

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

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Abstract

We provide new theory and evidence on the resilience of internal city structure after a large shock. We analyze the atomic bombing of Hiroshima, which destroyed the city center but not its outskirts. Exploiting newly digitized data on block-level population and employment, we document that the city structure recovered within five years after the bombing. We then develop a dynamic quantitative model of internal city structure, which incorporates commuting, forward-looking location choices, migration frictions, agglomeration forces, and heterogeneous location fundamentals. Strong agglomeration forces in our estimated model can explain the recovery of Hiroshima. While we find an alternative equilibrium in which the city center did not recover, self-fulfilling expectations selected the equilibrium in which the city center recovered. These results highlight the importance of agglomeration forces, multiple equilibria, and expectations in the dynamics of city structure.

Key words: agglomeration, history, expectations, atomic bombing, spatial dynamics

JEL classification: C73, N45, O18, R12, R23

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1 Introduction

Cities have faced a host of shocks throughout history. Wars, natural disasters, pandemics, and technological shocks have all impacted city structure – the spatial distribution of economic activities within cities, particularly the concentration of activities in the center relative to the periphery. However, there remains substantial debate about whether city structure is resilient to large shocks (Glaeser 2022). Is city structure resilient to large shocks? If so, what are the mechanisms behind this resilience? Answering these questions would aid the reconstruction of war-torn cities, improve urban revitalization efforts, and inform planning for future shocks. However, there are two important challenges in answering these questions. First, we rarely observe a large shock to city structure that allows us to trace out spatially-granular data on economic activities over a long period of time. Second, we need a quantifiable model of the dynamics of internal city structure that allows us to disentangle the mechanisms underlying the resilience of city structure.

In this paper, we shed light on the resilience of city structure by analyzing the atomic bombing of Hiroshima, one of the most remarkable examples of urban resilience in human history. The atomic bombing completely destroyed the city center while sparing its outskirts. This distinctive and massive shock provides a unique laboratory for studying the dynamics of city structure. We collect and digitize new granular historical data on the distribution of economic activities within Hiroshima. Using this data, we first document that the city structure of Hiroshima recovered to its pre-war state within five years after the bombing. We then construct and calibrate a new dynamic quantitative model of internal city structure, which explains this observed recovery. In our calibrated model, strong agglomeration forces created by population and employment density yield better local amenities and increase productivity. This provided the key incentive for people to again live and work in the city center. Furthermore, we show that these agglomeration forces induce multiple equilibria. In particular, there exists an alternative equilibrium in which the city center did not recover, in contrast to the observed recovery equilibrium. We argue that self-fulfilling expectations of recovery played an important role in realizing the recovery equilibrium.

We begin by describing the historical context and our newly collected data on the distribution of economic activities within Hiroshima. The majority of the administrative region of Hiroshima as of 1945 lay within 6 kilometers of the city center. On August 6, 1945, the atomic bomb hit near the city center and destroyed almost all structures within 2 kilometers of the city center, but many structures on the outskirts of the city were much less affected. Some areas on the outskirts even experienced an increase in population due to the inflow of survivors from the city center. Consequently, the atomic bombing was an extremely large shock to city structure: the pre-war city center now had the lowest population and employment density in the city. To conduct our quantitative analysis at a spatially granular level, we collect and digitize new historical data on population, employment,

wartime destruction, and fundamental characteristics at the city block level within Hiroshima. Importantly, our dataset covers both the pre-bombing and immediate post-bombing periods, allowing us to investigate the recovery of central Hiroshima in detail.

Through descriptive and reduced-form analyses, we reveal that the structure of Hiroshima was resilient to this unprecedented shock. Our findings are twofold. First, the destroyed city center again became the main concentration of economic activity within five years of the atomic bombing. Second, the recovery of central Hiroshima cannot be explained by various observed fundamental location characteristics, which refer to characteristics of a location that could directly affect amenities and productivity independently of the local density of economic activities (e.g., altitude, access to natural water). There are two possible explanations for these findings. First, while our results suggest that the recovery of the city center is not explained by its observed locational advantages, it is possible that the destroyed city center retained some unobserved locational advantages that survived the bombing (e.g., scenic views). Second, people may have expected the recovery of the destroyed city center when making location choices, and the incentive to again live and work in the city center came from agglomeration forces due to expected high density as in the pre-war period. We analyze these two possible explanations using our structural model.

We develop a new dynamic quantitative model of internal city structure. Our model is the first quantitative urban model that accommodates commuting, forward-looking location choice, migration frictions, agglomeration forces, and heterogeneous location fundamentals. The commuting patterns within a city are endogenously determined by individual choices of workplace and residence. Individuals correctly anticipate the future path of the economy when making location decisions, and neighborhood amenities and productivity depend on population and employment density. Location-specific fundamental amenities and productivity capture the heterogeneous advantages of locations in a city that are independent of population and employment density. In addition, our model incorporates migration frictions, which induce history-dependence in city structure. These model elements are necessary to capture alternative possible determinants of the dynamics of internal city structure.

We calibrate our model and evaluate its performance to explain the recovery of central Hiroshima. We estimate the model using the observed location choices of people in Hiroshima from 1955 to 1975, after the period of rapid recovery, because sufficient data for calibrating our model are available for this time period. We leverage the structure of the model to estimate model parameters and compute unobserved location characteristics. Our key parameters describe how the agglomeration forces increase amenities and productivity as population and employment density rise. We estimate these forces under the identification assumption that exogenous changes in the amenities and productivity of each block over time are uncorrelated with distance from the city center, while allowing for arbitrary heterogeneity in the levels of location-specific amenities and productivity. We

find strong agglomeration forces in both amenities and productivity. Then, we assess how well our calibrated model fits the location choice data for 1950 when people had returned to the destroyed city center. The endogenous mechanisms of our model successfully account for the resurgence observed in the data.

We highlight that in our calibrated model, agglomeration forces play a key role in explaining the recovery of central Hiroshima. We carry out a counterfactual analysis in which agglomeration forces in amenities and productivity are absent and fundamental productivity and amenities for 1950 are equal to the estimated values for 1955–1975. We find that our calibrated model without agglomeration forces cannot predict the recovery of the city center, consistent with the idea that agglomeration forces played an important role in the resurgence of the center. Theoretically, in the presence of strong agglomeration forces, there is potential for multiple equilibria because the city center would not be attractive if its recovery were not expected in the near future. To investigate this, we numerically solve the model for an alternative rational expectations equilibrium in which the population and employment densities of the city center do not recover. This suggests that the observed pattern of recovery is one equilibrium selected from multiple, and that self-fulfilling expectations of recovery played an important role in selecting this equilibrium. We argue that certain factors, such as government recovery plans, the anchoring effect of salient location characteristics in the city center (e.g., tram networks, destroyed Hiroshima castle), property rights, and popular narratives of rebuilding, may have induced expectations that the destroyed city center would return to its high density as in the pre-war period. Our results highlight the importance of these factors in the rapid recovery of city structure through fostering the formation of such recovery expectations.

Overall, our analysis of Hiroshima highlights the role of agglomeration forces, multiple equilibria, and expectations in the economic dynamics of city structure. For cities recovering from a large shock, our findings indicate the importance of agglomeration forces and creating potentially self-fulfilling expectations for recovery. Our results further suggest that policymakers could substantially change the dynamics of city structure if they could influence expectations about a city's future.

This paper contributes to studies on the determinants of the spatial distribution of economic activities, particularly the concentration of economic activity in space. This is at the core of urban economics and economic geography. A theoretical literature has uncovered the importance of fundamental location characteristics and agglomeration forces in shaping the spatial distribution of economic activities (Henderson 1974; Fujita 1989; Fujita and Thisse 1996; Fujita, Krugman and Venables 1999; Redding and Rossi-Hansberg 2017). Moreover, when agglomeration forces are important relative to heterogeneity in location characteristics so that there are multiple equilibria, initial conditions (“history”) or self-fulfilling expectations may determine the spatial distribution of economic activities by selecting a particular equilibrium (Krugman 1991; Matsuyama 1991). We

empirically contribute to this discussion by analyzing the atomic bombing of Hiroshima as a large exogenous shock to city structure and showing the importance of agglomeration forces, multiple equilibria, and expectations in the economic dynamics of city structure.¹

Many empirical studies have investigated the importance of historical shocks as determinants of the spatial distribution of economic activities. Previous studies exploiting war-time destruction across cities and regions have typically found that large shocks have only temporary impacts (Davis and Weinstein 2002, 2008; Brakman, Garretsen and Schramm 2004; Bosker, Brakman, Garretsen and Schramm 2007; Miguel and Roland 2011; Feigenbaum, Lee and Mezzanotti 2022).² Among others, Davis and Weinstein (2002) finds that the population distribution *across* Japanese cities after World War II converged with its pre-war trends, including Hiroshima. Yet, studies that exploit shocks other than war-time destruction often find that large shocks can have persistent or permanent effects on the spatial distribution of economic activities (as reviewed in Glaeser 2022 and Lin and Rauch 2022).³ Our paper is distinctive from these studies in three important ways. First, we use new spatially granular data to analyze the spatial distribution of economic activities *within* a city.⁴ Second, we use the atomic bombing of Hiroshima as an exogenous and unprecedentedly large shock to the internal structure of a city. Most importantly, we construct and apply a novel dynamic quantitative urban model to this historical shock to investigate why we observe such resilience in Hiroshima, highlighting the role of agglomeration forces and self-fulfilling expectations in overcoming the catastrophe. In particular, the importance of self-fulfilling expectations can reconcile the above-mentioned empirical studies that are split on the persistence of historical shocks: we often observe a resilient spatial distribution of economic activities because expectations of recovery tend to emerge after war-time destruction, but not in other contexts with different expectations.

¹The potential importance of self-fulfilling expectations in creating a resilient spatial distribution of economic activities has been theoretically recognized. For instance, Fujita and Thisse (1996) states “[a]nother reason for [a spatial structure’s] inertia...is the formation of self-fulfilling prophecies about the development of some areas. Indeed, it seems reasonable to consider existing cities as focal points that help agents coordinate their spatial decisions. In such a context, reshaping the urban landscape would then require major changes in agents’ expectations.” We highlight the empirical relevance of such a theoretical prediction about city structure through the atomic bombing of Hiroshima.

²Harada, Ito and Smith (forthcoming) and Redding and Sturm (2023) estimate the long-run impact of bombing on neighborhood quality within Tokyo and London. Our results do not contradict theirs because we ask a different question: why did the destroyed city center regain its highest population and employment density in the city? Further, we do not analyze neighborhood quality in our study because such data is unavailable in our context.

³Examples include Arthur (1994), Redding, Sturm and Wolf (2011), Bleakley and Lin (2012), Schumann (2014), Siodla (2015), Hornbeck and Keniston (2017), Michaels and Rauch (2018), Brooks and Lutz (2019), Ambrus, Field and Gonzalez (2020), Kocornik-Mina, McDermott, Michaels and Rauch (2020), Heblich, Trew and Zylberberg (2021), Allen and Donaldson (2022), Brooks, Rose and Veuger (2022), Yamasaki, Nakajima and Teshima (2022), Yamagishi and Sato (2023).

⁴Internal city structure is analyzed in the canonical urban economics literature (Fujita and Ogawa 1982; Fujita 1989; Lucas and Rossi-Hansberg 2002) and recent quantitative urban models (Ahlfeldt, Redding, Sturm and Wolf 2015; Heblich, Redding and Sturm 2020). However, these models are static and not suited for analyzing the historical-shock dependence of economic activities in a city. The empirical literature on the within-city setting is also relatively recent, as reviewed by Lin and Rauch (2022).

This paper contributes empirically to the discussion about the role of expectations in the evolution of the spatial economy. [Krugman \(1991\)](#) and [Matsuyama \(1991\)](#) show that self-fulfilling expectations can induce a transition from one steady state to another when multiple equilibria exist, implying that the initial condition determined by history can be overcome by expectations.⁵ A spatial economy with strong agglomeration forces relative to heterogeneity in fundamental locational advantages is a primary example in which multiple equilibria and equilibrium selection matter ([Fujita et al. 1999](#); [Redding and Rossi-Hansberg 2017](#)).⁶ Our contribution is to provide empirical evidence of the importance of self-fulfilling expectations in the spatial economy, which has been scarce as pointed out by [Lin and Rauch \(2022\)](#).

Our structural analysis also relates to recent advancements in quantitative spatial models ([Redding and Rossi-Hansberg 2017](#)). To analyze the resilience of city structure, we develop a new quantitative urban model with commuting, forward-looking location choices, migration frictions, agglomeration forces, and heterogeneous location fundamentals. This new model can be used in other empirical settings. Studies that consider commuting and agglomeration forces within cities (e.g., [Ahlfeldt et al. 2015](#); [Monte, Redding and Rossi-Hansberg 2018](#); [Dingel and Tintelnot 2020](#); [Tsivanidis 2022](#)) do not accommodate forward-looking migration decisions or dynamic migration frictions, while those with forward-looking migration decisions ([Desmet, Nagy and Rossi-Hansberg 2018](#); [Caliendo, Dvorkin and Parro 2019](#); [Balboni 2021](#); [Heblich et al. 2021](#); [Warnes 2021](#); [Allen and Donaldson 2022](#); [Almagro and Domínguez-Iino 2022](#); [Kleinman, Liu and Redding 2023](#)) do not incorporate commuting or agglomeration forces.⁷ Importantly, we integrate these elements into a single framework that is otherwise parsimonious since data availability in historical contexts is often limited. The tractability of the model is particularly useful in applying our model to data-scarce environments.

Lastly, this paper relates to studies on the recovery of Hiroshima from the atomic bombing ([Hiroshima City Government, 1971](#); [1983](#)). There is little econometric analysis on the distribution of economic activities within the city and the resurgence of the city center. Our paper formally analyzes the recovery pattern using newly-digitized granular historical data on population and employment and a novel quantitative economic model. This provides new evidence on the resilience of Hiroshima's city structure and a new approach to understanding the underlying economic mechanisms behind the resilience.

⁵[Fukao and Bénabou \(1993\)](#) corrects a mathematical problem in [Krugman \(1991\)](#). See [Rauch \(1993\)](#), [Holmes \(1999\)](#), [Baldwin \(2001\)](#), [Ottaviano \(2001\)](#), [Oyama \(2009\)](#), and [Barreda-Tarrazona, Kundu and Østbye \(2021\)](#) for further developments in self-fulfilling expectations and economic geography.

⁶Self-fulfilling expectations also matter in other important economic contexts with multiple equilibria, such as bank runs ([Diamond and Dybvig 1983](#)), structural transformation in economic development ([Murphy, Shleifer and Vishny 1989](#)), and health insurance ([Foley-Fisher, Narajabad and Verani 2020](#)).

⁷Migration frictions induce history-dependence in our model since they imply that equilibrium depends on initial conditions. In an extension of our model, we include an additional source of history-dependence by incorporating the lagged agglomeration forces of amenities and productivity à la [Allen and Donaldson \(2022\)](#).

The rest of the paper is structured as follows. Section 2 describes the historical context and data. Section 3 presents the reduced-form analysis and Section 4 introduces the theoretical framework. Section 5 calibrates the model and demonstrates that our model accurately fits the recovery of central Hiroshima. In Section 6 we undertake a counterfactual analysis to show the roles of agglomeration forces and expectations in the recovery. Section 7 concludes.

2 Historical Background and Data

This section briefly describes the history of Hiroshima and our study data. In Subsection 2.1, we summarize the history of the city prior to the atomic bombing and the impact of the bombing on the city. In Subsection 2.2, we describe how we construct new spatially-granular data on population, employment and other characteristics of Hiroshima. Appendix A provides further details.

2.1 Historical Background

The development of Hiroshima started in the late 16th century when Terumoto Mōri, a local samurai lord, built Hiroshima castle.⁸ Hiroshima has been a major city in the *Chugoku* region of Japan since then thanks to its proximity to the sea and rivers. Early in the 20th century, the city grew quickly. In 1935, 310,118 people lived in Hiroshima, which made it the seventh-largest city in Japan by population. As Japan gradually transitioned to a war economy through the Second Sino-Japanese War (1937–1945) and Pacific War (1941–1945), growth slowed and then reversed. Before the atomic bombing, the city had an estimated population of 350,000. As the U.S. overwhelmed Japan during World War II (WWII), most Japanese cities endured extensive non-atomic air raids (Davis and Weinstein 2002). However, the U.S. avoided bombing Hiroshima to preserve the city as the “best laboratory” for demonstrating the effects of the atomic bomb.⁹ Consequently, the atomic bombing was essentially the only direct destruction the city experienced during WWII.

On August 6, 1945, the U.S. Air Force dropped the atomic bomb “Little Boy” near the center of Hiroshima. This was the first time the atomic bomb was used to kill people in human history. The damage to people and buildings was unprecedentedly catastrophic.¹⁰ The city government of

⁸In this paper we use the word “Hiroshima” to refer to the administrative Hiroshima City (*Hiroshima-shi*). We sometimes explicitly state Hiroshima City to clearly distinguish it from Hiroshima Prefecture.

⁹Based on “Minutes of the Second Meeting of the Target Committee Los Alamos, May 10-11, 1945” (<http://www.dannen.com/decision/targets.html> Last accessed on October 28, 2023), the target of the bombing was determined based on the city’s size and its flat terrain to best measure the damage of the bombing. Notably, local economic conditions were not considered in selecting targets.

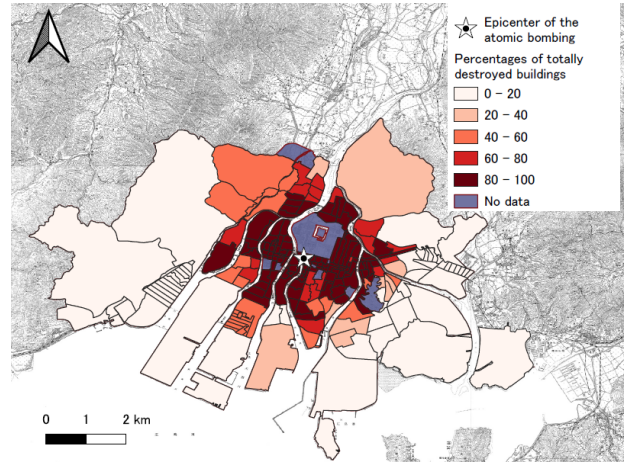
¹⁰This damage was much more severe than in other cities that endured extensive air raids. For example, the population of Tokyo was approximately 7 million in 1940. During the war, U.S. air raids on Tokyo killed over 100,000 civilians and damaged approximately 700,000 housing units. Source: <https://tokyo-sensai.net/about/tokyoraids/> (In Japanese, last accessed on October 28, 2023). While the absolute numbers are large in Tokyo, the percentage rates in Hiroshima are substantially greater than in Tokyo due to its smaller population size.

Figure 1: Destruction of the Atomic Bombing in Hiroshima

(a) Total Destruction Near the Epicenter



(b) Block-level Destruction Rate of Buildings



Note: Panel (a) is a photograph from the United States Strategic Bombing Survey made available by the U.S. National Archives and Records Administration. Panel (b) shows a map of Hiroshima at the time of the bombing, along with block-level data (197 blocks in total) on the fraction of totally destroyed buildings and the epicenter ([Hiroshima City Government 1971](#); [Takezaki and Soda 2001](#)). Remote islands (*nino-shima*, *kanawa-jima*, *touge-shima*) are omitted for better visibility. We use as the background image the 1950 topographic map taken from Time Series Topographic Map Viewer of Japan ([Tani 2017](#), <https://ktgis.net/kjmapw/>).

Hiroshima estimates that 140,000 people died by the end of 1945 as a result of the atomic bombing, although it is difficult to determine the exact number.¹¹ The death rate was near 100 percent for those within 1 kilometer of the epicenter. The bomb also destroyed a large number of buildings: 51,787 out of 76,237 buildings in Hiroshima were totally destroyed and 18,720 were partly destroyed. The vast majority of buildings within two kilometers of the city center were completely destroyed. This can be seen in Figure 1a, which was taken near the epicenter of the bombing. The population of Hiroshima dropped to 136,518 as of November 1945, about one-third of the pre-war population.

In contrast to the total destruction in central Hiroshima, the outskirts of the city were much less damaged. Figure 1b shows the fraction of completely destroyed buildings at the block level ([Hiroshima City Government 1971](#); [Takezaki and Soda 2001](#)). While nearly all buildings in the dark-colored areas close to the epicenter were destroyed, buildings in the light-colored areas away from the epicenter were much less damaged. As a result, the outskirts of Hiroshima experienced a significant increase in population as survivors from the city center flooded in. As of November 1, 1945, Hiroshima beyond 3 kilometers from the epicenter had 142 percent of its pre-bombing population.

¹¹The real death toll is likely to be even higher because the atomic bombing caused severe injuries and diseases that killed many after 1945. Source: <https://www.city.hiroshima.lg.jp/site/english/9803.html> (last accessed on October 28, 2023).

The war ended on August 15, 1945. People initially doubted whether Hiroshima could recover. Despite then-limited scientific knowledge, radioactive contamination was a major concern immediately after the bombing. Rumors circulated that “nothing will grow here for 75 years.”¹² However, the serious radioactive contamination caused by the bombing decayed rapidly.¹³ Furthermore, a large typhoon hit Hiroshima on September 17, 1945, about six weeks after the bombing. According to the U.S. Atomic Bomb Casualty Commission, the typhoon probably washed away much contaminated material, bringing the radioactivity down to a relatively safe level (Takahashi 2008). Given this evidence, we do not consider potential radioactive contamination in analyzing the recovery of Hiroshima because living in Hiroshima was unlikely to be meaningfully unhealthy after this typhoon.¹⁴

Despite initial pessimism, people gradually became optimistic about Hiroshima’s destroyed city center (Hiroshima City Government 1971). Although it is difficult to identify one single factor, several may have contributed to such optimism. We name a few. First, the city government of Hiroshima published a recovery plan. Even though the government faced a serious budget shortage and could not implement most of its plan for several years after the bombing, the plan might have induced optimism about Hiroshima’s future.¹⁵ Second, the presence of salient location characteristics in the city center, such as the transportation network and the destroyed Hiroshima castle, may have anchored people’s expectations for recovery despite the severe damage. Third, pre-war private property ownership was preserved, though almost all homeowners near the city center lost their home. Moreover, many landowners and homeowners close to the city center were killed by the bombing.¹⁶ Finally, rebuilding narratives may have been shared by people and coordinated their expectations. Since our analysis highlights that expectations of recovery may have played a key role in the recovery, we further discuss the formation of such expectations in Section 6.3.

Notwithstanding the lack of strong public actions, Hiroshima experienced a strong recovery due to private efforts. In 1955, Hiroshima had a population of 357,287, larger than the 1935 population.

¹²Source: <https://www.bbc.com/news/world-asia-53660059> (last accessed on October 28, 2023).

¹³According to the Hiroshima City Government (<https://www.city.hiroshima.lg.jp/site/english/9809.html>, last accessed on October 28, 2023), the radiation level at the epicenter was 1/1,000th a day after the bombing and 1/1,000,000th a week later.

¹⁴Note that considering potential radioactive contamination would, if anything, reinforce the main finding of our reduced-form analysis (Section 3) that the city center recovered. Since radioactive contamination is a bad that makes the city center less attractive, failing to control for it would underestimate the strength of the recovery.

¹⁵Despite the exceptionally catastrophic damage, Hiroshima could not get a special budgetary treatment until the enactment of the Hiroshima Peace Memorial City Construction Law in 1949. The city focused on providing public housing, but it could only provide 3,000 units during 1945–1950 when over 70,000 buildings were destroyed in excess of fifty percent. Consistent with the limited public housing supply, controlling for public housing does not account for the recovery (see Appendix B.1). The restoration of the pre-war infrastructure was also prioritized, but this does not provide a particular advantage to the city center as the city outskirts also had comparable infrastructure.

¹⁶In an extension of our model, we introduce attachment of surviving property owners to their original locations. We highlight that location attachment alone cannot explain the recovery of the city center because many property owners were killed by the bombing (see also Section 6.3 and Appendix D.6).

Hiroshima continued to grow and physically expanded along the way.¹⁷ Today, Hiroshima has a population of approximately 1.2 million, making it the 10th largest Japanese municipality and the largest in the *Chugoku* region of Japan.

2.2 Data

We have collected and digitized various sources of information on economic activity in Hiroshima before and after the war. Here, we provide a brief overview of our data sources. Appendix A provides more details

Spatial units The spatial unit of our analysis is a city block (*cho-cho-moku*) in Hiroshima.¹⁸ As our primary definition of city blocks, we use the block boundaries as of the bombing constructed by [Takezaki and Soda \(2001\)](#). To make the comparison between the pre-war and the post-war periods, we focus on areas that were part of Hiroshima as of the bombing.¹⁹ Throughout this paper, we use the block definitions of 1945. We address the revisions of the block boundaries over time by converting all data to the 1945 block definitions based on areal weighting interpolation, and we digitize the block boundaries of 1966 and 1976 to implement this. Throughout the paper, the number of blocks is 174 and the average size of blocks is 0.32 square kilometers. This implies that our spatial unit of analysis is generally small, although there is some heterogeneity in the size of blocks.²⁰ The average block-level population in 1936 was 1,880 for all blocks and 1,642 for blocks within 3 kilometers of the central business district (CBD).

Destruction by the atomic bombing We primarily use the fraction of totally destroyed buildings as a measure of the severity of destruction.²¹ The block-level destruction rate is reported in [Hiroshima City Government \(1971\)](#). We augment the digitization by [Takezaki and Soda \(2001\)](#) by consulting [Hiroshima City Government \(1971\)](#) to correct typos in their data and obtain additional information on missing values. Panel (b) of Figure 1 in the previous section illustrates the share of completely destroyed buildings in each block.

¹⁷As shown in [Davis and Weinstein \(2002\)](#), the aggregate city population recovered its pre-war trend around twenty years after the atomic bombing.

¹⁸Note that a Japanese city block is generally smaller than a US census tract, which has a population of around 4,000, but larger than a US census block, which has 40 housing units.

¹⁹The city boundaries gradually expanded since 1955 through municipal mergers as the Hiroshima metropolitan area grew. The administrative Hiroshima as of 1945 roughly corresponds to the four central wards (*Naka-ku, Nishi-ku, Minami-ku, Higashi-ku*) of Hiroshima today. The expansion of the administrative boundaries and commuting zones of Hiroshima implies that our data is more concentrated within the relatively central locations as time elapses.

²⁰The average area size for blocks is 0.04 square kilometers within 1 kilometer of the CBD and 0.13 square kilometers within 3 kilometers of the CBD. In contrast, the average block area is 2.19 square kilometers among blocks more than 3 kilometers from the CBD.

²¹This is similar to [Davis and Weinstein \(2002\)](#) and [Brakman et al. \(2004\)](#).

Population We collect and digitize population data at the block level. We refer to the Statistical Handbook of Hiroshima (*Hiroshima-shi toukei sho*) for 1933–1936 and the Statistical Abstract of Hiroshima (*Hiroshima shisei youran*) for 1945–1953. We also exploit data from the Population Census of 1955.²² Panel (a) of Figure 2 provides a visualization of Hiroshima’s population over time. The population of Hiroshima was increasing prior to the atomic bombing, dropped significantly after the bombing, and resumed growth again after WWII. We also observe that the center of Hiroshima declined as a share of the population over time, reflecting the suburbanization of the city that absorbed most post-war population growth. Note that this declining trend was already observed pre-WWII, suggesting that a lower central population share after the WWII does not necessarily mean that recovery was incomplete.

