.

[19] Discussions with developers suggest that building height has limited influence on construction time. Iconic projects such as the Empire State Building, completed in 1 year and 45 days, illustrate that factors other than scale often determine construction timelines.

The baseline scenario captures outcomes in the absence of policy interventions, and provides the reference point against which all counterfactuals are evaluated.

4.1 Aggregate Outcomes

We aggregate outcomes at the city and market level, focusing on two primary benchmarks at the 10-year horizon: the expected number of net additional housing units, $\mathbf{E}[AptNet_j|t = 10]$, and the expected rent per unit, $\mathbf{E}[Rent_j|t = 10]$. We also compute related measures including: the expected number of units $\mathbf{E}[Apt|t = 10]$, expected density $\mathbf{E}[Density|t = 10]$, the present value of all parcels Π, and the average share of option value $\mathbf{E}[Option|t = 10]$. Aggregated outcomes are defined as

$$\begin{aligned}
\mathbf{E}[Apt_j|\mathcal{P}_0, t = 10] &= \sum_{i \in j} \mathbf{P}_i(\mathcal{P}_0; \Theta|t = 10) F_i^*(\mathcal{P}_0; \Theta) + (1 - \mathbf{P}_i(\mathcal{P}_0; \Theta|t = 10))\, F_i \\
\mathbf{E}[AptNet_j|\mathcal{P}_0, t = 10] &= \sum_{i \in j} \mathbf{P}_i(\mathcal{P}_0; \Theta|t = 10)(F_i^*(\mathcal{P}_0; \Theta) - F_i) \\
\mathbf{E}[Rent_j|\mathcal{P}_0, t = 10] &= \frac{\sum_{i \in j} \mathbf{Rent}_i(\mathcal{P}_0; \Theta|t)}{\mathbf{E}[Apt_j|\mathcal{P}_0]} \\
\mathbf{E}[Density_j|\mathcal{P}_0, t = 10] &= \frac{1}{n_j} \sum_{i \in j} \mathbf{P}_i(\mathcal{P}_0; \Theta|t = 10) F_i^*(\mathcal{P}_0; \Theta) + (1 - \mathbf{P}_i(\mathcal{P}_0; \Theta|t = 10))\, F_i \\
\mathbf{E}[\Pi_j|\mathcal{P}_0] &= \sum_{i \in j} \pi_i(\mathcal{P}_0; \Theta) \\
\mathbf{E}[Option_j|\mathcal{P}_0, t = 10] &= \frac{\sum_{i \in j} \tilde{\pi}_i(\mathcal{P}_0; \Theta)}{\sum_{i \in j} \pi_i(\mathcal{P}_0; \Theta)}.
\end{aligned} \tag{13}$$

where $\tilde{\pi}_i(\mathcal{P}_0; \Theta)$ is the redevelopment option value. Together, these aggregates summarize supply, rents, and asset values, providing the key metrics through which we evaluate counterfactual policy scenarios.

4.2 Baseline Results

Baseline Citywide Outcomes: Table 4 (first row) reports the citywide aggregates under the baseline scenario. The model projects construction of 193,587 housing units over ten years, consistent with New York City's historical production of 10,000–28,000 units annually since 2010 (NYC housing production). After accounting for demolitions, net new construction is 129,837 units. Panel A of Figure 3 shows the spatial distribution of new housing, concentrated in Brooklyn and Queens along the East River and in Manhattan's Chelsea and Hudson Yards, reflecting sustained demand in these neighborhoods. Citywide expected rent rises from $2,001

to $3,050 per unit per month at the 10-year horizon. This increase reflects three components: (1) an additional discount from another decade of depreciation on non-redeveloped properties; (2) replacement effects, $\Gamma(\cdot)$, whereby older depreciated units are substituted with newer construction that commands higher rents; and (3) expected rental growth, g_i, which shifts $\mathbf{E}[R_i]$.[20]

Density, Asset Valuation, and Option Value. At the 10-year horizon, average residential density rises to 2.83 units per 2,500 square feet of land. As expected, density declines with distance from central Manhattan, consistent with the classical urban model (Alonso, 1964; Mills, 1967; Muth, 1969). The model values New York City's residential assets at $1,099 billion, closely matching the Department of Finance's reported valuation (Tax Lot Assessment Portal) despite our focus on non-residential parcels. The redevelopment option accounts for 5.8% of total residential asset value, a relatively low share, reflecting that most parcels are already developed. Panel D of Figure A3 shows that the option share rises to 20% in neighborhoods with substantial redevelopment potential, such as Long Island City in Queens or aging stock in the Bronx.

Parcel-Level Heterogeneity. Parcel heterogeneity shapes redevelopment dynamics. Panels B and C of Figure 3 show the average development probability by (i) current built space (Panel B) and (ii) potential rent (Panel C).[21] In Panel B, the probability of redevelopment rises with building age (depreciation lowers the value of current cash flows, increasing redevelopment incentives) and with unused capacity (the gap between maximum and built FAR). At the same time, higher existing density raises the opportunity cost of redevelopment, delaying investment. Panel C shows that parcels with higher potential rents (R_i) and stronger rent growth g_i face higher redevelopment probabilities.

External Validation. Finally, we validate the model against observed property transactions. For each community district, we compute the average model-implied price per unit, $1/n_j \sum_{i \in j} (\pi_i(\mathcal{P}_0; \Theta)/F_i)$. Figure 4 compares these predictions to the average price per unit of multi-family transactions from CoStar between 2010 and 2024. The correlation is 0.90, indicating that the calibration closely tracks market valuations, thus providing a credible basis for policy counterfactuals.

[20] In the baseline scenario, g_i does not vary with future expected supply, $g_i^S(\mathcal{P}_0) = g_i$, because the calibrated growth rate already incorporates developers' expectations under the status quo.

[21] Table A2 reports conditional partial correlations between parcel characteristics and model outputs, showing that built space is a key determinant of both the probability and intensity of redevelopment.

4.3 Robustness to Underlying Parameters

In the remaining panels of Table 4, we assess the sensitivity of aggregate outcomes to alternative elasticity assumptions, highlighting how the model traces the trade-off between development costs and returns. In these scenarios we do not endogenize developers' expectations about future supply. The objective is to illustrate how outcomes vary with parameter changes, not to evaluate a counterfactual where one parameter shifts exogenously. Expected rents, however, do adjust to anticipated future supply and feed back into R_i.

Sensitivity to Elasticity Assumptions. Shorter construction durations raise expected apartment production, density, and property values by increasing the value of the redevelopment option. In contrast, higher height elasticity in construction costs sharply reduces new development and lowers option values, underscoring the central role of construction technology in shaping urban outcomes (Ahlfeldt et al., 2023). Higher returns to height and faster rental depreciation both stimulate redevelopment, but through distinct mechanisms. Greater returns to height increase the payoff (value) from new projects, while depreciation erodes the value of existing assets, making redevelopment more attractive. Together, these channels demonstrate how both technological progress and aging assets shape citywide supply and valuations.

Alternative Model Assumptions. The final panel of Table 4 reports baseline outcomes under alternative model assumptions. The second row indicates that when developers are required to build at allowable density (i.e., not optimizing F), aggregate outcomes remain essentially unchanged. This result reflects the fact that in New York City, zoning regulations are often binding (Brueckner et al., 2024), so developers tend to build up to the regulatory limit. In contrast, when density is unconstrained, construction activity rises by an order of magnitude. Under this benchmark, average rents fall to $2,330, indicating that supply effects become strong enough to offset the replacement effect observed in the baseline.

5 Policy Counterfactuals

We quantify the impact of policy instruments on urban development by comparing outcomes to the baseline without intervention. A central preview is that while policies expand supply or add affordable units, they rarely reduce rents. New construction typically replaces older, cheaper stock. The higher rents on new units outweigh the downward pressure from additional supply. As a result, affordability gains arise only at someone's expense—either the average market-rate tenant, through higher rents (cross-subsidization), or taxpayers, through

reduced fiscal revenues.

To compute counterfactuals, each parcel is parameterized as in Section 3, using the estimates in Table 2 unless otherwise noted. Policy interventions modify the regulatory framework at $t = 0$, shifting from the baseline environment $\mathcal{P}_0$ to $\mathcal{P} = \{\alpha \geq 0, \phi \geq 0, \tau \geq 0\}$. Deviations from baseline outcomes are denoted Δ. For example, the market-level change in net units under policy $\mathcal{P}$ is

$$\begin{aligned}\Delta\mathbf{E}[AptNet_j \quad | \quad & \mathcal{P}, t = 10] \\ = \quad & \mathbf{E}[AptNet_j|\mathcal{P}, t = 10] - \mathbf{E}[AptNet_j|\mathcal{P}_0, t = 10] \\ = \quad & \sum_{i \in j} \mathbf{P}_i(\mathcal{P}; \Theta|t = 10)(F_i^*(\mathcal{P}; \Theta) - F_i) - \sum_{i \in j} \mathbf{P}_i(\mathcal{P}_0; \Theta|t = 10)(F_i^*(\mathcal{P}_0; \Theta) - F_i)\end{aligned}$$

All counterfactual outcomes are expressed as deviations from baseline, with monetary measures reported in percentage changes. One additional measure, absent from the baseline, is the expected number of affordable units: $\Delta\mathbf{E}[\text{Aff}_j|\mathcal{P}, t = 10] = \mathbf{E}[\text{Aff}_j|\mathcal{P}, t = 10]$, since $\mathbf{E}[\text{Aff}_j|\mathcal{P}_0, t = 10] = 0$ when $\alpha = 0$.

Alongside total and affordable units, we also evaluate policy costs including changes in development density, the present value of tax revenues, and the aggregate value of residential assets. The last measure is salient because large swings may create political risks, either from residents if values rise too sharply or from developers if values fall. Explicitly quantifying these fiscal costs lies outside the scope of this study, but they remain an important dimension of policy evaluation.

5.1 Policy Counterfactuals: Benefits and Costs

Figure 5 summarizes the counterfactuals, highlighting the trade-offs across policies. Panel A reports benefits, measured as expected changes in affordable and market-rate housing. Panel B reports costs, measured as changes in density and tax revenues.

We evaluate six interventions: (1) upzoning, which increases allowable density; (2) tax exemptions, which provide fiscal incentives for development; (3) affordability mandates, which require a share of units to be affordable; (4) incentive zoning, which combines mandates with density bonuses; (5) fiscal incentives, which pair mandates with tax exemptions; and (6) combined incentives, which incorporate all three tools. Sections 5.3 and 5.4 provide detailed descriptions of these policy designs.

5.1.1 Panel A: Housing Production

An optimal affordability policy expands the supply of affordable units while minimizing adverse effects on market-rate production. In Figure 5 , the red 45-degree line marks this benchmark: movements to the right indicate stronger affordability gains. By construction, movement along the frontier reflects substitution, as affordable units displace market-rate units.

The results reveal substantial heterogeneity across policy interventions. Upzoning (Policy [1]) produces the largest gain in market-rate housing and the largest density increase but moves away from the affordability objective. Tax exemptions of 20 years (Policy [2]) also expand overall supply although primarily in the market-rate segment. An affordability mandate (Policy [3]) directly shifts production toward affordable units but suppresses total supply. Incentive zoning (Policy [4]) combines mandates with density bonuses, producing affordable units while keeping overall supply roughly constant. Fiscal incentives (Policy [5]), which pairs mandates with exemptions, raise affordable supply but reduce overall production. The combined package (Policy [6]) delivers the most affordable units while still expanding supply relative to the baseline.

5.1.2 Panel B: Costs of Policy Interventions

Panel B of Figure 5 captures fiscal and density costs of each policy intervention. The two dimensions are (i) fiscal burden, measured by changes in expected tax revenues (y-axis), and (ii) density increases (x-axis).[22] Policies near the origin are cost-neutral, minimizing both fiscal losses and density pressures.

The variation across policies is substantial. Upzoning (Policy [1]) produces major density increases with little fiscal effect, expanding supply but straining infrastructure. Tax exemptions (Policy [2]) sharply reduce tax revenues while moderately increasing density. Affordability mandates (Policy [3]) reduce both density and revenues. Incentive zoning (Policy [4]) raises density but keeps revenue losses contained. Fiscal incentives (Policy [5]) impose the steepest revenue losses with limited density impact, relying on sustained public subsidy. The combined policy (Policy [6]) imposes the highest cost on both dimensions, cutting revenues and raising density.

These results underscore the trade-offs policymakers face in choosing among zoning and

[22]Higher density raises demand for infrastructure and services, including roads, transit, utilities, schools, and emergency response. It also increases congestion, environmental strain, and maintenance costs. These considerations frame the cost side of density-enhancing policies.

fiscal instruments. Upzoning (Policy [1]) expands market-rate supply at low fiscal cost but fails to address affordability. Incentive-based approaches (Policies [4] and [5]) deliver affordability gains but do so at the expense of either forgone revenues or density pressures. A combined package (Policy [6]) achieves the strongest affordability outcomes yet only by imposing the highest cost across both fiscal and density margins. Policy choice, therefore, depends on how jurisdictions balance affordability objectives against fiscal sustainability and infrastructure capacity.

5.2 Change in Expected Rent and Its Decomposition

Figure 6 reports the change in citywide expected rent relative to baseline. Most policies modestly increase rents. The one exception is fiscal incentive zoning, which slightly reduces rents (–0.5%) but only at the cost of steep fiscal losses (–10% of tax revenues, Panel B of Figure 5). Here, density rises only marginally and a share α of each building is allocated to affordable units. This limits replacement effects but does not deliver long-run affordability gains.

By contrast, the largest rent increases occur under policies that add the most housing: upzoning (Policy [1]) and the combined package (Policy [6]), which raise expected rents by 2.15% and 1.42% over baseline, respectively. To interpret these patterns, we decompose rent changes into three channels: (i)affordable share effect: shifts in average rent due to inclusion of below-market units; (ii) supply effect: downward pressure from additional units in the neighborhood; and (iii) replacement effect: the upward pressure from replacing older, lower-rent stock with new, higher-rent units.

Across policies, replacement effects dominate supply effects. Under upzoning, expected rent rises by about $100 per unit per month from replacement, while supply expansion lowers rent by about $30. Adding a mandate (Policy [4]) moderates the increase but only modestly. Redevelopment is concentrated on depreciated parcels, where new construction replaces older low-rent units with higher-quality stock, and on high-quality sites, where added height and density push rents above their pre-redevelopment baseline. Stronger mandates dampen these pressures but also deter redevelopment when α is large. As a result, aside from fiscal incentive zoning, only very large density increases ($\phi > 10$) succeed in lowering expected rents.

5.3 Unilateral Policies

Panel A of Table 5 reports the effects of three standalone interventions: a 25% density bonus (upzoning), a 20-year tax exemption, and a 30% affordability mandate. Upzoning ex-

pands supply the most, adding 70,300 net new units but generating no affordable housing. An affordability mandate of 30% creates 51,075 affordable units but reduces the supply of market-rate units by 61,828, leaving total supply unchanged. Tax exemptions stimulate development more moderately, adding 40,738 net new units.

From a cost perspective, the patterns differ. Upzoning raises both density and tax revenues. The affordability mandate keeps density nearly unchanged (–0.5%) but reallocates supply from market-rate units to affordable units. Tax exemptions impose the steepest fiscal burden, reducing tax revenues by 10.9%.

