The Economic Dynamics of City Structure: Evidence from Hiroshima's Recovery

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Introduction

- City structure often (but not always) exhibits remarkable resilience after a devastating shock
    - Rebuilding of destroyed areas after wars and natural disasters.
- **What drives the resilience of city structure?**
    - Important for considering future rebuilding events (e.g., Ukraine)
    - More broadly, suggestive of the effects of place-based policies on cities.
- To answer this, we analyze **the atomic bombing of Hiroshima** with new data and a new model.

Our paper

- We analyze **the atomic bombing of Hiroshima** to investigate the resilience of city structure and its underlying mechanisms
- **We newly digitize granular historical data** on population, employment, and locational characteristics within Hiroshima city.
- **Strong resilience: totally destroyed city center recovered in population density just five years after the bombing**.
    - Moreover, it is not the case that the city center could recover because it had very favorable locational characteristics (natural conditions, transportation acccess etc).
- To further understand the mechanisms behind the recovery, we **develop and calibrate a novel dynamic urban model**.
- **Strong agglomeration forces and expectations in the recovery are essential for the rebuilding of central Hiroshima.**

Literature

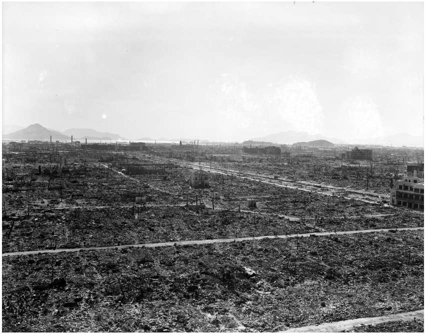
- **History (in)dependence in the spatial economy:** Davis and Weinstein (2002, 2008); Bosker et al. (2007); Miguel and Roland (2011); Redding et al. (2011); Bleakley and Lin (2012); Schumann (2014); Siodla (2015); Hornbeck and Keniston (2017); Michaels and Rauch (2018); Brooks and Lutz (2019); Ahlfeldt et al. (2020); Heblich et al. (2021); Yamasaki et al. (2021); Allen and Donaldson (2022); Yamagishi and Sato (2022)
- **Fundamental locational characteristics shaping city structure:** Alonso (1964); Muth (1967); Mills (1969); Fujita (1989); Anas et al. (1998); Glaeser and Kahn (2004); Saiz (2010); Lee and Lin (2018); Harari (2020)
- **Expectations in the spatial economy:** Krugman (1991); Matsuyama (1991); Fukao and Bénabou (1993); Ottaviano (2001); Baldwin (2001); Oyama (2009); Barreda-Tarrazona et al. (2021)
- **Quantitative dynamic spatial economics models:** Desmet et al. (2018); Caliendo et al. (2019); Barboni (2021); Heblich et al. (2021); Kleinman et al. (2022); Allen and Donaldson (2022).
- **Studies on the recovery of Hiroshima:** Hiroshima City Government (1971; 1983).

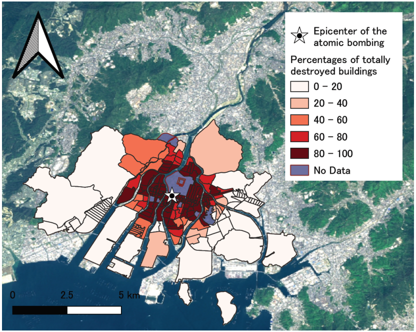
1. **Background**
2. Descriptive and reduced-form evidence
3. Model
4. Quantification
5. The role of agglomeration economies
6. The role of expectations in the recovery
7. Conclusion

Atomic bombing in Hiroshima

- We analyze the atomic bombing of Hiroshima.
  - Mainly focus on Hiroshima due to data availability and city size, but we also present similar reduce-form results for Nagasaki.
- Since the construction of the Hiroshima castle in the Samurai era, Hiroshima has been a major city in Japan.
  - Population around 1940 was about 400,000.
- The atomic bomb (known as "Little Boy") was dropped by US Army Air Forces on August 6, 1945, close to Hiroshima's city center.
- Soon after the bombing, radioactive contamination became not severe as it mitigated rapidly
  - Especially after a large typhoon in September 1945 that washed away contaminated substances.

Atomic bombing in Hiroshima as a shock to city structure





- Catastrophic damage, especially near the city center.
  - The death rate was near 100% for those within 1km from the epicenter.
  - Almost all buildings within 2km from the epicenter were totally destroyed.
- But city outskirts avoided the severest destruction, and even experienced population *increase*.
  - On November 1, 1945, areas more than 3km away from the epicenter had 142% of the pre-bombing population.