Employment We collect and digitize employment data at the block level from various sources.²³ For the year 1938, we refer to the Survey of Commerce and Industry in Hiroshima (*Hiroshima-shi shoukou-gyou keiei chousa*) which records the number of establishments at the block level. The number of commercial buildings right after the bombing is available in the Statistical Abstract of Hiroshima (*Hiroshima shisei youran*). For 1953, we exploit the Survey on the Daytime Population of Hiroshima (*Hiroshima-shi chukan jinko chosa*), where we assume that the daytime population approximates employment. From 1957 to 1975, we use the Business Establishment Statistical Survey (*Jigyousho toukei chousa*).²⁴ Based on these data, we approximate block level employment every five years from 1950 to 1975. Panel (b) of Figure 2 shows employment in Hiroshima over time. Total employment dropped significantly in 1945 after the bombing, but increased again post-war, and the number of workers employed in the central area recovered to its pre-war level. The share of employment in the city center rose throughout the post-war period, implying an increased concentration of employment.

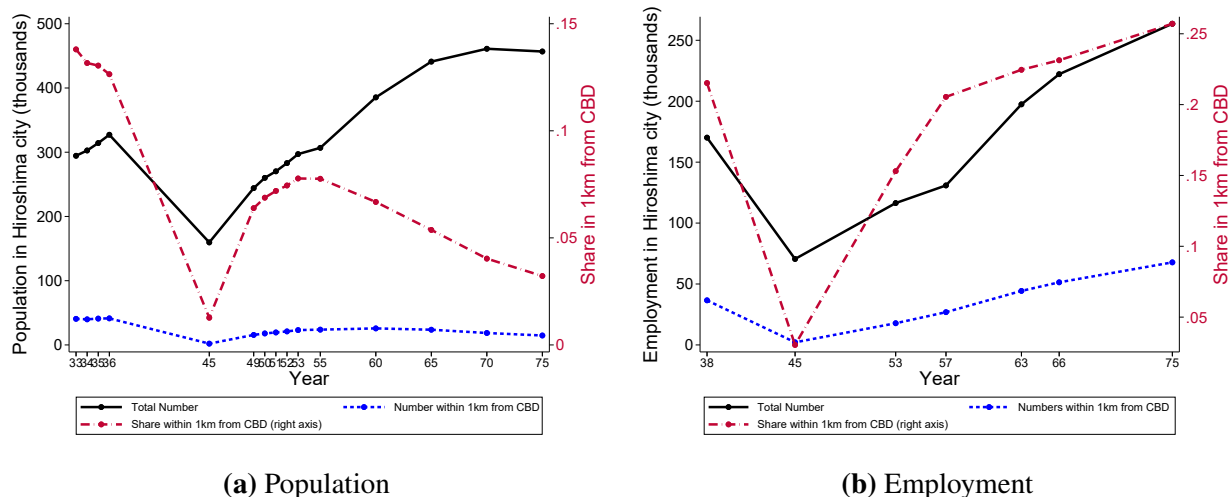
Commuting and transportation networks We use trip-level microdata from the 1987 Hiroshima City Person-Trip Survey to analyze commuting patterns. These data capture the workplace, residence, and representative travel mode for each commuting trip. We also collect and digitize road networks, bus networks, and train networks in Hiroshima and compute bilateral travel time between

²²For 1945–1950, population is reported using a more aggregated block definition. We combine this information with the block-level destruction rate of buildings to predict the block-level population distribution (see Appendix A for details).

²³Throughout this paper, we focus on employment in manufacturing or services and abstract from agricultural employment. This is a relatively moderate restriction because we focus on an urban area in which agricultural employment is small. Even in 1950, in which agricultural employment was large within the entire Japanese economy, the Population Census suggests that less than 10 percent of workers in Hiroshima City were engaged in agriculture.

²⁴For 1953–1963, employment is reported using less geographically granular units than blocks. We address this by combining the best available block-level information to approximate the block-level employment distribution. When employment data is unavailable but establishment data is available, we follow [Ahlfeldt et al. \(2015\)](#) and assume that the number of establishments is proportional to employment.

Figure 2: Population and Employment Over Time in Hiroshima City



Note: The figures show total population and employment within the entire city and within one kilometer of the CBD (left axis), as well as the shares of population and employment within one kilometer of the CBD (right axis). See Section A of the Appendix for data construction.

blocks for different modes: walk, bike, car, bus, and train. Although Hiroshima’s public transportation networks were generally stable after the war, there were some changes, notably the discontinuation of the *Ujina* line in 1966.²⁵ To address this, we use the public transportation networks of 1950 for years prior to 1966 and those of 1987 for later years.

Location characteristics We collect various information on the location characteristics of each block. In particular, we exploit data on altitude, ruggedness, soil condition, geographical coordinates, distance to the (pre-war) city center (CBD), distance to train stations, distance to Hiroshima port (*Ujina* port), distance to bodies of water, and distance to cultural assets for each block. Distances are calculated using the centroid of each block shape. The pre-war CBD is defined as the mid-point of the *Kamiya-cho* block and *Hacchobori* blocks, which were the two prominent central areas of pre-war Hiroshima. Note, however, that the recovery of the city center documented below implies that the pre-war city center corresponds to the post-recovery city center.

3 Reduced-form Evidence

In this section we analyze population density to illustrate the pattern of destruction and recovery in the city structure of Hiroshima. Subsection 3.1 describes how the atomic bombing destroyed central Hiroshima and how the city subsequently recovered to its pre-war city structure. In Subsection 3.2,

²⁵Two new lines (*Hijiyama/Minami line* and *Eba line*) opened in 1944 for military purposes, and these lines have been maintained after the war. These lines improved transportation access in the outskirts.

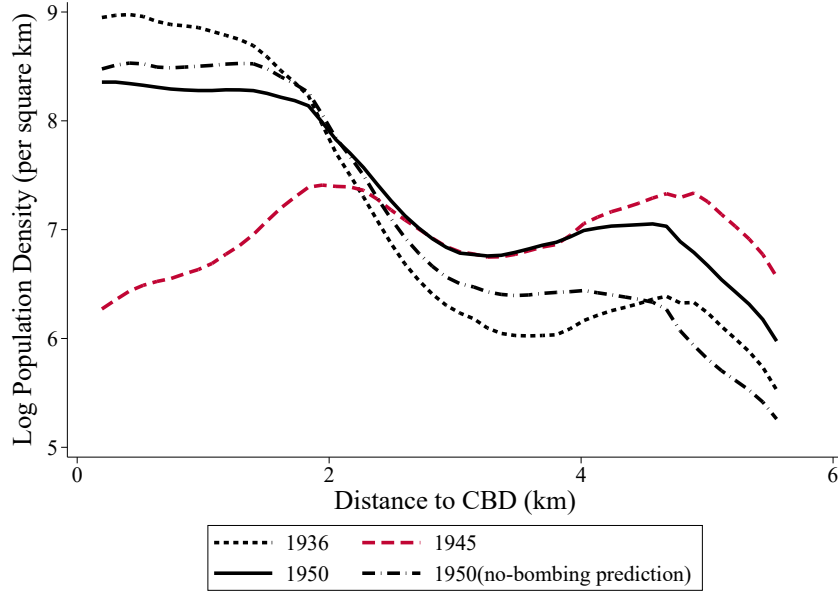
we formalize this recovery result in a regression analysis. We also find that the recovery tendency is robust to controlling for observable prominent location characteristics, which refer to characteristics of a location that directly affects amenities and productivity independently of the local density of economic activities (e.g., altitude, access to natural water). The result that such observed characteristics do not explain the recovery motivates our structural analysis of mechanisms behind the recovery, in which agglomeration forces and unobserved location characteristics can provide the incentive to again live and work in the city center.

3.1 Descriptive Evidence on the Destruction and Recovery of City Structure

In Figure 3 we non-parametrically plot population density within Hiroshima by distance to the CBD, where we normalize the total population of the city to 100,000 for all years to facilitate comparisons of the inner-city structure across years. The figure shows that the city structure of Hiroshima was completely changed by the atomic bombing but quickly recovered to the pre-WWII city structure. In 1936, the city had a typical monocentric city structure: the city center had the highest population density and density fell as one moved away from the center. This monocentric pattern was completely reversed by the atomic bomb hitting the densely populated city center. Figure 3 shows that, after the bombing, the city center was totally destroyed and consequently had the lowest population density in the city. In contrast, areas two kilometers away from the city center, which avoided total destruction (see Figure 1b), became the most crowded places in the city. Areas further away from the city center also experienced a significant increase in population density as many survivors from the center escaped to the outskirts.

Despite the “reversal” of the monocentric city pattern after the bombing, the monocentric structure had already re-emerged in 1950, just five years after the bombing. The rate of population recovery in the city center was remarkable. While the recovery from total destruction is qualitatively clear, the recovery may not have been perfect, as the concentration of population around the CBD appears to be less dense in 1950 than in 1936. However, this does not necessarily imply that the recovery was incomplete because the city center already had a slow rate of population growth prior to the war. This can be illustrated by comparing the actual population distribution in 1950 and a predicted 1950 distribution, based on extrapolating pre-war population growth trends from 1936 to 1950. The next section formalizes this recovery result via a regression analysis, which allows us to consider the statistical significance of our findings and incorporate various location characteristics as controls.

Figure 3: Population Density by Distance to City Center



Note: The figure shows the local polynomial regression of log population density on distance to the central business district (CBD) using block-level data for different years. To eliminate the effect of changes in the total population, we normalize the total population each year to 100,000. The predicted population distribution of 1950 is generated from the 1936 population distribution, assuming that each block has annual population growth rate equal to the pre-war 1933–1936 rate.

3.2 Regression Analysis of the Recovery of Central Hiroshima

We now analyze the magnitude of the recovery at the spatially granular level of blocks. Note that recovery implies that the set of blocks that lost more population due to the atomic bombing grew faster in the post-war period. We operationalize this idea by the following regression model:

$$\ln \left(\frac{\text{Popdens}_{i,t}}{\text{Popdens}_{i,1945}} \right) = \gamma \ln \left(\frac{\text{Popdens}_{i,1945}}{\text{Popdens}_{i,1936}} \right) + \eta X_i + v_i, \quad (1)$$

where i is the block; t is the post-war year such as 1950; X_i is the vector of location characteristics such as natural conditions and transportation access; and v_i is the error term. We regress the post-war log change in population density on the log change in population density from 1936 to 1945, reflecting the damage from atomic bombing.²⁶ The estimated coefficient of γ represents the degree of recovery back to the pre-war city structure.²⁷ In particular, if $\gamma = 0$, it means that the population

²⁶We use 1936 population density because it is the closest observation we have before 1945. In our data, $\text{Popdens}_{i,1945}$, measured November 1945, is positive for all blocks i so the log variables in equation (1) are well-defined (see Appendix A for details).

²⁷Since we include a constant in X_i , γ is invariant to population level in year t . Put differently, the coefficient γ captures the degree of convergence to the pre-war population distribution, where the total city population is normalized to the pre-war one.

density lost during the war did not recover in the post-war period. This would imply that the shock of atomic bombing has permanent effects on the city population distribution. In contrast, if $\gamma = -1$, the lost population density completely recovered in the post-war period, so that the shock has only temporary effects on population distribution. In some specifications we also control for location characteristics X_i such as altitude and distance to bodies of water, allowing us to investigate how the degree of recovery γ changes after conditioning on the location characteristics. We interpret this regression as capturing the correlation between population density lost during the war and the post-war population growth, either unconditional or conditional on location characteristics X_i . It does not necessarily have a causal interpretation.

Panel (a) of Figure 4 illustrates the relationship between the wartime and post-war population density growth rates for each block as of 1950, along with the regression line from (1). The fitted line is somewhat less steep but already close to a slope of -1 , implying that a strong resurgence among destroyed areas had already occurred just five years after the bombing. Panel (b) of Figure 4 demonstrates that a similar result is obtained when examining the population distribution in 1960, suggesting that the recovery was essentially completed by 1950. Therefore, we confine our regression analysis to the recovery from 1945 to 1950.²⁸

Column (1) of Table 1 provides detailed regression results depicted in Figure 4. The coefficient is -0.712 in 1950, which is statistically distinguishable from zero and the null hypothesis of complete persistence is rejected. Although we can also statistically reject the null hypothesis of purely temporary shocks ($\gamma = -1$), the results suggest a strong recovery within just five years.

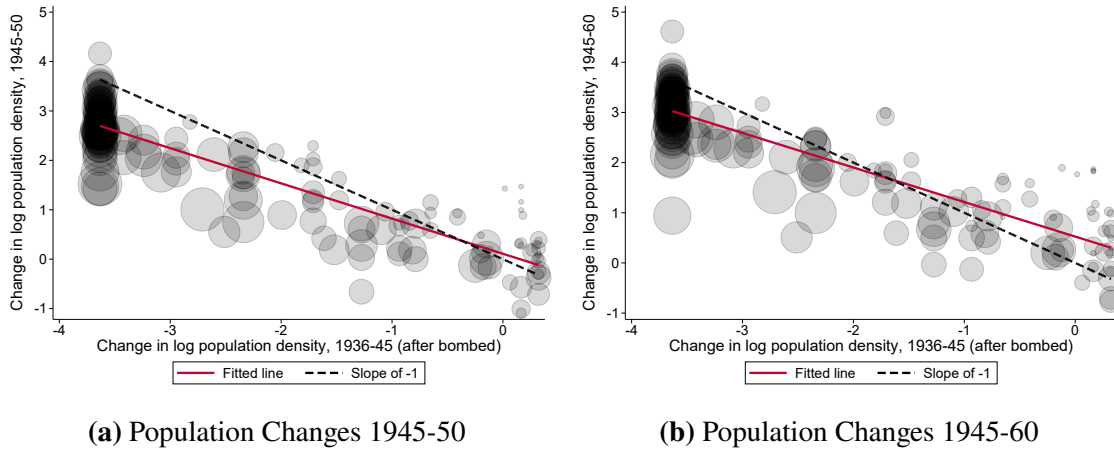
Accounting for location characteristics We have documented the quick recovery of Hiroshima’s city center. We now examine the extent to which the recovery of the city center can be explained by observed location characteristics that could directly affect amenities and productivity independently of the local density of economic activities, such as altitude and or access to natural water. In Section 6 we use our calibrated model to highlight that the expectations of high density in the destroyed central areas may have played a crucial role in inducing their recovery.

Before proceeding with the regression analyses, we discuss heuristically why the locational advantage of central Hiroshima may not account for its resurgence. Following [Krugman \(1993\)](#), we consider the following two types of location characteristics: natural location characteristics (“first nature”) and manmade location characteristics (“second nature”). First, natural conditions within the city, such as altitude and distance to water, are homogeneous. This is intuitive because our geographic scope is limited and most of the city area lies within 6 kilometers of the city center.²⁹ Second,

²⁸We obtain very similar regression results for 1960.

²⁹In particular, the majority of Hiroshima is located in the delta of the *Ota* river, characterized by flat terrain with loose soil. The flat terrain was an important reason why the US chose Hiroshima as the target of the bombing (see footnote 9). Moreover, much of the city close to water area, as the city is cut through by many branches of the *Ota* and

Figure 4: Relationship Between the Population Change from 1945–1950 and the Population Change due to the Atomic Bombing by Block



Note: Figures plot changes in the log of population density from 1945 to 1950 or 1960 with those from 1936 to 1945, which is largely driven by the atomic bombing. Each circle represents a block (i.e., an observation), where the size of the circle is proportional to the population density in 1936. We plot the (unweighted) linear fit between these two variables (solid line) as well as a line of slope -1 (dashed line), which would be obtained if the population change during the bombing period was completely reversed in the post-war period.

the key manmade advantages of central Hiroshima were substantially damaged by the bombing. The city center of Hiroshima, areas around *Hacchobori* and *Kamiya-cho*, is located next to Hiroshima castle, a historical amenity which had been a symbol of the city since the samurai period. The center was also adjacent to the former center, called *Nakajima-cho*, which developed during the samurai period due to its convenient access to the castle and water transportation. The city center also had easy access to the tram network. These advantages were lost following the bombing. Hiroshima castle was totally destroyed as was *Nakajima-cho*. Although the city center may have retained some advantage in transportation access, access to jobs would have been substantially worsened as central neighborhoods were completely destroyed and other areas of the city likely enjoyed better conditions after the bombing.³⁰

We now use our regression model (1) to formally assess the role of locational advantages. Specifically, we control for the observable characteristics of each block. If the recovery were primarily driven by the attractive location characteristics of the destroyed areas, then γ would approach zero, such that the recovery tendency is no longer observed after conditioning on these location characteristics. For natural location characteristics, we control for distance to nearest water, altitude and faces the sea to the south.

³⁰For instance, areas around Hiroshima station also provided convenient access to transportation but experienced much less destruction from the bombing, which could have made Hiroshima station the potential new center of Hiroshima. In a different Japanese city (Yokohama), [Takano \(2022\)](#) documents that the city center moved to an area with transportation advantages after the requisition of the former city center by the US army for nearly ten years.

Table 1: Changes in Population Density and War-time Damage

	(1)	(2)	(3)	(4)	(5)	(6)
	Change in log population density 1945–1950					
Changes in log population density 1936–1945 (γ)	-0.712*** (0.026)	-0.783*** (0.038)	-0.959*** (0.101)	-0.926*** (0.092)	-0.925*** (0.092)	-0.891*** (0.096)
p -value from testing $\gamma = -1$	0.000	0.000	0.687	0.422	0.420	0.262
Natural location characteristics (first nature)		✓		✓	✓	✓
Manmade location characteristics (second nature)			✓	✓	✓	✓
Pre-war trends in population					✓	
Within 3 km of the city center						✓
Number of blocks	174	174	174	174	174	158
R-squared	0.809	0.831	0.829	0.856	0.858	0.865

Note: We report the OLS estimates of equation (1). Natural location characteristics consist of log distance to the pre-war city center, log distance to the nearest water, the altitude and its square, the slope and its square, geographical coordinates (latitude, longitude, and their interaction), and a dummy for bad soil conditions. Manmade location characteristics consist of log distance to the nearest station, log distance to Hiroshima port (Ujina port), log distance to the nearest cultural asset, and the initial housing stock condition (the fractions of the half-destroyed, moderately-destroyed, and intact buildings). In column 5, we also control for of the pre-war (1933–1936) population growth rate and its square. In column 6, we confine the sample to blocks within 3 kilometers of the city center, where fundamental conditions are more homogeneous. We report the p -value from testing the null $\gamma = -1$, meaning that the population density converged back to the 1936 city structure. Heteroskedasticity-robust standard errors in parentheses. ***: Significant at the 1% level.

ruggedness, an indicator of bad soil conditions, geographic coordinates, and geographical distance to the (pre-war) city center. As manmade location characteristics that can be considered as given right after the bombing, we control for distance to the nearest train station as of 1950, distance to Hiroshima port, distance to the nearest cultural asset, and the quality of housing stock after the bombing.³¹

Columns (2)–(4) of Table 1 present the regression results when controlling for location characteristics. Column (2) controls for natural conditions. We find that first-nature characteristics do not account for the recovery as the coefficient γ actually moves closer to negative one. Column (3) controls for manmade conditions. Here, we find that $\gamma = -0.959$, which is even closer to -1 and now statistically indistinguishable from $\gamma = -1$. Finally, we find γ close to -1 in Column (4), which controls for both first-nature and second-nature location characteristics. Overall, observed location characteristics do not explain the recovery, as the degree of recovery γ becomes stronger after conditioning on observed location characteristics.

We further investigate the robustness of these results in two ways. Column (5) of Table 1 addresses the concern that our recovery result may be driven by the pre-war trend by controlling for the block-level trend of population during 1933–1936. The estimated coefficient is close to that in Column (4), suggesting that accounting for the pre-trend at the block-level does not affect our

³¹We measure the quality of housing stock by the fractions of half-destroyed, moderately-destroyed, and intact buildings. As an additional control on the housing condition, in a robustness check, we additionally control for the number of public housing units supplied during 1945–1950. This has little effect on the regression results (see Appendix B.1 for details).

results. Column (6) of Table 1 mitigates the potential heterogeneity in unobserved location characteristics by restricting our sample to blocks within 3 kilometers of the city center where location characteristics are likely more homogeneous, but γ is still indistinguishable from -1 .³² Therefore, the main mechanism behind the recovery should be able to explain the recovery without appealing primarily to location characteristics.

3.3 Further Reduced-form Evidence

We provide further evidence on the recovery of the city center. First, we document that the recovery is observed not only in the population distribution but also in the distributions of employment and land prices. Second, we use an alternative regression specification to address the concern that population measurement errors might spuriously yield the recovery result. Third, we find that controlling for the location characteristics of adjacent blocks does not alter our baseline results. Finally, we show that recovery to the pre-war city structure was also observed in Nagasaki, the second city hit by the atomic bombing, and discuss the implications.

Recovery in employment distribution In Section B.1 of the Appendix we analyze the impact of the atomic bombing on the distribution of employment. We find that the regression results are very similar to those in Table 1 for the population distribution. Recovery occurred not only for the residential population but also in the spatial distribution of commercial activity.

Recovery in land price distribution While we do not have comprehensive land price data during our sample period, we are able to measure the location with the highest land price in the city, which could be interpreted as the center of the city. In both 1931 and 1959, the highest land price was observed near *Hacchobori*, the city center both before and after the war.³³ Thus, the resurgence of central Hiroshima is also observed in land prices.

Robustness to measurement errors (Alternative regression specification) A potential concern for the regression model (1) is that measurement error in the 1945 population may yield a negative bias on the coefficient γ . To see this, note that a positive measurement error in $\text{Popdens}_{i,1945}$ decreases the outcome variable in equation (1) while increasing the explanatory variable of interest. To address this, we use an alternative regression specification: regressing log 1950 population

³²Table A.2 in the Appendix suggests that the standard deviations of the observed location characteristics are smaller for blocks in 3 kilometers of the city center. A similar idea has been invoked in Schumann (2014) in a different context.

³³The block containing the plot with the highest land price is the *Horikawa-cho* block adjacent to the *Hacchobori* block. Other available evidence on pre-war land prices suggests a similar conclusion (Nozawa 1934; Hayakawa and Nakaouji 1965).

density on log 1936 population density, log 1945 population density, and observed location characteristics.³⁴ In Table B.2 in the Appendix, we find that the coefficient of log 1936 population density is positive but that of log 1945 population density is close to zero. This result suggests the recovery of the destroyed center because the population distribution in 1950 is positively associated with the 1936 distribution but not with the 1945 distribution. Moreover, as in Table 1, the observed location characteristics do not explain the recovery as controlling for them does not change the above results. Overall, our main conclusion in Table 1 also holds in this alternative specification.

Characteristics of neighboring blocks In Section B.1 of the Appendix, we consider the possibility that the post-war population growth rate of a block may depend not only on its own characteristics, but also on the characteristics of neighboring blocks. To consider the characteristics of neighbors, we adopt the so-called “SLX model” from the spatial econometrics literature (Halleck Vega and Elhorst 2015) and add spatial lags of the following three neighborhood characteristics to our main regression (1): (i) the log change in population induced by the bombing $\ln(\text{Popdens}_{i,1945}/\text{Popdens}_{i,1936})$, (ii) the location characteristics X_i , and (iii) the population distribution right after the war, which is meant to capture market access after the bombing.³⁵ Table B.3 shows that including these spatial lag variables has only a modest impact on our regression results.

The recovery of Nagasaki In Section B.2 of the Appendix we examine the population data for Nagasaki, the second city destroyed by an atomic bomb. As in Hiroshima, the damage in Nagasaki was catastrophic: around 70,000 people were killed and almost all buildings within 2km of the epicenter was totally destroyed (Nagasaki City Government 1977). However, in Nagasaki, the atomic bomb hit the outskirts of the city (see Figure B.1a).³⁶ This is in contrast to Hiroshima, where the atomic bomb hit the city center. Despite this difference, recovery to the pre-war city structure was also observed in Nagasaki. Figure B.1b shows a fitted line from estimating equation (1) for Nagasaki. Our coefficient of interest is around -0.88 and statistically indistinguishable from -1 , suggesting the complete recovery of the population distribution in Nagasaki. This similar pattern of recovery in Nagasaki offers two additional implications. First, it bolsters the external validity of our Hiroshima recovery result. Second, it may limit the importance of potentially lower development costs on large empty plots or creative destruction in our context (Hornbeck and Keniston 2017) because the center

³⁴Formally, the regression model is $\ln \text{Popdens}_{i,t} = \gamma_1 \ln \text{Popdens}_{i,1945} + \gamma_2 \ln \text{Popdens}_{i,1936} + \eta X_i + v_i$. This model under the constraint $\gamma_1 + \gamma_2 = 1$ is equivalent to model (1), but we do not impose this constraint here.

³⁵In particular, the market access term addresses the possibility that the city center could recover as the “donut hole of the city:” it might still have relatively good market access thanks to its central location despite its destruction.

³⁶The target point of Nagasaki was selected by historical coincidence. The US initially intended to bomb Kokura, but changed target to the city center of Nagasaki due to weather conditions. The weather conditions also prevented an attack on the city center of Nagasaki, and consequently the bomb was dropped onto the outskirts of Nagasaki. See <https://www.peace-nagasaki.go.jp/abombrecords/b020101.html> (last accessed on October 28, 2023).

of economic activities could have shifted toward the totally destroyed periphery of Nagasaki if these factors had been crucial, but we do not find such a shift.³⁷

Taken together, our reduced-form analysis has revealed that (i) the population distribution in the city recovered back to the pre-war state within five years after the bombing, and (ii) the recovery is not driven by the prominent location characteristics we have controlled for. There are two possible explanations for these findings. First, there could be some unobserved locational advantages in the destroyed city center that persisted through the bombing (e.g., scenic views). Second, people may have expected the recovery of the destroyed city center when making location choices, and the incentive to again live and work in the city center came from agglomeration forces due to expected high density as in the pre-war period. To analyze these possibilities, we develop and calibrate a quantitative spatial model that incorporates both agglomeration forces and unobserved location characteristics as potential explanations for the recovery.

4 Theoretical Framework

In this section we present a dynamic quantitative spatial model to understand the mechanisms of the recovery. To account for the impact of the atomic bombing on the dynamics of internal city structure during the recovery, the model incorporates forward-looking location choice, migration frictions, commuting, agglomeration forces, and heterogeneous location fundamentals. First, individuals make decisions about their residence and workplace subject to migration frictions. They do so taking into account continuation values, defined by the expected future value of living and working in their chosen locations. Second, their residence and workplace are potentially different, which defines the equilibrium commuting patterns within the city. Finally, locations differ in productivity and amenities that are determined by both agglomeration forces and location fundamentals. Our model is the first tractable dynamic quantitative model of internal city structure that possesses these elements in a unified framework. Appendix C provides the details of the derivations.