5.4 Mandatory Carrot & Stick Zoning

Panel B of Table 5 reports outcomes for policies that combine affordability mandates with zoning or fiscal incentives. We compare three approaches: Density Incentive Zoning (mandate plus density bonus), Fiscal Incentive Zoning (mandate plus tax exemption), and the Combined Incentive Policy (mandate, bonus, and exemption). These *Carrot & Stick Zoning* policies are designed to mitigate the trade-offs of standalone tools.

The largest affordability gains come from the Combined Incentive Policy, which generates 114,130 affordable units compared to 79,934 under Density Incentive Zoning and 72,043 under Fiscal Incentive Zoning. Density Incentive Zoning reallocates production, reducing market-rate housing by 27,247 units relative to baseline. Fiscal Incentive Zoning produces sharper supply losses with 44,990 fewer market-rate units and large revenue reductions. In contrast, the Combined Policy modestly expands market-rate housing (+1,267 units) despite the mandate, although it carries the largest fiscal and density costs.

Figure A4 highlights spatial heterogeneity in these outcomes. While mandates reduce overall housing production citywide, the distribution of impacts vary by policy. Neighborhoods with parcels near redevelopment thresholds, such as the Bronx, respond more to fiscal incentives, while high-value areas like Western Queens and Brooklyn respond more strongly to zoning relaxations. These patterns underscore that uniform policies yield uneven spatial outcomes, reinforcing the importance of tailoring interventions to local market conditions.

5.5 Voluntary Carrot & Stick Zoning

Panel C of Table 5 reports outcomes for voluntary versions of the Carrot & Stick policies. In this regime, developers adopt policy $\mathcal{P}$ only if it raises property value relative to the baseline, i.e., if $\pi_i(\mathcal{P}) \geq \pi_i(\mathcal{P}_0)$. Participation, therefore, occurs only for parcels where

incentives outweigh the regulatory burden, effectively self-targeting affordability subsidies to viable projects. By construction, voluntary adoption avoids the inefficiencies of blanket mandates and better aligns developer incentives with affordability objectives. These policies deliver affordability gains where they are most cost-effective, while minimizing unintended reductions in supply or asset values elsewhere.

5.6 Synthesis and Implications of Counterfactuals

The counterfactuals highlight a central affordability puzzle: even substantial policy interventions rarely reduce average rents. Affordability gains emerge only with offsetting costs. In a framework where developers act rationally, new construction occurs only when profitable, shifting the composition of the housing stock toward newer, higher-rent units. This replacement does not imply a direct welfare loss for tenants, since higher rents reflect higher-quality housing, but it does constrain the ability of policies to lower average rents.

By contrast, the fiscal costs of affordability policies are clear. Tax exemptions erode revenues, density increases strain infrastructure, and mandates or incentive zoning expand affordable supply only by crowding out market-rate production. The one exception is Fiscal Incentive Zoning, where rents fall modestly, but only at the cost of steep revenue losses. Removing height limits could, in principle, deliver larger rent reductions, but at the price of unsustainable infrastructure demands.

6 Conclusion

Our analysis helps explain why affordability pressures persist despite active zoning and fiscal interventions. In a world of lumpy and time-consuming redevelopment, policies that aim at stimulating development operate through developers' rational decisions rules on the timing and intensity of development. As a result, new construction primarily replaces older, depreciated units with higher-quality stock. This replacement channel often dominates the downward price effect of added units, so most policy designs expand supply without reducing average rents. For renters, new supply rarely lowers costs absent mandates or subsidies; for developers, decisions hinge on profitability thresholds; and for governments, securing affordability typically trades off with fiscal capacity or infrastructure.

Embedding *carrots* (density bonuses, tax exemptions) and *sticks* (affordability mandates) directly in developers' timing and density choices clarifies the mechanisms at work. Tax exemptions raise redevelopment probabilities. Density bonuses increase project size and can

delay timing if very large. And affordable mandates shift the composition toward affordable units while dampening overall production. Because development decisions depend on location, the current asset, and costs, effects are spatially heterogeneous. Parcels near expansion barriers respond most to incentives, while high-amenity locations benefit disproportionately from upzoning. Citywide policies, therefore, carry uneven neighborhood impacts, fiscal trade-offs, and distributional consequences across stakeholders.

Calibrated to New York City, the model matches observed production and prices and yields two lessons. First, affordability depends on the composition of the housing stock, not only the number of units. Redevelopment increases supply but replaces older, cheaper units with new construction, so average rents can rise even as more housing is built. This effect is compounded by the heterogeneity of the existing built environment, which amplifies differences in how policies shape outcomes across neighborhoods. Second, policy packages must be priced: upzoning strains infrastructure, exemptions erode the tax base, and mandates reduce market-rate output even as they add affordable units.

The broader implication is that durable, heterogeneous urban assets transmit policy through timing, quality, and location, creating trade-offs that are unavoidable but manageable. Effective strategies pair calibrated incentives with infrastructure funding, recognize neighborhood heterogeneity, and evaluate success on distributional margins—who is built for, where, and at what fiscal price—rather than on citywide averages. Although our calibration centers on New York City, the framework generalizes across contexts, from large high-demand markets to smaller cities where supply shocks quickly dampen rent growth, and it applies to both new construction and redevelopment. Ultimately, the model clarifies not only the trade-offs policymakers face, but also how the competing interests of renters seeking affordability, developers requiring profitability, and governments balancing fiscal and infrastructural limits shape the feasibility and distributional consequences of housing policy.

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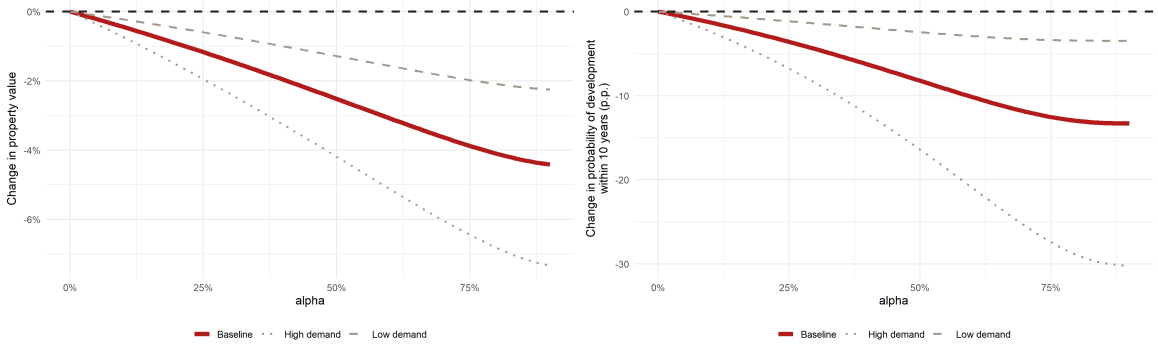
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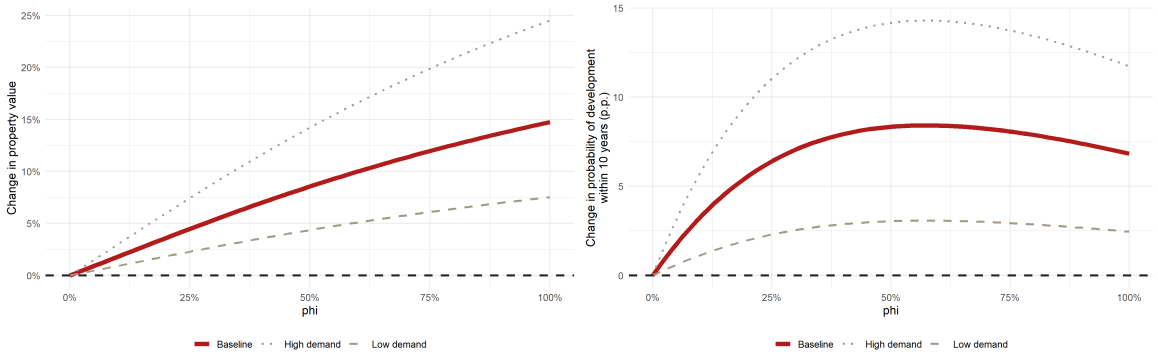
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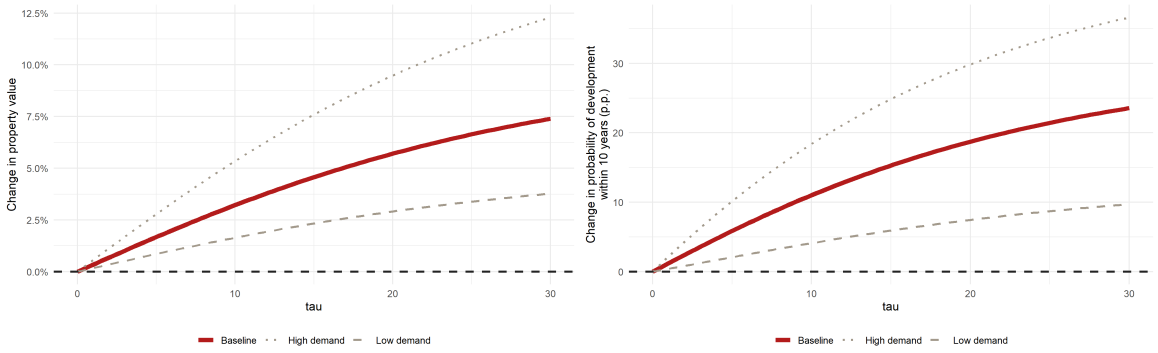
Figure 1: Property value and development probability with respect to policy instruments



A. Mandatory share for public goods (α)



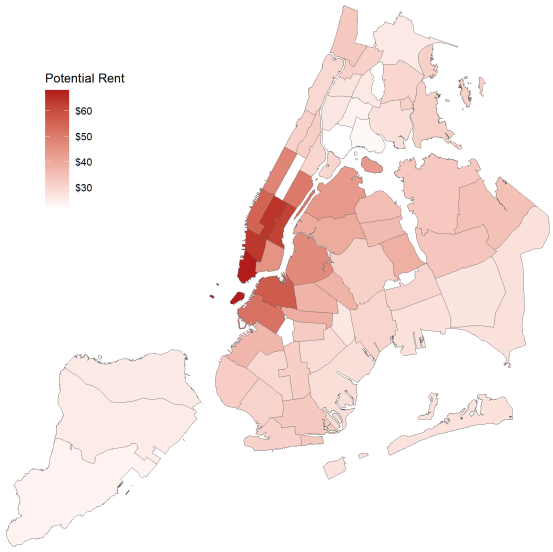
B. Density Bonuses (ϕ)



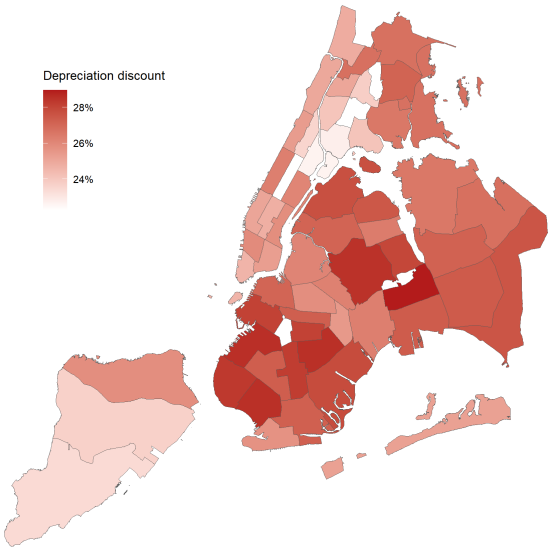
C. Length of Tax Exemptions (τ)

Note: These figures show the effects of changing the policy instruments on the change in the property value (left panels) and the change in the probability of development starting within 10 years (right panels). These figures are obtained for a parcel of land built at 40% of its capacity with $F_0 = 2$ and $\bar{F} = 5$. The other parameters are shown in Table 2 or the mean values of parcel level data shown in 3.

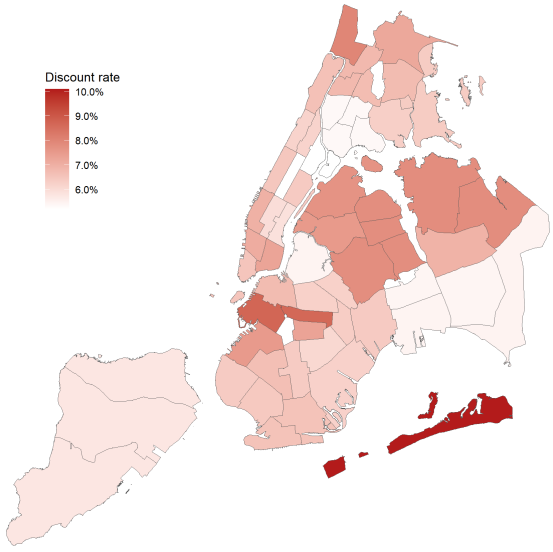
Figure 2: Spatial variations of key variables



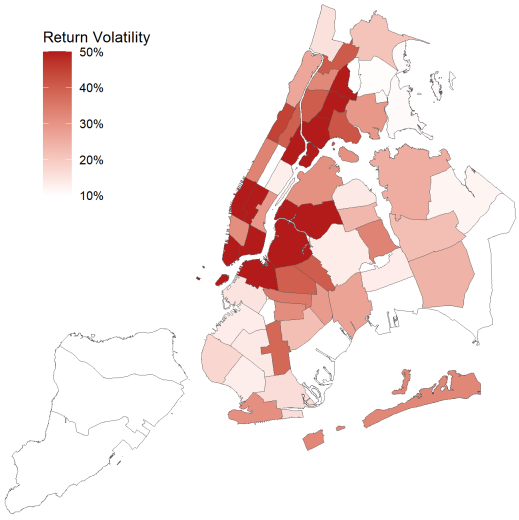
A. Potential Rent per Unit (R_i)



B. Rental Depreciation Rate (z_i)



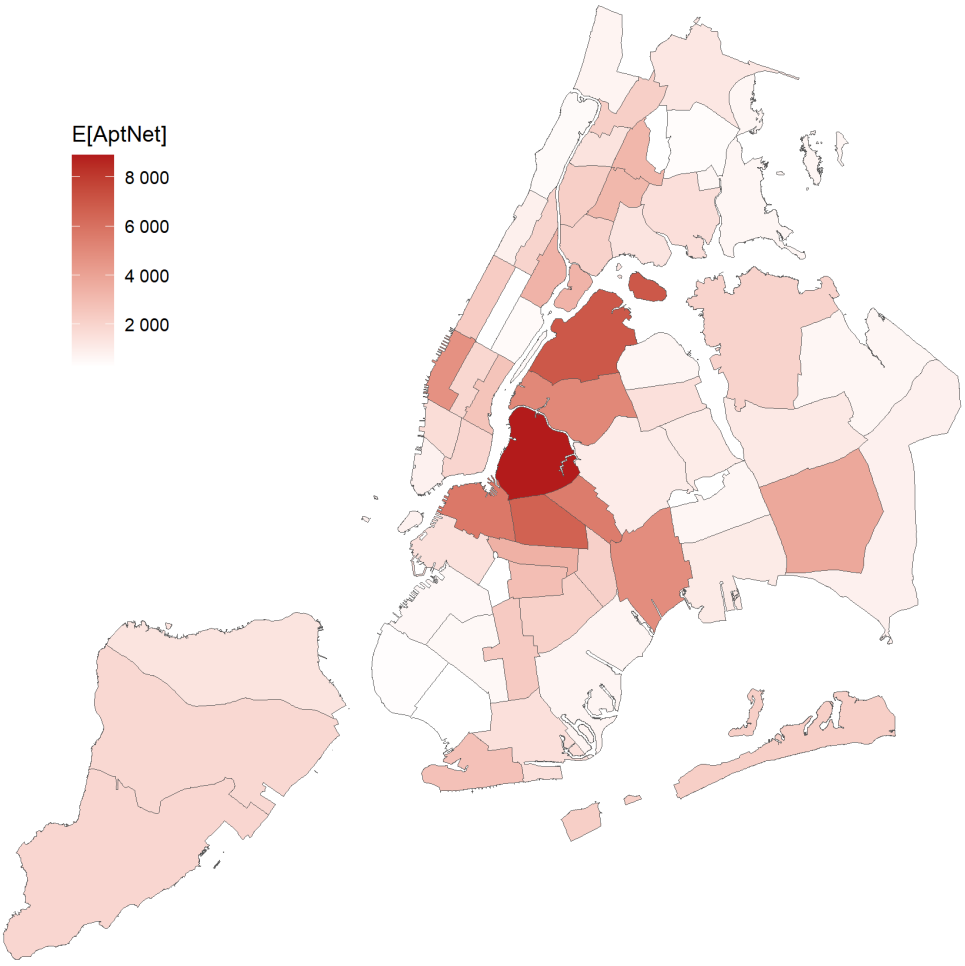
C. Physical Discount Rate ($\tilde{\delta}_i$)