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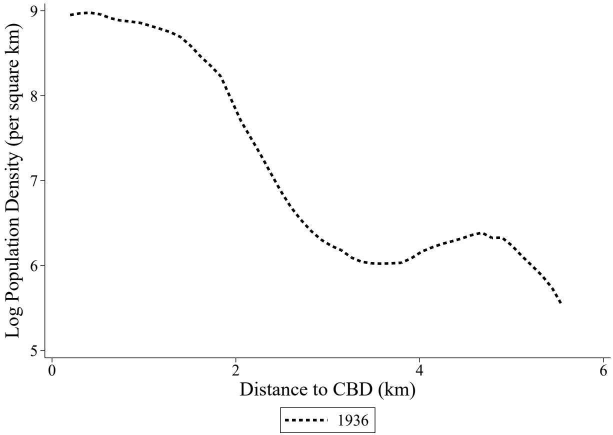
Data

- The unit of analysis is the "block" (*cho cho moku*). We use 174 blocks in Hiroshima city.
  - Average block size is $0.32km^2$
  - Blocks tend to be larger as we move away from the CBD.
- **We have collected and digitized a variety of historical sources on Hiroshima, beginning in the 1930s**. Data sources
  - Fraction of destroyed buildings by atomic bombing in each block
  - Population in each block from 1933 to 1975
  - Employment and establishment from 1938 to 1975
  - Commuting pattern
  - Proxies of fundamental locational amenities and productivity
  - Other Geographical Information System (GIS) data

Population and employment over time

- We focus on the administrative Hiroshima city as of the bombing (1945) throughout our analysis.
  - Approximately equals the metropolitan area of Hiroshima in the pre-war period.

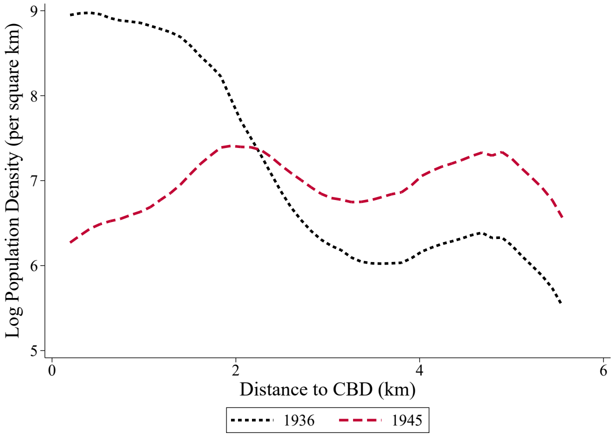
Dynamics of population density



Note: The figure shows the non-parametric regression of the log of population density on the distance to the CBD using the block-level data for different years.

- The monocentric city structure in the pre-war period.

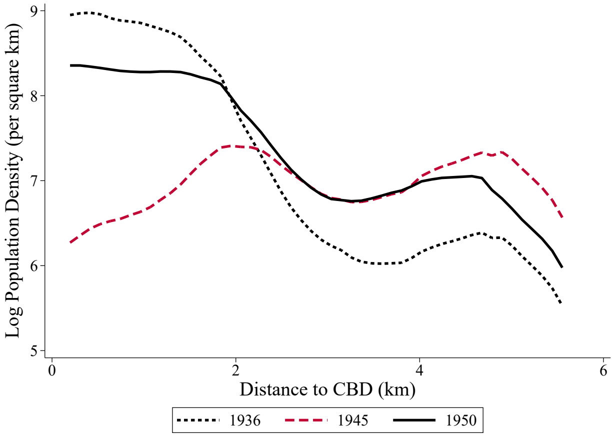
Dynamics of population density



Note: The figure shows the non-parametric regression of the log of population density on the distance to the CBD using the block-level data for different years.

- The monocentric city structure was reversed in 1945.

Dynamics of population density



Note: The figure shows the non-parametric regression of the log of population density on the distance to the CBD using the block-level data for different years.

- The monocentric city structure recovered already in 1950. Considering pre-war trend

Reduced-form evidence

- We estimate the following reduced-form model analogous to Davis and Weinstein (2002):

$$\ln\left(\frac{\text{Popdens}_{i,t}}{\text{Popdens}_{i,1945}}\right) = \gamma \times \ln\left(\frac{\text{Popdens}_{i,1945}}{\text{Popdens}_{i,1936}}\right) + \eta X_i + v_i,$$

- Descriptive regression of the post-war population growth rate on the destruction rate of the population.

- γ describes how the shock is persistent in the data.
  - $\gamma = 0$ suggests no recovery:

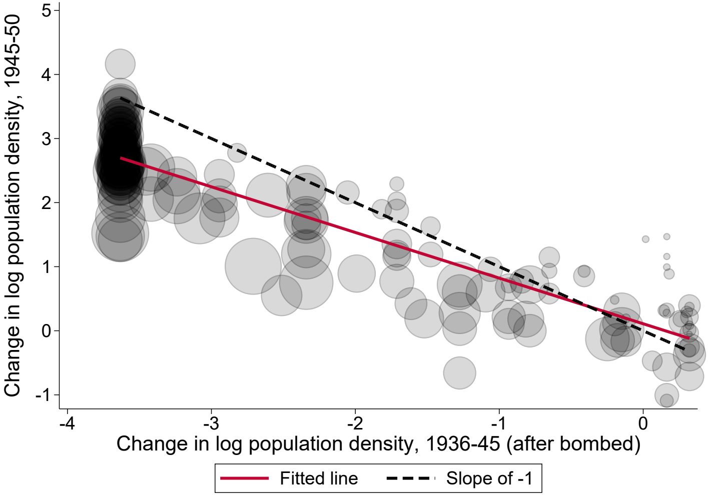
$$\ln \text{Popdens}_{i,t} = \ln \text{Popdens}_{i,1945} + \eta X_i + v_i,$$