Time is discrete and indexed by t . We consider a single city (Hiroshima City) embedded in a large economy (Hiroshima Prefecture or Japan). The city consists of a discrete set of locations represented by \mathcal{C} . We typically use subscript n to refer to the place of residence of a worker and subscript i to refer to their place of work.³⁸ The number of locations in the city $N = |\mathcal{C}|$ is fixed over time. The city is located in a larger economy that is modelled as a single location, denoted

³⁷The limited importance of large empty lots or creative destruction in our context may be due to construction technology. While the demolition of old buildings facilitates high-rise buildings by providing a large vacant lot and may enhance productivity (Hornbeck and Keniston 2017), Japanese technology for high-rise buildings right after WWII was relatively limited (Yamasaki et al. 2022). The shortage of construction materials made high-rise buildings even more unavailable (Hiroshima City Government 1971).

³⁸Where necessary, we also use the subscript n' to denote residence locations and i' for workplaces.

by o . Locations in the city correspond to blocks and are differentiated by fundamental productivity, amenities, land endowments, and geography. Fundamental productivity and amenities capture exogenous locational advantages for production and residence, respectively, and can change over time. The land endowment of each block is constant over time.

Individuals in the economy live for a finite time, T . The mass of the population in the larger economy is denoted by M and is exogenous. While we assume that M is time-invariant, the total population of the city changes over time through migration flows. This allows us to focus on the distribution of individuals within the city. Individuals are endowed with one unit of labor that is supplied inelastically and they are geographically mobile across locations in a city. They commute from their residential block to their workplace block subject to commuting costs. Individuals outside the city (o) are prohibited from commuting into the city for work. Production occurs in every location in the economy and firms produce a homogeneous final good that can be freely traded across locations. In each period, an individual may receive an opportunity to change their residence and workplace. Individuals receive such an opportunity with some exogenous probability. Given an opportunity to change locations, individuals choose their locations in a forward-looking way, taking into account the expected future values of living and working in particular locations. These forward-looking location choices allow us to characterize the transitions of the population and employment distributions in the city, which depend on agents' expectations about the future.

4.1 Production

Firms in the economy are competitive and produce a homogeneous final good. The production technology of a representative firm in location $i \in \mathcal{C}$ is:

$$Y_{it} = A_{it}L_{it}, \quad (2)$$

where Y_{it} is production in location i , A_{it} is productivity and L_{it} is employment in location i at time t . Productivity (A_{it}) is determined by fundamental productivity and employment density in the location:

$$A_{it} = a_{it} \left(\frac{L_{it}}{S_i} \right)^\alpha, \quad (3)$$

where a_{it} represents the exogenous component of productivity and S_i is the area size of location i that is time-invariant. The parameter α controls the contemporaneous productivity agglomeration forces with respect to employment density, and a positive value of α implies higher employment density increases productivity.³⁹

³⁹This is in line with empirical findings (Ciccone and Hall 1996; Arzaghi and Henderson 2008) and microfounded by different mechanisms in agglomeration economies (Duranton and Puga 2004). In addition, this may also reflect congestion forces from land prices that are increasing in density. We do not explicitly include land in production for simplicity, as we do not observe block-level land prices in the data.

The homogeneous good is freely traded and chosen as the numeraire.⁴⁰ The zero-profit condition implies that the wage rate at location i in period t is $w_{it} = A_{it}$. Therefore, the wage rate in any particular location is a function of exogenous productivity and employment density in that location.⁴¹

4.2 Preferences

Individuals live for finite periods, consume only a homogeneous tradable good, and inelastically supply one unit of labor. Individuals are hand-to-mouth, always spending their wage w_{it} in period t . Their period utility from living in location n and working in location i at period t is:

$$\ln u_{int} = \ln B_{nt} + \ln w_{it} - \ln \kappa_{int}, \quad (4)$$

where B_{nt} is the common utility benefit from residential amenities at residential place n in period t , w_{it} is labor earnings in workplace i , and κ_{int} is the utility cost due to commuting from n to i .⁴² The value of amenities in a residential place (B_{nt}) depends on the fundamental value of amenities and population density:

$$B_{nt} = b_{nt} \left(\frac{R_{nt}}{S_n} \right)^\beta, \quad (5)$$

where b_{nt} is an exogenous component in the value of amenities for each location, and R_{nt} is the population of location n in period t . In this specification, the elasticity of amenities with respect to population density (β) captures the strength of the net agglomeration effect in a residential place. Specifically, we capture net residential agglomeration forces through housing prices and consumption amenities. In Appendix C.5, we provide a microfoundation for this specification.⁴³

Outside of the city (o), individuals receive common utility u_{ot} in period t , which is exogenous in every period. Because u_{ot} governs the attractiveness of living in Hiroshima City relative to the outside economy, it captures aggregate shocks that affect the whole city of Hiroshima.

4.3 Forward-looking Location Choices

Workers are forward-looking in making migration decisions subject to the exogenous migration frictions. At the end of period t , share $\theta_t \in (0, 1)$ of workers in the economy can change their

⁴⁰We can incorporate block-specific transportation costs of the homogeneous good to the outside world as follows. Suppose that the numeraire produced in Hiroshima is sold outside the city and exporting from location i to the outside world involves an iceberg cost, implying that $\tau_i \geq 1$ units of goods must be shipped to sell one unit. This is isomorphic to the case with productivity A_{it}/τ_i in our model.

⁴¹Given the linear technology and perfect competition, producers always earn zero profit. Thus considering dynamic incentives does not change our arguments as long as firms correctly expect that future profits are always zero. In addition, firms obtain zero profit at every location under a competitive wage rate, and no firm has an incentive to enter or exit in any location.

⁴²In Section 5.1, we compute $\ln \kappa_{int}$ as the expected commuting cost in a travel mode choice model.

⁴³We do not explicitly model consumption of land for simplicity since we do not observe block-level land prices in the data.

location pairs and share of $1 - \theta_t$ of workers will remain in their current location choices next period $t + 1$.⁴⁴ If $\theta_t = 1$, all workers are able to change their location pairs. A low value of θ_t leads to stickiness in workers' location decisions.⁴⁵ Intuitively, due to the high fixed cost of moving, migration happens when an exogenous event arrives, such as job loss or life-cycle shocks (Heblich et al. 2021). θ_t is interpreted as the probability of experiencing such an event.

When a worker obtains the opportunity to change their locations at the end of period t , they draw idiosyncratic shocks related to location choice in period $t + 1$. For an individual worker, the idiosyncratic shock is independently drawn from a time-invariant independent Type-I extreme distribution $F(\varepsilon) = \exp(-\exp(-(\varepsilon + \Gamma)))$ where Γ is the Euler-Mascheroni constant. At the end of period t , workers decide their residence and workplace for the next period considering the option value of their location choice $\{V_{int+1}\}$ associated with each workplace and residence pair.

Consider a worker ω living in n and working in i at period t . When the worker can move to different location pairs next period, they solve the following location choice problem:

$$v_{int}(\omega) = \ln u_{int} + \max \{ \rho_{t+1} V_{i'n't+1} + \sigma_{t+1} \varepsilon_{i'n't+1} ; \rho_{t+1} V_{ot+1} + \sigma_{t+1} \varepsilon_{ot+1} \} \quad (6)$$

for $t = 1, 2, \dots, T - 1$. $V_{i'n't+1}$ refers to the value function implied by choosing a different pair of residence n' and workplace i' in period $t + 1$ and V_{ot+1} is the option value of choosing to live outside the city. $\rho_{t+1} \in (0, 1)$ is the discount factor governing the importance of the future values and σ_{t+1} is a positive constant governing the variance of the idiosyncratic shocks. An individual makes a forward-looking migration decision to choose their residence and workplace at $t + 1$ given a path of the exogenous and endogenous variables. In particular, an individual correctly anticipates the path of the population distribution (R_{nt}) and employment distribution (L_{it}) that are endogenously determined in equilibrium. As we focus on migration within a city, we assume away bilateral mobility costs as they are likely sufficiently small and homogeneous relative to inter-city migration costs.⁴⁶

With the idiosyncratic shocks following a type-1 extreme value distribution and migration frictions, we can express the option value of living in n and working in i assessed in period $t = 1, 2, \dots, T - 1$ by

$$V_{int} = \ln u_{int} + (1 - \theta_{t+1}) \rho_{t+1} V_{int+1} + \theta_{t+1} \sigma_{t+1} \ln \left[\sum_{i' \in \mathcal{C}} \sum_{n' \in \mathcal{C}} \exp(\rho_{t+1} V_{i'n't+1})^{1/\sigma_{t+1}} + \exp(\rho_{t+1} V_{ot+1})^{1/\sigma_{t+1}} \right]. \quad (7)$$

⁴⁴We allow people to choose the same location for their residence and workplace.

⁴⁵This Calvo-style migration friction is also adopted in other recent quantitative spatial models to capture the persistence of migration decisions (Caliendo et al. 2019 Section 5.3; Heblich et al. 2021). This approach is attractive in a setting such as ours in which bilateral migration flows are unobserved.

⁴⁶A reason to assume away bilateral migration costs is that unlike Caliendo et al. (2019) we do not observe bilateral migration flows. This is likely inconsequential as Gechter and Tsivanidis (2023) estimates that in a within-city setting, the fixed cost of moving is substantially larger than the moving cost that increases with moving distance.

The first term is the current utility from residence n and workplace i . The second term is the expected value of staying at the same location pair in the next period when no migration opportunity realizes, with probability $1 - \theta_{t+1}$. The third term is the expected value when a worker is able to change their location pair, with probability θ_{t+1} .

For workers residing outside of the city, their option value for $t = 1, 2, \dots, T - 1$ is:

$$V_{ot} = \ln u_{ot} + (1 - \theta_{t+1})\rho_{t+1}V_{ot+1} + \theta_{t+1}\sigma_{t+1} \ln \left[\sum_{i' \in \mathcal{C}} \sum_{n' \in \mathcal{C}} \exp(\rho_{t+1}V_{i'n't+1})^{1/\sigma_{t+1}} + \exp(\rho_{t+1}V_{ot+1})^{1/\sigma_{t+1}} \right]. \quad (8)$$

When workers have an opportunity to migrate, they can choose any location pair. Therefore the last term in the value function is the same as in equation (7). For the last period $t = T$, equations (7) and (8) are written as $V_{inT} = \ln u_{inT}$ and $V_{oT} = \ln u_{oT}$ because future considerations are absent.

Using our assumption that the idiosyncratic shocks are independent and follow a type-I extreme value distribution $F(\varepsilon)$, we derive the share of workers that live in n and work in i in the next period $t + 1$ when they have a migration opportunity:

$$\lambda_{int+1} = \frac{\exp(V_{int+1})^{\rho_{t+1}/\sigma_{t+1}}}{\sum_{i' \in \mathcal{C}} \sum_{n' \in \mathcal{C}} \exp(V_{i'n't+1})^{\rho_{t+1}/\sigma_{t+1}} + \exp(V_{ot+1})^{\rho_{t+1}/\sigma_{t+1}}}, \quad i, n \in \mathcal{C}. \quad (9)$$

This probability λ_{int+1} characterizes the location dynamics of workers in the city for period $t + 1$. Workers choose their pair of residence and workplace, correctly anticipating future changes in commuting costs, wages, and residential amenities. Since there is no residence-workplace specific migration cost, equation (9) applies to all workers with a migration opportunity in period t . In addition, the share of workers that live outside of the city in period $t + 1$ conditional on being able to change their location pair is given by probability $\lambda_{ot+1} = 1 - \sum_{i \in \mathcal{C}} \sum_{n \in \mathcal{C}} \lambda_{int+1}$.

Using these choice probabilities for workers, we can express the mass of workers in the city who live in n and work in i in period $t + 1$ as:

$$L_{int+1} = (1 - \theta_{t+1})L_{int} + \theta_{t+1}\lambda_{int+1}M. \quad (10)$$

This is the number of commuters within the city. On the right-hand side, the first term is equal to the number of commuters who retain the same workplace and residence as the last period, and the second term is the total number of workers who either move in from outside of the city or change location pairs within the city. Since the commuting market clears, the mass of workers in workplace i becomes:

$$L_{it+1} = (1 - \theta_{t+1})L_{it} + \theta_{t+1} \left[\sum_{n \in \mathcal{C}} \lambda_{int+1} \right] M, \quad (11)$$

where the mass of workers in workplace i is the sum of workers who have no opportunity to change locations and those who join workplace i in period t . Analogously, the mass of workers residing in

n becomes:

$$R_{nt+1} = (1 - \theta_{t+1})R_{nt} + \theta_{t+1} \left[\sum_{i \in \mathcal{C}} \lambda_{int+1} \right] M. \quad (12)$$

Lastly, the total population in the city in period $t + 1$ is given by $L_{t+1} = \sum_{i \in \mathcal{C}} \sum_{n \in \mathcal{C}} L_{int+1}$.

Conditional on the wage variation and exogenous location characteristics, the mobility of workers in our model is controlled by the parameter of Calvo-style stickiness θ_t and taste shocks σ_t . We emphasize that they have different interpretations. Calvo-style migration frictions capture the immobility of workers even if they would like to change their locations. Intuitively, this reflects any constraint that prevents workers from relocating. In contrast, the dispersion of taste shocks captures the individual valuation attached to the location pair and controls the degree of sorting in response to utility differences. In the present model, we introduce both migration frictions and idiosyncratic shocks to capture both mobility constraints and the sorting of workers into their residence and workplace choices. We discuss how we can identify these two parameters from the data in Subsection 5.1 below.

4.4 General Equilibrium

We now define a forward-looking competitive equilibrium in this economy. The economy starts with the initial distributions of population (R_{n0}) and employment (L_{i0}). The exogenous variables of the model are block-level fundamental productivity (a_{it}) and amenities (b_{nt}), the fixed sizes of blocks (S_n), bilateral commuting costs (κ_{int}), the degree of worker location stickiness (θ_t) and utility outside the city (u_{ot}). The economy-wide parameters in the model are the agglomeration forces in productivity (α), agglomeration forces in amenities (β), a discount factor of workers (ρ_t), the variance of idiosyncratic shocks in location choices (σ_t) and a mass of workers in the economy (M). Then, a forward-looking equilibrium is defined as follows:

Definition 1. *Given the exogenous variables of the model and economy-wide parameters, a forward-looking equilibrium is characterized by the sequences of wages $\{w_{it}\}$, population $\{R_{nt}\}$, employment $\{L_{it}\}$, and value functions associated with location choices $\{V_{int}\}$ such that (i) the value functions of workers for their location choices $\{V_{int}, V_{ot}\}$ satisfy (7) and (8) with $V_{inT} = \ln u_{inT}$ and $V_{oT} = \ln u_{oT}$ for the last period T , (ii) the commuting market clears in the city and the masses of workers in workplaces and residential places are given by (11) and (12), and (iii) firms maximize their profits and the zero-profit condition leads to a wage rate equal to (3).*

Since productivity and amenities evolve with employment density and population density, we can summarize the forward-looking equilibrium by population, employment, and the value function adjusted by the value of living outside of the city. Equations (3), (7), (8), (11), and (12) constitute $N^2 + 3N$ equations for each t , which can be solved for $N^2 + 3N$ endogenous variables for each

t . The location choices of people are based on their current real income but also the option values associated with each pair of locations, and they determine the future path of location choices taking into account future shocks.

We define a steady-state equilibrium for the economy as one where population and employment distributions are constant. The steady state equilibrium in this economy exists and is unique when the net agglomeration forces are small for both productivity and amenities. We summarize these results in the following proposition:

Proposition 1. *(i) Given the initial state and exogenous factors, a forward-looking competitive equilibrium such that, for all periods $t = 1, 2, \dots, T$, $R_{nt} \geq (1 - \theta_t)R_{nt-1}$ and $L_{it} \geq (1 - \theta_t)L_{it-1}$, exists; (ii) A steady-state equilibrium exists when $\alpha \neq \sigma/\rho$ and $\beta \neq \sigma/\rho$ for some steady state level of (ρ, σ) ; (iii) Sufficient conditions for the existence of a unique steady state are negative net agglomeration forces: $\alpha \leq 0$ and $\beta \leq 0$.*

Appendix C.3 provides the proof. While Proposition 1 (i) and (ii) show the existence of an equilibrium and a steady state, there may be multiple steady states and multiple equilibrium paths. Proposition 1 (iii) shows that the steady state is unique if agglomeration forces (α, β) are negative, which implies that the net dispersion forces dominate the agglomeration forces both in productivity and amenities. In this case, the economy will converge to this unique steady state in the long run, although there could be multiple paths toward the steady state. In other cases, there can be multiple steady states, which can happen when net agglomeration forces are positive according to Proposition 1 (iii). After a shock that affects the initial condition, both the initial conditions and expectations about the future distribution of population and employment matter in determining which steady state or path realizes (Krugman 1991; Matsuyama 1991).

In our calibration, we solve the model backward for the observed changes in population and employment. We do not require that the economy is exactly in the steady state in the last period T , but we assume that it is sufficiently close to the steady state so that the commuting gravity equation approximately holds, which we estimate in our calibration in Subsection 5.1. Our calibration does not require the uniqueness of the steady state nor a unique path to the steady state because it relies only on the observed equilibrium. This feature allows us to calibrate the model when there are multiple steady states so that different expectations may lead to different steady states. When we undertake counterfactuals, we explicitly acknowledge the potential for multiple equilibria.

5 Quantitative Analysis

Our goal in this section is to show how the present model can be matched to the observations in Hiroshima. Our quantification proceeds in three steps which we discuss in turn. Appendix D presents further details on the calibration.

In Subsection 5.1 we first obtain commuting costs (κ_{int}) by estimating a model of travel mode choice. Our model accommodates two aspects of migration frictions: the dispersion of idiosyncratic taste shocks (σ_t) and the stickiness of migration decisions (θ_t). We calibrate each using different information. The dispersion of idiosyncratic taste shocks (σ_t) is calibrated based on the calibrated discount factor (ρ_t) and the commuting elasticity (ρ_t/σ_t) estimated by a gravity equation for commuting. We infer the stickiness (θ_t) from additional data on the share of people who remain in the same residence over time. The outside utility (u_{ot}) is chosen to match the observed total population of the city.

Given the parameters, in Subsection 5.2, we leverage the structure of the model to back out the composites of amenities and productivity that rationalize the observed population and employment changes over time. Intuitively, changes in population and employment by block allow us to invert the option values associated with each location. These option values reflect the attractiveness of each location as a residence or workplace, which is a composite of location fundamentals and agglomeration forces.

In Subsection 5.3, we estimate the key parameters that govern the strength of the agglomeration forces in productivity (α) and amenities (β). We first recover the unobserved fundamentals in productivity and amenities based on the recovered option values and variations of population density and employment density over time. For these fundamentals, we then define the moment conditions and estimate the agglomeration force parameters. In the estimation, we use the location choice data from 1955 to 1975. In Subsection 5.4 we discuss the robustness of our estimated values for agglomeration forces.

Having fully quantified our model, in Subsection 5.5 we investigate how well our model fits the observed changes in population and employment distributions in the recovery period. To this end, we first use the location choice data for 1950 to back out the locational advantages in the recovery period. We then decompose these advantages into two components: (i) advantages in productivity and amenities explained by the model, and (ii) structural residuals in productivity and amenities. We demonstrate that our model predicts the central recovery only with the first model-based component.

5.1 Step #1: Parameter Calibration ($\rho_t, \sigma_t, \kappa_{int}, \theta_t, u_{ot}$)

Travel mode choice and commuting costs (κ_{int}) To estimate commuting costs, we extend the model to incorporate choice of travel modes following [Ahlfeldt et al. \(2015\)](#) and [Tsivanidis \(2022\)](#). There are five modes of transportation: walk, bicycle, car, bus, and train. In each period, a worker chooses the mode of transportation that minimizes the realization of observed and idiosyncratic travel costs, given their workplace and residence. We assume that the idiosyncratic travel cost follows a Gumbel distribution with two nests: (i) public modes: walk, bus and train; and (ii) private modes: bicycle and car. We estimate this nested discrete choice model of travel mode by exploiting

the 1987 Hiroshima City Person Trip Survey and compute the expected commuting cost for two types of workers who may or may not use cars.⁴⁷ We then estimate the overall expected travel cost for residence n and workplace i before the realization of the idiosyncratic travel costs, using information on the car ownership rate in Japan in different years. Finally, we substitute the expected travel cost into the commuting cost (κ_{int}) in (4). We discuss the details in Appendix D.1.

Commuting gravity (ρ_t/σ_t) We suppose that the economy approximates a steady state on reaching the last period and estimate the commuting elasticity of workers using the 1987 Hiroshima City Person Trip Survey.⁴⁸ Plugging the average commuting time in 1987 from above into the equilibrium commuting pattern in the steady state yields the gravity equation:

$$\ln L_{in} = -\frac{\rho}{\sigma}\bar{c}_{in} + \mathbb{W}_i + \mathbb{H}_n + \eta, \quad (13)$$

where \bar{c}_{in} is the log bilateral commuting costs determined by travel time, \mathbb{W}_i and \mathbb{H}_n are workplace and residence indicators and η is a constant. ρ/σ corresponds to the commuting elasticity with respect to commuting cost in our model, which is decreasing in σ (the dispersion parameter of the idiosyncratic shock) and increasing in ρ (the discount factor). Lower σ and higher ρ imply a higher sensitivity of migration decisions to utility differentials. We estimate (13) using Pseudo-Poisson Maximum Likelihood to allow for heteroskedasticity and zero bilateral commuting flows for some pairs. Our baseline parameter estimate is $\rho/\sigma = 8.019$, which is close to estimates of the elasticity of commuting flows with respect to commuting costs in [Dingel and Tintelnot \(2020\)](#). In the following, we set ρ_t/σ_t to be 8 for all t . See Appendix D.1 for the detailed estimation results.

Discount factor (ρ_t) We assume that the annual discount rate is 8.5 percent. This value is consistent with the discount rate widely used in the context of developing countries (e.g., [Garcia-Cicco, Pancrazi and Uribe 2010](#)), which is consistent with the relatively low GDP per capita of Japan right after the war.⁴⁹ Since one period in our calibration corresponds to five years, we set $\rho_t = (1/1.085)^5 \simeq 0.66$ for all t .

Migration frictions (θ_t) Individuals can change their residence and workplace in period t with probability θ_t . We assume that people change their residence when obtaining a migration opportunity and match this migration friction parameter to the probability that people change their residence during five years, the length of one period in calibration. The 1960 Population Census reports that around 86 percent of people stayed in the same residence from one year before. Thus, we set the parameter $\theta_t = 1 - (0.86)^5 \simeq 0.53$ for all $t \geq 1955$.⁵⁰

⁴⁷When a car is unavailable for a worker, the nest of private modes is reduced to a single choice (bicycle).

⁴⁸Alternatively, we can suppose that individuals can always migrate ($\theta_t = 1$) after the last period.

⁴⁹Japan's GDP per capita in 1950 was less than one-fifth of that of the U.S.

⁵⁰Although in a different context, this value is very close to the 0.52 used in the model of [Heblich et al. \(2021\)](#).

Utility outside the city (u_{ot}) We set the outside utility (u_{ot}) for each period to match the total population of Hiroshima City. Formally, we choose the outside value to match the observed total population in the city, \mathbb{M}_t . The model predicted population of the city is $(1 - \lambda_{ot})M = \mathbb{M}_t$, where λ_{ot} is the probability of choosing to live and work outside the city computed in the model. Since the relative location choice probability in a city is independent of the outside utility conditional on living in the city, the value of the outside option only affects the total population of Hiroshima in our model.

5.2 Step #2: Inversion of the Option Values

When individuals are forward-looking, their location choices depend on current real income and the option value associated with each location. In this step, we back out the option values by leveraging the population and employment dynamics of the model. Specifically, for $t = 1, 2, \dots, T - 1$, the option value of location n as a residential place can be summarized by the continuation value of amenities in the location:

$$\Xi_{nt} = b_{nt} \left(\frac{R_{nt}}{S_n} \right)^\beta \prod_{\tau=t+1}^T \left[b_{n\tau} \left(\frac{R_{n\tau}}{S_n} \right)^\beta \right]^{\prod_{s=t+1}^{\tau} \rho_s (1-\theta_s)}. \quad (14)$$

Analogously, the option value of location i as a workplace can be written as:

$$\Omega_{it} = a_{it} \left(\frac{L_{it}}{S_i} \right)^\alpha \prod_{\tau=t+1}^T \left[a_{i\tau} \left(\frac{L_{i\tau}}{S_i} \right)^\alpha \right]^{\prod_{s=t+1}^{\tau} \rho_s (1-\theta_s)}. \quad (15)$$

These option values express the attractiveness of each location as a residence and workplace. They are a composite of amenities and productivity that include both fundamental amenities (b_{nt}) and productivity (a_{it}), and the agglomeration forces from future population and employment density.

When $\theta_t = 1$, all workers can change locations every period and therefore the future values of their choices are independent of current location choices. In contrast, rare migration opportunities (small θ_t) lead to more weight placed on the future evolution of amenities and productivity since workers are less likely to change their locations. In sum, these option values reflect the value of amenities and productivity for each location when workers choose locations in a forward-looking way.

Equations (11) and (12) imply that the option values (Ξ_{nt}, Ω_{it}) satisfy the following equations:

$$\begin{aligned} R_{nt} - (1 - \theta_t)R_{nt-1} &= \sum_{i \in \mathcal{C}} \frac{K_{int} \Xi_{nt}^{\rho_t / \sigma_t}}{\sum_{n' \in \mathcal{C}} K_{in't} \Xi_{n't}^{\rho_t / \sigma_t}} (L_{it} - (1 - \theta_t)L_{it-1}), \\ L_{it} - (1 - \theta_t)L_{it-1} &= \sum_{n \in \mathcal{C}} \frac{K_{int} \Omega_{it}^{\rho_t / \sigma_t}}{\sum_{i' \in \mathcal{C}} K_{i'nt} \Omega_{i't}^{\rho_t / \sigma_t}} (R_{nt} - (1 - \theta_t)R_{nt-1}), \end{aligned} \quad (16)$$

where K_{int} summarizes current and future commuting costs (see equation D.4 in the Appendix for the definition). Intuitively, equation (16) states that the number of residents that actively choose to live in block n for period t ($R_{nt} - (1 - \theta_t)R_{nt-1}$) is written as the sum of the products of the number of workers that actively choose to work in block i for period t ($L_{it} - (1 - \theta_t)L_{it-1}$) and their conditional residential choice probability for location n ($K_{int}\Xi_{nt}^{\rho_t/\sigma_t} / (\sum_{n' \in \mathcal{C}} K_{in't}\Xi_{n't}^{\rho_t/\sigma_t})$).

We solve the system of equations (16) for the option values (Ξ_{nt}, Ω_{it}) conditional on observed population (R_{nt}), employment (L_{it}), commuting costs (K_{int}), and migration frictions (θ_t).⁵¹ We can recover unique (Ξ_{nt}, Ω_{it}) that rationalize the observed changes in the mass of workers without using any information on the unobserved characteristics and without making assumptions about the strength of agglomeration forces.