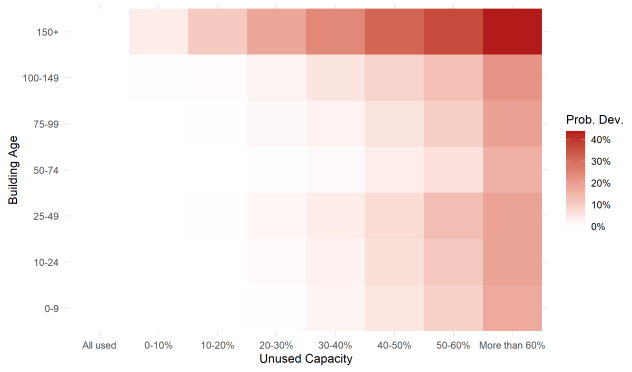
D. Rent Growth Volatility (σ_i)

Note: These maps show the average across all parcels of each community district of key parameters of the calibration. Panel A shows the potential rent per unit of density R_i that reflects market-rate rents for one non-obsolete unit, obtained by adjusting the annual rent for the average age and size of buildings within each neighborhood. Panel B shows the average discount due to the aging of properties z_i. Panel C shows the physical discount rate $\tilde{\delta}_i$ that is computed as the sum of the cap rate and rent growth collected through Costar. Panel D shows the volatility of rent growth calibrated to match observed construction activity across New York City's community districts.

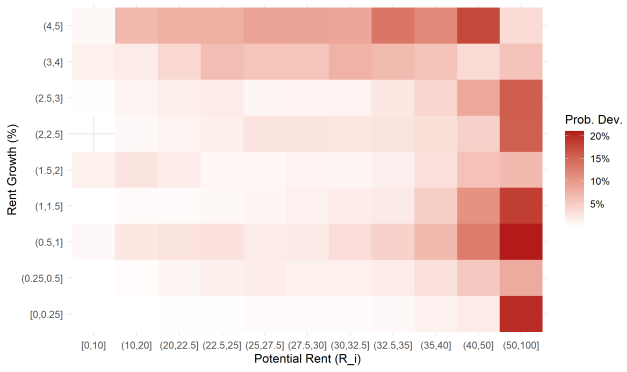
Figure 3: New Supply Expectations and Determinants of Probability of Development



A. Expected Net Additions



B. Built Environment



C. Rental Potential

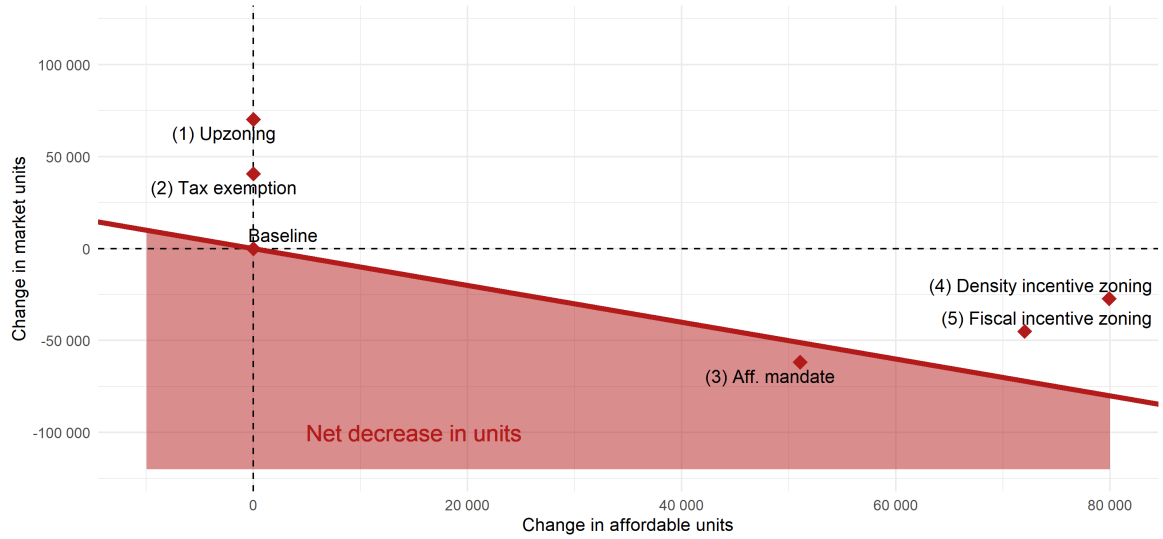
Note: Panel A shows shows the expected number of apartments constructed minus expected demolished units in each community district within a 10-year horizon, $E[AptNet_j|\mathcal{P}_0] = \sum_{i \in j} \mathbf{P}_i^{dev}(\mathcal{P}_0, \Theta | t = 10)(F_i^*(\mathcal{P}_0, \Theta) - F_i)$ *using the model baseline calibration with parameters described in Table 2. The bottom panels show the unconditional average probability of development computed for each grid cell. Panel B splits cells into deciles based on the current density* (F_i) *and the current age of the building* (age_i)*. Panel C splits cells into deciles based on the potential rent* (R_i) *and the current growth rate* (g_i)*.*

Figure 4: Model Fit

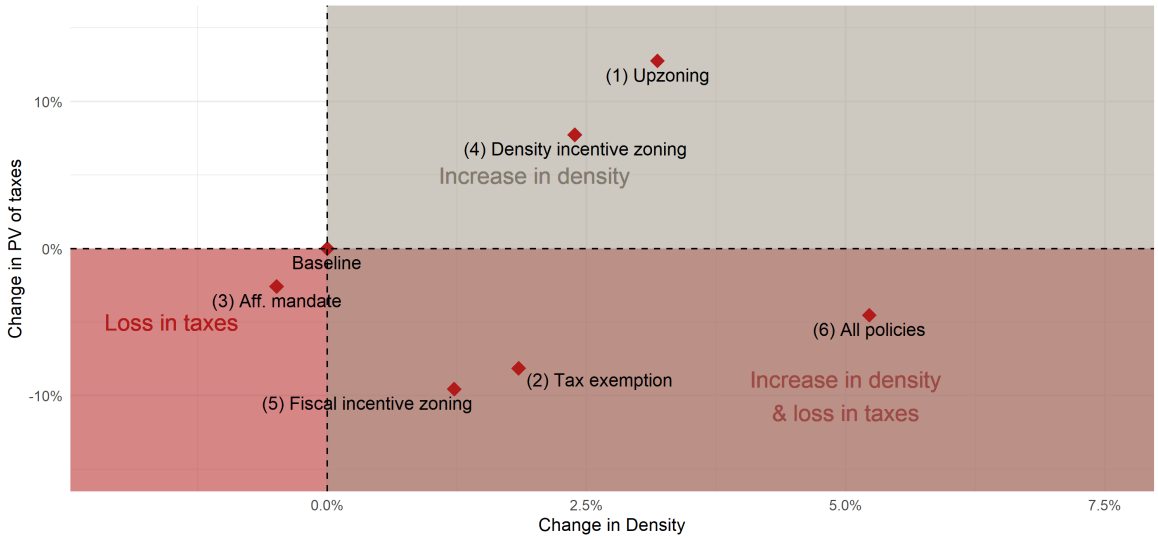


Note: This scatter plot shows the relationship between the log of the model's mean price per unit of density $\sum \pi_i / F_i(.)$ *in each NYC community district against the log of the unconditional mean price per apartments of Multi-Family buildings using transaction from CoStar since 2010. .*

Figure 5: Summary of Policy Counterfactuals Benefits and Costs



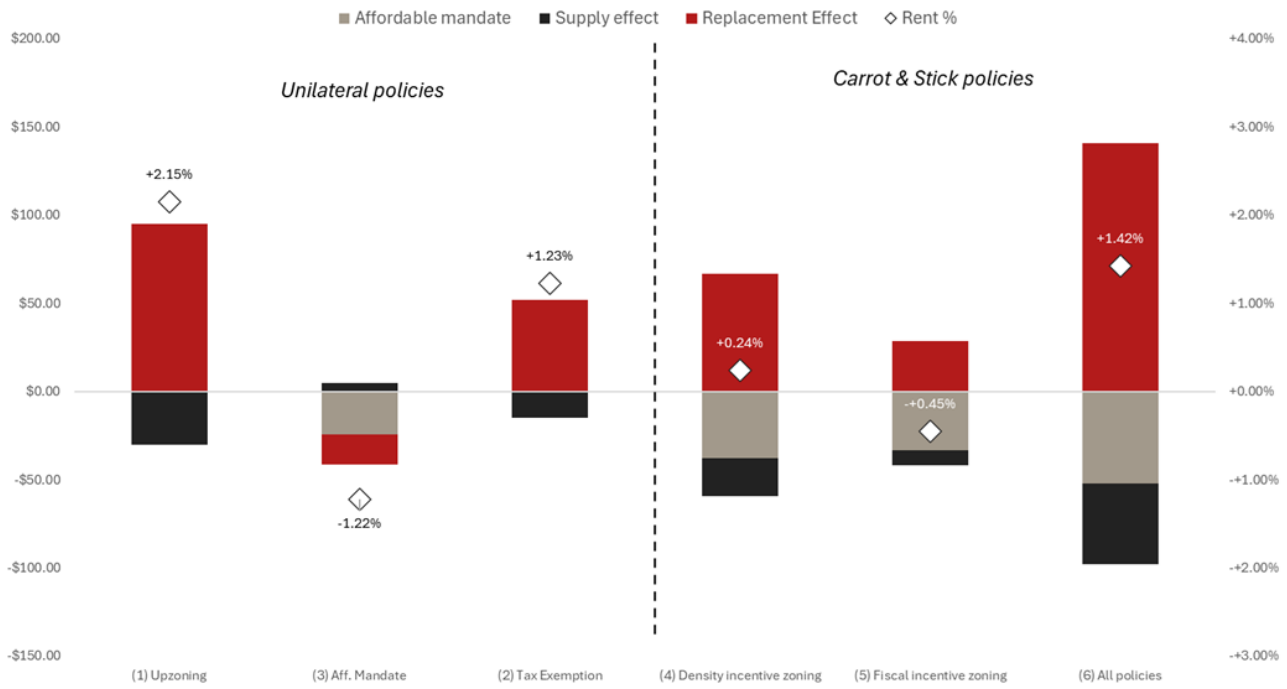
A. Benefits – Housing Production



B. Costs – Public Expenses

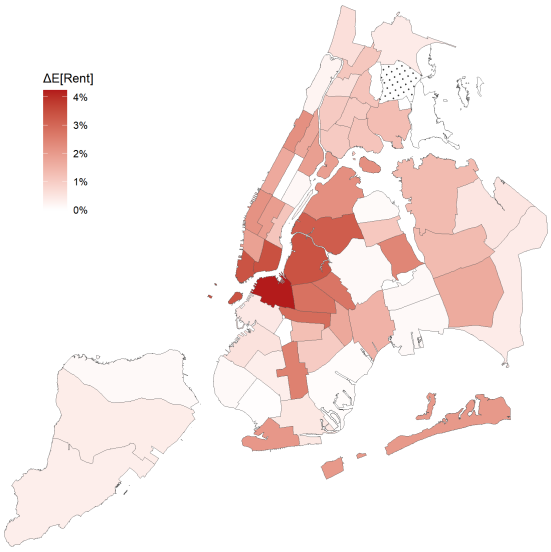
Note: This chart summarizes the policy counterfactual results. Panel A shows the expected change in affordable (x-axis) and market-rent units (y-axis). Panel B shows the expected additional costs for the city, including the change in density (x-axis) and the change in expected tax revenue (y-axis). Policy (1) Upzoning corresponds to an increase in allowable density of 25%, Polity (2) Tax exemption corresponds to a 20-year property tax exemption, and Policy (3) corresponds to a 30% affordability mandate. Policies (4), (5), and (6) are combinations of these. All of these counterfactuals are computed above the baseline scenario over a 10-year horizon.