  - $\gamma = -1$ suggests complete recovery:

$$\ln \text{Popdens}_{i,t} = \ln \text{Popdens}_{i,1936} + \eta X_i + v_i$$

- X_i is the locational characteristics of block i, such as natural conditions and transportation access
  - If fundamentals explain the post-war population growth (i.e., the recovery), then controlling for them would drive γ closer to zero. List of controls

Reduced-form evidence

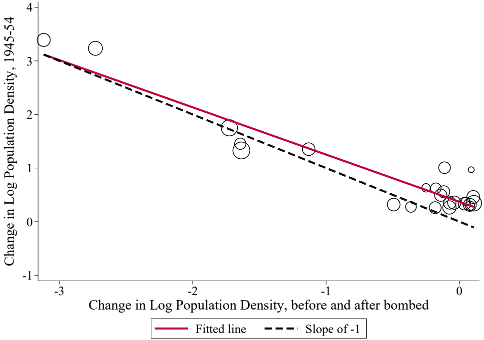


- γ is far from 0 but close to -1 (strong recovery).

Reduced-form evidence

	(1)	(2)	(3)	(4)	(5)	(6)
	Change in log population density 1945 - 1950			Change in log population density 1945 - 1960		
Change in log population density 1936-1945	-0.712	-0.931	-0.979	-0.688	-0.929	-1.007
	(0.026)	(0.100)	(0.097)	(0.030)	(0.101)	(0.117)
p-value from testing $\gamma = -1$	0.000	0.499	0.835	0.000	0.492	0.949
Control variables		✓	✓		✓	✓
Within 3 km from the city center			✓			✓
Number of blocks	174	174	158	174	174	158
R-squared	0.809	0.862	0.880	0.772	0.854	0.862

- Controlling for locational characteristics, we cannot reject $\gamma = -1$ (complete recovery) List of controls
- Therefore, it is unlikely that the city center could recover because it is innately an attractive place
  - $\gamma = -1$ even by focusing on smaller homogeneous areas (within 3km from the CBD)
  - Other robustness checks lead to similar conclusion Further robustness on reduced-form analysis



- The bomb hit an outskirt of Nagasaki, while it hit the city center in Hiroshima
- But we obtain $\gamma = -1$ (complete recovery) also for Nagasaki.
  - Recovery despite lacking potential locational advantages of pre-war city center

Summary of the reduced-form findings

- **Extremely large shock on city structure** – the city had a monocentric city structure but the atomic bombing reversed the pattern.
  - The center became the *least* populated place.
- However, **strong resilience:** the city center recovered just in five years
- Moreover, we find **little evidence that the fundamental locational advantages of the city center explain the recovery**
  - People chose to live in the city center again not because it was innately a good place
- To further explore the mechanisms behind the recovery, we now **take a structural approach**

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Overview of our structural analysis

- We first construct a **novel dynamic quantitative urban model,** which can capture
  - **Heterogeneity in locational characteristics**
  - **Initial distribution of population and employment** (history)
  - **Expectations in the future city structure**
- We **calibrate it to the post-recovery data (1950–1975)**
  - Due to data unavailability, we could not use the pre-war period data for calibration
- Show that the **calibrated model can well explain the data of the recovery period (1945–1950).**
- Through counterfactual analyses, we highlight that **agglomeration economies and expectations in the recovery are they key for the rebuilding of central Hiroshima**.

Model overview

- A first quantitative urban model with all of the following key features:
  1. Commuting: Workplace and residence can be different.
  2. Forward-looking migration decisions: Workers solve the dynamic problem of workplace and residence choice.
  3. History dependence in migration frictions and history-dependent fundamentals.
- At the same time, the model is parsimonious in many aspects due to the relatively limited data availability in Hiroshima around the atomic bombing.

Model overview

The option value of living in n and working in i assessed in period t is:

$$V_{int} = \ln u_{int} + (1-\theta_{t+1})\rho V_{int+1} + \underbrace{\theta_{t+1}}_{\text{Migration opportunity}} \sigma \ln \sum_{d\in\{\mathcal{C}\times\mathcal{C},\,o\}} \exp(V_{dt+1})^{\rho/\sigma}.$$

$$\ln u_{int} = \underbrace{\ln B_{nt}}_{\text{Amenity}} + \underbrace{\ln w_{it}}_{\text{Wage}} - \ln \kappa_{int}.$$