5.3 Step #3: Estimation of Agglomeration Parameters (α, β)

Next, we back out fundamental productivity (a_{it}) and amenities (b_{nt}) by using observed employment and population density, according to the inverted option values (Ξ_{nt}, Ω_{it}). Given the values of agglomeration forces (α, β), we use (14) and (15) to derive the fundamentals by location for each period $t = 1955, 1960, \dots, 1975$. Then, we assume that the fundamental productivity and amenities consist of location-fixed components ($\{a_i^F\}, \{b_n^F\}$), time-trend components ($\{a_t^*\}, \{b_t^*\}$), and time-varying errors ($\{a_{it}^{\text{Var}}\}, \{b_{nt}^{\text{Var}}\}$):

$$\ln a_{it} = \ln a_i^F + \ln a_t^* + \ln a_{it}^{\text{Var}}, \quad \ln b_{nt} = \ln b_n^F + \ln b_t^* + \ln b_{nt}^{\text{Var}}. \quad (17)$$

The location-specific productivity and amenities capture the fundamental advantages of locations and the trends of productivity and amenities reflect the change in their levels over time within the city. ($\{a_{it}^{\text{Var}}\}, \{b_{nt}^{\text{Var}}\}$) are the structural residuals in our model that allow us to perfectly match the observed population and employment distributions.

Averaging out the trend terms and taking differences between two consecutive periods, we have:

$$\Delta \ln \left(\frac{a_{it}}{\tilde{a}_t} \right) = \Delta \ln \left(\frac{a_{it}^{\text{Var}}}{\tilde{a}_t^{\text{Var}}} \right), \quad \Delta \ln \left(\frac{b_{nt}}{\tilde{b}_t} \right) = \Delta \ln \left(\frac{b_{nt}^{\text{Var}}}{\tilde{b}_t^{\text{Var}}} \right), \quad (18)$$

where we use a notation for a geometric mean across locations such that $\tilde{a}_t = \exp \left(\frac{1}{N} \sum_{i \in \mathcal{C}} \ln a_{it} \right)$.

The structural residuals of productivity and amenities in (18) difference out both common trends across all blocks in the city in each year and time-invariant locational advantages. Using (18), we

⁵¹The solution is up to scale because equations (16) exploit only information on the relative migration probabilities across blocks within the city. Since we take the total population of Hiroshima City from the data and assume that the outside utility (u_{ot}) adjusts to rationalize it (see Subsection 5.1), we do not need to determine the absolute levels of $\{\Xi_{nt}\}$ and $\{\Omega_{it}\}$ governing migration between Hiroshima City and the outside world. We normalize the geometric mean of $\{\Xi_{nt}\}$ and $\{\Omega_{it}\}$ to one.

consider the following moment conditions:

$$\begin{aligned}\mathbb{E}[\Delta \ln(a_{it}/\tilde{a}_t) \times \mathbb{1}_i(k)] &= 0, \\ \mathbb{E}[\Delta \ln(b_{nt}/\tilde{b}_t) \times \mathbb{1}_n(k)] &= 0,\end{aligned}\tag{19}$$

where $\mathbb{1}_n(k)$ is an indicator such that location n is in grid k , where the grid is defined based on the distance from the CBD. We define five grid cells based on the distance from the CBD and equally allocate blocks into those grid cells in our baseline specification.⁵² We use the moment conditions (19) to estimate the parameters for agglomeration forces.

Our identification assumption for using the moment conditions (19) is that log changes in the idiosyncratic terms of fundamental productivity and amenities are not correlated with distance from the city center. In other words, the systematic change in the gradient of economic activity relative to the distance from the CBD is explained, on average, by the mechanisms of the model rather than by systematic changes in the pattern of structural residuals (18). This identification assumption seems plausible in post-recovery Hiroshima because the spatial extent of our study is small and all blocks in the data would experience similar changes in the economic and political environment.⁵³

To address the potential concern of suburbanization in the post-recovery periods that could be partially driven by systematic increases in attractiveness for either production or residence further away from the CBD over time, we also estimate the set of parameters only using blocks within 3 kilometers of the CBD. Figure D.2 graphically illustrates that our GMM estimates indicate the moment conditions appear plausible regardless of the distance from the city center.

Table 2: Generalized Method of Moments Estimates for Agglomeration Parameters

	(1) Productivity	(2) Amenities	(3) Productivity	(4) Amenities
Elasticity of employment density (α)	0.193*** (0.0003)		0.196*** (0.0001)	
Elasticity of population density (β)		0.184*** (0.0004)		0.203*** (0.0004)
Sample of blocks	All blocks in the city		Blocks within 3 km of CBD	
Sample of periods	Every 5 years from 1955 to 1975		Every 5 years from 1955 to 1975	
Instruments	5 grids for CBD distance		5 grids for CBD distance	

Note: This table reports estimates of the two-step generalized method of moments (GMM) exploiting the moment conditions (19). The Eicker-White heteroskedasticity-robust standard errors are in parentheses. We use data for five periods (1955, 60, 65, 70 and 75). We define five grid cells according to the distance to the CBD for the moment conditions. In Columns (1) and (2) we use all 174 blocks in the city. In Columns (3) and (4) we use 158 blocks that lie within 3 kilometers of the CBD. *** indicates significance at the 1 percent level.

⁵²We carry out a robustness check for the sensitivity of estimates to the number of grid cells (using ten cells). See Table D.2 in Appendix D.5.

⁵³The effect of radioactivity faded away quickly from 1945 (see Section 2.1), and hence is unimportant for changes in amenities and productivity, as our estimation data start in 1950.

Table 2 reports the estimation results using the two-step generalized method of moments (GMM). Columns (1) and (2) report our baseline estimates of the agglomeration parameters for productivity (α) and amenities (β), respectively. Overall productivity (A_{it}) in the workplace rises by around 19 percent when current employment density doubles. Turning to amenities, doubling population density is associated with around 18 percent increase in the value of amenities. In Columns (3) and (4) in Table 2 we show similar results when we restrict our sample to blocks within 3 kilometers of the CBD in our estimation.

Since we estimate strong positive agglomeration forces in both amenities and productivity, the model could have multiple equilibria in light of Proposition 1. Although the direct comparison is difficult due to differences in models and empirical contexts, our estimates of agglomeration forces are broadly in line with those in the existing literature. Our estimated elasticity of productivity with respect to employment density is 0.19. While larger than the 0.03–0.08 of the survey by [Rosenthal and Strange \(2004\)](#), this is relatively close to several recent estimates (e.g., [Kline and Moretti 2014](#); [Heblich et al. 2020](#); [Tsivanidis 2022](#); [Allen and Donaldson 2022](#)) and also well within the range of estimates in the meta-analysis by [Melo, Graham and Noland \(2009\)](#). Our estimated elasticity of amenities with respect to population density is 0.18. This value is close to the estimates of [Ahlfeldt et al. \(2015\)](#) and [Heblich et al. \(2020\)](#), while smaller than [Tsivanidis \(2022\)](#).

5.4 Robustness of Agglomeration Parameter Estimates

Instruments based on pre-war population density A potential concern with defining instruments based on distances to the CBD is that the results could be sensitive to the definition of the city center. To address this, we instead use population density in 1936 to define the grid cells. We report the estimation results in Table D.2 in Appendix D.5. We find similar results: the agglomeration parameters for productivity and amenities are 0.178 and 0.165, respectively.

Spatial spillovers in productivity and amenities So far, we have assumed that agglomeration forces in productivity and amenities are at work only in the local block. While this is consistent with empirical evidence that agglomeration forces are highly localized (e.g., [Arzaghi and Henderson 2008](#); [Ahlfeldt et al. 2015](#); [Gechter and Tsivanidis 2023](#)), there could be spatial spillovers across blocks, so productivity in each block depends on its own employment and that of surrounding blocks. To consider the spatial spread of spillovers, we estimate the agglomeration forces when productivity and amenities are a function of employment and population density, with weights decreasing exponentially with travel time. Specifically, following [Ahlfeldt et al. \(2015\)](#), productivity in block i is: $A_{it} = a_{it} \left[\sum_{i' \in \mathcal{C}} e^{-\delta \tau_{ii'}} \left(\frac{L_{i't}}{S_n} \right) \right]^\alpha$, where δ is a parameter characterizing the spatial decay of productivity and τ_{in} is travel time between blocks. When $\delta \rightarrow \infty$, there is no spatial spread of spillovers as in our baseline specification. We specify amenities in an analogous way. Figure D.3

in Appendix D.5 shows the estimated values of the agglomeration parameters (α , β) given different values of spatial decay (δ). As we can see in the figure, the estimated values of the agglomeration parameters range from 0.18 to 0.26 for productivity and from 0.17 to 0.22 for amenities, which are close to the baseline estimates.

Lagged effects of agglomeration forces Our main model assumes that the amenities and productivity of each block depend on its current population and employment densities. However, they could also depend on its past population and employment density. First, current productivity could reflect the histories of capital, public goods and innovation as determined by past economic activities; second, current amenities could depend on the stock of housing or local infrastructure that is related to past population.⁵⁴ In addition to migration frictions, these effects may also induce history dependence. To take this into account, we specify productivity and amenities in period t as a function of current employment and population density and the previous employment and population densities in period $t - 1$, following [Allen and Donaldson \(2022\)](#). We estimate the parameters characterizing both the current and lagged spillover effects using similar moment conditions. Table D.3 in Appendix D.5 shows the results. For productivity, the elasticity of current (historical) employment density is 0.228 (-0.064). For amenities, the elasticity of current (historical) population density is 0.175 (0.015). Overall, the influence of lagged population and employment density is small relative to that of current density, and the strength of contemporaneous density remains similar to our baseline estimates.⁵⁵

5.5 Accounting for the Recovery: Location Choice for 1950

We are now in position to assess how well our calibrated model fits population and employment changes during the recovery period from 1945 to 1950, which are not used for calibration. To this end, we evaluate how well the endogenous component of location advantages and the time-invariant unobserved characteristics can fit the workplace and residence choices of 1950, the first location choices made in our model after the atomic bombing. Intuitively, we evaluate how much of the incentive to work or live in a given location during the recovery period can be explained by our model.

We first use equations (14) and (15) to construct the predicted option values of each location as a residence ($\Xi_{n,1950}^F$) and workplace ($\Omega_{i,1950}^F$), then substitute them into equation (16) to solve for the

⁵⁴[Allen and Donaldson \(2022\)](#) provide microfoundations for these specifications. In a previous version of this paper, we also provided alternative microfoundations in the within-city context.

⁵⁵Our estimates of agglomeration forces in productivity are broadly similar to those in [Allen and Donaldson \(2022\)](#), which uses long-run county-level data from the U.S. Yet, they find negative contemporaneous agglomeration forces in amenities. This difference may arise from the difference in spatial extent. The negative agglomeration forces in amenities may capture congestion in a local housing market, while our estimates of positive agglomeration forces may capture consumption externalities or neighborhood network effects.

predicted population and employment in 1950 (see Appendix D.6 for more details). By construction, the option values in our model are a composite of (i) location-fixed advantages, (ii) the endogenous components of agglomeration forces, (iii) future option values associated with the location, and (iv) idiosyncratic shocks. Among these, factors (i) – (iii) capture the location advantages that our model can explain. In contrast, the idiosyncratic terms (iv), corresponding to $(\{a_{it}^{\text{Var}}\}, \{b_{nt}^{\text{Var}}\})$ in equation (18), are structural residuals required to make the model prediction perfectly match the observed data, which absorb any other characteristics unrelated to the model specification.

Therefore, to evaluate how well our model can fit the recovery, we exclude the structural errors when constructing the model-predicted option values for residence $\{\Xi_{n,1950}^F\}$ and workplace choices $\{\Omega_{i,1950}^F\}$. In obtaining the predicted location decisions for the recovery period (1945–1950), we use the parameter values from our main calibration except we set a higher migration opportunity $\theta_{1950} = 0.9$ as available evidence suggests the mobility rate was substantially higher, possibly for war-related reasons such as job loss, housing destruction, and the end of temporal reallocation during the war (see Appendix A for more details).

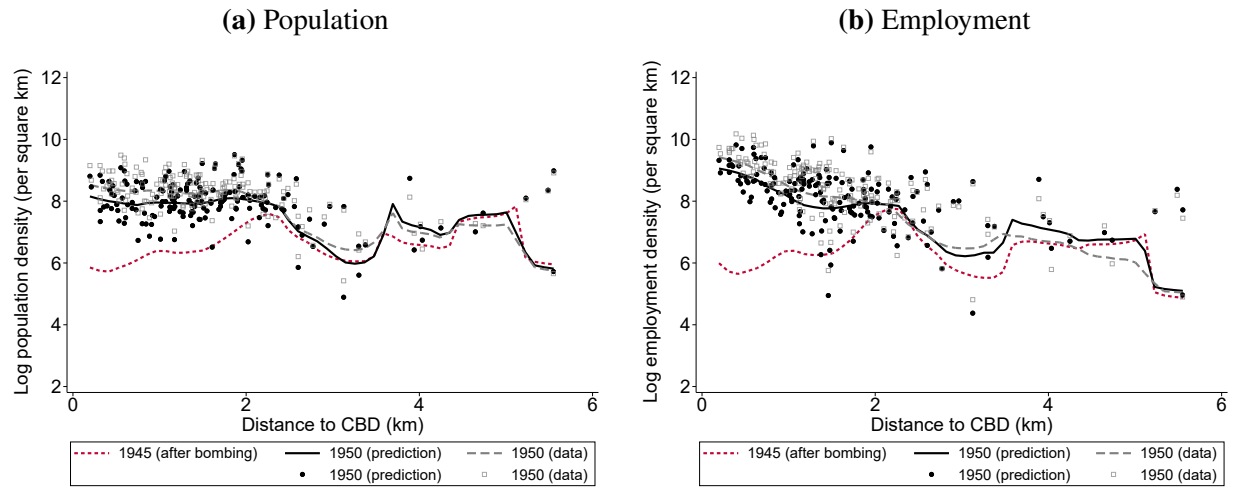
Importantly, we assume the block-fixed amenities and productivity, (a_{i1950}, b_{n1950}) , equal the averages estimated for the post-recovery period 1955–1975. The validity of this assumption can be checked by comparing the 1955–1975 fixed amenities and productivity with the 1950 exogenous amenities and productivity, which we can compute by netting out the agglomeration forces and future values from the option values $(\{\Xi_{n,1950}^F\}, \{\Omega_{i,1950}^F\})$. We find they are quite similar, with correlation coefficients of 0.98 for productivity and 0.99 for amenities.

Figure 5 illustrates the population and employment distributions predicted by our model for 1950. The horizontal axis is distance to the CBD, and the vertical axis shows population and employment density after the bombing in 1945, as observed in 1950 and as predicted by the model for 1950. For both population and employment, we find that our calibrated model successfully predicts the recovery of the city center, which we indeed observe in the data. The linear regression of the log of observed population (employment) density in 1950 on those predicted by the model yields a coefficient of 0.88 (1.01) with a high R-squared around 0.88 (0.91).⁵⁶ This result shows that our calibrated model successfully explains the fast and strong recovery from 1945 to 1950.⁵⁷

⁵⁶Note that the prediction of our model is substantially more accurate than just capturing the general tendency that blocks closer to the city center tend to have higher density in 1950. Indeed, regressing log population (employment) density on the log distance from the city center yields a R-squared around 0.20 (0.49), which is considerably lower than the R-squared from our model prediction.

⁵⁷Since our prediction does not include idiosyncratic amenity and productivity shocks in the recovery period, which may capture factors such as the recovery plan and property rights, these shocks may not be essential in inducing the recovery (see also Section 6.3).

Figure 5: Recovery of Population and Employment: Endogenous Part Explained by Our Model



Note: Each figure plots log population density (Panel a) and employment density (Panel b) with local polynomial regressions of each on distance from the CBD. We estimate three separate regressions: the observed 1945 population and employment densities (small dashed line); the observed 1950 population and employment densities (long dashed line); and the 1950 population and employment densities inferred under the counterfactual scenario in which we exclude the structural error components of amenities and productivity (solid line). Each dot represents a block, with different colors for the predicted density and the observed density.

6 The Role of Agglomeration Forces

Having demonstrated that our calibrated model can account for the recovery of central Hiroshima, we now analyze the role of agglomeration forces in the recovery. In Subsection 6.1 we undertake a counterfactual experiment in which we exclude agglomeration forces in both productivity and amenities from our calibrated model. We show that our model agglomeration forces provided the key incentive for people to again live and work in the city center. In Subsection 6.2 we investigate the existence of multiple equilibria. Consistent with the importance of agglomeration forces, we numerically find an alternative equilibrium in which the city center did not recover. This suggests that expectations can be self-fulfilling by selecting the recovery equilibrium among multiple equilibria. Lastly, in Subsection 6.3 we briefly explore the potential factors contributing to the formation of expectations, as we remain agnostic about *why* the expectations of recovery emerged. We argue that factors, such as government recovery plans, the anchoring effect of salient location characteristics in the city center (e.g., tram networks, Hiroshima castle), property rights, and popular narratives of rebuilding, may have allowed people to expect that the city center would recover.

6.1 Agglomeration Forces as the Key Driver of the Recovery

The recovery of the city center is achieved when individuals regard it as an attractive residence and workplace. Strong agglomeration forces can be a primary source of attractiveness. These forces

operate by increasing the expected population and employment density, which in turn leads to improved amenities and productivity. An alternative possibility is that the city center has attractive location fundamentals so that it attracts population and employment regardless of agglomeration forces. Which forces induced the recovery of central Hiroshima in our calibrated model? To investigate this, we compute counterfactual population and employment distribution for 1950 when spillovers in amenities and productivity are absent.

We solve the model for counterfactual equilibrium for 1950 population and employment distribution, using the same parameter values as Subsection 5.5 but setting both agglomeration parameters, α and β , to zero.⁵⁸ As in the baseline, individuals make forward-looking migration decisions taking into account future fundamental productivity, amenities, and commuting costs. Notably, as in Subsection 5.5, we assume that the fundamental amenities and productivity during the recovery period equal the average amenities and productivity during 1955-1975.⁵⁹ If agglomeration forces play the key role in explaining the attractiveness of the city center in our model, then this counterfactual exercise would not be able to predict the recovery.⁶⁰

Figure 6 shows the counterfactual population and employment densities in the absence of agglomeration forces. The model no longer predicts the recovery of population and employment in central Hiroshima. This is in stark contrast to the result of our main calibrated model in Figure 5. Given that the only deviation from our main calibrated model is the shutdown of agglomeration forces, this result highlights that agglomeration forces play the key model role in fitting the recovery of the city center. Note that as discussed in the last paragraph of Section 3, the importance of agglomeration forces is in line with our reduced-form results that the observed fundamental location characteristics, which are independent of agglomeration forces, do not explain the recovery.

6.2 Multiple Equilibria and Self-fulfilling Expectations in the Recovery

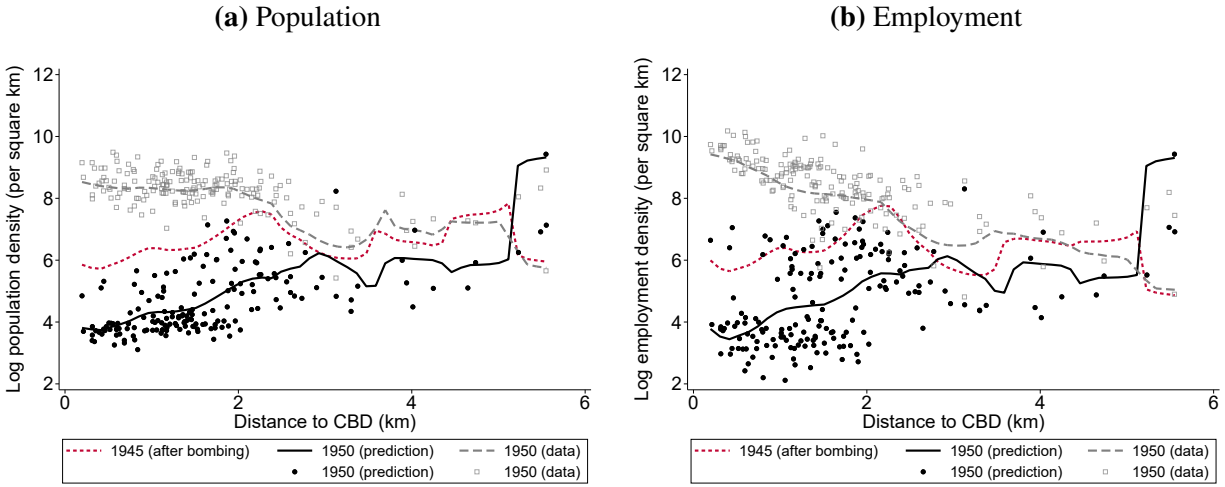
This section examines an alternative equilibrium in which the recovery does not occur. When agglomeration forces are important, the model may have multiple equilibria because whether the city center remains attractive depends on whether people expect a high density city center in the near future. There could exist an alternative equilibrium in which central Hiroshima does not recover. If

⁵⁸To focus on the population and employment distributions within the city, we assume in this counterfactual that the total population matches the observed data.

⁵⁹This assumption on fundamental amenities and productivity is important because even without agglomeration forces our model can fit any population and employment distribution in 1950 as long as the structural errors (a_{i1950}, b_{n1950}) can take any value. Therefore, the role of agglomeration forces highlighted in this subsection presumes that the levels of fundamental amenities and productivity are similar to those in the post-recovery period 1955–1975. Consistent with this assumption, we find that the values of the structural errors (a_{i1950}, b_{n1950}) are similar to the 1955–1975 fundamentals. See previous discussion in Subsection 5.5.

⁶⁰The parameters (α, β) capture not only pure externalities of density but also other channels through which population or employment density affects productivity and amenities. In this counterfactual, we turn off all these density effects simultaneously.

Figure 6: Population and Employment Distributions With No Agglomeration Forces



Note: Each figure plots log population density (Panel a) and employment density (Panel b) with local polynomial regressions of each on distance from the CBD. We run three separate regressions: one for the observed 1945 population and employment densities (small dashed line), one for the observed 1950 population and employment densities (long dashed line), and one for the inferred 1950 population and employment densities when we shut down agglomeration forces in both productivity and amenities (solid line). Each dot represents a block, with different colors for the predicted density and the observed density.

so, the selection of the recovery equilibrium among multiple equilibria is crucial in explaining the recovery of central Hiroshima.

Specifically, we present an example of an alternative rational-expectations equilibrium in which the city center does not recover. We use the parameters values and fundamentals estimated in Section 5 and assume that the total population matches the observed data. To find an alternative equilibrium, we start off with guesses of population and employment in 1975 that are different from the observed data.⁶¹ We then solve for the dynamics of population and employment consistent with equilibrium conditions dating back to 1945. Subsequently, we update our initial guess for 1975 until the backward solution in 1945 becomes sufficiently close to the initial conditions observed in 1945.

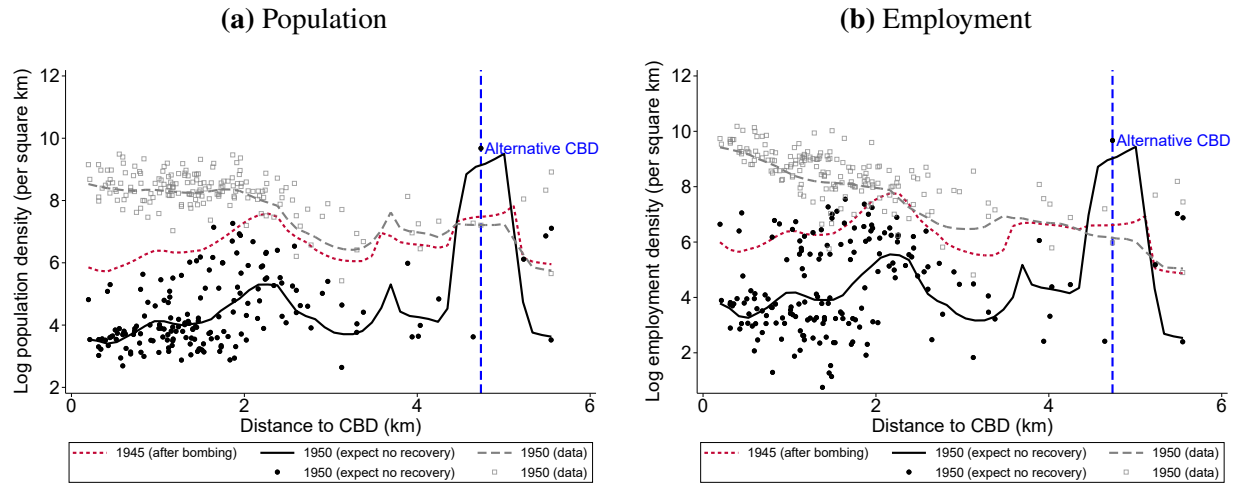
Figure 7 provides a visualization of population and employment densities in an alternative equilibrium. We compare these with the realizations of population and employment in 1950 and the initial pattern of 1945. We label a block with a high concentration of population and employment in this counterfactual as an alternative CBD.⁶² In Panel (a) we find that pre-war central Hiroshima does not recover, and its population density is even lower than the initial level in 1945. In Panel (b) we find a similar pattern for employment. These results are consistent with the idea that a totally

⁶¹To construct initial guesses for the population and employment distributions in 1975, we simulate population and employment dynamics forward in time from 1950, assuming that people have a myopic expectation that the population and employment distribution in period $t + 1$ will be the same as in period t .

⁶²This block (*nihomachi*) is a plausible candidate for an alternative CBD as it hosts high productivity firms such as *Toyo kogyo* (currently known as a large automotive manufacturer, Mazda Motor) and is close to Hiroshima port.

different city structure could have emerged as an alternative equilibrium.

Figure 7: Population and Employment Distribution in an Alternative Equilibrium



Note: Each figure plots log population density (Panel a) and employment density (Panel b) with local polynomial regressions of each on distance from the CBD. We run three separate regressions: one for the observed 1945 population and employment densities (small dashed line), one for the observed 1950 population and employment density in data (long dashed line), and one for the inferred 1950 population and employment densities in an alternative equilibrium (solid line) when people expect that the pre-war CBD will not recover and an alternative block located at the vertical dashed line will grow. Each dot represents a block, with different colors for the predicted density and the observed density. The location with growing population and employment density is labeled “alternative CBD”.

This multiplicity of equilibria highlights the importance of self-fulfilling expectations as an equilibrium selection device (Krugman 1991; Matsuyama 1991). In our rational-expectations model, if people expect the recovery, then the recovery equilibrium would realize because such expectations make the city center an attractive residence and workplace due to agglomeration forces. In contrast, if people do not expect the recovery of the city center, then no recovery equilibrium realizes as the city center remains unattractive. Therefore, our result highlights that in our model the formation of expectations in recovery is crucial in inducing the recovery of central Hiroshima after the bombing.

6.3 Discussion: Origins of Expectations in the Recovery

Our analysis has demonstrated the importance of expectations in the recovery. The expectation that blocks with high pre-war density would regain high density post-war is crucial in explaining the recovery of central Hiroshima. Nevertheless, we have remained agnostic as to why individuals would believe in recovery despite such a catastrophic shock. This section discusses several factors that may have influenced the coordination of individual expectations.

First, the presence of a government recovery plan would have facilitated the formation of expectations, despite the fact that publication of the plan lagged behind the onset of the recovery.⁶³

⁶³It is unlikely that zoning laws in Hiroshima contributed to the recovery in 1945-50 because the first post-war zoning

Moreover, the government was substantially underfunded, as discussed in Subsection 3.3, and implementation of the plan faced substantial difficulty.⁶⁴

Another possibility is that the tangible presence of some location characteristics in the city center might have induced an anchoring effect of expectations. The first example is the transportation system, especially the train network. While the direct benefit of access to trains does not appear to be essential to the recovery as we control for transportation access in both the reduced-form and structural analyses, the relatively quick restoration of the pre-war train network may have anchored people's expectations of reconstruction. Another example is Hiroshima castle. Although the castle itself was completely destroyed by the bombing and was unlikely to provide direct amenity values, its salience may have made it difficult for people to expect a situation in which the city center moves away from the castle.