Figure 6: Counterfactual Policies and Decomposition of Average Expected Rent

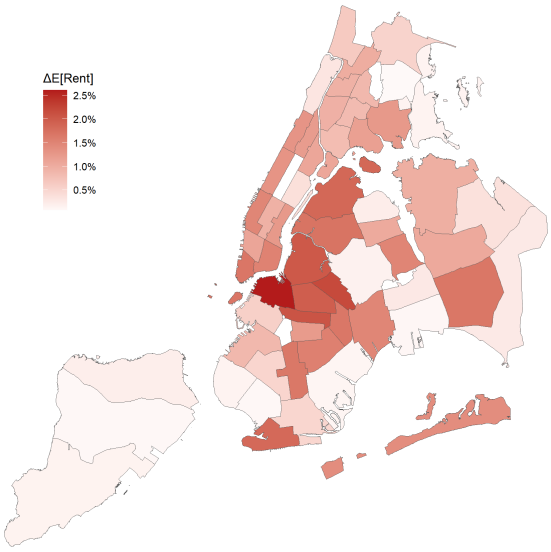


Note: The points shows the average expected rent change from policy counterfactuals compared to the baseline expectation at horizon 10 years which is then decomposed into three elements in the bar graphs. The textitAffordable mandate contribution is computed by removing the effect of α in the determination of rental income, though keeping the expected construction activity unchanged. The Supply effect *is computed as the difference between rent if the additional supply add no effects on market rents. The* Replacement Effects *is the difference between average rent changes and the former two components and represents the effects of the change in built space (from old obsolete to newer units) on average rents. Policy (1) Upzoning corresponds to an increase in allowable density of 25%, Polity (2) Tax exemption corresponds to a 20-year property tax exemption, and Policy (3) corresponds to a 25% affordability mandate. Policies (4), (5), and (6) are combinations of these. All of these counterfactuals are computed above the baseline scenario over a 10-year horizon.*

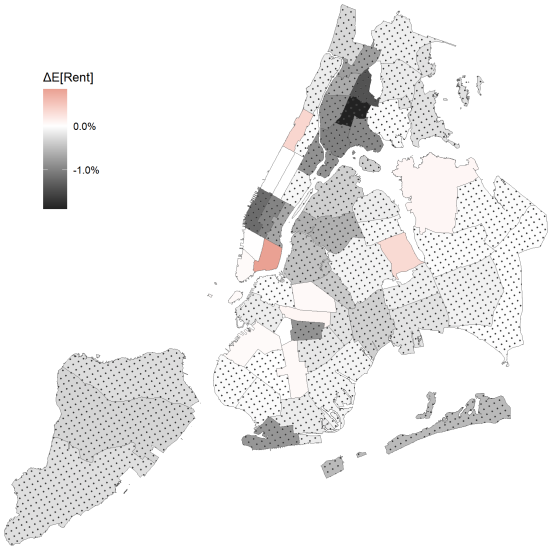
Figure 7: Counterfactuals – Change in Expected Average Rent



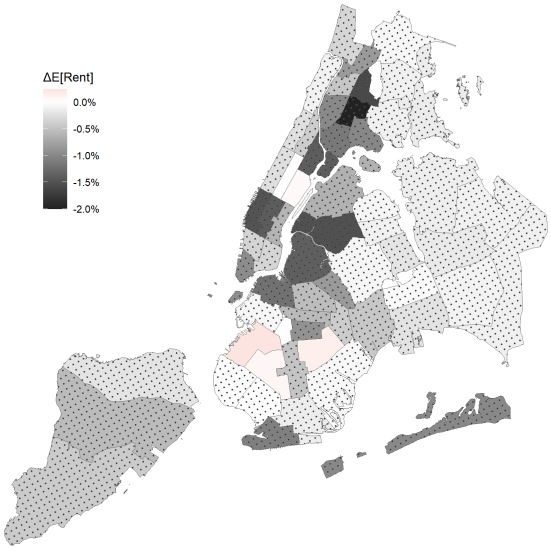
A. Upzoning ($\phi = .25$)



B. Tax Exemptions ($\tau = 20$)



C. Density Incentive Zoning ($\alpha = 0.3$ & $\phi = .25$)



D. Fiscal Incentive Zoning ($\alpha = 0.3$ & $\tau = 20$)

Note: These maps show the percentage change in average expected rent per unit for different counterfactual policy analyses. It shows for each community district the change compared to the baseline outcomes with horizon 10-year.

Table 1: Parcel Level Comparative Statics and Sensitivity Analyses

This table reports the change in property value and the change in the probability of development within 10 years with respect to the policy instruments obtained for a parcel of land built at 40% of its capacity with $F_0 = 2$ and $\bar{F} = 5$. All other parameters and elasticities are either shown in Table 2 or the mean values of parcel level data shown in 3..

	Change in Property Value (%)	Change in Prob. Dev. (p.p.)
Mandating 20% of Affordable Housing ($\alpha = 0.20$)		
Baseline	-0.83	-0.98
Parcel closer to redevelopment ($F_0 = F_0/2$ and $age = 2age$)	-2.40	-1.16
Higher potential rent ($R = 2R$)	-2.09	-4.80
Higher affordable rental discount ($\epsilon_\alpha = 2\epsilon_\alpha$)	-1.73	-2.26
Higher affordable construction discount ($\eta_\alpha = 2\eta_\alpha$)	-0.59	-0.36
Increase Maximum Allowed Density by 50% ($\phi = 0.50$)		
Baseline	8.55	3.58
Parcel closer to redevelopment ($F_0 = F_0/2$ and $age = 2age$)	14.33	-5.50
Higher potential rent ($R = 2R$)	21.62	14.57
Higher value from height ($\epsilon_F = 1.5\epsilon_F$)	10.45	4.66
Higher cost from height ($\eta_F = 1.5\eta_F$)	3.27	0.13
20-years Property Tax Exemption ($\tau = 20$)		
Baseline	4.04	6.34
Parcel closer to redevelopment ($F_0 = F_0/2$ and $age = 2age$)	13.53	11.19
Higher potential rent ($R = 2R$)	10.21	23.75
Higher property tax rate ($\psi = 1.5\psi$)	6.56	9.12

Table 2: Baseline Model Elasticities and Parameters

This table reports the non-parcel specific baseline parameters of the vector Θ. The sources, calibrations, and estimations are detailed in Sections 3.

Parameters	Description	Value	Methods & main sources
	The Rental Scaling function		
ε_F	Density elasticity of rent	0.07	Calibration – Literature
ε_z	Age elasticity of rent	-0.078	Estimation – Table A1
ε_α	Non-market units rental discount	$\{0.25; 0.50; 0.75\}$	Calibration – Literature
	The demolition cost function		
η_D	Demolition cost elasticity of density	0.774	Target: Fixed cost demolition (55%)
k_d	Baseline demolition cost per density unit	15.20	Target: Share of development cost (15%)
	The construction cost function		
η_F	Density elasticity of construction cost	0.60	Calibration – Literature
η_α	Affordable housing construction cost discount	0.20	Calibration - RCLO report
k_c	Baseline construction cost per density unit	113.04	Target: Land-value ratio (25.26%)
	Others		
ψ	Real estate tax rate (% of rental income)	16.30	Estimation - DoF & Costar
d	Construction periods (years)	3.08	Estimation – DCP
r	Risk free rate (%)	3.79	Estimation – FED
ς	Supply elasticity of rent	-0.10	Calibration – Literature

Table 3: Summary statistics of lot levels data

This table presents summary statistics for the 781,226 parcels included in the baseline analysis. Annual rent per unit is derived from the 2023 ACS 5-Year at the census block level, interpolated to individual parcels, and normalized by the average unit size. Potential rent reflects market-rate rents for one non-obsolete unit, obtained by adjusting the rent for the average age and size of buildings within each neighborhood. Normalized built FAR and maximum FAR are expressed on a per-unit basis on a parcel size of 2,500 square feet. The Empty indicator equals one for parcels with no existing construction. Age measures the number of years since the last recorded renovation or construction. Obsolescence captures the depreciation in market-rate rent due to property aging. Caprate and rent growth are sourced from Costar, following their definitions for NYC residential markets. The discount rate is the sum of the cap rate and rent growth, and the volatility of rent growth is calibrated to match observed construction activity across New York City's community districts.

Inputs	Mean	St. Dev.	Min	Median	Max
Annual rent per unit (th. $)	24.119	7.678	4.163	22.679	82.775
Potential rent per unit – R_i	31.776	9.017	5.624	30.280	99.427
Normalized built FAR – F_i	2.660	3.268	0.000	1.738	191.226
Normalized max FAR – $\bar{F}_i$	3.661	4.057	0.837	2.120	191.226
Empty indicator	0.029	0.168	0	0	1
Age (years)	72.891	36.717	0	84	302
Obsolescence – z_i	0.733	0.062	0.641	0.707	1.000
Caprate (%) – $r - \delta_i$	0.053	0.003	0.042	0.052	0.062
Rent Growth (%)	0.012	0.012	-0.006	0.009	0.048
Discount rate (%)	0.066	0.011	0.045	0.063	0.101
Volatility of rental growth (%) – σ_i	0.207	0.117	0.100	0.150	0.500

Table 4: Baseline Calibration Outcomes and Robustness to Parameter Change

This table reports the aggregate outcomes of our baseline calibration and additional sensitivity analyses performed by varying model's parameter assumptions. Column (1) shows the 10-year horizon expected number of units constructed (or under construction), Column (2) shows expected net unit addition, Column (3) shows the expected monthly rent, Column (4) shows the expected density in 10 years, Columns (5) and (6) shows the present value of the property taxes and of the parcels, and Column (7) shows the average value of the redevelopment option. The first line shows the results using the baseline calibration described in Table 2, and the other lines show the same outcomes by varying one of the underlying model assumptions or parameters as described. The "No development" scenario imposes an infinite cost to redevelopment.

	$E[Units]$ # of Apt.	$E[unitsNet]$ # of Apt	$E[Rent]$ $ per month	$E[Density]$ Units per parcel	PV(taxes) ($billion)	PV ($billion)	Option Value (%)
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Baseline	193,001	129,253	3,050	2.83	239.61	1,098.84	5.84
			Varying key underlying model's elasticities				
Shorter duration time ($d = d/2$)	233,397	144,102	3,071	2.85	257.45	1,126.36	8.14
Higher cost to height ($\eta_F = 1.5\eta_F$)	89,985	62,744	2,978	2.74	229.35	1,081.82	4.35
Higher return to height ($\epsilon_F = 2\epsilon_F$)	248,307	163,007	3,085	2.87	278.11	1,257.30	6.95
Higher depreciation ($\epsilon_z = 2\epsilon_z$)	326,299	175,655	3,136	2.89	210.21	871.02	12.18
Higher Tax rate ($\psi = 2\psi$)	142,159	95,707	3,022	2.78	471.20	879.54	5.27
			Other model benchmarks				
No development ($k_c = \infty$)	0	0	2,926	2.66	201.57	1,034.72	0
No endogenous density choice ($F_i^* = \bar{F}_i$)	193,844	130,097	3,050	2.83	239.62	1,098.78	5.83
No maximum allowable density ($\bar{F}_i = \infty$)	1,958,223	1,894,713	2,686	5.09	1,517.68	5,398.78	80.83

Table 5: Counterfactual Results

This table reports the aggregate outcomes of our counterfactual policy analyses. It reports the change of various outcomes described in columns from a counterfactual regulatory environment $\mathcal{P}$, described in the rows, to the baseline calibration $\mathcal{P}_0$. All results are computed with a 10-year horizon. In the first column, we show the change in the expected number of apartments net of demolished units. In the second and third columns, we separate between affordable and market-rent net expected units built. Column (4) shows the percentage change in citywide expected rent per unit. Column (5), shows the average change in expected density in percentage, with density computed as the expected number of apartments per parcel of 2,500 sqft. In Columns (6) and (7), we show the percentage change in the present value of property taxes, and total residential assets, respectively. The last three rows show the aggregate changes if the policy bundle $\mathcal{P}$ is a non-obligatory policy. In these counterfactuals, developers of each parcel select to used the policy bundle as opposed to the status-quo baseline policy $\mathcal{P}_0$ if $\pi_i(\mathcal{P}) \geq \pi_i(\mathcal{P}_0)$.

		Built Environment				Public Potential Costs		
		$\Delta E[AptNet]$ # of Apt.	$\Delta E[\text{Aff}Net]$ # of Apt	$\Delta E[MarketNet]$ # of Apt.	$\Delta E[Rent]$ (%)	$\Delta E[Density]$ (%)	$\Delta PVTax$ (%)	ΔPV (%)
		(1)	(2)	(3)	(4)	(5)	(6)	(7)
			Unilateral Policy					
(1)	*Upzoning* - $\phi = 25\%$	$70,298$	0	$70,298$	2.15	3.19	12.76	4.43
(2)	*Tax abatement* - $\tau = 20$	$40,738$	0	$40,738$	1.23	1.85	-8.13	2.45
(3)	*Affordable mandate* - $\alpha = 30\%$	$-10,753$	$51,075$	$-61,828$	-1.22	-0.49	-2.57	-0.99
			Mandatory Carrot & Stick Zoning					
(4)	*Density Incentive Zoning* - $\alpha = 30\%$ & $\phi = 25\%$	$52,686$	$79,934$	$-27,247$	0.24	2.39	7.73	2.64
(5)	*Fiscal Incentive Zoning* - $\alpha = 30\%$ & $\tau = 20$	$27,053$	$72,043$	$-44,990$	-0.45	1.23	-9.55	1.04
(6)	*All* - $\alpha = 30\%$, $\phi = 25\%$, & $\tau = 20$	$115,397$	$114,130$	$1,267$	1.42	5.23	-4.53	6.27
			Voluntary Carrot & Stick Zoning					
(7)	*Density Incentive Zoning* - $\alpha = 30\%$ & $\phi = 25\%$	$52,143$	$75,576$	$-23,433$	0.28	2.36	7.73	2.65
(8)	*Fiscal Incentive Zoning* - $\alpha = 30\%$ & $\tau = 20$	$27,053$	$72,043$	$-44,990$	-0.45	1.23	-9.55	1.04
(9)	*All* - $\alpha = 30\%$, $\phi = 25\%$, & $\tau = 20$	$115,397$	$114,130$	$1,267$	1.42	5.23	-4.53	6.27

Appendix

A Additional Tables & Figures

Table A1: Estimation of the age elasticity

*This table reports the estimates of $log(PPU)_{ijt} = \beta_j + \beta_t + \epsilon_Z log(Age_i) + X_i\beta + \nu_i$, where $log(PPU)$ is the log of the building price divided by the number of apartment units transaction in year t in location j, β_j and β_t are spatial and time fixed effects, respectively, Age is the number of years since the last recorded renovation or building year, X_i are covariates listed in the table. The sample consists of all building transactions from 2000 in New York City, collected from Costar. Estimates followed by ***, **, and * are statistically significant at the 1%, 5%, and 10% levels, respectively.*

	Dependent variable:						
	log(PPU)						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
logAge	-0.078^{***}	-0.074^{***}	-0.068^{***}	-0.071^{***}	-0.145^{***}	-0.077^{***}	-0.072^{***}
	(0.009)	(0.009)	(0.010)	(0.010)	(0.009)	(0.009)	(0.009)
log(NumberOfUnits)					-0.279^{***}	-0.243^{***}	-0.259^{***}
					(0.005)	(0.005)	(0.007)
log(mean_size_apt)						0.511^{***}	0.498^{***}
						(0.010)	(0.011)
log(NumberOfFloors)							0.058^{***}
							(0.020)
Community District FE	X	X					
Year FE	X						
Boro x year YE		X					
Community district x year FE			X	X	X	X	X
Neighrboorhoods FE				X	X	X	X
Observations	22,105	22,105	22,105	22,105	22,105	22,105	22,105
R^2	0.545	0.556	0.599	0.622	0.672	0.710	0.711
Adjusted R^2	0.543	0.552	0.573	0.594	0.648	0.689	0.689

Table A2: Partial Correlations Between Inputs and Outcomes of Baseline Model

This table reports the partial correlations between key inputs (rows) and outcomes (columns) of our baseline model results. The partial correlations are conditional on community districts as well as all other inputs listed in the rows. It uses the outcomes of the model with horizon 10-years for the 781,226 parcels under the baseline calibration described in Table 2. In Column (1), the outcome is the estimated probability of redevelopment decision $\mathbf{P}_i(\mathcal{P}_0;\Theta)$. In Column (2), the optimal density chosen endogenously to maximize property value ($\bar{F}^*(\mathcal{P}_0;\Theta)$) In Column (3), the log of the present value of the parcel $\pi_i(\mathcal{P}_0;\Theta)$. In Column (4), the option value share of total value $\tilde{\pi}_i(\mathcal{P}_0;\Theta)/\pi_i(\mathcal{P}_0;\Theta)$. In Column (5), the present value per unit of built units $\pi_i(\mathcal{P}_0;\Theta)/F_i$.