$w_{it} = A_{it}$

Local labor market

$$B_{nt} = b_{nt}\left(\frac{R_{nt}}{S_n}\right)^{\beta_1}\left(\frac{R_{nt-1}}{S_n}\right)^{\beta_2}$$

$$A_{it} = a_{it}\left(\frac{L_{it}}{S_i}\right)^{\alpha_1}\left(\frac{L_{it-1}}{S_i}\right)^{\alpha_2}$$

agglomeration

$$\lambda_{int+1} = \frac{\exp(V_{int+1})^{\rho/\sigma}}{\sum_{d\in\{\mathcal{C}\times\mathcal{C},\,o\}}\exp(V_{dt+1})^{\rho/\sigma}}, \quad i,n\in\mathcal{C}$$

The mass of workers who live in n and work in i in period $t+1$ is:

$$L_{int+1} = (1-\theta_{t+1})L_{int} + \theta_{t+1}\lambda_{int+1}\mathcal{M}$$

Details of the model

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Overview of model quantification

The quantification of the model proceeds in steps:

1. Calibrating parameters $\kappa_{int}, \rho, \sigma, \theta_t, u_{ot}$. Details
2. From the observed flow of population and employment, back out the "attractiveness" of each block as residence and workplace. Details
3. Estimate the amenity and productivity spillovers $(\alpha_1, \alpha_2, \beta_1, \beta_2)$ by GMM. Details
   - Identification assumption: changes in amenities and productivity of each block over time are best explained by the model, not by structural errors.
   - Net positive agglomeration forces: $(\alpha_1, \alpha_2, \beta_1, \beta_2) =$ (0.24, -0.07, 0.20, 0.02)

Remark:

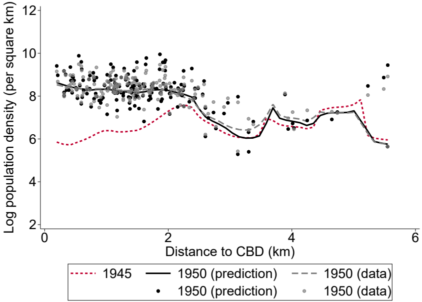
- For estimation, we use population and employment data 1950–1975 with the 5-years interval.
  - We then examine how much the model can explain the 1945-1950 data, which reflects the response to the historical shock. This period is not used for estimation.

Model fit: Accounting for the recovery period 1945–1950.

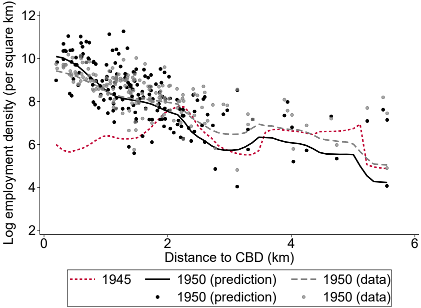
- **How well does our model explain the recovery of central Hiroshima in 1945–1950?**
- We assess how well our model can explain the recovery without structural errors of the model.
- Assumptions:
  - The spillover parameters (β_1, β_2), the block-fixed amenities $\bar{b}_n$, and composite amenities in 1955 $\Xi_{n,55}$ are the same as our calibration from 1955-1975.
  - Higher mobility right after the war $(\theta_{1950} = 0.9)$.
  - At 1945, people evaluate the amenities of each location while anticipating that the 1950 population distribution observed in data would realize
- The employment distribution is simulated under analogous assumptions on productivity.

Model fit: Accounting for the recovery period 1945–1950.

Our calibrated model successfully predicts the rebuilding during 1945–1950. Method



Population density



Employment density

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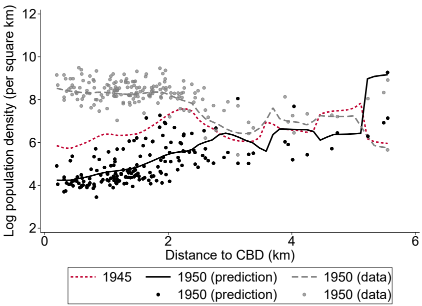
The role of agglomeration economies

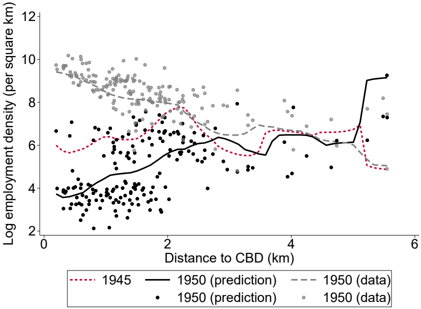
When shutting down the agglomeration forces (positive spillovers of population and employment density), the model fails to predict the recovery of the city center

Method

⇒ **The attractiveness of destroyed city center was coming from density, not other locational characteristics (natural conditions, infrastructure etc.)**



Population density



Employment density

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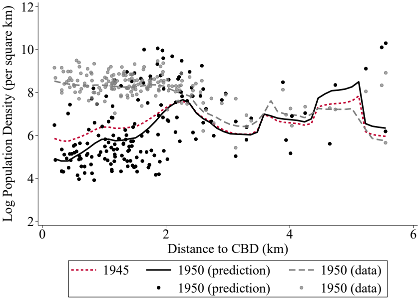
Expectations in the recovery

- We have highlighted that the key incentive for living and working in the city center is coming from agglomeration forces.
- This implicitly assumes that **people expect in the recovery of the city center** when choosing their workplace and residence.
- To show the importance of expectations in the recovery, **we contrast our main model with the case in which people do not expect in the recovery.**