Land ownership is an additional factor to consider. Note that in our context the recovery is unlikely to be explained by a strong tendency of original landowners to return to their home location. In particular, personal land ownership was quite rare in pre-WWII Japan: the rate of land ownership in urban areas of pre-WWII Japan was likely less than 10 percent (Kato 1988).⁶⁵ Moreover, unlike conventional air raids, the death rate near the epicenter of the atomic bombing was nearly 100 percent, implying that the number of surviving landowners would be relatively small.⁶⁶ That said, even the small number of landowners that returned to their original location may have played an important role in forming expectations in the recovery.

Lastly, the narrative of “rebuilding from the atomic bombing” may have sounded like a compelling success story and been shared widely (Shiller 2017).⁶⁷ As long as individuals were aware that many others shared this narrative, they could expect that the city structure would look like the pre-war Hiroshima in their memory, thereby inducing the recovery of the pre-war city center.⁶⁸

of Hiroshima was not published until 1949. At that point, the recovery was nearly complete. In addition, there were only four types of zones (commercial, residential, industrial, and unspecified), and the zoning allowed substantial mixed land use (Asano 2012).

⁶⁴Appendix B.1 reports that controlling for the number of public housing units supplied during 1945–1950 does not alter our regression results, which would be plausible given the limited supply due to the budget shortage.

⁶⁵The fraction of households owning a home was also quite low in pre-WWII urban areas in Japan at around 25 percent (Hinokidani and Sumita 1988).

⁶⁶The turnover of business owners was also high. According to Hiroshima City Government (1983), in 1958, approximately 28 percent of stores on a shopping street called *Hondori* remained in the same location as before the war, while the remaining 72 percent of stores started operating after the bombing. Although the majority were newcomers, landownership may have influenced their expectations regarding the recovery of business activities. We further analyze the role of surviving landowners in our counterfactual analysis. Specifically, we assume that landowners consisted of 20 percent of the total population in 1936 and those who survived the bombing returned to their place in 1950 due to their location attachment. Yet, we do not find the strong recovery of the central Hiroshima relative to the observations. See details in Appendix D.6.

⁶⁷Although it is challenging to empirically assess how powerful and widespread such a narrative was, the 1946 Statistical Abstract of Hiroshima is suggestive in stating ‘... rumors like “nothing will grow here for 75 years” immediately disappeared among people with their burning desire to rebuild...’ (p. 4, translated by the authors).

⁶⁸This relates to the idea of “memory-based expectations,” in which people form expectations based on their past

These underlying factors may influence the attractiveness of each location by either directly improving location-specific amenities (b_{nt}) and productivity (a_{it}), or via expectation channels. However, as discussed in Subsections 5.5 and 6.1, the ability of our calibrated model to explain the recovery comes from agglomeration forces, not location-specific amenities and productivity. In the expectations channel, several factors may alter expectations regarding the future population and employment distributions after the bombing, thereby affecting the attractiveness of each location via agglomeration forces. The self-fulfilling nature of expectations found in Subsection 6.2 suggests the possibility that the above-mentioned factors may have played a key role in inducing the recovery through the expectations channel.

7 Conclusion

How resilient is city structure – the spatial distribution of economic activities within cities – to large shocks? What induces the resilience of city structure? To answer these questions, we examine the atomic bombing of Hiroshima, which drastically changed the city’s structure by completely destroying the city center while sparing the city’s outskirts. We collect and digitize new historical data on Hiroshima’s population, employment, wartime destruction, and fundamental location characteristics at the city block level. Then, we document the strong resilience of Hiroshima’s city structure: the destroyed city center recovered in its population density just five years after the atomic bombing. Our reduced-form analysis reveals that controlling for prominent observable location characteristics, such as altitudes or access to natural water, does not explain the recovery.

To identify the mechanism behind the recovery, we develop and calibrate a novel dynamic quantitative model of internal city structure that incorporates commuting, forward-looking migration decisions, migration frictions, agglomeration forces, and heterogeneous fundamentals across locations. Estimating the model with post-recovery data (1955–1975), we find strong agglomeration forces in productivity and amenities. The calibrated model successfully explains the resurgence of population and employment in the city center after the bombing (1945–1950).

In our model, agglomeration forces play a crucial role in explaining why the city center again became an attractive workplace and residence after the bombing. In the presence of strong agglomeration forces, multiple equilibria may exist because the city center does not become attractive if it is not expected to achieve high density. We find that there exists an alternative forward-looking equilibrium where the city center fails to recover. This suggests that the recovery may have cru-

experiences (Malmendier and Wachter 2022). To gauge its potential importance, we calculate the predicted population and employment densities when everyone has “purely memory-based expectations.” Specifically, we simulate the model as in Subsection 5.5 assuming that workers expect the population distribution in 1936 and employment distribution in 1938 to be realized again in 1950. The simulation shows that such purely memory-based expectations also induce the recovery of the city center, suggesting that such expectations are comparable to rational expectations in our context.

cially depended on people's expectations, as they can be self-fulfilling and select the equilibrium of recovery. In this sense, the recovery of central Hiroshima might not have been possible without people's expectations of the recovery. We argue that certain factors, such as government recovery plans, the anchoring effect of salient location characteristics in the city center (e.g., tram networks, Hiroshima castle), property rights, and popular narratives of rebuilding, may have led people to expect that the destroyed areas would once again achieve high density as in the pre-war period. Taken together, our quantitative findings highlight the role of agglomeration forces, multiple equilibria, and expectations in the resilience of city structure. This suggests an important policy implication: when fostering resilience, policymakers should pay attention to coordinating agents' expectations about recovery.

Beyond the context of Hiroshima's resilience, agglomeration economies and expectations are important determinants of the dynamics of city structure. Therefore, our findings suggest that policymakers may be able to substantially change the dynamics of city structure if they could influence expectations about future city structure. Our theoretical framework developed in this paper could serve as a useful starting point for performing quantitative analyses to understand how the organization of economic activity within cities evolves over time. However, our model does not incorporate an explicit process in which people form expectations. Developing additional understanding of the ways in which agents can form expectations about a city's future structure is an interesting area for further research.

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Online Appendix to: “The Economic Dynamics of City Structure: Evidence from Hiroshima’s Recovery”

Kohei Takeda

Atsushi Yamagishi

Appendix A describes the details of data construction. Appendix B provides additional reduced-form results, including additional analysis on Nagasaki. Appendix C presents detailed derivations in the model. Appendix D provides details for Sections 5 and 6 in the main text.

A Data Appendix

A.1 Basic Data

Maps, spatial units and sample selection The city block (*cho cho moku*) is our spatial unit of analysis. As our main definition of geography and city blocks, we use the GIS data of block boundaries as of the bombing constructed by [Takezaki and Soda \(2001\)](#). We make several adjustments to create our final sample. First, although [Takezaki and Soda \(2001\)](#) follows the map of officially-published block boundaries (*Hiroshima shin-shi*), it was constructed after the war, and a few blocks do not correspond to our population data. We address this issue by suitably aggregating blocks in [Takezaki and Soda \(2001\)](#).¹ Second, we drop some blocks that experienced exceptional events that are outside the scope of our model. We drop blocks that later constitute Hiroshima Peace Memorial Park, Hiroshima-shi Chuo Park, and Hijiyama Park. Second, we drop three blocks that exhibit unusually large changes in population or employment in some periods, which is likely due to idiosyncratic events outside of the model.² Third, we drop observations that have missing observations in the destruction rate of buildings or the establishment counts in 1938. Finally, to ensure that our geographical scope is small, we drop two blocks whose centroids are more than 6 kilometers from the city center. We also drop an unpopulated remote island (*touge-shima*) from our sample.³ In our final sample, there are 174 blocks. We also digitize the block boundaries as of 1966 and 1976 to deal with changes in the block boundaries. For 1966, we use the map found in the report of the 1965 block-level population of Hiroshima (*Hiroshima-shi machi-betsu jinkou setai shiryō shōwa 40-nen kokusei chosa yori*). For 1976, we use the Hiroshima City map (*Hiroshima shigai chizu*) issued by a private publisher (*Shobun-sya*) in 1976.

¹We aggregate two blocks (*Akebomo-machi* and *Kougo kita-machi*) that are recorded in a disaggregated way in [Takezaki and Soda \(2001\)](#). We also combine the *Yaga machi* and *Yaga shin-machi*, and *Funairi minami-machi* and *Funairi kawaguchi-machi*.

²We drop *Hakushima kita-machi*, *Iwamiya-cho*, and *Toriya-cho*. While we are not completely sure of why these blocks exhibit a sudden change in population or employment, we speculate that the presence of schools in *Hakushima kita-machi* and *Iwamiya-cho*, and a very small size of *Toriya-cho* (less than 0.0025km^2) made them prone to idiosyncratic shocks.

³We keep a remote island called *kanawa-jima*, belonging to the *niho machi* block in our sample because it is relatively close to the mainland and it had a major shipyard.

Destruction by the atomic bombing The severity of destruction can be measured primarily in two ways: the ratio of buildings destroyed and the ratio of people killed. In this paper, we primarily focus on the building data for two reasons. First, the kill ratio is less reliable because it was extremely difficult to check who was killed in the totally destroyed city. [Hiroshima City Government \(1971\)](#) contains many missing values for the kill ratio due to the absence of reliable data on the kill rate. In contrast, the destruction rate of buildings was easier to record even a while after the bombing and hence has way fewer missing values. Second, [Hiroshima City Government \(1971\)](#) records the “immediate” death rate by the bombing; however, the definition of the “immediate” is unclear and seemingly inconsistent across blocks in [Hiroshima City Government \(1971\)](#). This is important in the context of Hiroshima because many people died days, months, or even years after the bombing due to the sickness caused by the radiation. Third, previous research on the impact of bombing on the city populations ([Davis and Weinstein 2002](#); [Brakman, Garretsen and Schramm 2004](#)) indicates that the damage to buildings is a better measure of the damage level than casualties.

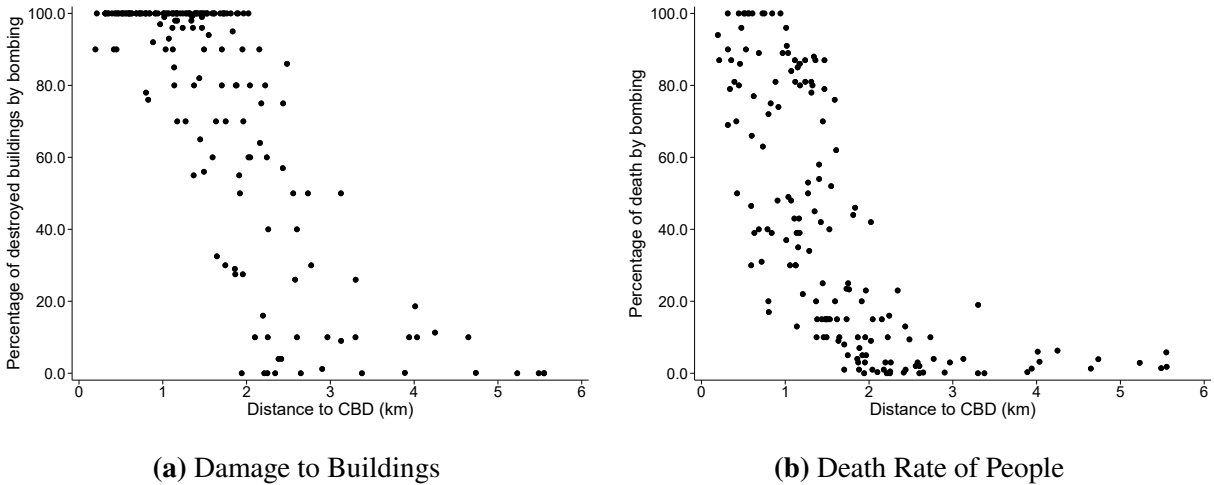
We base our analysis on the digitization of [Hiroshima City Government \(1971\)](#) by [Takezaki and Soda \(2001\)](#), but we consulted [Hiroshima City Government \(1971\)](#) to (i) correct errors in [Hiroshima City Government \(1971\)](#) or [Takezaki and Soda \(2001\)](#) and (ii) obtain the building destruction rate or the kill rate when they can be credibly inferred from the text information. We plot the building destruction rate against the distance from the CBD in Figure A.1a. Blocks within 2 kilometers of the CBD were quite severely destroyed, while those further than 2 kilometers from the CBD tend to experience much less damage. A similar plot for the kill rate is in Figure A.1b. The severest damage tends to concentrate in a smaller area (particularly within 1 kilometer of the CBD), and the data has more variation conditional on the same distance from the CBD, partially because the data is noisier.

A.2 Population and Employment

Population We collect and digitize block-level population data. For 1933–1936, we use the Statistical Handbook of Hiroshima City (*Hiroshima-shi toukei sho*) that reports the population at the block level. For 1945–1953, we use the Statistical Abstract of Hiroshima City (*Hiroshima shisei youran*). Since 1955, we use the population census data. Two issues must be addressed to make the population data comparable from 1933 to 1975. First, the block boundaries changed over time and the city’s shape also changed due to landfills and flood control. Second, prior to 1951, population data is available only at a less spatially granular level than blocks.

To address these issues, we first base our definition of blocks as of 1945 and focus on block areas that existed from 1945 to 1975. Then, when the block boundary changes since 1945, we evenly distribute the population based on the overlapping area. To address the changes in the size of blocks due to landfills and flood control, we focus on land areas both in 1945 and 1975. Our focus on the 1945 blocks allows us to ignore new landfills. However, flood control, especially the

Figure A.1: Damage to Buildings and Death Rate of People



Note: The left panel plots percentage of totally destroyed buildings by the atomic bombing in each block. The right panel plots percentage of people killed by the atomic bombing in each block. Source is [Hiroshima City Government \(1971\)](#).

redesign of the *ota* river, which started at full scale in 1961 and was almost completed in 1965, is still an issue because some land areas in 1945 later went under the river. This implies that some blocks in our data are smaller than their original size as of 1945. To address this, we calculate the percentage change in the area before and after this flood control and multiply by this percentage all population variables prior to 1965, which again implicitly assumes that the population is evenly distributed within each block.

Second, prior to 1951, population data is available only at a less spatially granular level than the blocks. To construct the block-level population data in 1945, we combine the block-level information on the rate of totally destroyed buildings from [Hiroshima City Government \(1971\)](#) and the population change ratio from the pre-bombing period to November 1 1945 from the Statistical Abstract of Hiroshima City for each distance bin from the epicenter of the atomic bomb. We first calculate the fraction of totally destroyed buildings by the distance to the city center by aggregating the data from [Hiroshima City Government \(1971\)](#). We then regress the population change ratio onto the quadratic function of the fraction of totally destroyed buildings. As seen in Figure A.2a the regression model fits the data well. Note also that the predicted population in November 1945 is strictly positive even for blocks with the 100% destruction rate. We use this model to predict the population change ratio by using the block-level total destruction of buildings. Finally, we multiply this ratio with the 1936 block-level population to approximate the 1945 block-level population. We validate our method of imputing the 1945 population after the bombing using different data. The 1946 edition of *Hiroshima shisei youran* reports in a map the population level before (August of 1945) and after (August of 1946) the bombing for each school district. While we do not know the

exact border of school districts, we can compute the population change ratio between the two periods, which we expect to be highly correlated with the population change due to the atomic bombing. We then compare the population change rate of each school district with that of the census block that appears closest to the relevant school district on the map. Figure A.3 shows the scatter plot and the fitted line. We obtain a very high correlation (around 0.86) between these two despite the data limitations that the population was measured at different timing and the correspondence of school districts and the block was measured with error.

To construct the block-level population data in 1949 and 1950, we use population data that is recorded at a less spatially granular level, called *shucchojo*, taken from the 1949 and 1950 Statistical Abstract of Hiroshima.⁴ *Shucchojo* divides the city into 18 districts based on the administrative area of each branch of the city government office. In principle, each *shucchojo* district is aggregated from blocks.⁵ Assuming that within each *shucchojo*, the population share is the same as in 1951, we approximate the block-level population data by multiplying this share by the population of the *shucchojo*.

Our main analysis does not use population data from 1946–1948 because the block-level data is hard to construct. However, the population data for 1946, 1947, and 1948 is available in the Statistical Abstract of Hiroshima City separately for distance categories from the epicenter of the bombing. In Figure A.4, we plot the time series of the population share of areas within 1 kilometer of the epicenter using this data. The figure shows that the recovery process had already started strongly in 1946, although the recovery was relatively slow until April 1946. Moreover, the recovery was complete in the sense that the population share of the central area exceeded the predicted share based on the pre-war trend.

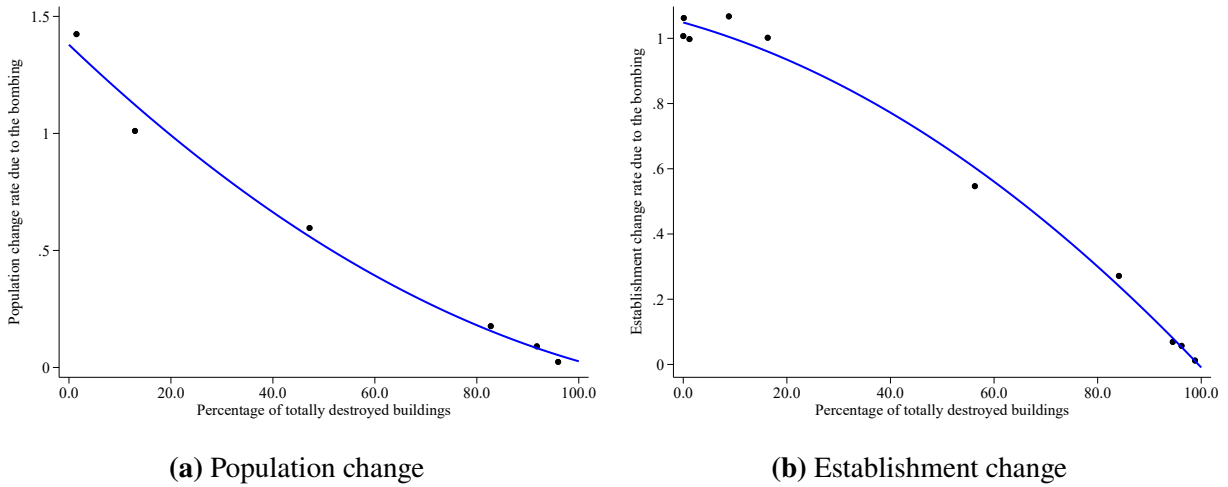
Employment We collect and digitize block-level employment data from various historical sources. The Survey of Commerce and Industry in Hiroshima City (*Hiroshima-shi shoukou-gyou keiei chousa*) records the number of establishments (factories and commercial stores) at the block level for the year 1938. For 1946, the number of buildings used for business purposes is taken from the Statistical Abstract of Hiroshima City (*Hiroshima shisei youran*). For the year 1953, we rely on the Survey on the Daytime Population of Hiroshima (*Hiroshima-shi chukan jinko chosa*), assuming that the daytime population approximates employment. From 1957 to 1975, we use the Business Establishment Statistical Survey (*jigyousho toukei chousa*).

Throughout this paper, we focus on employment in the manufacturing or service sectors and

⁴Similar to the block-level data, we have also adjusted the shrink in the area of *shucchojo* districts by defining the area change of each district before and after the *ota* river flood control. We multiply the original population by this area change rate to obtain the *shicchojo* level population.

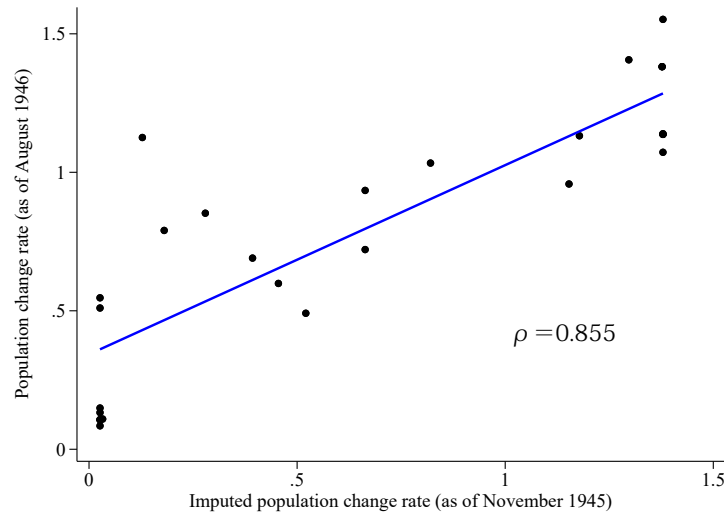
⁵There are a few exceptions in which a block overlaps multiple *shucchojo* districts. In this case we assume that a block belongs to the district in which more of the block residents live.

Figure A.2: Population and Establishment Change on the Rate of Totally-destroyed Buildings



Note: The left panel shows the scatter plot of the percentage of totally destroyed buildings and the population change rate due to the bombing for distance categories from the epicenter (within 1km, 1-1.5km, 1.5-2km, 2-2.5km, 2.5-3km, more than 3km away). The population change is from the 1946 Statistical Abstract of Hiroshima City and the destruction rate is a population-weighted average of the block-level destruction rate from [Hiroshima City Government \(1971\)](#). The right panel shows the scatter plot of the percentage of totally destroyed buildings and the establishment change rate due to the bombing for distance categories from the epicenter (0.5km grids up to 5km). The establishment change is from the 1946 Statistical Abstract of Hiroshima City. In both panels, we fit the quadratic model and plot it.

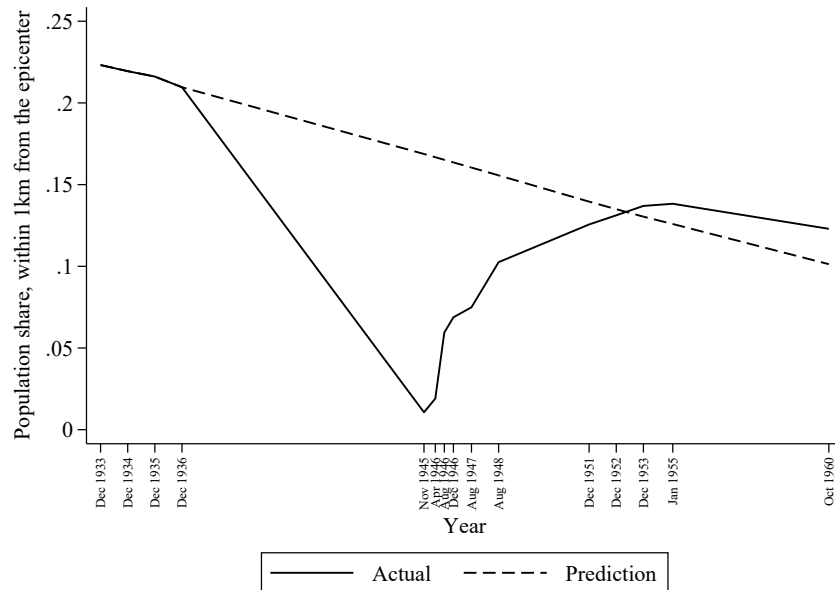
Figure A.3: Validation of Our 1945 Population Data with Alternative Population Data in 1946



Note: We validate our method of imputing the 1945 population after the bombing using different population data taken from the 1946 edition of *Hiroshima shisei youran* at the school district level. The horizontal axis shows the predicted population change rate as of November 1945 based on the imputed destruction rate of buildings for each school district. The vertical axis shows the population change rate as of August 1946, taken from the data. We also plot a linear regression line.

ignore agricultural employment. This is a relatively moderate restriction because we focus on an

Figure A.4: Actual and Predicted Population Share Within 1km from the Epicenter



Note: This figure shows the population share of areas within 1 kilometer of the epicenter. For 1945–1948, we observe the population in the Statistical Abstract of Hiroshima. For the remaining years, we aggregate the block-level population to the distance bins from the epicenter according to the definition of Hiroshima City Government (1971). The predicted population share extrapolates the pre-war linear trend to the post-WWII period, analogous to Figure 2 of Davis and Weinstein (2002).

urban area throughout our sample period.⁶

Three issues must be addressed to make the block-level employment data comparable between 1938 and 1975. First, similar to population, the block boundary and the land area changed over time. Second, the employment information for 1945–1963 is only available at a less spatially granular level than blocks. Third, for 1938 and 1945, we know the number of establishments but not the number of workers. For the first issue, we address it using the same strategy as the population data.

We now describe how we address the second issue. We calculate the number of establishments as of November 1945, when our first post-war population data is available. We first extract the number of buildings for shops, restaurants, banks, hotels, associations, and entertainment facilities before and after the bombing (August 1946) from the 1946 Statistical Abstract of Hiroshima City. We also

⁶While most of our data already focus on non-agricultural employment, the 1953 data report total employment, including agricultural employment. To account for this, the number of agricultural workers in 1953 is estimated using the following method. First, we obtain the share of agricultural households from the 1950 Statistical Abstract of Hiroshima. Using the number of agricultural workers from the 1950 Population Census, we estimate that roughly half of agricultural household members are counted as employed. This allows us to calculate the fraction of agricultural workers in the overall population. We multiply it by the block-level population in 1953 to approximate agricultural employment at the block level in 1953. Even in 1950, when agricultural employment was still significant in the Japanese economy, less than 10 percent of workers were in the agricultural sector in Hiroshima City.

approximate the establishment distribution right after the bombing (August 1945) by multiplying the number of establishments before the bombing by the proportion of completely destroyed buildings.⁷ Using linear interpolation, we can approximate the number of establishments for each distance bin in November 1945 based on the data from August 1945 and 1946. Second, we regress the rate of change in the number of establishments from the pre-war period to November 1945 on the ratio of totally destroyed buildings and its square. Figure A.2b shows that the regression model fits the data well. Finally, we multiply the number of establishments in 1938 by the predicted change rate using the block-level ratio of the totally destroyed buildings and the estimated regression model shown in Figure A.2b.⁸

To construct the block-level employment distribution for 1950–1963, we rely on the employment distribution that is recorded at a less spatially granular level (*shucchojo*).⁹ Since our 1957 employment data aggregates seven peripheral districts into one, we define it as the “others” district and use 12 *shucchojo* areas. The number of workers at the *shucchojo* level is available for 1953, 1957, and 1963. To calculate the employment at the block level, we multiply the number of workers in the *shucchojo* and the employment share of that block in 1966. This procedure assumes that the employment share *within* the *shucchojo* district is approximated by the 1966 distribution, but allows for the employment changes across *shucchojo* districts. Finally, to approximate the employment distribution in 1950, we assume that the employment distribution in 1950 is the same as in 1953 except for the total number of workers, which we scale down by the growth rate in the total population.