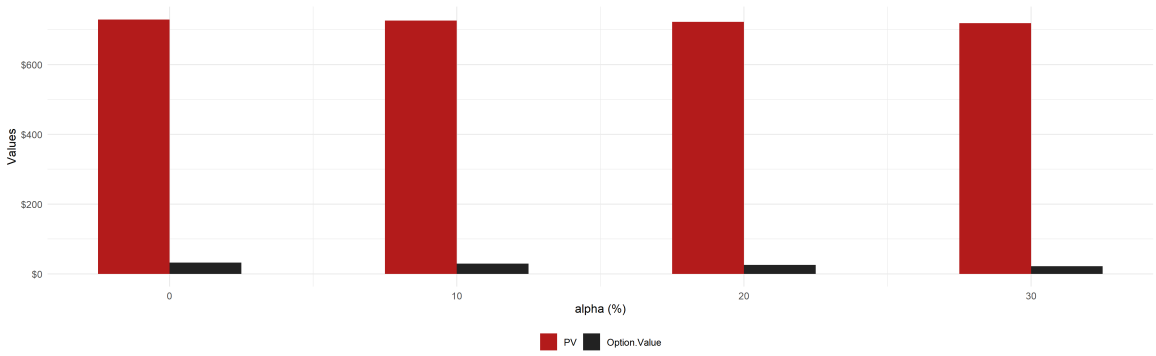
	Baseline Outcomes:				
	Prob	F opt	log(PV)	Option	PV/F
	All parcels				*Built parcels*
	(1)	(2)	(3)	(4)	(5)
Rent potential (R_i)	0.147	0.094	0.435	0.086	0.108
Rent growth	0.025	0.004	0.009	0.029	0.027
Physical discount rate ($\tilde{\delta}_i$)	−0.031	−0.016	−0.014	−0.038	−0.029
Current age (age_i)	0.087	0.010	−0.245	0.058	−0.030
Current density (F_i)	−0.210	0.755	0.581	−0.308	−0.019
Non-built parcel ($\mathbf{1}_{F_i=0}$)	0.793	0.156	−0.457	0.895	

Table A3: Share of Parcels that Opt-in *Voluntary* Policy Interventions

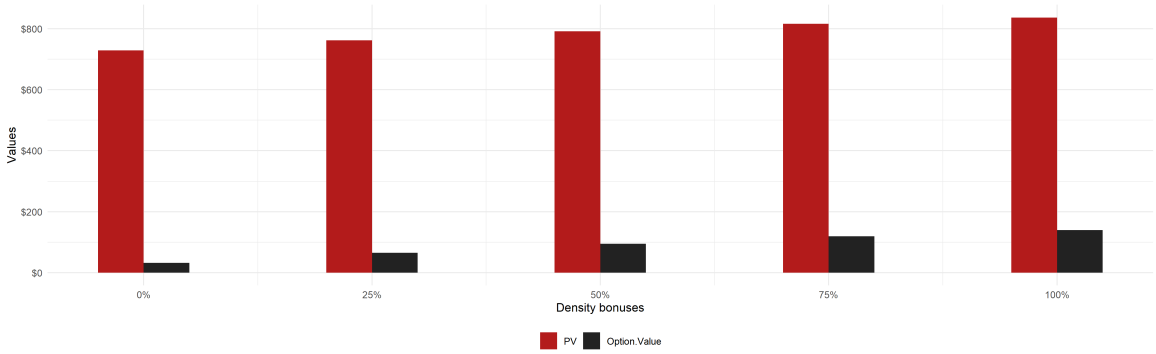
This table reports the number and the share of parcels that would opt-in the policy bundle $\mathcal{P}$ under voluntary adoptions. These parcels are defined as those that are better off under the new policy as in the baseline policy ($\pi_i(\mathcal{P}) \geq \pi_i(\mathcal{P}_0)$).

	Number of Parcels	Share (%)
All Parcels	781,226	100.0
(7) Density Incentive Zoning ($\alpha = 0.2$ & $\phi = 0.25$)	338,568	43.3
but not in fiscal IZ	57,049	7.3
(8) Fiscal Incentive Zoning ($\alpha = 0.2$ & $\tau = 30$)	292,713	37.5
but not in density IZ	11,194	1.4
(9) All Policies	456,452	58.4
but not in density IZ (i.e., switchers with τ)	117,884	15.1
but not in fiscal IZ (i.e., switchers with ϕ)	163,739	21.0

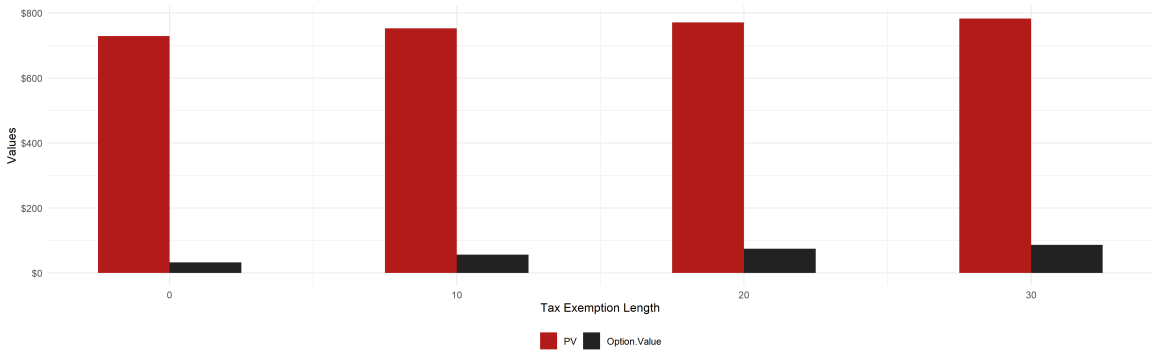
Figure A1: Policy instruments influence the redevelopment option value



A. Mandatory Share for Public Goods (α)



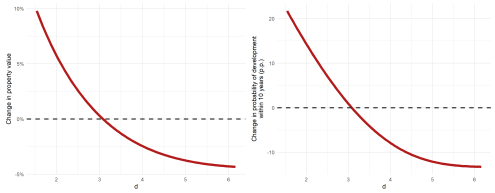
B. Density Bonuses (ϕ)



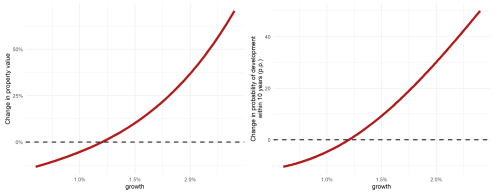
C. Length of Tax Exemptions (τ)

Note: These figures show the effects of changing the policy instruments on the present value of the current building and the present values of the redevelopment option. This option value is calculated as the difference between the current value of the parcel and its counterpart, where no development is allowed. These figures are obtained for a parcel of land built at 40% of its capacity with $F_0 = 2$ and $\bar{F} = 5$. All other elasticities are the baseline case shown in Table 2 or the mean values of parcel level data shown in 3.

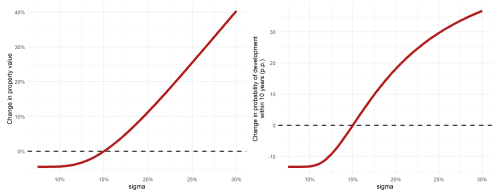
Figure A2: Effects of Parameter Changes on Parcel Value and Probability of Development



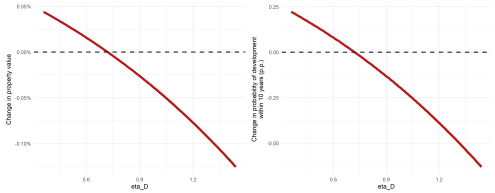
A. Construction Duration – d



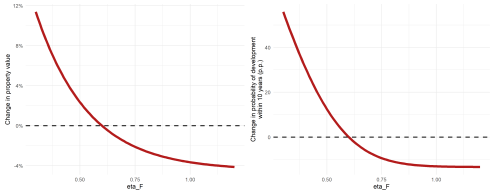
B. Rent growth



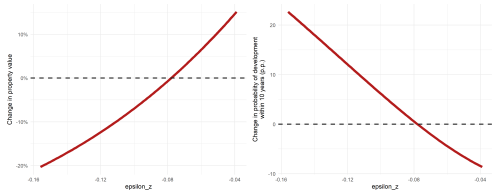
C. Volatility of Return – σ_i



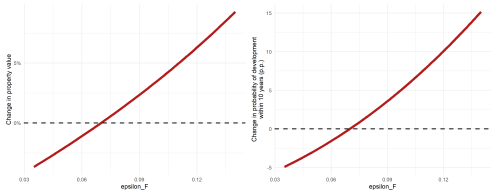
D. Height Elasticity of Demolition – η_D



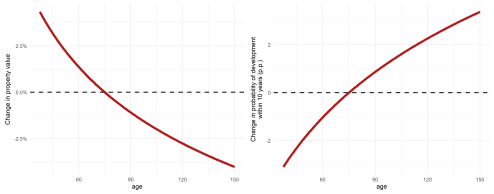
E. Height Elasticity of Construction – η_F



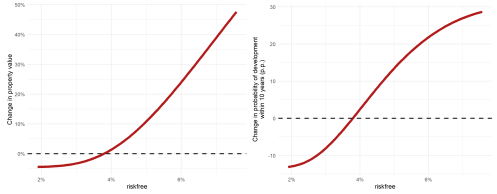
F. Age Elasticity of Rent – ϵ_z



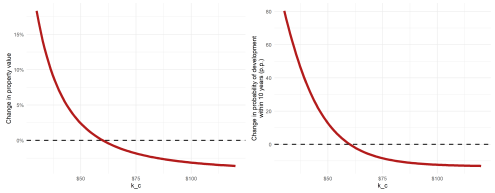
G. Height Elasticity of Rent – ϵ_F



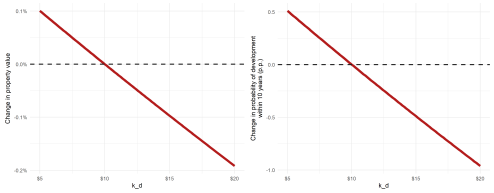
H. Property age



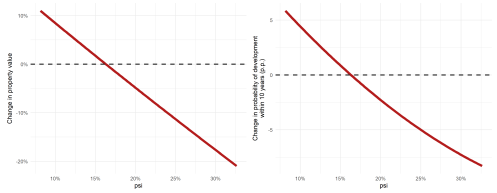
I. Risk-free Rate – r



J. Baseline Construction Cost – k_c



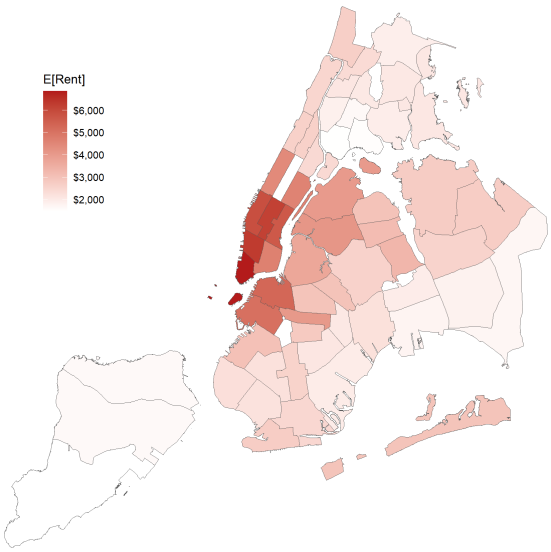
K. Baseline Demolition Cost – k_d



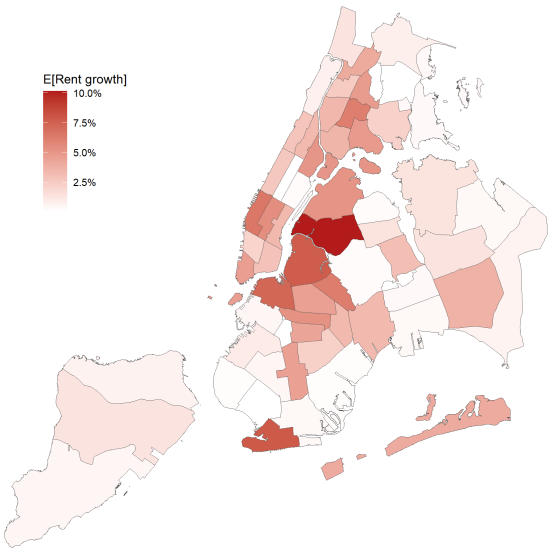
L. Property Tax Rate – ψ

Note: These figures show the effects of changing the baseline parameters on the change in the property value (left panels) and the change in the probability of development starting within 10 years (right panels). These figures are obtained for a parcel of land built at 40% of its capacity with $F_0 = 2$ and $\overline{F} = 5$. All other elasticities are the baseline case shown in Table 2 or the mean values of parcel level data shown in 3.

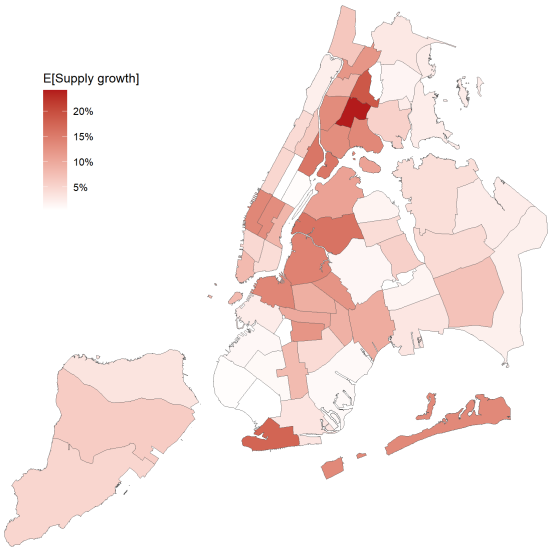
Figure A3: Baseline - Market-level Aggregated Outcomes



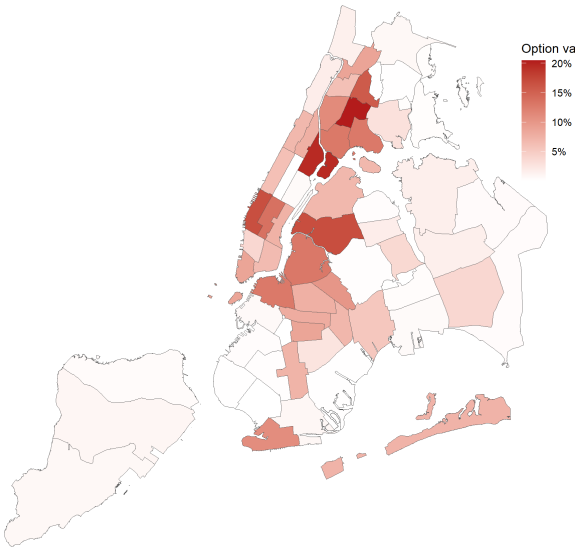
A. Expected Rent



B. Expected Rent growth



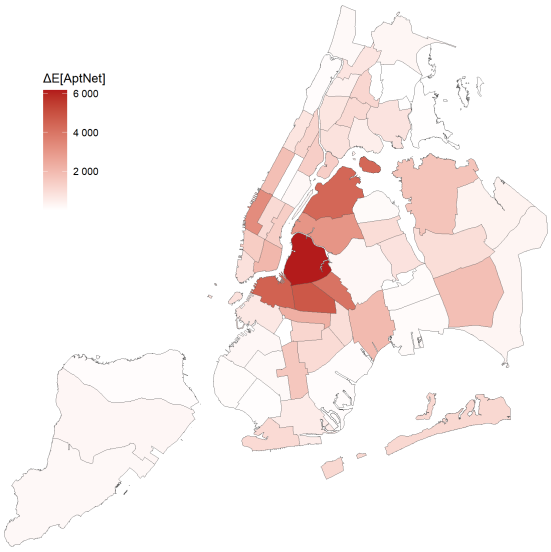
C. Expected Supply growth



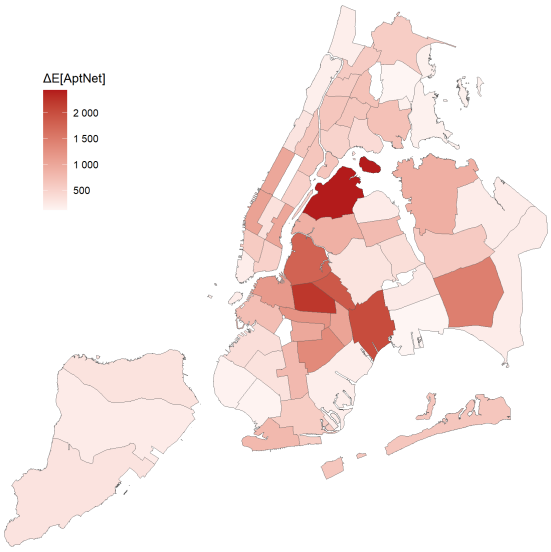
D. Share of Redevelopment Option Value

Note: These maps show the market-level aggregated outcomes of our baseline simulation as described in Table 2. Panel A showsthe expected net units addition, Panel B shows the expected density in 10 years, Panel C shows the sum of the residential parcel present values, and panel D the average value of the redevelopment option.