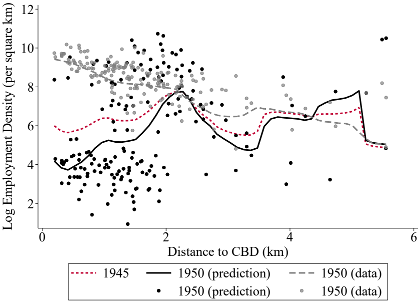
The role of expectations in the recovery

When people do not expect the recovery of the city center, the recovery does not happen as they avoid living and working in the city center Method

⇒ **People indeed chose to live and work in the center again because high density was expected in the near future**



Population density



Employment density

On the emergence of expectations in the recovery

- What we have highlighted: expectations in the recovery are essential in explaining the recovery of Hiroshima.
- Our model and data do not allow us to investigate *why* the expectations in the recovery emerged.
- Potential explanations:
  - The presence of public recovery plan
  - Surviving tram system
  - Remaining property rights
  - Narratives of rebuilding
  - Memory of the pre-war Hiroshima
- The direct impacts of these factors seem limited because of limited importance of fundamental amenities and productivity in explaining the recovery.
- However, they may have induced it indirectly through forming expectations in the recovery.

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Conclusion

- What is driving the remarkable resilience of the city structure after a catastrophic shock?
- We investigate the atomic bombing of Hiroshima, with new data and a new dynamic urban model.
- The totally-destroyed central Hiroshima recovered just five years after the bombing.
- The incentive to rebuild the destroyed central Hiroshima was coming from agglomeration economies, rather than its locational advantages.
- People chose to live and work in the city center again because they expected the high density in the near future
    - If they had not expected the recovery, the destroyed city center would not have recovered.

Appendix slides

Data sources

- Population (newly digitized)
    - 1933-1936. *Hiroshima-shi toukei sho*
    - 1945–1953. *Hiroshima shisei youran*
    - 1955–. Population census.
    - Block-level population in 1945 is estimated using less granular population data and the damage records.
- Employment/Establishment (newly digitized)
    - 1938. *Hiroshima-shi shoukou gyou keiei chosa*
    - 1946. *Hiroshima shisei youran*
    - 1953. *Hiroshima chukan jinko chosa*
    - 1957-. Business establishment statistical survey
    - We use a less granular level in 1946 and the destruction of buildings, and the 1938 distribution of establishments to estimate the block-level employment in 1945.
    - We use a less granular level in 1953, 1957, 1963 and the block-level data in 1966 to approximate the block-level employment 1945–1963.

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Data sources

- Damage by atomic bombing.
  - *Hiroshima genbaku sensai-shi* on the kill ratio and the ratio of destructed buildings.
  - Takezaki and Soda (2001) provides the GIS version.
- Commuting.
  - 1987 person-trip survey. Microdata provided by the Chugoku Region Development Bureau.
- Proxies of fundamental locational amenities and productivity.
  - Various sources, but mainly from digital national land information (the Ministry of Land, Infrastructure, Transport and Tourism) and the Hiroshima city government.
- Maps.
  - As our main definition of geographic units, we use the block boundaries as of the bombing (Takezaki and Soda 2001).
  - Newly-digitized commercial maps published in 1966 and 1976 to deal with the redrawing of the block boundaries.

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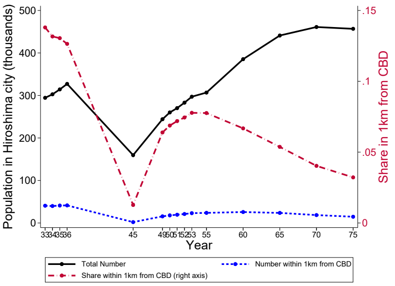
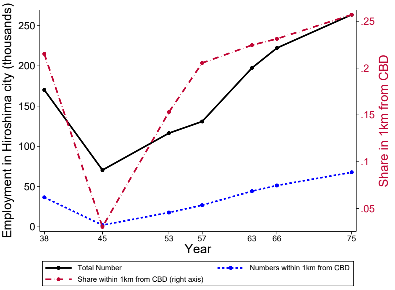
Population and employment over time



Population



Employment

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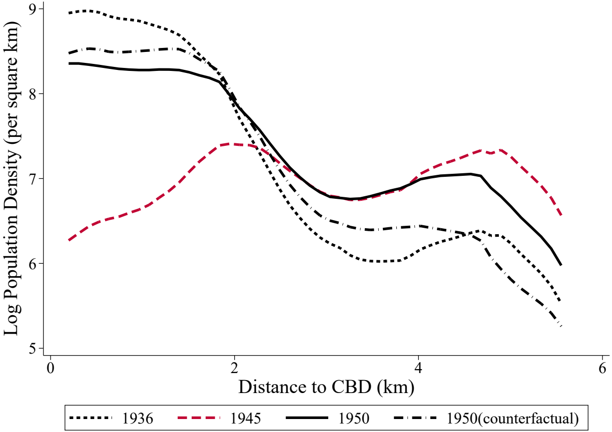
Dynamics of population density



Note: The figure shows the non-parametric regression of the log of population density on the distance to the CBD using the block-level data for different years.