Finally, we need to construct the block-level employment data from the block-level establishment data. Following prior studies (e.g., Ahlfeldt, Redding, Sturm and Wolf 2015), we assume that employment is proportional to the number of establishments. To determine the total size of employment in 1938 and 1945, we multiply the total population by the labor force participation rate in 1936, which is 44.2 percent according to the 1936 Statistical Handbook of Hiroshima City (*Hiroshima-shi toukei sho*).¹⁰

A.3 Other Data

Commuting and transportation network We use the trip-level microdata of the 1987 Hiroshima City Person-Trip Survey for metropolitan area residents. It was large-scale (about 7 percent of the

⁷We compute the average fraction of completely destroyed buildings for each bin from the block-level data of the fraction of completely destroyed buildings (Hiroshima City Government 1971), using the 1938 number of establishments as weights.

⁸The predicted model yields a negative rate of change in the number of establishments for a total destruction rate of 100 percent. To address this, we apply the predicted change rate for blocks with a 100 percent destruction rate to those with a 99 percent destruction rate.

⁹The issues of some blocks belonging to two *shucchojo* districts and changing land areas are addressed in the same way as the population data.

¹⁰In our structural estimation, however, the total employment equals the total population because our model assumes that everyone works. We normalize the total population to the total employment.

Table A.1: Summary Statistics for Population and Employment

	All blocks in the city (174 blocks)		Within 3km from CBD (158 blocks)	
	Mean	Standard deviation	Mean	Standard deviation
Population in 1936	1,880	2,153	1,642	1,103
Population per $1km^2$ in 1936	23,761	14,104	25,752	13,138
Population in 1945	917	2,927	459	916
Population per $1km^2$ in 1945	3,566	5,496	3,374	5,158
Population in 1950	1,495	2,683	1,026	1,091
Population per $1km^2$ in 1950	11,877	6,616	12,583	6,374
Population in 1960	2,215	3,648	1,537	1,689
Population per $1km^2$ in 1960	16,725	8,548	17,737	8,188
Population in 1975	2,625	5,423	1,501	2,694
Population per $1km^2$ in 1975	12,758	5,046	13,065	4,906
Employment in 1938	978	835	949	626
Employment per $1km^2$ in 1938	42,517	41,449	46,512	41,422
Employment in 1945	405	1,056	259	420
Employment per $1km^2$ in 1945	5,507	8,035	5,602	8,072
Employment in 1953	669	965	505	465
Employment per $1km^2$ in 1953	7,358	6,083	7,909	6,099
Employment in 1966	1,277	1,516	1,060	792
Employment per $1km^2$ in 1966	18,499	17,408	20,111	17,463
Employment in 1975	1,515	1,880	1,211	993
Employment per $1km^2$ in 1975	21,017	21,948	22,821	22,243

population was surveyed) and representative. To further enhance representativeness based on residence, age, and gender, we use the sampling weights provided in the survey. The unit of observation is a trip, and for each trip, origin, destination, and mode(s) of transportation are recorded. We use the following representative modes of transportation: walk, bicycle, car, bus, and train. The representative mode is defined as follows: First, the representative mode is “train” if the trip uses a train or tram. Then, for trips that have not been coded, we code them as “bus” if they use buses. We code trips that have not been coded as “car” if they use a motorcycle or automobile. We code trips that have not been coded as “bicycle” if they use a bicycle. Finally, we code a trip as “walk” if it uses walking.

Using the microdata from the 1987 person-trip survey, we estimate the mode choice model based on the travels of workers from home to workplace.¹¹ To measure the travel time between each workplace-residence pair, we also collect and digitize road networks in 1987, bus networks, and train networks in Hiroshima City, and compute the bilateral travel time between the centroids of blocks for each mode: walk, bike, car, bus, and train.¹² Although public transportation networks

¹¹As an alternative measure of a bilateral commuting matrix, we also try the geographical distance between blocks. We measure the bilateral distance by the geographical distance between the centroids of two areas. We estimate the gravity equation by constructing a bilateral commuting matrix between 66 areas within our sample area, using individual-level information on the residence and the workplace. The 66 areas are constructed by suitably aggregating blocks. Our main conclusions do not change.

¹²We use QGIS to compute the travel time. Based on available evidence, we assume the following travel speeds: 5

were generally stable during our sample period, there were a few notable changes, including the discontinuation of the *Ujina* line in 1966. To address this, we also digitize the bus and train networks in 1950. Prior to 1966, we use the public transportation networks of 1950, and after that, we use those of 1987. Throughout our sample period, we use the 1987 road network for data quality, which is reasonable given that the road network in Hiroshima has not changed significantly from the pre-war period. To formally verify this, we digitize the road networks on the published city maps prior to the bombing and in 1950.¹³ We then compare the travel times to the city center under these networks to the travel times under the road network of 1987. The correlation between the pre-bombing period and 1987 is around 0.95, and the correlation between 1950 and 1987 is around 0.97.

Location characteristics We first explain the natural location characteristics. The altitude and the ruggedness are taken from the Digital National Land Information.¹⁴ For each 250 m × 250m squares, the data record the average altitude and the average degree of slopes. We assign the value at the centroid of each block. Second, we obtain the location of water areas separately for the pre-war and post-war periods. We use the digital map of [Takezaki and Soda \(2001\)](#) for the pre-war period and the Basic National Land Information data for the post-war period. Finally, we take the soil condition from the Land Classification Basic Investigation.¹⁵ We use the data on the surface strata and assign the soil condition to each block using the centroid location.

We next explain our data on non-natural location characteristics. We collect information on the location of train stations in 1950 from the Digital National Land Information.¹⁶ The location of the city center is defined as the midpoint of the *Hacchobori* block and *Kamiya-cho* block. The location of Hiroshima port (*Ujina* port) is taken from Google Maps. The list of cultural assets (*bunkazai*) in the city is taken from the Hiroshima Metropolitan Area and Hiroshima Prefecture Open Data Portal Site.¹⁷ We compute all the distances using the centroid of each block. Finally, we digitize the location and the number of units of each public housing from the 1949 and 1950 Statistical Abstract of Hiroshima City (*Hiroshima shisei youran*).¹⁸ The data cover all public housing units constructed

km/h for walking, 12 km/h for bicycling, 25 km/h for driving a car, 15 km/h for bus, 12 km/h for tram, and 36 km/h for other trains. When calculating the travel time by bicycle, car, bus, and train, we assume walking occurs outside its network.

¹³For the pre-bombing map, we digitize a map created by the US Army based on pre-bombing resources (https://maps.lib.utexas.edu/maps/ams/japan_city_plans/). For 1950, we digitize the Geospatial Information Authority of Japan Map.

¹⁴Source: <https://nlftp.mlit.go.jp/ksj/gml/datalist/KsjTmplt-G04-d.html>, in Japanese. Last accessed on October 28, 2023

¹⁵Source is a map with a scale of 1 to 50,000; https://nlftp.mlit.go.jp/kokjo/inspect/landclassification/land/l_national_map_5-1.html, in Japanese. Last accessed on October 28, 2023.

¹⁶Source: https://nlftp.mlit.go.jp/ksj/gml/datalist/KsjTmplt-N05-v1_3.html, in Japanese. Last accessed on October 28, 2023.

¹⁷Source: <https://hiroshima-opendata.dataeye.jp/resources/9843>. Last accessed on October 28, 2023.

¹⁸In some cases, the location information in the data does not allow us to identify the block the public housing is located in uniquely. We still assign the single block based on our best guess on the location of that public housing.

in Hiroshima from 1946 to 1950.

Table A.2: Summary Statistics for Block Characteristics

	All blocks in the city (174 blocks)		Within 3km from CBD (158 blocks)	
	Mean	Standard deviation	Mean	Standard deviation
Block area (km^2)	0.321	0.971	0.132	0.39
Distance to the CBD (km)	1.66	1.06	1.4	0.652
Distance to Hiroshima port (km)	4.74	1.08	4.72	0.985
Distance to the nearest station (m)	336	319	285	232
Distance to the nearest water area (m)	248	229	226	185
Distance to the nearest cultural asset (m)	808	637	684	412
Altitude (m)	5.91	14.4	4.25	7.56
Average slope (degree)	0.814	2.4	0.611	2.07
Indicator of bad soil condition	0.96	0.197	0.981	0.137
Latitude	34.4	0.0104	34.4	0.00917
Longitude	132	0.0167	132	0.0123
Annual population growth rate 1933–1936	1.03	0.0355	1.03	0.0344
Rate of total destroyed Building	74.5	35.4	81.1	29.8
Rate of half-damaged buildings	18.6	26	15.2	23.6
Rate of mildly-damaged buildings	6.65	17.7	3.38	12.1
Rate of intact building	0.685	3.99	0.316	1.66

Land prices We obtain the location with the highest unit land price within Hiroshima.¹⁹ The 1931 Statistical Yearbook of Hiroshima City reports for the location in 1931. The National Tax Agency reports the location with the highest land price in each prefecture in 1959, and the highest land price in Hiroshima prefecture was in Hiroshima city.²⁰

Migration rate Our primary data source for the migration rate is the 1960 population census. It asks whether a respondent changed their address, including moving within the same municipality. In densely populated areas of Hiroshima prefecture, 85.9 percent of people in prime age answered they did not.²¹ Converting this into a 5-year interval, we calculate the rate of moving within five years is $\theta \simeq 0.53$. However, this migration probability seems too small for the period right after the war. Many people reallocated for wartime reasons and they would have lower mobility costs (e.g., lower attachment to their current residence, higher probability of intending job switching). According to the city population registry (reported in *Hiroshima shisei youran*), more than 50,000 people moved out of Hiroshima City in 1949. Since the population of Hiroshima City at the end of 1948 was about 24,000 (1952 *Hiroshima shisei youran*), this implies an annual migration rate of 21 percent even if intra-city migration is ignored. We assume that the relative frequency of intra-city

¹⁹In Japan, to our knowledge, digitized comprehensive land price data in the pre-WWII period is available only in Tokyo and Kyoto (Yamagishi and Sato 2023).

²⁰This can be found in Weekly Tax Communication (*Shukan zeimu tsushin*), volume 444, issue of February 22, 1960.

²¹The prime-age means between the ages of 15 and 59. Data source: <https://www.e-stat.go.jp/stat-search/files?page=1&layout=datalist&toukei=00200521&tstat=000001036867&cycle=0&tclass1=000001038047&tclass2val=0>, in Japanese. Last accessed on October 28, 2023.

migration and inter-city migration right after the war is similar to that in 1960.²² This suggests an annual rate of staying of 0.64, corresponding to a rate of moving within five years $\theta \simeq 0.9$. Note that our migration rate for the period 1945–1950 is primarily based on the migration data from 1949. This might understate the migration rate if the mobility right after the war was even higher than the 1949 migration rate.

B Additional Reduced-form Evidence

B.1 Robustness Checks

Employment Table B.1 reports the regression results of the equation (1) for employment, in the same manner as Table 1 for the population. The estimated coefficients are very similar to Table 1, but somewhat closer to -1 . In Columns (3)–(6), we cannot reject the null hypothesis of $\gamma = -1$, implying the complete recovery to the pre-war employment distribution.

Table B.1: Changes in Employment Density and the War-time Damage

	(1)	(2)	(3)	(4)	(5)	(6)
	Change in log employment density 1945–50					
Change in log employment density 1938–45 (γ)	-0.750*** (0.036)	-0.857*** (0.036)	-1.031*** (0.065)	-0.985*** (0.057)	-0.987*** (0.057)	-0.938*** (0.055)
p -value from testing $\gamma = -1$	0.000	0.000	0.635	0.802	0.824	0.268
Natural location characteristics (first nature)		✓		✓	✓	✓
Manmade location characteristics (second nature)			✓	✓	✓	✓
Pre-war trends in population					✓	
Within 3 km from the city center						✓
Number of blocks	174	174	174	174	174	158
R-squared	0.757	0.799	0.806	0.852	0.859	0.895

Note: We report the OLS estimation result of equation (1). Natural locational characteristics consist of log distance to the pre-war city center, log distance to the nearest water area, the altitude and its square, the slope and its square, geographical coordinates (latitude, longitude, and their interaction), and a dummy for a bad soil conditions. Manmade location characteristics consist of log distance to the nearest station, log distance to Hiroshima port (Ujina port), log distance to the nearest cultural asset, and the initial housing stock condition (the fractions of the half-destroyed, moderately-destroyed, and intact buildings). In column 5, We also control for the pre-war (1933-1936) population growth rate and its square. In column 6, we confine the sample to blocks within 3 kilometers of the city center, in which fundamental conditions are more homogeneous. We report the p -value from testing the null $\gamma = -1$, meaning that the employment density converged back to the 1938 one. Heteroskedasticity-robust standard errors in parentheses. ***: Significant at the 1% level.

Robustness to measurement errors Table B.2 presents the OLS estimation results of the model $\ln \text{Popdens}_{i,t} = \gamma_1 \ln \text{Popdens}_{i,1945} + \gamma_2 \ln \text{Popdens}_{i,1936} + \eta X_i + v_i$. In all columns, γ_1 is positive and statistically significantly different from zero. This suggests that the population distribution in 1950 is positively related to the 1936 distribution. In contrast, the estimate of γ_2 is much smaller and not statistically significant in columns 3–6. Therefore, we find little evidence that the 1945

²²For the prime-aged people, this ratio in the densely-populated area of Hiroshima prefecture is around 7:10, implying that the annual migration rate is roughly 0.36.

population distribution affects the 1950 population distribution. Importantly, the observed location characteristics do not seem to account for the recovery because the above conclusion is unaffected by controlling for them.

Table B.2: OLS with two explanatory variables..

	(1)	(2)	(3)	(4)	(5)	(6)
	Log population density in 1950					
Log population density in 1936	0.494*** (0.039)	0.458*** (0.048)	0.538*** (0.096)	0.465*** (0.091)	0.450*** (0.095)	0.385*** (0.104)
Log population density in 1945 (after the bombing)	0.089*** (0.030)	0.066* (0.037)	0.042 (0.082)	0.078 (0.080)	0.084 (0.082)	0.103 (0.088)
Natural location characteristics (first nature)		✓		✓	✓	✓
Manmade location characteristics (second nature)			✓	✓	✓	✓
Pre-war trends in population					✓	
Within 3 km from the city center						✓
Number of blocks	174	174	174	174	174	158
R-squared	0.583	0.629	0.599	0.664	0.673	0.508

Note: This table presents the OLS estimation results of the model $\ln \text{Popdens}_{i,t} = \gamma_1 \ln \text{Popdens}_{i,1945} + \gamma_2 \ln \text{Popdens}_{i,1936} + \eta X_i + v_i$. Natural locational characteristics consist of log distance to the pre-war city center, log distance to the nearest water area, the altitude and its square, the slope and its square, geographical coordinates (latitude, longitude, and their interaction), and a dummy for a bad soil conditions. Manmade location characteristics consist of log distance to the nearest station, log distance to Hiroshima port (Ujina port), log distance to the nearest cultural asset, and the initial housing stock condition (the fractions of the half-destroyed, moderately-destroyed, and intact buildings). In column 5, We also control for the pre-war (1933-1936) population growth rate and its square. In column 6, we confine the sample to blocks within 3 kilometers from the city center, in which fundamental conditions are more homogeneous. We report the p -value from testing the null $\gamma = -1$, meaning that the population density converged back to the 1936 one. Heteroskedasticity-robust standard errors in parentheses. ***: Significant at the 1% level. *: Significant at the 10% level.

Characteristics of neighboring blocks Post-war population growth of block i may depend not only on its own characteristics but also on the characteristics of adjacent blocks $i' \neq i$. To consider the characteristics of neighbors, we adopt the “SLX model” in spatial econometrics literature (Hal-leck Vega and Elhorst 2015) and control for the spatial lag of the following three types of dependent variables in our main regression equation (1). The spatial lag of $\ln \left(\frac{\text{Popdens}_{i,1945}}{\text{Popdens}_{i,1936}} \right)$ summarizing the wartime destruction rate of surrounding blocks and the spatial lag of X_i summarizes the location characteristics of neighboring blocks. We use the exponential spatial weighting matrix by using geographical distances between centroids of blocks in kilometers, implying that the characteristics of blocks close to block i are given more weights.²³ We also construct the spatial lag of population right after the bombing, which is meant to capture the market access of a given block.²⁴ In addition to our baseline control variables on block characteristics, we additionally control for these spatial lag variables in our main regression analysis. Table B.3 shows that the inclusion of these spatial lag

²³Following the decay of agglomeration forces in Ahlfeldt et al. (2015), we set the spatial decay parameter at 4.32.

²⁴We set the spatial decay parameter at 0.05 given the commuting cost estimate with respect to geographical distance in Hiroshima, which was reported in a previous version of this paper.

variables does not change our conclusion about the coefficient γ associated with $\ln\left(\frac{\text{Popdens}_{i,1945}}{\text{Popdens}_{i,1936}}\right)$. In particular, we cannot reject the null of complete recovery ($\gamma = -1$) in all specifications. Overall, the results suggest that considering the characteristics of adjacent blocks does not change our conclusion.

Table B.3: Controlling for Characteristics of Neighboring Blocks

	(1)	(2)	(3)
	Change in log population density 1945–50		
Change in log population density 1936-45	-0.940*** (0.090)	-0.857*** (0.099)	-0.897*** (0.097)
<i>p</i> -value from testing $\gamma = -1$	0.511	0.156	0.291
Location characteristics (first nature and second nature)	✓	✓	✓
Spatial lag of change in log population density 1936-45	✓		
Spatial lag of control variables (block characteristics)		✓	
Spatial lag of population right after the bombing			✓
Number of blocks	174	174	174
R-squared	0.861	0.894	0.856

Note: We report the OLS estimation result of equation (1) for population density, while controlling for a spatial lag of dependent variables based on geographic distances between centroids of blocks. We control for log distance to the pre-war city center, log distance to the nearest water area, the altitude and its square, the slope and its square, geographical coordinates (latitude, longitude, and their interaction), a dummy for a bad soil conditions, log distance to the nearest station, log distance to Hiroshima port (Ujina port), log distance to the nearest cultural asset, and the initial housing stock condition (the fractions of the half-destroyed, moderately-destroyed, and intact buildings). The spatial lags of the change in log population density 1936-45 and block characteristics are constructed using exponential weights, where the decay parameter is set at 4.32. We construct the spatial lag of each control variable (except for latitudes and longitudes) and use them as separate controls, using the decay parameter 4.32. The spatial lag of population right after the bombing is constructed using the decay parameter 0.05. Column (1) includes the spatial lag of the population density change due to the war. Column (2) controls for the spatial lag of block characteristics. Column (3) controls for the spatial lag of population level right after the bombing. We report the *p*-value from testing the null $\gamma = -1$, meaning that the employment density converged back to the 1938 one. Heteroskedasticity-robust standard errors in parentheses. ***: Significant at the 1% level.

Public housing In many cities in Japan, the supply of public housing was a primary policy led by the government right after the war. To assess how much the recovery of central Hiroshima was driven by the provision of public housing after the bombing, we additionally control for the number of public housing units in our baseline specification of the reduced form in Column (4) of Table 1. We find that $\gamma = 0.941$ with a standard error of 0.090, which is close to our estimate in Column (4) of Table 1 in the main text. We cannot reject the null hypothesis of the coefficient $\gamma = -1$ with *p*-value, 0.518. This suggests that the provision of public housing alone did not effectively result in the recovery of the central part of the city.

B.2 Nagasaki

We also analyze the atomic bombing in Nagasaki, the second and last city to experience an atomic bombing as of the time this paper is written. We exploit the data on population at the school district

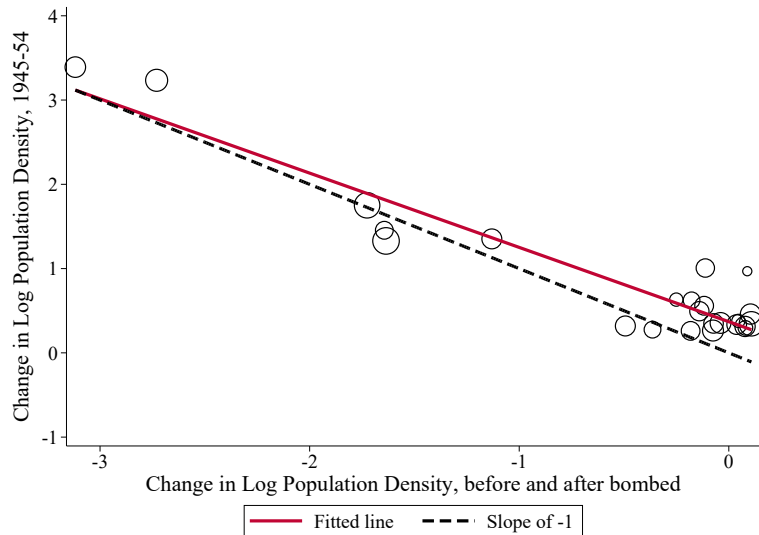
level in Nagasaki for May 1945 (pre-bombing), October 1945 (post-bombing) and March 1954. The data is sourced from [Nagasaki City Government \(1983\)](#).

Figure B.1: The Map and the Reduced-form Result of Nagasaki

(a) Map of Physical Damages Caused by the Atomic Bombing (Nagasaki)



(b) Change in Population Density (Nagasaki)



Note: The map in Figure B.1a shows the epicenter of the bombing in Nagasaki, as well as major facilities and the extent of the damage to structures. This map is provided by the Atomic Bomb Disease Institute at Nagasaki University. Figure B.1b plots the change in the log of population density from 1945 to 1954 compared to those from May 1945 to October 1945 in Nagasaki. Each circle represents a school district (i.e., an observation), where the size of the circle is proportional to the population density in May 1945. There are 23 school districts in our sample. We plot the (unweighted) linear fit between these two variables (solid line) as well as the slope of -1 (dashed line). Indeed, if they matter, the destroyed areas may be advantageous in attracting more residents, and their population may be higher than in the pre-war period relative to the undestroyed areas.

Figure B.1a is the damage map of Nagasaki. The atomic bomb hit the outskirts of the city and the epicenter is more than 2 kilometers away from the city center, where Nagasaki City Hall and Nagasaki Prefectural Office were located. In Figure B.1b we show the relationship between the changes in log population density in 1945–54 (Vertical axis) and those from May 1945 to October 1945. This is the same as in Figure 4 for Hiroshima. Despite the fact that the atomic bomb hit a different part of the city in the case of Nagasaki, the figure shows a very similar pattern to the case of Hiroshima.

The estimated slope of the fitted line in the figure is -0.882 with a standard error of 0.101 . We cannot reject the null hypothesis of $\gamma = -1$ at the conventional level. This is suggestive of the recovery of the pre-bombing city structure in Nagasaki, which reinforces the external validity of our results from Hiroshima. Moreover, in Nagasaki, the center of economic activities did not shift toward the destroyed area. This suggests limited importance of low development costs or

creative destruction in our context (Hornbeck and Keniston 2017) because the destroyed peripheral areas could attract more population and employment than the pre-war period if these factors were dominant.

C Theoretical Appendix

C.1 Value Function

When an individual is able to change the location choices, she solves the problem of location choice (6) in the main text. The idiosyncratic taste shocks are drawn from the time-invariant and independent mean-zero Type I extreme distribution: $F(\varepsilon) = \exp(-\exp(-(\varepsilon + \Gamma)))$ where Γ is Euler-Mascheroni constant: $\Gamma \equiv -\int_0^\infty \ln xe^{-x} dx$.

For $i, n \in \mathcal{C}$, we have distribution functions:

$$G_{int+1}(s) = \text{Prob}[\rho_{t+1}V_{int+1} + \sigma_{t+1}\varepsilon_{int+1} \leq s] = \exp\left[-\exp\left(-\left(\frac{s - \rho_{t+1}V_{int+1}}{\sigma_{t+1}} + \Gamma\right)\right)\right].$$

Therefore, $\rho_{t+1}V_{int+1} + \sigma_{t+1}\varepsilon_{int+1}$ follows the Gumbel distribution with mean $\rho_{t+1}V_{int+1}$ and the scale parameter σ_{t+1} . The large value of σ_{t+1} leads to large variation. Define

$$V_{t+1}^* \equiv \max\{\rho_{t+1}V_{int+1} + \sigma_{t+1}\varepsilon_{int+1}; \rho_{t+1}V_{ot+1} + \sigma_{t+1}\varepsilon_{ot+1}\}$$

Then, we have

$$H_{t+1}(s) = \text{Prob}[V_{t+1}^* \leq s] = \left(\prod_{i \in \mathcal{C}} \prod_{n \in \mathcal{C}} G_{int+1}(s)\right) \times G_{ot+1}(s)$$

which corresponds to the maximum of the Gumbel random variables. It can be shown that this also follows the Gumbel distribution with mean

$$\mu_{t+1} = \mathbb{E}_{t+1}[s] = \sigma_{t+1} \ln \left[\sum_{i \in \mathcal{C}} \sum_{n \in \mathcal{C}} \exp(V_{int+1})^{\rho_{t+1}/\sigma_{t+1}} + \exp(V_{ot+1})^{\rho_{t+1}/\sigma_{t+1}} \right] \quad (\text{C.1})$$

Therefore, we have value functions (7) and (8) in the main text.