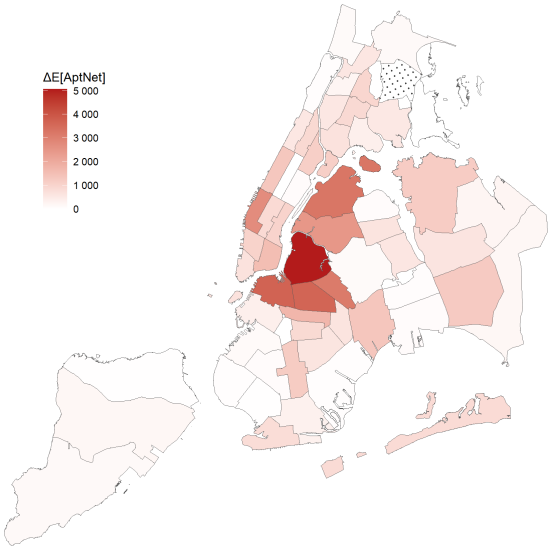
Figure A4: Counterfactuals – Net change in housing units



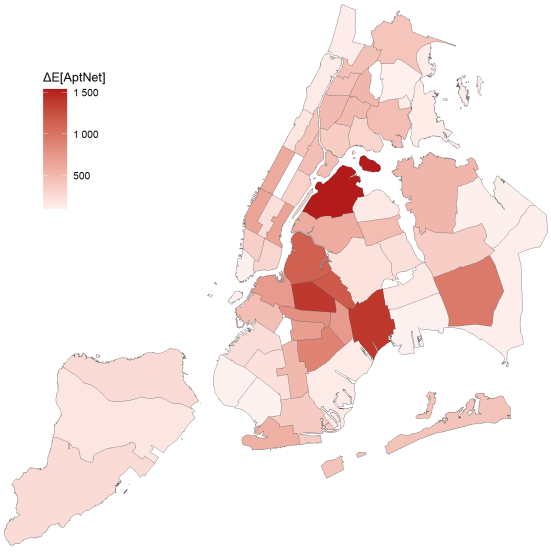
A. Upzoning ($\phi = .25$)



B. Tax exemptions ($\tau = 30$)



C. Density incentive zoning ($\alpha = 0.2$ & $\phi = .25$)



D. Fiscal incentive zoning ($\alpha = 0.2$ & $\tau = 30$)

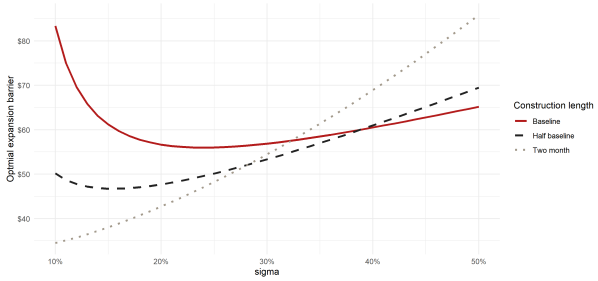
Note: These maps show the expected net change in the number of housing units constructed for different counterfactual policy analyses. It shows for each market the change compared to the baseline outcomes with horizon 10-year as shown in Figure 3.

B Relevance of Non-instantaneous Construction Duration

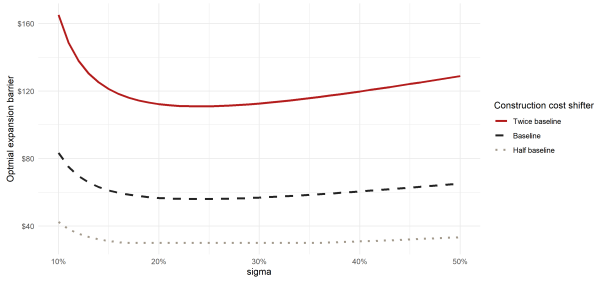
B.1 Relevance of Non-instantaneous Construction Duration

The impact of uncertainty on investment behavior changes fundamentally when construction is not instantaneous. With instantaneous investment, uncertainty delays investment by raising the expansion barrier. Figure B1, Panel A, shows this for short construction durations ($d \to 0$): higher uncertainty increases R^{e*}, so developers require higher rents before initiating construction.[23] In low-volatility markets, however, the effect is non-monotonic: higher uncertainty lowers the expansion barrier, enabling earlier investment. This departs from Capozza and Li (1994) because with longer construction periods developers must account not only when to invest but also whether conditions will remain favorable throughout construction. Panel B extends the analysis by varying construction costs, which produces only a parallel shift in the expansion barrier, confirming that the non-monotonicity is driven by uncertainty and the construction duration rather than cost.

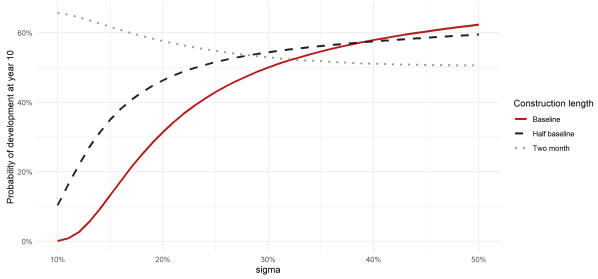
Figure B1: Uncertainty, construction length, construction cost, and probability of development



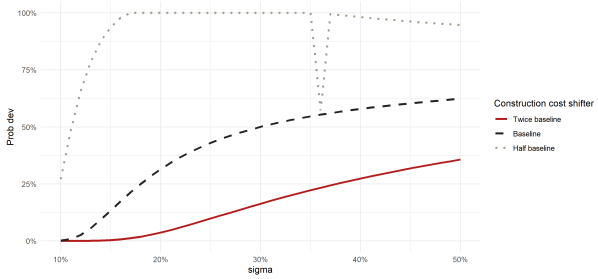
A. Expansion barrier and construction duration



B. Expansion barrier and construction cost



C. Development probability and construction duration



D. Development probability and construction cost

Note: This chart shows the effects of varying the underlying rental volatility σ on the optimal expansion barrier (panels A and B) and the probability of development within 10 years (panels C and D). Each line shows this effect for different assumptions regarding the length of construction d (left panels) or the baseline cost of construction k_c (right panels). These figures are obtained for a parcel of land built at 40% of its capacity with $F_0 = 2$ and $\bar{F} = 5$. The other parameters are shown in Table 2 or the mean values of parcel level data shown in 3.

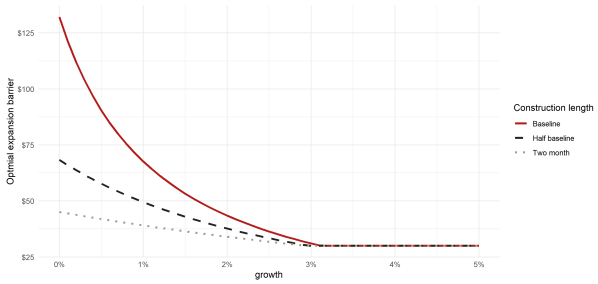
Building on this, Panel C turns from the barrier to the probability of development. Development probability increases with uncertainty, with the effect stronger when d is long. For long construction periods d, developers hesitate at moderate uncertainty, waiting for clearer signals.

[23] Figure B2 shows how rental growth interacts with construction duration and cost to affect development probabilities.

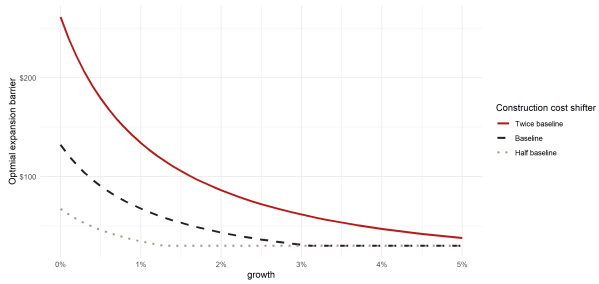
Once uncertainty is high enough, the probability of investment rises sharply. This pattern differs from the *incremental* investment framework in Bar-Ilan and Strange (1999), where uncertainty lowers investment intensity at every stage by discouraging additional capital. Unlike *lumpy* investment, where uncertainty affects the timing and size of a one-time decision, in *incremental* investment, firms make many small decisions over time, each negatively affected by uncertainty. Continuous adjustment, therefore, implies that investment is always scaled down in response to uncertainty. In our setting of *lumpy and lengthy* investment, uncertainty alters timing but once investment occurs, intensity is unaffected.

Models that assume instantaneous or incremental investment therefore tend to overstate development probabilities and inflate housing supply forecasts. By contrast, our framework captures the lumpy, uncertain nature of redevelopment, producing more realistic estimates of expected development. This improves the accuracy of policy evaluations, an effect not captured by shifts in construction costs (Panel D).

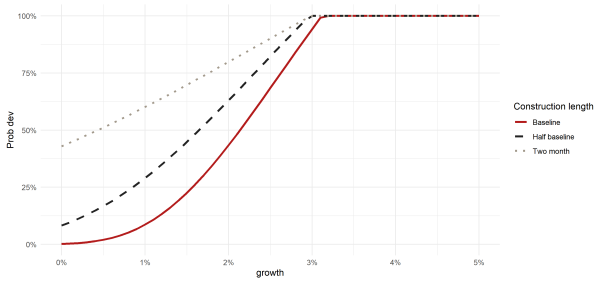
Figure B2: Rental growth, construction length, construction cost, and probability of development



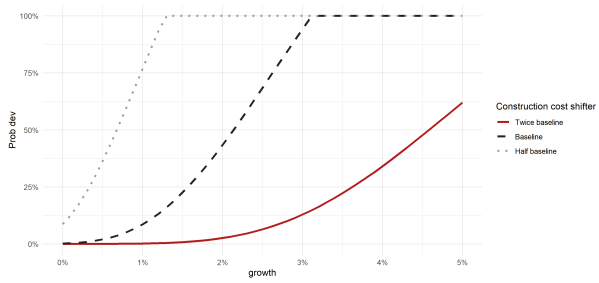
A. Expansion barrier and construction duration



B. Expansion barrier and construction cost



C. Development probability and construction duration



D. Development probability and construction cost

Note: This chart shows the effects of varying the underlying rental volatility σ on the optimal expansion barrier (panels A and B) and the probability of development within 10 years (panels C and D). Each line shows this effect for different assumptions regarding the length of construction d (left panels) or the baseline cost of construction k_c (right panels). These figures are obtained for a parcel of land built at 40% of its capacity with $F_0 = 2$ and $\bar{F} = 5$. The other parameters are shown in Table 2 or the mean values of parcel level data shown in 3.

C Proofs

C.1 Foundations for Risk-Neutral Pricing of Rents.

To obtain analytical valuations of development options, we represent rent R_t as a geometric Brownian motion under the risk-neutral measure $\mathbb{Q}$. Rents are not traded claims, but their risk can be priced consistently through a common kernel linked to traded real-estate instruments. Residential property values are therefore the present value of net rents:

$$V_t = \mathbf{E}_{\mathbb{Q}}\left[\int_0^{\infty} e^{-ru} R_{t+u}\, du\right] = \frac{R_t}{r-\delta}, \qquad \delta < r.$$

This parallels income-capitalization approaches in urban economics, with V_t inheriting rent dynamics (Glaeser and Gyourko (2005); Epple et al. (2010)). Applying Itô's Lemma gives

$$dV_t = \delta V_t\, dt + \sigma V_t\, dW_t.$$

Four assumptions underlie this representation: (A1) asset value derives solely from net rental income; (A2) rents equal net operating income, so there is no wedge with value; (A3) rents are discounted at a constant r; and (A4) rent risk is spanned by traded real-estate instruments such as REITs or CMBS. These assumptions parallel standard income-capitalization methods. The measure $\mathbb{Q}$ is best viewed as a pricing device calibrated to observed valuations. Although real estate markets are incomplete, *good-deal bounds* narrow admissible measures, permitting valuation under $\mathbb{Q}$ without perfect replication (see Cochrane and Saa-Requejo (2000)).[24]

C.2 Proof of Proposition 1.

Property Value Under the New Regulatory Environment.

$$\begin{aligned}\pi(R, F_B, F, \alpha, \phi, \tau; \Theta) = {} & \underbrace{\mathbf{E}_{\mathbb{Q}}\left\{\int_0^{T_{R^e}} e^{-ru}\ (1-\psi)\ \Gamma(F_B, z_B, 0) R_u\, \mathrm{d}u\right\}}_{\text{Value before completed development}} \\ & - \underbrace{\mathbf{E}_{\mathbb{Q}}\left\{e^{-rT_{R^e}}\gamma(F_B)\right\}}_{\text{Demolition costs}} - \underbrace{\mathbf{E}_{\mathbb{Q}}\left\{\int_{T_{R_e}}^{H_{R^e}} e^{-ru}\kappa(F,\alpha)\,\mathbf{1}_{R_u > R^e}\,\mathrm{d}u\right\}}_{\text{Development costs}} \\ & + \underbrace{\mathbf{E}_{\mathbb{Q}}\left\{\int_{H_{R^e}}^{\infty} e^{-ru}\,\Gamma(F,0,\alpha) R_u\,\mathrm{d}u\right\}}_{\text{Value after development gross of tax}} - \underbrace{\mathbf{E}_{\mathbb{Q}}\left\{\int_{H_{R^e}+\tau}^{\infty} e^{-ru}\psi\,\Gamma(F,0,\alpha) R_u\,\mathrm{d}u\right\}}_{\text{Property taxes after } \tau \text{ years of exemption}}\end{aligned} \tag{C.1}$$

where $T_{R^e}(W) = \inf\{t \geq 0 : W_t = R^e\}$, and $H_{R^e}(W) = \inf\{t \geq 0 : (t - g_t^{R^e}(W)) \geq d, W_t \geq R^e\}$ with $g_t^{R^e}(W) = \sup\{s \leq t : W_s = R^e\}$ (Chesney et al., 1997).