- The case for the recovery is stronger once we account for the pre-war trend of population density.

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List of controls

- Natural conditions: Altitude, slope, distance to water area, soil condition, geographical coordinates.
- Human-made conditions: Distance to the nearest train station, distance to the nearest cultural asset (*bunkazai*), housing stock conditions after the bombing (fraction of half-destructed, moderately-destructed, and intact buildings).
- Pre-trend + catch-all for unobserved attractiveness: Pre-war trend (1933-1936) of the population.
- (Robustness) The spatial lag of (i) the population change rate 1936–1945, (ii) the spatial lag of natural conditions and human-made conditions, and (iii) 1945 population
  - The spatial weight matrix is set based on the spatial decay of spillovers in Ahlfeldt et al. (2015) or a gravity model estimate based on geographical distance in 1987 Hiroshima Person Trip Survey Data.
- (Robustness) The number of public housing units.

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Further results on reduced-form results

- Recovery in employment distribution. $\gamma \simeq -0.86 \sim -1$.
- Recovery in land prices. The location with the highest land price in a city is the same before and after the war.
- Timing of the recovery: the population increase of the center had already started in 1946.
- The characteristics of neighboring blocks (the spatial lag of explanatory variables in the "SLX" model).
  - Wartime population change rate of neighboring blocks
  - Locational characteristics of neighboring blocks
  - 1945 population of neighboring blocks (proxy for market access)
- Public recovery policies (public housing): controlling for public housing does not change the results. Other plans were not well implemented right after the war due to budget shortage.

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Production

- Discrete blocks in a city, and continuum of individuals living for finite time up to period T.
  - We assume that the last period is approximately the steady state.
- Competitive firms producing homogeneous tradable goods and workers commute between blocks subject to commuting costs.
- Firms in block i in period t has the linear production technology:

$$y_{it} = A_{it} L_{it}$$

- **Contemporaneous and lagged productivity spillovers with respect to employment density** (Allen and Donaldson 2022): microfoundations

$$A_{it} = a_{it} \left(\frac{L_{it}}{S_i} \right)^{\alpha_1} \left(\frac{L_{it-1}}{S_i} \right)^{\alpha_2}$$

- Perfect competition implies the wage rate in i: $w_{it} = A_{it}$.

Preferences

- Period utility of workers living in n and working in i in period t:

$$\ln u_{int} = \ln B_{nt} + \ln w_{it} - \ln \kappa_{int},$$

where κ_{int} is the bilateral commuting cost.

- **Contemporaneous and lagged spillovers in amenities with respect to population density** (Allen and Donaldson 2022): microfoundation

$$B_{nt} = b_{nt} \left(\frac{R_{nt}}{S_n} \right)^{\beta_1} \left(\frac{R_{nt-1}}{S_n} \right)^{\beta_2}$$

- Workers also have an option to live and work outside the city that yields exogenous utility u_{ot}.

Migration

- With probability θ_{t+1}, people get a migration opportunity at the end of period t to choose new workplace and residence in $t+1$.
  - **Calvo-style migration friction** (Heblich et al. 2021).

- Following Caliendo et al. (2019), the **forward-looking migration decision** is made to solve the following:

$$\max\left\{\rho V_{j\ell t+1} + \sigma\varepsilon_{j\ell t+1}\ ;\ \rho V_{ot+1} + \sigma\varepsilon_{ot+1}\right\},$$

  - $V_{j\ell t+1}$ is the value function of living in ℓ and working in j.
  - ρ is the discount factor.
  - $\varepsilon_{j\ell t+1}$ is the idiosyncratic preference to the workplace-residence pair following the Gumbel distribution and σ governs its variance. Bellman equations

- Agents expect all future variables, including the location choices of the other workers, from $t+1$ in making the migration decision at the end of period t.

- **Workplace-residence choice probability**:

$$\lambda_{j\ell t+1} = \frac{\exp(V_{j\ell t+1})^{\rho/\sigma}}{\sum_{\iota\in\{(j',\ell'),o\}}\exp(V_{\iota t+1})^{\rho/\sigma}}$$

Equilibrium

- Mass of workers living in n and working in i is

$$L_{int+1} = (1 - \theta_{t+1})L_{int} + \lambda_{int+1}\theta_{t+1}\mathcal{M},$$

  where $\mathcal{M}$ is the total mass of agents in this economy including those living outside Hiroshima.

- Equilibrium conditions:
  1. Value functions solve the Bellman equation. Bellman equations
  2. Commuting market clear in the city: the employment and population at each block are consistent with the flow equation above.
  3. Workers optimally choose their workplace and residence.
  4. Firms maximize their profits and zero profit condition.