C.2 Location Choice

We transform the variable: $z_{t+1} = \varepsilon + \sigma_{t+1}\Gamma$. When an individual can switch the location, the probability that she chooses a location pair of workplace i and residential place n in period $t + 1$ is

$$\begin{aligned} \lambda_{int+1} &= \\ & \int_{-\infty}^{\infty} \left[\prod_{i' \in \mathcal{C}} \prod_{n' \in \mathcal{C}} \exp\left(-e^{-\frac{1}{\sigma_{t+1}}(z_{t+1} + \rho_{t+1}(V_{int+1} - V_{i'n't+1}))}\right) \exp\left(-e^{-\frac{1}{\sigma_{t+1}}(z_{t+1} + \rho_{t+1}(V_{int+1} - V_{ot+1}))}\right) \right] \frac{e^{-z_{t+1}/\sigma_{t+1}}}{\sigma_{t+1}} dz_{t+1} \\ &= \int_{-\infty}^{\infty} \exp\left[-e^{-z_{t+1}/\sigma_{t+1}} \left(\sum_{i' \in \mathcal{C}} \sum_{n' \in \mathcal{C}} e^{-\frac{\rho_{t+1}}{\sigma_{t+1}}(V_{int+1} - V_{i'n't+1})} + e^{-\frac{\rho_{t+1}}{\sigma_{t+1}}(V_{int+1} - V_{ot+1})} \right)\right] \frac{e^{-z_{t+1}/\sigma_{t+1}}}{\sigma_{t+1}} dz_{t+1} \end{aligned}$$

Letting $s_{t+1} = e^{-z_{t+1}/\sigma_{t+1}}$, this becomes

$$\begin{aligned}
& \int_0^\infty \exp \left[-s_{t+1} \left(\sum_{i' \in \mathcal{C}} \sum_{n' \in \mathcal{C}} \exp \left(-\frac{\rho_{t+1}}{\sigma_{t+1}} (V_{int+1} - V_{i'n't+1}) \right) + \exp \left(-\frac{\rho_{t+1}}{\sigma_{t+1}} (V_{int+1} - V_{ot+1}) \right) \right) \right] ds_{t+1} \\
&= \left[\frac{\exp \left(-s_{t+1} \left(\sum_{i' \in \mathcal{C}} \sum_{n' \in \mathcal{C}} \exp \left(-\frac{\rho_{t+1}}{\sigma_{t+1}} (V_{int+1} - V_{i'n't+1}) \right) + \exp \left(-\frac{\rho_{t+1}}{\sigma_{t+1}} (V_{int+1} - V_{ot+1}) \right) \right) \right)}{- \left(\sum_{i' \in \mathcal{C}} \sum_{n' \in \mathcal{C}} \exp \left(-\frac{\rho_{t+1}}{\sigma_{t+1}} (V_{int+1} - V_{i'n't+1}) \right) + \exp \left(-\frac{\rho_{t+1}}{\sigma_{t+1}} (V_{int+1} - V_{ot+1}) \right) \right)} \right]_0^\infty \\
&= \frac{\exp(V_{int+1})^{\rho_{t+1}/\sigma_{t+1}}}{\sum_{i' \in \mathcal{C}} \sum_{n' \in \mathcal{C}} \exp(V_{i'n't+1})^{\rho_{t+1}/\sigma_{t+1}} + \exp(V_{ot+1})^{\rho_{t+1}/\sigma_{t+1}}}
\end{aligned} \tag{C.2}$$

Analogously, the probability that an individual worker lives outside of the city is:

$$\lambda_{ot+1} = \frac{\exp(V_{ot+1})^{\rho_{t+1}/\sigma_{t+1}}}{\sum_{i' \in \mathcal{C}} \sum_{n' \in \mathcal{C}} \exp(V_{i'n't+1})^{\rho_{t+1}/\sigma_{t+1}} + \exp(V_{ot+1})^{\rho_{t+1}/\sigma_{t+1}}} \tag{C.3}$$

An individual can change the residential place and workplace with the exogenous probability, $\theta_{t+1} \in (0, 1)$. Using the probabilities of location choice, the mass of workers choosing location i as a workplace and location n as a residential place in period $t + 1$ can be expressed by:

$$\begin{aligned}
L_{int+1} &= (1 - \theta_{t+1})L_{int} + \theta_{t+1}\lambda_{int+1}L_t + \theta_{t+1}\lambda_{int+1}(M - L_t) \\
&= (1 - \theta_{t+1})L_{int} + \theta_{t+1}\lambda_{int+1}M
\end{aligned}$$

We can use the same idea to derive the dynamics of population (11) and employment (12):

$$R_{nt+1} = \sum_{i \in \mathcal{C}} L_{int+1} = (1 - \theta_{t+1})R_{nt} + \theta_{t+1} \left[\sum_{i \in \mathcal{C}} \lambda_{int+1} \right] M \tag{C.4}$$

$$L_{it+1} = \sum_{n \in \mathcal{C}} L_{int+1} = (1 - \theta_{t+1})L_{it} + \theta_{t+1} \left[\sum_{n \in \mathcal{C}} \lambda_{int+1} \right] M \tag{C.5}$$

The total population of the city is

$$L_{t+1} = \sum_{i \in \mathcal{C}} \sum_{n \in \mathcal{C}} L_{int+1} = (1 - \theta_{t+1})L_t + \theta_{t+1}(1 - \lambda_{ot+1})M \tag{C.6}$$

C.3 Equilibrium

Let $\tilde{V}_{int} = V_{int} - V_{ot}$ and $\tilde{u}_{int} \equiv u_{int}/u_{ot}$. Bellman equations imply

$$\tilde{V}_{int} = \ln \tilde{u}_{int} + (1 - \theta_{t+1})\rho_{t+1}\tilde{V}_{int+1}$$

Iterating this, we obtain

$$\begin{aligned}
\tilde{V}_{int} &= \ln \tilde{u}_{int} + \sum_{\tau=t+1}^T \left\{ \prod_{s=t+1}^{\tau} \rho_s (1 - \theta_s) \right\} \ln \tilde{u}_{in\tau} \\
&= \ln \left\{ \tilde{u}_{int} \prod_{\tau=t+1}^T (\tilde{u}_{in\tau})^{\prod_{s=t+1}^{\tau} \rho_s (1 - \theta_s)} \right\} \\
&= \ln \left\{ \frac{a_{it} b_{nt}}{\kappa_{int} u_{ot}} \left(\frac{L_{it}}{S_i} \right)^{\alpha} \left(\frac{R_{nt}}{S_n} \right)^{\beta} \prod_{\tau=t+1}^T \left(\frac{a_{i\tau} b_{n\tau}}{\kappa_{in\tau} u_{o\tau}} \left(\frac{L_{i\tau}}{S_i} \right)^{\alpha} \left(\frac{R_{n\tau}}{S_n} \right)^{\beta} \right)^{\prod_{s=t+1}^{\tau} \rho_s (1 - \theta_s)} \right\}.
\end{aligned} \tag{C.7}$$

The probability (C.2) can be expressed as

$$\lambda_{int+1} = \frac{\exp(\tilde{V}_{int+1})^{\rho_{t+1}/\sigma_{t+1}}}{\sum_{i' \in \mathcal{C}} \sum_{n' \in \mathcal{C}} \exp(\tilde{V}_{i'n't+1})^{\rho_{t+1}/\sigma_{t+1}} + 1} \tag{C.8}$$

Therefore, we obtain the population in location n :

$$R_{nt+1} = (1 - \theta_{t+1})R_{nt} + \theta_{t+1} \left[\sum_{i \in \mathcal{C}} \frac{\exp(\tilde{V}_{int+1})^{\rho_{t+1}/\sigma_{t+1}}}{\sum_{i' \in \mathcal{C}} \sum_{n' \in \mathcal{C}} \exp(\tilde{V}_{i'n't+1})^{\rho_{t+1}/\sigma_{t+1}} + 1} \right] M \tag{C.9}$$

and employment in location i :

$$L_{it+1} = (1 - \theta_{t+1})L_{it} + \theta_{t+1} \left[\sum_{n \in \mathcal{C}} \frac{\exp(\tilde{V}_{int+1})^{\rho_{t+1}/\sigma_{t+1}}}{\sum_{i' \in \mathcal{C}} \sum_{n' \in \mathcal{C}} \exp(\tilde{V}_{i'n't+1})^{\rho_{t+1}/\sigma_{t+1}} + 1} \right] M \tag{C.10}$$

The equilibrium is characterized by $\{R_{nt}, L_{it}\}$ solving (C.7), (C.9) and (C.10) jointly.

We show the existence of the forward-looking competitive equilibrium in which population and employment satisfy $R_{nt+1} \geq (1 - \theta_{t+1})R_{nt}$ and $L_{it+1} \geq (1 - \theta_{t+1})L_{it}$ given θ_{t+1} . To simplify the notation, we suppose $(1 - \theta_{t+\tau})\rho_{t+\tau} \rightarrow 0$ for $\tau \geq 2$. Yet, our following augment can be applied to the general case. In this case the forward-looking equilibrium is characterized by $\{R_{nt}\}$ and $\{L_{it}\}$ solving the system of equations:

$$\begin{aligned}
R_{nt+1} &= (1 - \theta_{t+1})R_{nt} + \sum_{i \in \mathcal{C}} \frac{\mathcal{X}_{int+1} R_{nt+1}^{\beta \varkappa_{t+1}}}{\sum_{n' \in \mathcal{C}} \mathcal{X}_{in't+1} R_{n't}^{\beta \varkappa_{t+1}}} (L_{it+1} - (1 - \theta_{t+1})L_{it}), \\
L_{it+1} &= (1 - \theta_{t+1})L_{it} + \sum_{n \in \mathcal{C}} \frac{\mathcal{X}_{int+1} L_{it+1}^{\alpha \varkappa_{t+1}}}{\sum_{i' \in \mathcal{C}} \mathcal{X}_{i'n't+1} L_{i't+1}^{\alpha \varkappa_{t+1}}} (R_{nt+1} - (1 - \theta_{t+1})R_{nt}),
\end{aligned} \tag{C.11}$$

where $\varkappa_{t+1} \equiv \rho_{t+1}/\sigma_{t+1}$ and \mathcal{X}_{int+1} is exogenous factors.

We suppose that $R_{nt+1} \geq (1 - \theta_{t+1})R_{nt}$ and $L_{it+1} \geq (1 - \theta_{t+1})L_{it}$ for any $\{\theta_t\}$. Therefore, we characterize the equilibrium in which population and employment are increasing given the friction

of mobility. This is in line with our quantification in the next section. Letting $\mathbf{X} = (\mathbf{R}, \mathbf{L})$ be a vector of population and employment and we define the operator $J(\mathbf{X})$ such that ι -th element $J_\iota(\mathbf{X})$ corresponds to the right-hand side of (C.11). When $R_{nt+1} \geq (1 - \theta_{t+1})R_{nt}$ and $L_{it+1} \geq (1 - \theta_{t+1})L_{it}$, we can define the convex subset of \mathbb{R}_{++}^{2N} where the operator J is mapping from the subset to itself. The operator J is continuous mapping. Therefore, by Brouwer's fixed-point theorem, there exist forward-looking equilibrium such that they satisfy $R_{nt+1} \geq (1 - \theta_{t+1})R_{nt}$ and $L_{it+1} \geq (1 - \theta_{t+1})L_{it}$.

C.4 Steady State Equilibrium

If the steady state equilibrium exists, it is a stationary steady state where all variables in the model are not changing over time, and we therefore drop time subscripts of variables for describing the steady state. In such a stationary steady state, the conditional probabilities that workers commute to i given residential place n become:

$$\lambda_{i|n}^L = \frac{\lambda_{in}}{\sum_{j \in \mathcal{C}} \lambda_{jn}} = \frac{\mathcal{A}_{in} L_i^{\alpha\varpi}}{\sum_{i' \in \mathcal{C}} \mathcal{A}_{i'n} L_{i'}^{\alpha\varpi}}$$

where we let $\varpi \equiv \rho/\sigma$ and $\mathcal{A}_{in} \equiv (a_i/\kappa_{in})^{\rho/\sigma}$ summarizes the time-invariant fundamental productivity consistent with the steady-state. Analogously the conditional probabilities that workers live in n given workplace i become:

$$\lambda_{n|i}^R = \frac{\lambda_{in}}{\sum_{n' \in \mathcal{C}} \lambda_{in'}} = \frac{\mathcal{B}_{in} R_n^{\beta\varpi}}{\sum_{n' \in \mathcal{C}} \mathcal{B}_{in'} R_{n'}^{\beta\varpi}}$$

where $\mathcal{B}_{in} \equiv (b_n/\kappa_{in})^{\rho/\sigma}$. In sum, the steady state equilibrium is characterized by variables $\{R_n, L_i, \Phi_i, Y_n\}$ solving the system of equations:

$$R_n^{1-\tilde{\beta}\varpi} = \sum_{i \in \mathcal{C}} \mathcal{B}_{in} \Phi_i^{-1} L_i, \quad \Phi_i = \sum_{n \in \mathcal{C}} \mathcal{B}_{in} R_n^{\beta\varpi}, \quad L_i^{1-\tilde{\alpha}\varpi} = \sum_{n \in \mathcal{C}} \mathcal{A}_{in} Y_n^{-1} R_n, \quad Y_n = \sum_{i \in \mathcal{C}} \mathcal{A}_{in} L_i^{\alpha\varpi}$$

To exploit the result of [Allen, Arkolakis and Li \(2020\)](#), we define the following matrix \mathbf{C} and \mathbf{D} that summarize the parameters from the left and right-hand sides of the system of equations, respectively:

$$\mathbf{C} = \begin{bmatrix} 1 - \beta\varpi & & & \\ & 1 & & \\ & & 1 - \alpha\varpi & \\ & & & 1 \end{bmatrix}, \quad \mathbf{D} = \begin{bmatrix} 0 & -1 & 1 & 0 \\ \beta\varpi & 0 & 0 & 0 \\ 1 & 0 & 0 & -1 \\ 0 & 0 & \alpha\varpi & 0 \end{bmatrix}$$

Matrix \mathbf{C} is a diagonal matrix and invertible when $\alpha \neq 1/\varpi$ and $\beta \neq 1/\varpi$, and steady state equilibrium exists when these conditions hold. Then, we define matrix $\mathbf{\Gamma} = |\mathbf{DC}^{-1}|$. Using the results in [Allen et al. \(2020\)](#), the system of equations has a unique up-to-scale solution if all eigenvalues

of the matrix Γ are no larger than one. In our case the sufficient conditions for a unique up-to-scale solution are:

$$\frac{|\beta\alpha| + 1}{|1 - \beta\alpha|} \leq 1, \quad \frac{|\alpha\alpha| + 1}{|1 - \alpha\alpha|} \leq 1$$

These conditions hold if and only if: $\beta \leq 0$ and $\alpha \leq 0$. The agglomeration forces in productivity (α) and amenities (β) are negative so that congestion force is dominating the agglomeration force in both workplace and residential place to ensure the unique up-to-scale solution. The total population in the city pins down the level of the solution, and we obtain a unique stationary steady state.

C.5 Microfoundations of Agglomeration Forces in Amenities

We show that the specification of preference and residential amenities (B_{nt}) is derived from a simple microfoundation.²⁵

Preference Conditional on a residential place and workplace, an individual decides their consumption pattern. Individuals consume nontradable local services and housing in their residences. The indirect utility of an individual that lives in n and works in i in period t is:

$$u_{int} = \frac{w_{it}}{(P_{nt})^\mu (Q_{nt})^{1-\mu}} \frac{\tilde{B}_{nt}}{\kappa_{int}} \quad (\text{C.12})$$

where w_{it} is wage in i ; P_{nt} is the price index of local services in n ; Q_{nt} is the housing price in n ; \tilde{B}_{nt} is unobserved fundamental amenities; and κ_{int} is commuting costs from n to i . μ is the share of expenditure devoted to local services, and $1 - \mu$ is the share of expenditure devoted to housing. The price index of local services is a CES function of the prices and number of varieties supplied, taking the form:

$$P_{nt} = \left[\sum_{s \in \mathcal{I}_{nt}} \left(\frac{p_{snt}}{\varphi_{snt}} \right)^{1-\rho} \right]^{1/(1-\rho)}, \quad \rho > 1, \quad (\text{C.13})$$

where ρ is the constant elasticity of substitution between varieties; we assume that varieties are substitutes ($\rho > 1$); \mathcal{I}_{nt} is the set of varieties available in n ; p_{snt} is the price of each variety; and φ_{snt} captures the quality of variety as reflected in consumer taste.

Housing market clearing In each block there are homogenous developers who supply housing by combining land and homogenous tradable goods. We adopt a similar setup for developers in [Sturm, Takeda and Venables \(2023\)](#). The housing market clearing condition is given by:

$$\frac{(1 - \mu)\bar{y}_{nt}R_{nt}}{Q_{nt}} = \left(\frac{Q_{nt}}{\eta\Lambda_{nt}} \right)^{1/(\eta-1)} S_n,$$

²⁵This theoretical framework is close to the literature on quantitative urban models ([Ahlfeldt et al. 2015](#)).

where \bar{y}_n is the average income of individuals living in n ; Q_{nt} is housing prices; S_n is the total amount of land; and Λ_{nt} is the exogenous productivity of developers that captures heterogeneity in construction costs across locations. η controls the housing supply elasticity and we posit $\eta > 1$. The left-hand side is the demand for housing and the right-hand side is the supply of housing. Therefore, housing prices in equilibrium are:

$$Q_{nt} = (\eta \Lambda_{nt})^{1/\eta} \left[\frac{(1 - \mu) \bar{y}_{nt} R_{nt}}{S_n} \right]^{(\eta-1)/\eta} \quad (\text{C.14})$$

Local services The CES demand system implies expenditures on a single variety in n are

$$e_{snt} = \left(\frac{p_{snt} / \varphi_{snt}}{P_{nt}} \right)^{1-\rho} \mu \bar{y}_{nt} R_{nt} \quad (\text{C.15})$$

In each block firms in the local service sector produce a variety using homogenous goods and maximize profit given (C.15). Production incurs fixed cost f units of homogeneous goods. Then, price of each variety is given by: $p_{snt} = \rho / (\rho - 1)$ and firms make zero profits if they sell output level $\bar{z} = (\rho - 1)f$. Then CES price index (C.13) can be written as:

$$P_{nt} = \frac{\rho}{\rho - 1} \frac{1}{\tilde{\varphi}_{nt}}, \quad \tilde{\varphi}_{nt} = \left[\sum_{s \in \mathcal{I}_{nt}} (\varphi_{snt})^{\rho-1} \right]^{1/(\rho-1)}, \quad (\text{C.16})$$

The market clearing condition for local services is:

$$\left(\frac{\rho}{\rho - 1} \right)^{-\rho} (\varphi_{snt})^{\rho-1} (P_{nt})^{\rho-1} \mu \bar{y}_{nt} R_{nt} = (\rho - 1)f, \quad (\text{C.17})$$

where the left-hand side is the demand for variety s , and the right-hand side is its supply. We substitute price index and use the definition of $\tilde{\varphi}_{nt}$ in (C.16) into (C.17) to derive the number of varieties:

$$N_{nt}^* = |\mathcal{I}_{nt}| = \frac{\mu \bar{y}_{nt} R_{nt}}{\rho f} \quad (\text{C.18})$$

We suppose that consumer taste (φ_{snt}) in n depends on average income in n (\bar{y}_{nt}) and idiosyncratic unobserved taste shocks (φ_{snt}^*):

$$\varphi_{snt} = \varphi_{snt}^* (\bar{y}_{nt})^\vartheta. \quad (\text{C.19})$$

Taste adjusted price (p_{snt} / φ_{snt}) is supposed to be decreasing in average income ($\vartheta > 0$), which is consistent with the better quality of consumption amenities in high-income areas (e.g., [Diamond 2016](#)). The generalized mean of order- r of unobserved consumer taste shocks is normalized: $\left[\frac{1}{N_{nt}^*} \sum_{s \in \mathcal{I}_{nt}} (\varphi_{snt}^*)^r \right]^{1/r} = 1$. When we substitute (C.19) into (C.16) together with (C.18), we obtain:

$$P_{nt} = \frac{\rho}{\rho - 1} (N_{nt})^{\frac{1}{1-\rho}} (\bar{y}_{nt})^\vartheta = \delta (\bar{y}_{nt})^{\frac{1}{1-\rho} + \vartheta} (R_{nt})^{\frac{1}{1-\rho}}, \quad (\text{C.20})$$

where we let δ refer a constant parameter.

Amenities Suppose $\frac{\eta-1}{\eta}(1-\mu) = \mu \left(\frac{1}{\rho-1} - \vartheta \right)$ for parameters. Using (C.14) for housing prices and (C.20) for price index, indirect utility (C.12) is written as:

$$u_{int} = \frac{w_{it} \tilde{B}_{nt}}{(\delta)^\mu (1-\mu)^{\frac{(\eta-1)(1-\mu)}{\eta}} (\eta \Lambda_{nt})^{\frac{1-\mu}{\eta}} \kappa_{int} (R_{nt})^{-\frac{\mu}{\rho-1} + \frac{\eta-1}{\eta}(1-\mu)} (S_n)^{-\frac{\eta-1}{\eta}(1-\mu)}}. \quad (\text{C.21})$$

We can manipulate (C.21) to derive the preference (4) and write amenities (B_{nt}) as a function of population density (R_{nt}/S_n) given in (5) in the main text. When we set the parameter of the elasticity of population density in amenities (β) such that $\beta = \mu\vartheta$, our specification of amenities (5) is consistent with this microfoundation.

D Calibration Appendix

D.1 Step # 1: Travel Mode Choice and Gravity Equation for Commuting

Travel mode choice (κ_{int}) To estimate the commuting cost, we follow [Tsivanidis \(2022\)](#) by extending the model to incorporate multiple travel modes. Suppose that the bilateral travel cost for an individual in travel mode m $\kappa_{int}^m(\omega)$ is given by $\kappa_{int}^m(\omega) \equiv \exp(c_{int}^m(\omega)) > 0$ with an inverse of mode-specific travel cost:

$$-c_{int}^m(\omega) \equiv -\delta \tau_{int}^m + \gamma^m + s_{int}^m(\omega),$$

where τ_{int}^m is the travel time in minutes between i and n ; δ captures the marginal increase in travel cost when travel time increases by one minute; γ^m is the mode-specific fixed cost; and $s_{int}^m(\omega)$ is an unobserved idiosyncratic shock to the commuting cost by the mode m between i and n . Workers choose the transit mode m to minimize the commuting cost (i.e., maximize $-c_{int+1}^m$) conditional on their location choice.

We assume that $s_{int}^m(\omega)$ follows the Gumbel distribution with two nests: the nest of public modes $\mathcal{B}_{\text{pub}} \equiv \{\text{Walk, Bus, Train}\}$ and the nest of private modes $\mathcal{B}_{\text{pri}} \equiv \{\text{Bike, Car}\}$. The former nest does not require owning a private vehicle. Using the well-known log-sum formula ([Train 2009](#)), we can write the expected commuting cost as

$$\bar{c}_{int}^{\text{car}} = -\ln \left[\exp(-\bar{c}_{int}^{\text{pub}}) + \exp(-\bar{c}_{int}^{\text{pri}}) \right], \quad \bar{c}_{int}^k \equiv -\nu_k \ln \left[\sum_{m \in \mathcal{B}_k} e^{-(\delta \tau_{int}^m - \gamma^m) / \nu_k} \right],$$

where ν_k is the dissimilarity parameter of nest $k \in [\text{pub}, \text{pri}]$.

We use the microdata of the 1987 travel survey of Hiroshima to estimate $(\delta, \gamma^m, \nu_{\text{pub}}, \nu_{\text{pri}})$ in this nested logit model by the maximum likelihood estimator. We obtain $\delta = 0.019$ with standard error 0.002. We also estimate that $\nu_{\text{pub}} = 0.129$ with standard error 0.014 and $\nu_{\text{pri}} = 0.117$ with

standard error 0.013, implying the strong substitution within each nest since both estimates are far from 1.

Then, we have $\mathbb{E}(\ln \kappa_{int}^m) = \bar{c}_{int}$, which we use as the log bilateral travel cost ($\ln \kappa_{int}$) in our main calibration. We suppose that with probability p_{car} , a worker can choose a car as a commuting mode. Otherwise, a car is unavailable so that the private nest is modified as $\mathcal{B}_{\text{pri,nocar}} \equiv \{\text{Bike}\}$. We set the probability p_{car} based on the car ownership rate in Japan: 10 percent in 1950; 20 percent in 1955; 30 percent in 1960; 40 percent in 1965; 50 percent in 1970; and 70 percent in 1975.²⁶ Then, the expected commuting cost is $\bar{c}_{int} = p_{\text{car}} \bar{c}_{int+1}^{\text{car}} + (1 - p_{\text{car}}) \bar{c}_{int+1}^{\text{nocar}}$, where $\bar{c}_{int+1}^{\text{nocar}}$ is defined in the same way as $\bar{c}_{int+1}^{\text{car}}$, except that the summation in $\bar{c}_{int+1}^{\text{pri}}$ is over $\mathcal{B}_{\text{pri,nocar}}$ because car is unavailable.

Gravity of commuting (ρ/σ) In the steady state, the number of commuters from n to i becomes:

$$L_{in} = \lambda_{in} M = \frac{\bar{u}_{in}^{\rho/\sigma}}{\sum_{i' \in \mathcal{C}} \sum_{n' \in \mathcal{C}} \bar{u}_{i'n'}^{\rho/\sigma}} M$$

where \bar{u}_{in} is ex-ante average utility for the location pair (i, n) . Taking the logarithm of this,

$$\ln L_{in} = \frac{\rho}{\sigma} (\ln B_n + \ln w_i - \ln \bar{\kappa}_{in}) + \ln \bar{M} \quad (\text{D.1})$$

where $\ln \bar{M} \equiv \ln \left[M \left(\sum_{i' \in \mathcal{C}} \sum_{n' \in \mathcal{C}} \bar{u}_{i'n'}^{\rho/\sigma} \right)^{-1} \right]$ and

$$-\ln \bar{\kappa}_{in} \equiv \mathbb{E} \left[\max_m -\ln \kappa_{in}^{m,\omega} \right] = \mathbb{E} \left[\max_m -c_{in}^{m,\omega} \right] = -\bar{c}_{in}$$

This corresponds to the gravity equation (13) in the main text. In estimating this gravity equation, we further suppose that there is an additional additive error term, which includes measurement errors.

Table D.1 presents the results of the estimation of the gravity equation for commuting. Columns (1) and (2) provide OLS results. In Columns (3) and (4) we use OLS but we add 1 to the commuting flow (L_{in}) so that we do not lose observations with zero commuting flows. We use the PPML for Columns (5) and (6). In each case, we also report a version of dropping the bilateral pair of less than 20 commuters to assess the robustness to sampling noises. Our preferred specification is Column (5) that possesses the theoretically desirable properties of the PPML (Santos Silva and Tenreiro 2006) and we set $\rho_t/\sigma_t = 8$ in our calibration.

²⁶Note that we have implicitly assumed $p_{\text{car}} = 1$ in estimating the nested logit model using the 1987 travel survey data, given the very high car ownership rate in 1987.

Table D.1: Gravity Estimates for Commuting

	(1)	(2)	(3)	(4)	(5)	(6)
	Log Commuting Flow		Log(Commuting Flow+1)		Commuting Flow	
Average commuting cost (\bar{c}_{in})	-4.082*** (0.156)	-3.976*** (0.170)	-5.758*** (0.179)	-3.931*** (0.169)	-8.019*** (0.195)	-7.031*** (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/ Pseudo R-squared	0.543	0.522	0.551	0.521	0.764	0.729

Note: We report estimates of gravity equation (13) for commuting by OLS in Columns 1 and 2. In Columns 3 and 4, we use OLS but add 1 to commuting flows so that we do not drop observations with zero commuting flows. We use the PPML in Columns 5 and 6. We use average commuting costs that we computed in mode choice and include origin and destination fixed effects. Note that Column 5 has slightly fewer observations than Column 3 because of computational issues in PPML (Correia et al. 2020). Standard errors in parentheses. ***: Significant at the 1% level.