[24] We calibrate δ from observed capitalization rates c_{obs} via $\delta = r - c_{\text{obs}}$, treating δ as a reduced-form risk premium. Developers need not fully hedge rent risk; viability is benchmarked against marginal investors' valuations.

Value before completed development We start the proof by working on the first integral in (C.1). This becomes

$$\mathbf{E}_{\mathbb{Q}}\left\{\int_0^{T_{R^e}} e^{-ru}\ (1-\psi)\ \Gamma(F_B, z_B, 0) R_u\, \mathrm{d}u\right\} = (1-\psi)\ \Gamma(F_B, z_B, 0) R\, \mathbf{E}_{\mathbb{Q}}\left\{\int_0^{T_a} e^{-ru} e^{\sigma Z_u}\, \mathrm{d}u\right\}$$

with $a = (1/\sigma)\ln(R^e/R)$. This last integral becomes

$$\mathbf{E}_{\mathbb{Q}}\left\{\int_0^{T_a} e^{-ru} e^{\sigma Z_u} \mathrm{d}u\right\} = \mathbf{E}_{\mathbb{Q}}\left\{\int_0^{\infty} e^{-ru} e^{\sigma Z_u} \mathrm{d}u\right\} - \mathbf{E}_{\mathbb{Q}}\left\{\int_{T_a}^{\infty} e^{-ru} e^{\sigma Z_u} \mathrm{d}u\right\}$$

Recall that $(W_t)_{t\geq 0}$ is a Brownian motion under the risk neutral measure $\mathbb{Q}$. We wish to change the probability measure to a new measure $\mathbb{P}$ so that $(Z_t)_{t\geq 0}$ becomes a Brownian motion under $\mathbb{P}$. From the equality $W_t = Z_t - bt = Z_t + \int_0^t (-b)\, \mathrm{d}s$ we can apply the Girsanov theorem and derive the appropriate density

$$\begin{aligned} \forall t \geq 0, \quad \left.\frac{\mathrm{d}\mathbb{Q}}{\mathrm{d}\mathbb{P}}\right|_{\mathcal{F}_t} &= \exp\left\{-\int_0^t (-b)\, \mathrm{d}Z_s - \frac{1}{2}\int_0^t (-b)^2\, \mathrm{d}s\right\} \\ &= \exp\left\{bZ_t - \frac{1}{2}b^2 t\right\} \end{aligned} \tag{C.2}$$

Under this change of measure, we obtain

$$\mathbf{E}_{\mathbb{Q}}\left\{\int_0^{T_a} e^{-ru} e^{\sigma Z_u}\, \mathrm{d}u\right\} = \mathbf{E}_{\mathbb{P}}\left\{\int_0^{\infty} e^{-\frac{\lambda^2}{2}u} e^{(\sigma+b)Z_u}\, \mathrm{d}u\right\} - \mathbf{E}_{\mathbb{P}}\left\{\int_{T_a}^{\infty} e^{-\frac{\lambda^2}{2}u} e^{(\sigma+b)Z_u}\, \mathrm{d}u\right\} \tag{C.3}$$

where $\lambda = \sqrt{2r + b^2}$

To continue, we make good use of the following result that can be found in Karatzas and Shreve (1991), p. 272.

Lemma 1 *If $\phi : \mathbb{R} \to \mathbb{R}$ is a piecewise continuous function with*

$$\int_{-\infty}^{\infty} e^{-|y|\sqrt{2\alpha}} |\phi(x+y)|\, \mathrm{d}y < \infty \quad , \forall x \in \mathbb{R}$$

*for some constant $\alpha > 0$ and $(W_t)_{t\geq 0}$ is a standard Brownian motion, the **resolvent operator** of Brownian motion $K_\alpha(\phi)$ is defined by*

$$K_\alpha(\phi) = \mathbf{E}\left\{\int_0^{\infty} e^{-\alpha t}\phi(W_t)\, \mathrm{d}t\right\} = \frac{1}{\sqrt{2\alpha}}\int_{-\infty}^{\infty} e^{-|y|\sqrt{2\alpha}}\phi(y)\, \mathrm{d}y$$

We obtain therefore,

$$\mathbf{E}_{\mathbb{P}}\left\{\int_0^{\infty} e^{-\frac{\lambda^2}{2}u} e^{(\sigma+b)Z_u}\, \mathrm{d}u\right\} = \frac{1}{\lambda}\int_{-\infty}^{\infty} e^{(\sigma+b)y} e^{-|y|\lambda}\, \mathrm{d}y \tag{C.4}$$

$$= \frac{1}{r-\delta}$$

We now turn our attention to the second integral in (C.3). We can write

$$\begin{aligned}
\mathbf{E}_{\mathbb{P}}\left\{\int_{T_a}^{\infty} e^{-\frac{\lambda^2}{2}u} e^{(\sigma+b)Z_u}\,\mathrm{d}u\right\} &= \mathbf{E}_{\mathbb{P}}\left\{e^{-\frac{\lambda^2}{2}T_a}\int_0^{\infty} e^{-\frac{\lambda^2}{2}u} e^{(\sigma+b)(Z_u+a)}\,\mathrm{d}u\right\} \\
&= e^{(\sigma+b)a}\mathbf{E}_{\mathbb{P}}\left\{e^{-\frac{\lambda^2}{2}T_a}\right\}\mathbf{E}_{\mathbb{P}}\left\{\int_0^{\infty} e^{-\frac{\lambda^2}{2}u} e^{(\sigma+b)Z_u}\,\mathrm{d}u\right\} \\
&= e^{(\sigma+b-\lambda)a}\mathbf{E}_{\mathbb{P}}\left\{\int_0^{\infty} e^{-\frac{\lambda^2}{2}u} e^{(\sigma+b)Z_u}\,\mathrm{d}u\right\} \\
&= \left(\frac{R^e}{R}\right)^{1+\xi}\mathbf{E}_{\mathbb{P}}\left\{\int_0^{\infty} e^{-\frac{\lambda^2}{2}u} e^{(\sigma+b)Z_u}\,\mathrm{d}u\right\} \\
&= \frac{1}{r-\delta}\left(\frac{R^e}{R}\right)^{1+\xi} \qquad \text{(C.5)}
\end{aligned}$$

since $e^{(\sigma+b-\lambda)a} = \left(\frac{R_e}{R}\right)^{1+\xi}$ with $\xi = \frac{b-\lambda}{\sigma}$ and the Laplace transform of the distribution of the first passage time of a Brownian motion $(Z_t)_{t\geq 0}$ to a level a yields

$$\begin{aligned}
\mathbf{E}_{\mathbb{P}}\left\{e^{-\frac{\lambda^2}{2}T_a}\right\} &= e^{-|a|\sqrt{2\lambda^2/2}} \\
&= e^{-\lambda a} \quad \text{since } a > 0
\end{aligned}$$

We combine results in (C.3), (C.4), and (C.5) to conclude

$$\mathbf{E}_{\mathbb{Q}}\left\{\int_0^{T_{R^e}} e^{-ru}\,(1-\psi)\,\Gamma(F_B, z_B, 0)R_u\,\mathrm{d}u\right\} = \Gamma(F_B, z_B, 0)\frac{1-\psi}{r-\delta}\left[R - R^e\left(\frac{R^e}{R}\right)^{\xi}\right]$$

Demolition costs We solve the second expectation in (C.1) as follows:

$$\mathbf{E}_{\mathbb{Q}}\left\{e^{-rT_{R^e}}\gamma(F_B)\right\} = \gamma(F_B)\left(\frac{R^e}{R}\right)^{\xi}$$

where we use consecutively the Girsanov theorem to change to the new measure $\mathbb{P}$ delineated above and the Laplace transform of the distribution of the first passage time of a Brownian motion $(Z_t)_{t\geq 0}$ to a level a with a and ξ defined in Proposition 1.

Development costs We can now move to the third integral in (C.1). This is equal to

$$\begin{aligned}
\mathbf{E}_{\mathbb{Q}}\left\{\int_{T_{R_e}}^{H_{R^e}} e^{-ru}\kappa(F,\alpha)\mathbf{1}_{R_u>R^e}\,\mathrm{d}u\right\} &= \mathbf{E}_{\mathbb{Q}}\left\{\int_0^{H_{R^e}} e^{-ru}\kappa(F,\alpha)\mathbf{1}_{R_u>R^e}\,\mathrm{d}u\right\} \\
&= \kappa(F,\alpha)\mathbf{E}_{\mathbb{Q}}\left\{\int_0^{H_{R^e}} e^{-ru}\mathbf{1}_{R_u>R_e}\,\mathrm{d}u\right\}
\end{aligned}$$

we can rewrite this last integral as

$$\mathbf{E}_{\mathbb{Q}}\left\{\int_0^{H_{R^e}} e^{-ru}\mathbf{1}_{R_u>R^e}\,\mathrm{d}u\right\} = \mathbf{E}_{\mathbb{Q}}\left\{\int_0^{H_{R^e}} e^{-ru}\,\mathrm{d}u\right\} - \mathbf{E}_{\mathbb{Q}}\left\{\int_0^{H_{R^e}} e^{-ru}\mathbf{1}_{R_u<R^e}\,\mathrm{d}u\right\} \tag{C.6}$$

To solve the first integral in (C.6) we recall the following lemma which derives the Laplace transform for the Parisian time H_0 due to Chesney et al. (1997).

Lemma 2 *If $(W_t)_{t\geq 0}$ is a Brownian motion starting from zero, let ρ be a positive number, the Laplace transform of the first time a positive Brownian excursion lasts more than d is*

$$\mathbf{E}_{\mathbb{Q}}\left[e^{-\rho H_0}\right] = \frac{1}{\Phi(\sqrt{2\rho d})} \quad \textit{for all } \rho > 0 \tag{C.7}$$

with

$$\Phi(x) = \int_0^{+\infty} z\exp(zx - \frac{z^2}{2})\,\mathrm{d}z = 1 + \sqrt{2\pi}x\exp\left(\frac{x^2}{2}\right)\mathcal{N}(x)$$

with $\mathcal{N}(.)$ the standard normal cumulative distribution function.

We also recall the law of Z_{H_0}. This can be inferred from Jeanblanc et al. (2009) p.249

Lemma 3 *Let $(W_t)_{t\geq 0}$ be a Brownian motion and $H_d(W) = \inf\{t \geq 0 : (t - g_t(W)) \geq d, W_t \geq 0\}$. The random variables H_d and W_{H_d} are independent and*

$$\mathbb{P}(W_{H_d} \in \mathrm{d}x) = \frac{x}{d}e^{-\frac{x^2}{2d}}\mathbf{1}_{x>0} \in \mathrm{d}x \tag{C.8}$$

We proceed to solve the first integral in (C.6) by changing to the new measure $\mathbb{P}$ delineated in (C.2) together with Lemma 2 and Lemma 3. This yields

$$\begin{aligned}\mathbf{E}_{\mathbb{Q}}\left\{\int_0^{H_{R^e}} e^{-ru}\,\mathrm{d}u\right\} &= \mathbf{E}_{\mathbb{Q}}\left\{\int_0^{\infty} e^{-ru}\,\mathrm{d}u\right\} - \mathbf{E}_{\mathbb{Q}}\left\{\int_{H_{R^e}}^{\infty} e^{-ru}\,\mathrm{d}u\right\} \\ &= \frac{1}{r}\left[1 - \frac{\Phi(b\sqrt{d})}{\Phi(\lambda\sqrt{d})}\left(\frac{R^e}{R}\right)^{\xi}\right]\end{aligned} \tag{C.9}$$

The last integral in (C.6) can also be solved to obtain successively

$$\begin{aligned}\mathbf{E}_{\mathbb{Q}}\left\{\int_0^{H_{R^e}} e^{-ru}\mathbf{1}_{R_u<R^e}\,\mathrm{d}u\right\} &= \mathbf{E}_{\mathbb{Q}}\left\{\int_0^{H_a} e^{-ru}\mathbf{1}_{Z_u<a}\,\mathrm{d}u\right\} \\ &= \mathbf{E}_{\mathbb{Q}}\left\{\int_0^{\infty} e^{-ru}\mathbf{1}_{Z_u<a}\,\mathrm{d}u\right\} - \mathbf{E}_{\mathbb{Q}}\left\{\int_{H_a}^{\infty} e^{-ru}\mathbf{1}_{Z_u<a}\,\mathrm{d}u\right\}\end{aligned}$$

Using the Girsanov theorem to change the measure delineated in (C.2)

$$\mathbf{E}_{\mathbb{Q}}\left\{\int_0^{H_{R^e}} e^{-ru}\mathbf{1}_{R_u<R^e}\,\mathrm{d}u\right\} = \mathbf{E}_{\mathbb{P}}\left\{\int_0^{\infty} e^{-\frac{\lambda^2}{2}u}e^{bZ_u}\mathbf{1}_{Z_u<a}\,\mathrm{d}u\right\} - \mathbf{E}_{\mathbb{P}}\left\{\int_{H_a}^{\infty} e^{-\frac{\lambda^2}{2}u}e^{bZ_u}\mathbf{1}_{Z_u<a}\,\mathrm{d}u\right\}$$

with $\lambda = \sqrt{2r+b^2}$. We obtain next with lemma 1,

$$\mathbf{E}_{\mathbb{P}}\left\{\int_0^{\infty} e^{-\frac{\lambda^2}{2}u}e^{bZ_u}\mathbf{1}_{Z_u<a}\,\mathrm{d}u\right\} = \frac{1}{\lambda}\int_{-\infty}^{a} e^{by}e^{-|y|\lambda}\,\mathrm{d}y$$

which after simplification becomes

$$\mathbf{E}_{\mathbb{P}}\left\{\int_0^{\infty} e^{-\frac{\lambda^2}{2}u}e^{bZ_u}\mathbf{1}_{Z_u<a}\,\mathrm{d}u\right\} = \frac{1}{r} + \frac{1}{\lambda(b-\lambda)}\left(\frac{R^e}{R}\right)^{\xi}$$

We can now work on the last term

$$\begin{aligned}\mathbf{E}_{\mathbb{P}}\left\{\int_{H_a}^{\infty} e^{-\frac{\lambda^2}{2}u}e^{bZ_u}\mathbf{1}_{Z_u<a}\,\mathrm{d}u\right\} &= \mathbf{E}_{\mathbb{P}}\left\{e^{-\frac{\lambda^2}{2}T_a}\int_{H_0}^{\infty} e^{-\frac{\lambda^2}{2}u}e^{b(Z_u+a)}\mathbf{1}_{Z_u<0}\,\mathrm{d}u\right\}\\ &= e^{ba-|a|\lambda}\mathbf{E}_{\mathbb{P}}\left\{e^{-\frac{\lambda^2}{2}H_0}\int_0^{\infty} e^{bZ_{u+H_0}}e^{-\frac{\lambda^2}{2}u}\mathbf{1}_{Z_{u+H_0}<0}\,\mathrm{d}u\right\} \quad \text{(C.10)}\end{aligned}$$