- We can analytically show: Proposition
  - the existence of equilibrium and the steady state
  - the uniqueness of the steady state when the net agglomeration economies are negative ($\alpha_1 + \alpha_2 < 0$ and $\beta_1 + \beta_2 < 0$)

Microfoundations of spillovers

Spillovers for productivity

- Production capital supply: Infrastructure depreciation or increased cost of new construction ($\alpha_2 < 0$)
- Idea creation: New ideas are less likely to be adopted when there are more incumbents ($\alpha_2 < 0$).

Spillovers for amenity

- Housing market: More housing stock implies lower housing cost ($\beta_2 > 0$)

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Bellman equations

The expected value of living in n and working in i at time t and the expected value of living and working outside Hiroshima solve the following:

$$V_{int} = \ln u_{int} + (1 - \theta_{t+1})\rho V_{int+1} + \theta_{t+1}\mu_{t+1}$$
$$V_{ot} = \ln u_{ot} + (1 - \theta_{t+1})\rho V_{ot+1} + \theta_{t+1}\mu_{t+1},$$

where

$$\mu_{t+1} = \sigma \ln \left(\sum_{(j,\ell)} \exp(V_{j\ell t+1})^{\rho/\sigma} + \exp(V_{ot+1})^{\rho/\sigma} \right).$$

μ_{t+1} is the "option value of moving," that is, the expected utility at time t by making the migration decision for $t+1$.

- We assume $V_{inT} = \ln u_{inT}$ and $V_{oT} = \ln u_{oT}$ for values in the last period.

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Characterization of the equilibria and the steady states

Proposition 1

(i) Given the initial state and exogenous factors, the forward-looking competitive equilibrium such that, for all periods $t = 1, 2, \cdots, T$, $R_{nt} \geq (1-\theta_t)R_{nt-1}$ and $L_{it} \geq (1-\theta_t)L_{it-1}$, exists. (ii) The steady-state equilibrium exists when $\alpha_1 + \alpha_2 \neq \sigma/\rho$ and $\beta_1 + \beta_2 \neq \sigma/\rho$. (iii) A sufficient conditions for the unique steady state are negative net spillovers: $\alpha_1 + \alpha_2 \leq 0$ and $\beta_1 + \beta_2 \leq 0$.

- When $\alpha_1 + \alpha_2 > 0$ or $\beta_1 + \beta_2 > 0$, the steady states can be multiple.
- We have numerically found multiple steady states under our estimates of $(\alpha_1, \alpha_2, \beta_1, \beta_2)$.

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Step 1: Calibration of parameters

- We obtain the bilateral commuting cost κ_{int} by a nested logit model of commuting mode choice estimated by 1987 trip survey data (c.f., Tsivanidis 2022). Details

- Based on the commuting gravity equation at the steady state, we estimate the commuting elasticity $\rho/\sigma = 8$. Estimation results
  - Close to the estimate of Dingel and Tintelnot (2022) and Ahlfeldt et al. (2015).

- We set $\rho = 0.66$ based on popular discount factor in developing countries (e.g., Garcia-Cicco et al. 2010).

- The Calvo migration friction is set to $\theta_t = 0.53$ after 1950.
  - Calibration is based on census data about the fraction of people changing their residence.

- u_{ot} is matched to the total population of the city.
  - Our focus is the population and employment distribution *within* the city.

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Step 2: Back out residence and workplace attractiveness

- The population and employment flow and the migration probabilities imply

$$R_{nt} - (1-\theta_t)R_{nt-1} = \sum_i \frac{K_{int}\Xi_{nt}^{\rho/\sigma}}{\sum_j K_{ijt}\Xi_{jt}^{\rho/\sigma}}[L_{it} - (1-\theta_t)L_{it-1}]$$

$$L_{it} - (1-\theta_t)L_{it-1} = \sum_n \frac{K_{int}\Omega_{it}^{\rho/\sigma}}{\sum_j K_{jnt}\Omega_{jt}^{\rho/\sigma}}[R_{nt} - (1-\theta_t)R_{nt-1}]$$

- (Ξ_{nt}, Ω_{it}) captures residence and workplace attractiveness.
- We can solve the above equations for Ξ_{nt} and Ω_{it}
  - The unique up-to-scale solution with a normalization for the geometric mean of Ξ_{nt} and Ω_{it}.
- This strategy is conditional on the observed equilibrium and it works even if the model has multiple equilibria.

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Step 3: Estimate the spillover parameters

- **Identification strategy:** Minimize the role of time-varying idiosyncratic fundamentals (=structural errors) in accounting for the attractiveness of each block.
- We first separate exogenous fundamentals and spillover effects.
- Given (β_1, β_2), we use

$$\Xi_{nt} = b_{nt} \left(\frac{R_{nt}}{S_n} \right)^{\beta_1} \left(\frac{R_{nt-1}}{S_n} \right)^{\beta_2} \Xi_{nt+1}^{\rho(1-\theta_{t+1})}$$

  to solve for exogenous part of amenities b_{nt}.
- Do analogous thing to recover fundamental productivity a_{it} from Ω_{nt} given (α_1, α_2).