D.2 Step # 2: Inversion of Option Values of Productivity and Amenities

Our focus in this step is to back out the continuation value of amenities (14) and productivity (15). The probability of location choices (C.8) becomes: $\lambda_{int} = \lambda_{ot} \exp(\tilde{V}_{int})^{\rho/\sigma}$. Then, (C.9) and (C.10) can be expressed by:

$$R_{nt} - (1 - \theta_t)R_{nt-1} = \lambda_{ot}\theta_t \left[\sum_{i \in \mathcal{C}} \exp(\tilde{V}_{int})^{\rho_t/\sigma_t} \right] M \quad (\text{D.2})$$

$$L_{it} - (1 - \theta_t)L_{it-1} = \lambda_{ot}\theta_t \left[\sum_{n \in \mathcal{C}} \exp(\tilde{V}_{int})^{\rho_t/\sigma_t} \right] M \quad (\text{D.3})$$

for all locations (i, n) in a city and periods $t = 1, \dots, T$. We also use the following notations

$$K_{int} \equiv \kappa_{int}^{-\rho_t/\sigma_t} \left[\prod_{\tau=t+1}^T \kappa_{in\tau}^{-\prod_{s=t+1}^{\tau} \rho_s(1-\theta_s)} \right]^{\rho_t/\sigma_t}, \quad v_t \equiv u_{ot}^{-\rho_t/\sigma_t} \left[\prod_{\tau=t+1}^T u_{o\tau}^{-\prod_{s=t+1}^{\tau} \rho_s(1-\theta_s)} \right]^{\rho_t/\sigma_t} \quad (\text{D.4})$$

for values of commuting costs and outside options.²⁷ Then, (D.2) and (D.3) become:

$$R_{nt} - (1 - \theta_t)R_{nt-1} = \lambda_{ot}\theta_t v_t M \Xi_{nt}^{\rho_t/\sigma_t} \sum_{i \in \mathcal{C}} K_{int} \Omega_{it}^{\rho_t/\sigma_t}, \quad (\text{D.5})$$

$$L_{it} - (1 - \theta_t)L_{it-1} = \lambda_{ot}\theta_t v_t M \Omega_{it}^{\rho_t/\sigma_t} \sum_{n \in \mathcal{C}} K_{int} \Xi_{nt}^{\rho_t/\sigma_t}. \quad (\text{D.6})$$

for periods $t = 1, 2, \dots, T$. Substituting (D.6) into (D.5) yields the system of equations (16) in the main text. Solving the system conditional on observations of population and employment $\{R_{nt}, L_{it}\}$ and parameter $\{\theta_t\}$, we obtain $\{\Xi_{nt}, \Omega_{it}\}$. Given $\rho_t/\sigma_t > 0$, this system of equations is solved for unique solutions $\{\Xi_{nt}, \Omega_{it}\}$ up to scale if $L_{it} - (1 - \theta_t)L_{it-1} \geq 0$ and $R_{nt} - (1 - \theta_t)R_{nt-1} \geq 0$ hold. This step does not require the parameter values of agglomeration.

²⁷For instance, in the last period ($t = 75$), it becomes $K_{in,75} = \kappa_{in,75}^{-\rho_{75}/\sigma_{75}}$. For period $t = 70$, $K_{in,70} = \kappa_{in,70}^{-\rho_{70}/\sigma_{70}} (K_{75})^{\rho_{75}(1-\theta_{75})\frac{\sigma_{75}}{\sigma_{70}}}$. We continue this to the initial period: $K_{in,50} = \kappa_{in,50}^{-\rho_{50}/\sigma_{50}} (K_{55})^{\rho_{55}(1-\theta_{55})\frac{\sigma_{55}}{\sigma_{50}}}$.

D.3 Step # 3: Estimation of Agglomeration Parameters (α, β)

Step 2 derives $\{\Xi_{nt}, \Omega_{it}\}$ consistent with observed data to be an equilibrium. By construction, in the last period T

$$\Xi_{nT} = b_{nT} \left(\frac{R_{nT}}{S_n} \right)^\beta. \quad (\text{D.7})$$

Given the observation of population (R_{nT}), block size (S_n) and parameters (α, β), we can invert this for fundamental amenities $\{b_{nT}\}$ in period T . In period $T - 1$ we have:

$$\Xi_{nT-1} = b_{nT-1} \left(\frac{R_{nT-1}}{S_n} \right)^\beta (\Xi_{nT})^{\rho_T(1-\theta_T)}. \quad (\text{D.8})$$

Given population density in period $T - 1$, parameter ρ_T , migration friction θ_T and option value $\{\Xi_{nT}\}$, we can invert this for the fundamental amenities in the previous period.²⁸ We continue this process and obtain the sequence of fundamental amenities: $\{b_{nt}\}_{t=1, \dots, T}$. For the productivity, we can decompose $\{\Omega_{it}\}_{t=1, 2, \dots, T}$ to obtain the sequence of fundamental productivity $\{a_{it}\}_{t=1, \dots, T}$ in analogous way.

We suppose that fundamental amenities and productivity $\{a_{it}, b_{nt}\}_{t=1, \dots, T}$ consist of location fixed components, time fixed components and variant terms:

$$\ln a_{it} = \ln a_i^F + \ln a_t^* + \ln a_{it}^{\text{Var}}, \quad \ln b_{nt} = \ln b_n^F + \ln b_t^* + \ln b_{nt}^{\text{Var}} \quad (\text{D.9})$$

where $\{a_i^F, b_n^F\}$ are location fixed productivity and amenities; $\{a_t^*, b_t^*\}$ are a trend of productivity and amenities common for all blocks; and $\{a_{it}^{\text{Var}}, b_{nt}^{\text{Var}}\}$ are idiosyncratic part of fundamental productivity and amenities. The location fixed productivity and amenities capture the first nature advantages of locations. Averaging out the trend yields:

$$\ln \left(\frac{a_{it}}{\tilde{a}_t} \right) = \ln \left(\frac{a_i^F}{\tilde{a}_t^F} \right) + \ln \left(\frac{a_{it}^{\text{Var}}}{\tilde{a}_t^{\text{Var}}} \right), \quad \ln \left(\frac{b_{nt}}{\tilde{b}_t} \right) = \ln \left(\frac{b_n^F}{\tilde{b}_t^F} \right) + \ln \left(\frac{b_{nt}^{\text{Var}}}{\tilde{b}_t^{\text{Var}}} \right),$$

where we use the geometric mean of variables (e.g., $\tilde{a}_t \equiv \frac{1}{N} \sum_{i \in \mathcal{C}} \ln a_{it}$). Then, we take the difference between periods and suppose the following moment conditions:

$$\mathbb{E}[\Delta \ln(a_{it}/\tilde{a}_t) \times \mathbb{1}_i(k)] = 0, \quad \mathbb{E}[\Delta \ln(b_{nt}/\tilde{b}_t) \times \mathbb{1}_n(k)] = 0, \quad (\text{D.10})$$

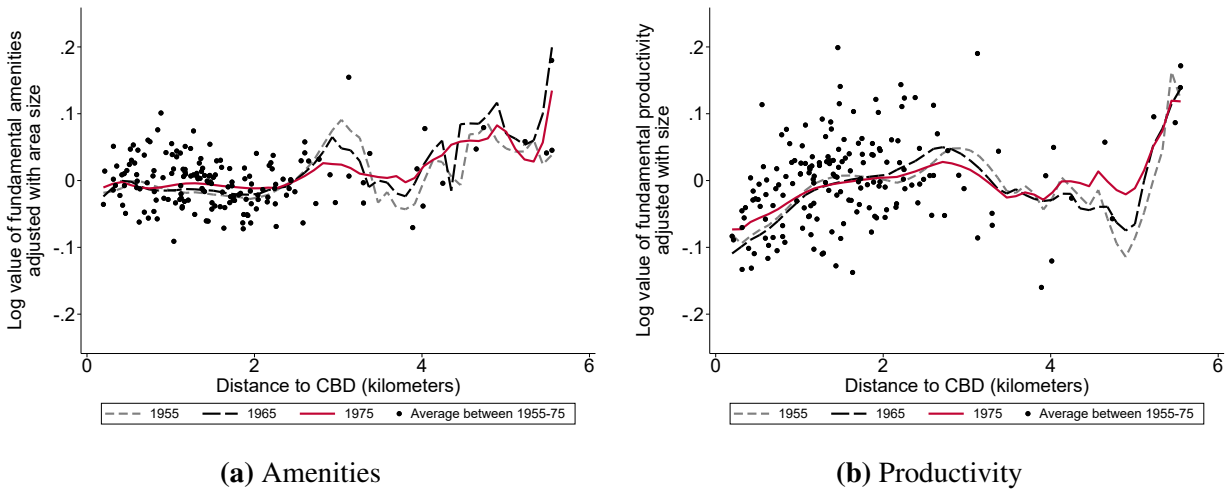
where $\mathbb{1}_i(k)$ is an indicator such that location i is in the grid k , which we define based on the distance from the CBD in our main estimation. We use the moment conditions (D.10) to estimate the set of parameters of agglomeration forces (α, β).

²⁸For instance, fundamental amenities in period $t = 75$ are given by: $b_{n,75} = \Xi_{n,75} \left(\frac{R_{n,75}}{S_n} \right)^{-\beta}$. And for period $t = 70$, $b_{n,70} = \Xi_{n,70} \left(\frac{R_{n,70}}{S_n} \right)^{-\beta} (\Xi_{n,75})^{-\rho_{75}(1-\theta_{75})}$.

D.4 Calibrated Amenities and Productivity

In Figure D.1 we show the polynomial fitted lines for the log of fundamental productivity (a_{it}) and amenities (b_{nt}) net the size effects for 1955, 1965 and 1975. We also show the average of them between 1955 and 1975. We adjust for the block size since the fundamental amenities and productivity tend to be mechanically undervalued for a smaller block. Intuitively, other things being equal, a smaller block is likely to have a higher population and employment density given the idiosyncratic preferences, irrespective of the block size. Thus, location-specific productivity and amenities may be undervalued in smaller blocks to offset such a small-block advantage. To adjust for this, we regress our estimate of the log of location-specific productivity and amenities on the log of area size, and we plot the residuals from the regressions.²⁹ We find that both productivity and amenities are not systematically related to the distance from the CBD. In particular, fundamental amenities and productivity in the central area of the city are not high relative to the outskirts.

Figure D.1: Fundamental Productivity and Amenities (Accounting for Block Size Heterogeneity)



Note: These figures display fundamental productivity (a_{it}) and amenities (b_{nt}) in our calibration after netting out the block size. Vertical axis shows the residuals of the linear regression of the log of fundamentals on the log of block sizes. We report local polynomial fitted lines for 1955, 1965 and 1975. In addition, we plot the average of the residuals over the period 1955-1975. Each dot represents a block. Horizontal axis is the distance from the CBD. Panel (a) shows the residuals in amenities and Panel (b) shows those in productivity.

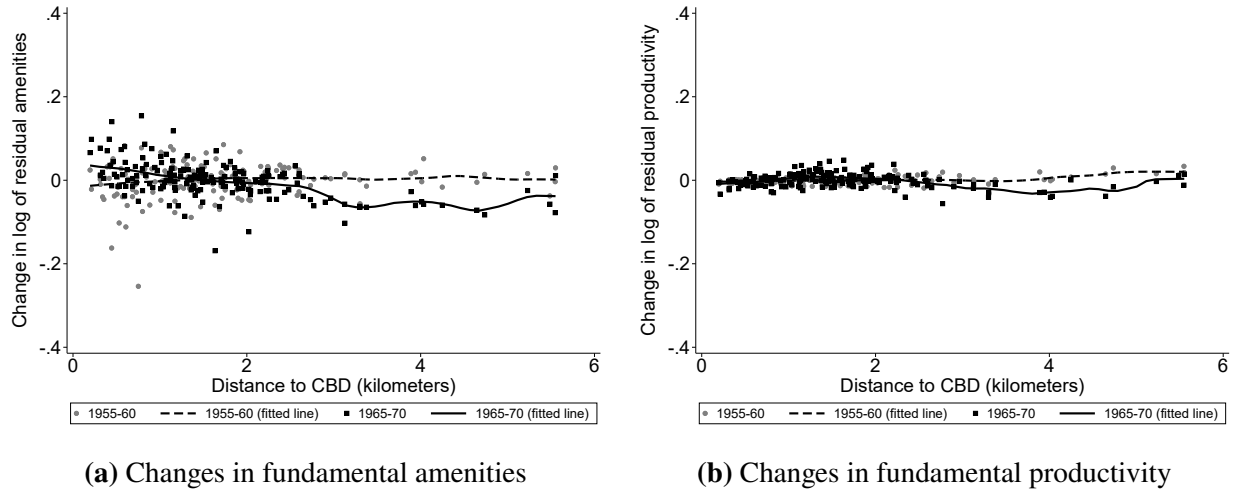
Next, we examine the moment conditions used for our estimation. In Figure D.2 we visualize the changes in residuals of fundamental amenities ($\Delta \ln \tilde{b}_{nt}$) and productivity ($\Delta \ln \tilde{a}_{it}$) for 1955-1960 and 1965-1970. We plot those to the distance from the CBD and show polynomial fitted lines.

The changes in residuals of amenities exhibit small variations in the city for both periods. This confirms that the idiosyncratic part of the fundamental location advantages in amenities and productivity is less important in explaining the variation of changes in population and employment. In

²⁹See Train (2009), Chapter 3, for the theoretical justification of using the log size in the adjustment.

particular, the flat pattern of the changes in amenities during the early period of 1955–1960 shows that the idiosyncratic factors in the structural residuals in amenities do not primarily explain the population changes. During 1965–1970, we observe some increase in the residuals in the area close to CBD while dropping in the periphery. This is consistent with the suburbanization that proceeds over these periods in many cities in Japan. For residuals of productivity, their variation is relatively small in the city for both periods. This implies that idiosyncratic shocks in fundamental productivity do not account for the variation in employment distribution in the city. Overall, these results for the idiosyncratic part of fundamental productivity and amenities reassure our identification assumption.

Figure D.2: Changes in Fundamental Amenities and Productivity for Different Periods



Note: These figures show changes in residuals of fundamental amenities ($\Delta \ln \tilde{b}_{nt}$) in Panel (a) and productivity ($\Delta \ln \tilde{a}_{it}$) in Panel (b) for 1955–1960 and 1965–1970. Each dot (square) represents a block for 1955–1960 (1965–1970), and we show local polynomial fitted lines: a dashed (solid) line for 1955–1960 (1965–1970). Horizontal axis is the distance from the CBD.

D.5 Robustness of Agglomeration Parameter Estimates

Moment conditions In the baseline, we (i) define five grid cells according to the distance from the CBD and (ii) exploit the population and employment data from 1955 to 1975. We conduct robustness checks for these specifications.

In Table D.2 we report the two-step GMM estimation for three robustness checks. First, in Columns (1) and (2), we define ten grid cells instead of five grid cells to examine the sensitivity of our estimates to the grouping of blocks. Second, in Columns (3) and (4), we define five grid cells according to the population density in 1936. This allows flexibility in defining the moment conditions without an arbitrary definition of the CBD.

Table D.2: Robustness: Generalized Method of Moments Estimates for Agglomeration Parameters

	(1) Productivity	(2) Amenities	(3) Productivity	(4) Amenities
Elasticity of employment density (α)	0.190*** (0.0001)		0.178*** (0.0001)	
Elasticity of population density (β)		0.192*** (0.0003)		0.165*** (0.0004)
Sample of blocks	All blocks in the city		All blocks in the city	
Sample of periods	Every 5 years from 1955 to 1975		Every 5 years from 1955 to 1975	
Instruments	10 grids for CBD distance		5 grids for pop. density in 1936	

Note: This table reports estimates of the generalized method of moments (GMM) for spillovers in productivity (α) and amenities (β). We conduct three robustness for our estimation. We use all 174 blocks in the city. In Columns (1) and (2) we define 10 grid cells based on distance to CBD and use them as instruments. In Columns (3) and (4) we define 5 grid cells based on population density in 1936 for instruments. ***: Significant at the 1% level.

Spatial spillovers in productivity and amenities We suppose that productivity and amenities have spatial spread of spillovers. Namely, we consider the functional forms similar to [Ahlfeldt et al. \(2015\)](#):

$$A_{it} = a_{it} \left[\sum_{i' \in \mathcal{C}} e^{-\delta \tau_{ii'}} \left(\frac{L_{i't}}{S_{i'}} \right) \right]^{\alpha}, \quad B_{nt} = b_{nt} \left[\sum_{n' \in \mathcal{C}} e^{-\delta \tau_{nn'}} \left(\frac{R_{n't}}{S_{n'}} \right) \right]^{\beta}, \quad (\text{D.11})$$

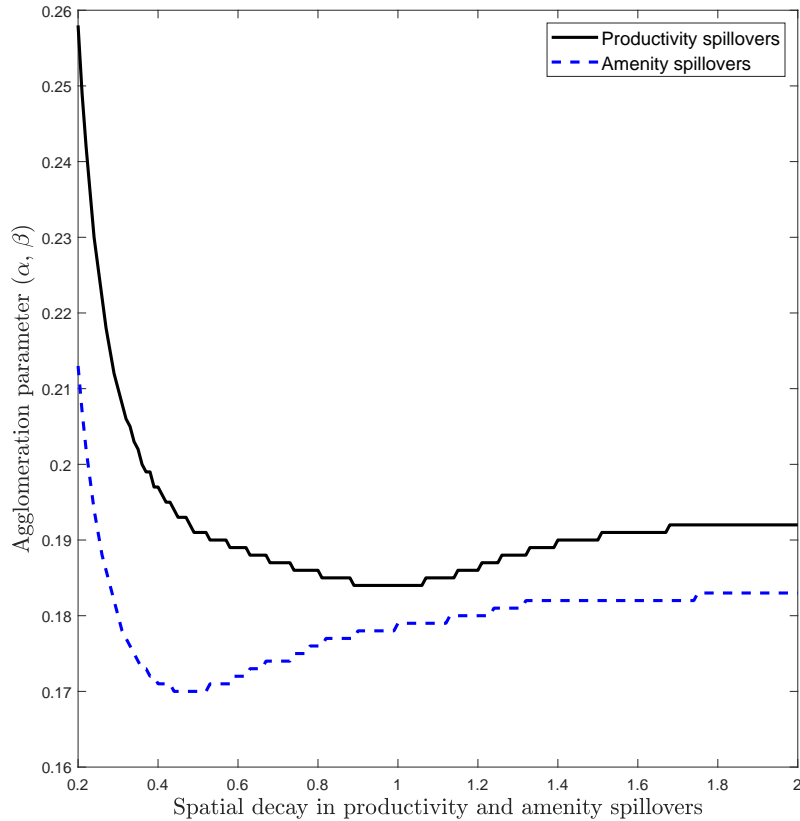
where δ governs the degree of spatial decay of spillovers; τ_{in} is travel time (walking time) between blocks; and (α, β) are agglomeration parameters. In Figure D.3 we show the estimated values of (α, β) given different values of spatial decay (δ). The horizontal axis shows values of spatial decay, and the vertical axis shows the estimated values of agglomeration parameters. The solid (dashed) line shows estimated values of agglomeration forces in productivity (amenities), respectively.

Lagged agglomeration forces Following [Allen and Donaldson \(2022\)](#), we suppose that productivity and amenities depend on past employment and population density:

$$A_{it} = a_{it} \left(\frac{L_{it}}{S_i} \right)^{\alpha_1} \left(\frac{L_{it-1}}{S_i} \right)^{\alpha_2}, \quad B_{nt} = b_{nt} \left(\frac{R_{nt}}{S_n} \right)^{\beta_1} \left(\frac{R_{nt-1}}{S_n} \right)^{\beta_2}, \quad (\text{D.12})$$

where parameters (α_2, β_2) control the spillovers from the lagged density. Given inverted option values in Step 2 in our calibration, we can compute fundamental productivity and amenities by the relationship (D.12) in the same way as in Step 3. We use similar moment conditions to estimate parameters (α_1, α_2) for agglomeration in productivity and (β_1, β_2) for agglomeration in amenities jointly. In Table D.3 we report the results. As in our baseline results in Table 2 in the main text, Columns (1) and (2) use all blocks in the city, while Columns (3) and (4) use blocks within 3 kilometers from the CBD. Overall, we find relatively small lagged effects on productivity and amenities. The contemporaneous effects are close to the baseline results.

Figure D.3: Spatial spillovers and estimation of agglomeration forces



Note: The figure shows the estimated parameters (α, β) given different values of spatial decay in the horizontal axis.

Table D.3: Robustness: GMM Estimates for Agglomeration Parameters with Lagged Effects

	(1)	(2)	(3)	(4)
	Productivity	Amenities	Productivity	Amenities
Elasticity of employment density (α_1)	0.228*** (0.0007)		0.232*** (0.0002)	
Elasticity of past employment density (α_2)	-0.064*** (0.0005)		-0.064*** (0.0003)	
Elasticity of population density (β_1)		0.175*** (0.0011)		0.198*** (0.0037)
Elasticity of past population density (β_2)		0.015*** (0.0010)		0.001*** (0.0040)
Sample of blocks	All blocks in the city		Blocks within 3 km to CBD	
Sample of periods	Every 5 years from 1955 to 1975		Every 5 years from 1955 to 1975	
Instruments	5 grids for CBD distance		5 grids for CBD distance	

Note: This table reports estimates of two-step GMM using data for five periods (1955, 60, 65, 70 and 75). We include lagged effects in productivity and amenities spillovers, which are controlled by two parameters (α_2, β_2). We use the same instruments as in the baseline. The standard errors are in parentheses. In Columns (1) and (2), we use all 174 blocks in the city and in Columns (3) and (4), we use 158 blocks in 3 kilometers to CBD. ***: Significant at the 1% level.

D.6 Simulating Population and Employment Density for 1945–1950

Having estimated model parameters (α, β) by exploiting the population and employment data from 1950 to 1975, we evaluate how much the model explains the population and employment change in the recovery period 1945–1950 after the atomic bombing. In particular, we compare the distribution of population and employment between observations and simulated ones in 1950 when we abstract the structural errors. we compute:

$$\begin{aligned} R_{n,50} &= (1 - \theta_{50})R_{n,45} + \sum_{i \in \mathcal{C}} \frac{K_{in,50} (\widetilde{\Xi}_{n,50})^{\rho_{50}/\sigma_{50}}}{\sum_{n' \in \mathcal{C}} K_{in',50} (\widetilde{\Xi}_{n',50})^{\rho_{50}/\sigma_{50}}} (L_{i,50} - (1 - \theta_{50})L_{i,45}), \\ L_{i,50} &= (1 - \theta_{50})L_{i,45} + \sum_{n \in \mathcal{C}} \frac{K_{in,50} (\widetilde{\Omega}_{i,50})^{\rho_{50}/\sigma_{50}}}{\sum_{i' \in \mathcal{C}} K_{i'n,50} (\widetilde{\Omega}_{i',50})^{\rho_{50}/\sigma_{50}}} (R_{n,50} - (1 - \theta_{50})R_{n,45}), \end{aligned} \quad (\text{D.13})$$

where we use

$$\widetilde{\Xi}_{n,50} \equiv \widetilde{b}_n \left(\frac{R_{n,50}}{S_n} \right)^\beta \Xi_{n,55}^{\rho_{55}(1-\theta_{55})}, \quad \widetilde{\Omega}_{i,50} \equiv \widetilde{a}_i \left(\frac{L_{i,50}}{S_i} \right)^\alpha \Omega_{i,55}^{\rho_{55}(1-\theta_{55})} \quad (\text{D.14})$$

on the right-hand side. They are constructed in the same way as equations (14) and (15), except that (a_{it}, b_{nt}) are replaced by the average amenities and productivity over 1955-75 $(\widetilde{a}_i, \widetilde{b}_n)$, which are our estimates of the block-specific amenities and productivity in (D.9). Importantly, using $(\widetilde{a}_i, \widetilde{b}_n)$ eliminates the idiosyncratic structural errors in amenities (b_{it}^{Var}) and productivity (a_{it}^{Var}) .³⁰ Note that the use of $\Xi_{n,55}$ and $\Omega_{i,55}$ as option values for 1955 implies that when making migration decisions for 1950, people are assumed to correctly anticipate what happens from 1955 and onward. This assumption is in line with the perfect foresight assumption in our calibration.

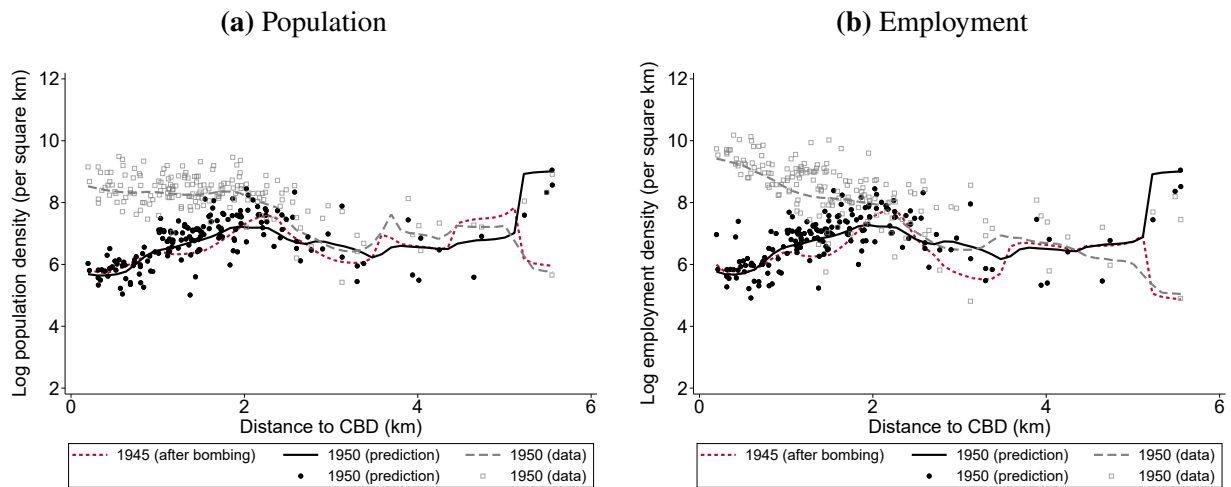
Since the structural errors in our model make our model perfectly match the observed population and employment distribution, we can compare the importance of endogenous forces in the model and structural errors in predicting the recovery by comparing the observed population and employment distribution and its prediction from equations (D.13) and (D.14). We discuss the results in Subsection 5.5 in the main text.

No agglomeration. In Subsection 6.1 we can similarly obtain the model prediction when there are no agglomeration forces by setting $\alpha = \beta = 0$ in equation (D.14) and eliminating the components of endogenous part in the future terms of option values $(\Xi_{n,55}, \Omega_{i,55})$. The comparison of model predictions with and without agglomeration forces indicates their importance in accounting for the recovery of central Hiroshima.

³⁰The year-fixed amenities and productivity $(\widetilde{a}_i^*, \widetilde{b}_i^*)$ in (D.9) are also excluded from (D.14), but this does not affect the model prediction because they appear both in the denominator and the numerator of (D.13).

Location attachment of landowners. As we discussed in Subsection 6.3, survived landowners may return to their place after the war due to their location attachment. This may result in more population in the city center, as in the pre-war population distribution, even without strong agglomeration forces. To assess this possibility, we consider a counterfactual in which we assume that (i) the size of landowners in 1936 (pre-war) was 20 percent of the population; (ii) landowners were distributed within the city proportionally to the population distribution in 1936; and (iii) landowners who survived atomic bombing returned to their homes and work in their home location in 1950. Note that 20% landownership rate assumed in (i) may overstate the importance of landowners, given the 10% landownership rate suggested by [Kato \(1988\)](#). We use the survival rate of people from *Hiroshima shisei youran* published in 1947, which documents the survival rate of people according to their distance from the center, in April 1946. With these assumptions, we compute a counterfactual equilibrium when there are no agglomeration forces. Figure D.4 shows its results for population and employment distribution in 1950. Compared to Figure 6 in the main text, we can see that both population and employment density are high close to the city center. Yet, they are significantly lower than the observations. This suggests that it is difficult to explain the recovery of the central area solely based on landownership and its direct effects. See related discussions in Subsection 6.3.

Figure D.4: Population and Employment Distributions When Landowners Return



Note: Each figure plots log population density (Panel a) and employment density (Panel b) with local polynomial regressions of each on distance from the CBD. We run three separate regressions: one for the observed 1945 population and employment densities (small dashed line), one for the observed 1950 population and employment densities (long dashed line), and one for the inferred 1950 population and employment densities when we shut down agglomeration forces in both productivity and amenities (solid line). Each dot represents a block, with different colors for the predicted density and the observed density.

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