Which is equal to

$$\frac{1}{\Phi(\lambda\sqrt{d})}\left(\frac{R^e}{R}\right)^{\xi}\int_0^{\infty}\mathbb{P}(Z_{H_0}\in\,\mathrm{d}x)e^{bx}\mathbf{E}_{\mathbb{P}}\left\{\int_0^{\infty} e^{-\frac{\lambda^2}{2}u}e^{bZ_u}\mathbf{1}_{Z_u<-x}\,\mathrm{d}u\right\} \quad \text{(C.11)}$$

but

$$\mathbf{E}_{\mathbb{P}}\left\{\int_0^{\infty} e^{-\frac{\lambda^2}{2}u}e^{bZ_u}\mathbf{1}_{Z_u<-x}\,\mathrm{d}u\right\} = \frac{1}{\lambda}\int_{-\infty}^{-x} e^{by}e^{-|y|\lambda}\,\mathrm{d}y$$

since $x>0$ then $y<0$. It follows that

$$\begin{aligned}\frac{1}{\lambda}\int_{-\infty}^{-x} e^{by}e^{-|y|\lambda}\,\mathrm{d}y &= \frac{1}{\lambda}\int_{-\infty}^{-x} e^{(b+\lambda)y}\,\mathrm{d}y\\ &= \frac{e^{-(b+\lambda)x}}{\lambda(b+\lambda)} \quad \text{(C.12)}\end{aligned}$$

Combining (C.11) and (C.12) yields

$$\begin{aligned}\mathbf{E}_{\mathbb{P}}\left\{\int_{H_a}^{\infty} e^{-\frac{\lambda^2}{2}u}e^{bZ_u}\mathbf{1}_{Z_u<a}\,\mathrm{d}u\right\} &= \frac{1}{\Phi(\lambda\sqrt{d})}\left(\frac{R^e}{R}\right)^{\xi}\int_0^{\infty}\frac{x}{d}e^{-\frac{x^2}{2d}}e^{bx}\frac{e^{-(b+\lambda)x}}{\lambda(b+\lambda)}\,\mathrm{d}x \\ &= \frac{1}{\lambda(b+\lambda)}\left(\frac{R^e}{R}\right)^{\xi}\frac{1}{\Phi(\lambda\sqrt{d})}\int_0^{\infty}\frac{x}{d}e^{-\frac{x^2}{2d}-\lambda x}\,\mathrm{d}x\end{aligned}$$

We proceed next with a change of variables $x = \sqrt{d}y$ and conclude

$$\begin{aligned}\mathbf{E}_{\mathbb{P}}\left\{\int_{H_a}^{\infty} e^{-\frac{\lambda^2}{2}u}e^{bZ_u}\mathbf{1}_{Z_u<a}\,\mathrm{d}u\right\} &= \frac{1}{\lambda(b+\lambda)}\left(\frac{R^e}{R}\right)^{\xi}\frac{1}{\Phi(\lambda\sqrt{d})}\int_0^{\infty} ye^{-\frac{y^2}{2}-\lambda\sqrt{d}y}\,\mathrm{d}y \\ &= \frac{1}{\lambda(b+\lambda)}\left(\frac{R^e}{R}\right)^{\xi}\frac{\Phi(-\lambda\sqrt{d})}{\Phi(\lambda\sqrt{d})} \qquad \text{(C.13)}\end{aligned}$$

Finally combining (C.10) and (C.13) yields the last integral from (C.6),

$$\mathbf{E}_{\mathbb{Q}}\left\{\int_0^{H_{R^e}} e^{-ru}\mathbf{1}_{R_u<R^e}\,\mathrm{d}u\right\} = \frac{1}{r}\left[1-\left[\frac{b+\lambda}{2\lambda}-\frac{b-\lambda}{2\lambda}\frac{\Phi(-\lambda\sqrt{d})}{\Phi(\lambda\sqrt{d})}\right]\left(\frac{R^e}{R}\right)^{\xi}\right] \qquad \text{(C.14)}$$

Combining (C.6), (C.9) and (C.14) yields

$$\mathbf{E}_{\mathbb{Q}}\left\{\int_0^{H_{R^e}} e^{-ru}\mathbf{1}_{R_u>R^e}\,\mathrm{d}u\right\} = \frac{1}{r}\left[\frac{b+\lambda}{2\lambda}-\frac{b-\lambda}{2\lambda}\frac{\Phi(-\lambda\sqrt{d})}{\Phi(\lambda\sqrt{d})}-\frac{\Phi(b\sqrt{d})}{\Phi(\lambda\sqrt{d})}\right]\left(\frac{R^e}{R}\right)^{\xi}$$

Value after development The expectation related to the present value of the proceeds after the stopping time H_{R^e} in (C.1) becomes

$$\mathbf{E}_{\mathbb{Q}}\left\{\int_{H_{R^e}}^{\infty} e^{-ru}\,\Gamma(F,0,\alpha)R_u\,\mathrm{d}u\right\} = \Gamma(F,0,\alpha)R\,\mathbf{E}_{\mathbb{Q}}\left\{\int_{H_a}^{\infty} e^{-ru}e^{\sigma Z_u}\,\mathrm{d}u\right\}$$

After the change of measure delineated in (C.2) the last expectation yields

$$\Gamma(F,0,\alpha)R\,\mathbf{E}_{\mathbb{Q}}\left\{\int_{H_a}^{\infty} e^{-ru}e^{\sigma Z_u}\,\mathrm{d}u\right\} = \Gamma(F,0,\alpha)R\,\mathbf{E}_{\mathbb{P}}\left\{\int_{H_a}^{\infty} e^{-\frac{\lambda^2}{2}u}e^{(b+\sigma)Z_u}\,\mathrm{d}u\right\}$$

We combine results from (C.10), (C.11), and (C.13) to solve this expectation.

$$\Gamma(F,0,\alpha)R\,\mathbf{E}_{\mathbb{P}}\left\{\int_{H_a}^{\infty} e^{-\frac{\lambda^2}{2}u}e^{(b+\sigma)Z_u}\,\mathrm{d}u\right\} = \frac{1}{r-\delta}\,\Gamma(F,0,\alpha)R^e\,\frac{\Phi\left((\sigma+b)\sqrt{d}\right)}{\Phi(\lambda\sqrt{d})}\left(\frac{R^e}{R}\right)^{\xi}$$

Property taxes after τ years of tax credits The last expectation related to the present value of the property taxes after τ years of tax exemptions in (C.1) is solved as follows,

$$\begin{aligned}\mathbf{E}_{\mathbb{Q}}\left\{\int_{H_{R^e}+\tau}^{\infty} e^{-ru}\psi\,\Gamma(F,0,\alpha)R_u\,\mathrm{d}u\right\} &= \psi\,\Gamma(F,0,\alpha)R\,\mathbf{E}_{\mathbb{Q}}\left\{\int_{H_a+\tau}^{\infty} e^{-ru}e^{\sigma Z_u}\,\mathrm{d}u\right\}\\ &= \psi\,\Gamma(F,0,\alpha)R\,\mathbf{E}_{\mathbb{P}}\left\{\int_{H_a}^{\infty} e^{-\frac{\lambda^2}{2}(u+\tau)}e^{(b+\sigma)Z_{u+\tau}}\,\mathrm{d}u\right\}\end{aligned}$$

where the second steps follows from the change of measure delineated in (C.2). Thanks to the equality in law between H_a and $H_0 + T_a$ for two independent copies, the independence of T_a and H_0, the Laplace transform of the distribution of the first passage time of a Brownian motion $(Z_t)_{t\geq 0}$ to a level a, and the Independence between H_0 and Z_{H_0} we can write

$$\begin{aligned}&\mathbf{E}_{\mathbb{P}}\left\{\int_{H_a}^{\infty} e^{-\frac{\lambda^2}{2}(u+\tau)}e^{(b+\sigma)Z_{u+\tau}}\,\mathrm{d}u\right\} =\\ &\qquad e^{(b+\sigma)a}\mathbf{E}_{\mathbb{P}}\left\{e^{-\frac{\lambda^2}{2}T_a}\right\}\mathbf{E}_{\mathbb{P}}\left\{e^{-\frac{\lambda^2}{2}H_0}\right\}\mathbf{E}_{\mathbb{P}}\left\{e^{(b+\sigma)Z_{H_0}}\right\}\mathbf{E}_{\mathbb{P}}\left\{\int_0^{\infty} e^{-\frac{\lambda^2}{2}(u+\tau)}e^{(b+\sigma)Z_{u+\tau}}\,\mathrm{d}u\right\} \quad \text{(C.15)}\end{aligned}$$

and the last integral becomes

$$\mathbf{E}_{\mathbb{P}}\left\{\int_0^{\infty} e^{-\frac{\lambda^2}{2}(u+\tau)}e^{(b+\sigma)Z_{u+\tau}}\,\mathrm{d}u\right\} = e^{-\lambda^2\frac{\tau}{2}}\mathbf{E}_{\mathbb{P}}\left\{e^{(b+\sigma)Z_\tau}\right\}\mathbf{E}_{\mathbb{P}}\left\{\int_0^{\infty} e^{-\frac{\lambda^2}{2}u}e^{(b+\sigma)Z_u}\,\mathrm{d}u\right\}$$

Z_τ is a Brownian motion under $\mathbb{P}$ distributed $\mathcal{N}(0,\tau)$. We recall that the moment generating function of a standard brownian motion Z_t evaluated at a is given by $\mathbf{E}\left\{e^{aZ_t}\right\} = e^{a^2\frac{t}{2}}$. It follows that

$$\mathbf{E}_{\mathbb{P}}\left\{\int_0^{\infty} e^{-\frac{\lambda^2}{2}(u+\tau)}e^{(b+\sigma)Z_{u+\tau}}\,\mathrm{d}u\right\} = e^{-\lambda^2\frac{\tau}{2}}e^{(b+\sigma)^2\frac{\tau}{2}}\mathbf{E}_{\mathbb{P}}\left\{\int_0^{\infty} e^{-\frac{\lambda^2}{2}u}e^{(b+\sigma)Z_u}\,\mathrm{d}u\right\} \quad \text{(C.16)}$$

Combining result from (C.15), (C.10), (C.11), (C.13), and (C.16) yields

$$\mathbf{E}_{\mathbb{Q}}\left\{\int_{H_{V^e}+\tau}^{\infty} e^{-ru}\psi\,\Gamma(F,0,\alpha)V_u\,\mathrm{d}u\right\} = \frac{\psi h}{r-\delta}\,\Gamma(F,0,\alpha)R^e\,\frac{\Phi\left((\sigma+b)\sqrt{d}\right)}{\Phi(\lambda\sqrt{d})}\left(\frac{R^e}{R}\right)^{\xi}$$

with $h = e^{\left[(b+\sigma)^2-\lambda^2\right]\frac{\tau}{2}}$. This concludes the proof.

C.3 Proof of Proposition 2.

We start by rearranging the property value in equation (3) in the following way:

$$\pi(R,R^e,F_B,F,\alpha,\phi,\tau;\Theta) = \Gamma(F_B,z_B,0)\frac{1-\psi}{r-\delta}R$$

$$+\left[\vartheta R^e-\gamma(F_B)-\frac{\kappa(F,\alpha)}{r}\Big(B(d)-A(d)\Big)\right]\left(\frac{R^e}{R}\right)^{\xi}$$

with $\vartheta=\Gamma(F,0,\alpha)\frac{1-\psi h}{r-\delta}C(d)-\Gamma(F_B,z_B,0)\frac{1-\psi}{r-\delta}$

We establish the expansion threshold under regulatory environment $\mathcal{P}$, denoted as R^{e*}, as the parameter that optimizes the property value. In other words,

$$R^{e*}=\arg\max\pi(R,R^e,F_B,F,\alpha,\phi,\tau;\Theta)$$

It follows that R^{e*} must satisfy the first order conditions and the second order conditions. The partial derivative of $\pi(R,R^e,F_B,F,\alpha,\phi,\tau;\Theta)$ with respect to R^e is equal to

$$\frac{\partial\pi(R,R^e,F_B,F,\alpha,\phi,\tau;\Theta)}{\partial R^e}=\vartheta\left(\frac{R^e}{V}\right)^{\xi}+\frac{\xi}{V}\left[\vartheta R^e-\gamma(F_B)-\frac{\kappa(F,\alpha)}{r}\Big(B(d)-A(d)\Big)\right]\left(\frac{R^e}{V}\right)^{\xi-1}$$

Which can be simplified to

$$\left(\frac{R^e}{R}\right)^{\xi}\left[\vartheta+\frac{\xi}{R^e}\left[\vartheta R^e-\gamma(F_B)-\frac{\kappa(F,\alpha)}{r}\Big(B(d)-A(d)\Big)\right]\right.$$

We know that $R^e>R$ so $R^e\neq 0$. This implies that first order conditions are satisfied if and only if

$$\vartheta+\frac{\xi}{V^e}\left[\vartheta R^e-\gamma(F_B)-\frac{\kappa(F,\alpha)}{r}\Big(B(d)-A(d)\Big)\right]=0$$

some further simplification yields R^{e*}.

$$R^{e*}=\frac{\xi}{1+\xi}\frac{1}{\vartheta}\left[\gamma(F_B)+\frac{\kappa(F,\alpha)}{r}\Big(B(d)-A(d)\Big)\right]$$

provided $\vartheta>0$

C.4 Proof of Proposition 3.

Recall that $R_t=Re^{\sigma Z_t}$, where $Z_t=bt+W_t$, and $b=\frac{1}{\sigma}(\delta-\frac{\sigma^2}{2})$. This implies that $T^{R^{e*}}(R)=\inf\{t\geq 0: Z_t=a\}$ with $a=(1/\sigma)\ln(R^{e*}/R)$. Recall that $(W_t)_{t\geq 0}$ is a Brownian motion under the risk neutral measure $\mathbb{Q}$ and that after changing the probability measure to a new measure $\mathbb{P}$, $(Z_t)_{t\geq 0}$ becomes a Brownian motion under $\mathbb{P}$. We recall the law of the hitting time $T^{R^{e*}}$ of the level R^{e*} from Jeanblanc et al. (2009) p.140

Lemma 4 *Let W_t be a Brownian motion and for any $x>0$ define $T_x(W)=\inf\{t\geq 0|W_t=x\}$. The density of the random variable T_x is given by $\mathbf{P}(T_x\in\ \mathrm{d}t)=\frac{x}{\sqrt{2\pi t^3}}\exp\left(-\frac{x^2}{2t}\right)\mathrm{d}t$*

We use Lemma 4 to conclude the proof.

C.5 Proof of Proposition 4.

Recall that under the risk-neutral measure $\mathbb{Q}$, the net residential rent per unit of new density R_t is modeled as a geometric Brownian motion. Denoting R as the observed rent at $t = 0$, we can rewrite the net residential market rent per new unit of built density at $t \geq 0$ as $R_t = Re^{(\delta - \frac{\sigma^2}{2})t + \sigma W_t} = Re^{\sigma Z_t}$, where $Z_t = bt + W_t$, $b = \frac{1}{\sigma}(\delta - \frac{\sigma^2}{2})$ and $R = R_0$.

We want $\mathbf{E}_{\mathbb{P}}\{R_T\}$ for some time T. This is equal to

$$\mathbf{E}_{\mathbb{P}}\{R_T\} = R\,\mathbf{E}_{\mathbb{P}}\{e^{\sigma Z_T}\}$$

Recall that Z_t is a Brownian motion under $\mathbb{P}$. We also recall that the moment-generating function of a standard Brownian motion Z_t evaluated at a is given by $\mathbf{E}\left\{e^{aZ_t}\right\} = e^{a^2\frac{t}{2}}$. This yields

$$\mathbf{E}_{\mathbb{P}}\{e^{\sigma Z_T}\} = e^{\sigma^2\frac{T}{2}}$$

This concludes the proof.