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Step 3: Estimate the spillover parameters

- As moment conditions, we posit that changes in the fundamental amenities and productivity are mean zero within the same distance bin k from the CBD (c.f., Ahlfeldt et al. 2015; Heblich et al. 2020):

$$\mathbb{E}[\Delta \ln a_{nt} \times \mathbb{I}_n(k)] = 0, \quad \mathbb{E}[\Delta \ln b_{it} \times \mathbb{I}_i(k)] = 0.$$

- Note that the first-difference means that we allow for any block-fixed amenities and productivity.
- We iterate over guessed $(\alpha_1, \alpha_2, \beta_1, \beta_2)$ to minimize the deviation from the moments.

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Step 3: Estimate the spillover parameters

- We get
$$(\alpha_1, \alpha_2, \beta_1, \beta_2) = (\mathbf{0.24}, -\mathbf{0.07}, \mathbf{0.20}, \mathbf{0.02})$$
which are all statistically different from zero. Table
- The first estimate of Allen-Donaldson spillovers in a within-city setting.
- $\alpha_1 + \alpha_2 > 0$ and $\beta_1 + \beta_2 > 0$ imply possibility of multiple steady-states.
  - We can show that $\alpha_1 + \alpha_2 \leq 0$ and $\beta_1 + \beta_2 \leq 0$ are *sufficient* for the unique steady state.
  - We numerically found multiple steady states because of positive net agglomeration forces.

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Estimating commuting cost

- Given the workplace i and residence n, a worker chooses a travel mode (walk, bus, train, bike, car) to minimize the travel cost.
- Nested logit: Public modes (walk, bus, train) and private modes (bike, car)
  - Travel time negatively impacts travel cost.
  - Strong substitution within nests ($\lambda \simeq 0.1$).
- We use the expected travel cost as the (log of the) bilateral travel cost.
- To calculate the commuting cost prior to 1987, we assume lower car ownership rate in prior years.

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Estimation results of the commuting gravity equation

The following standard gravity equation holds in a steady state:

$$\ln L_{in} = -\frac{\rho}{\sigma} D_{in} + \mathbb{W}_i + \mathbb{H}_n + \xi_{in},$$

The results from the 1987 person-trip survey of Hiroshima:

	(1)	(2)	(3)	(4)	(5)	(6)
	Log Commuting Flow		log (Commuting Flow + 1)		Commuting Flow	
Average commuting cost ($\bar{c}_{in}$)	-4.082	-3.976	-5.758	-3.931	-8.019	-7.031
	(0.156)	(0.170)	(0.179)	(0.169)	(0.195)	(0.215)
Estimation	OLS		OLS		PPML	
Number of observations	2,473	1,635	4,356	1,635	4,290	1,635
More than 20 commuters		✓		✓		✓
R-squared or Pseudo R-squared	0.543	0.522	0.551	0.521	0.764	0.729

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Estimation results of spillover parameters

	(1)	(2)	(3)	(4)
	All blocks		Blocks in 3 km to CBD	
	Productivity	Amenities	Productivity	Amenities
Elasticity of employment density (α_1)	0.237		0.239	
	(0.0010)		(0.0001)	
Elasticity of past employment density (α_2)	-0.065		-0.066	
	(0.0008)		(0.0001)	
Elasticity of population density (β_1)		0.198		0.222
		(0.0014)		(0.0046)
Elasticity of past population density (β_2)		0.023		0.006
		(0.0009)		(0.0043)

Note: This table reports estimates of the generalized method of moments (GMM) using data for five periods (1955, 60, 65, 70 and 75) and 174 blocks (all blocks) or 158 blocks (blocks in 3 kilometers to CBD). We divide the blocks into five grids according to the distance from the CBD. We use the two-step GMM estimation and the standard errors are in parentheses. In Column 1 and 2, we use all blocks and in Columns 3 and 4, we use blocks in 3 kilometers to CBD. We also report parameter values of migration frictions and commuting elasticity. Back

Making predictions for 1945–1950.

- We calculate the composite amenities Ξ_{n1950} to predict population distribution in 1945–1950.
  - The system of equations used in Step 2 of calibration determines the predicted population and employment Step2 equations

- When predicting the 1950 population without structural errors:

$$\Xi_{n,1950} = \bar{b}_n \left(\frac{R_{n,1950}}{S_n} \right)^{\beta_1} \left(\frac{R_{n,1945}}{S_n} \right)^{\beta_2} \Xi_{n,1955}^{\rho(1-\theta_{1955})}$$

- For the case of no agglomeration, we can formulate Ξ_{n1950} as the sum of discounted values of amenities.

$$\Xi_{n1950} = \mathbb{B}_{n1950} \equiv b_{n1950} \prod_{\tau=1955}^{T} (b_{n\tau})^{\prod_{s=t+1}^{\tau} \rho_s(1-\theta_s)}$$

- In the case of no expectations in the recovery, we use

$$\Xi_{n1950} = \mathbb{B}_{n1950} \left(\frac{R_{n1945}}{S_n} \right)^{\beta_2} \left(\frac{R_{n1945}}{S_n} \right)^{\beta_1 + (\beta_1+\beta_2) \sum_{\tau=t+1}^{T} \prod_{s=1955}^{\tau} \rho_s(1-\theta_s)}$$