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

Kohei Takeda
NUS

Atsushi Yamagishi
Princeton

July 30, 2023

Preliminary Draft

Abstract

This paper examines the resilience of city structure to a large shock and its underlying economic mechanisms. We analyze the atomic bombing of Hiroshima, which was an exogenous shock that leveled the city center but not its periphery, by combining newly digitized data with a dynamic quantitative urban model. We first construct spatially granular data within Hiroshima and document the resilience: the city center recovered just about five years after being destroyed. Importantly, we also show that the recovery of the city center is not necessarily explained by its fundamental locational characteristics. We then develop a novel dynamic urban economics model that allows us to disentangle the mechanisms underlying the recovery. Our calibrated model finds that strong agglomeration forces, together with individuals' expectations of the recovery, created a strong incentive to rebuild the city center quickly despite the catastrophic shock.

Keywords: agglomeration, history, expectations, quantitative spatial model, atomic bombing

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

*We are grateful to Steve Redding for his continued guidance and support. We particularly thank Leah Boustan and Nobuhiro Kiyotaki for their numerous helpful comments, and also Gabriel Ahlfeldt, Mark Bamba, Ellora Derenoncourt, Mayara Felix, Gene Grossman, Richard Hornbeck, Guy Michaels, Tomoya Mori, David Nagy, Kentaro Nakajima, Ezra Oberfield, Gianmarco Ottaviano, Pablo Ottonello, Luigi Pascali, Esteban Rossi-Hansberg, Yasuhiro Sato, Daniel Sturm, Katsuya Takii, Kensuke Teshima, David Weinstein, Junichi Yamasaki, Xuanli Zhu, and seminar and conference participants for their feedback. We thank Chugoku Region Development Bureau and Ministry of Land, Infrastructure, Transport and Tourism (MLIT) for providing access to the person-trip survey data. We acknowledge the financial support from the International Economics Section, Princeton University, the Institute of Economic Research, Hitotsubashi University, National University of Singapore, and the Funai Foundation for Information Technology. Hiroki Chiba provided excellent research assistance. An earlier version of this paper was circulated under the title "History versus Expectations in the Spatial Economy: Lessons from Hiroshima." We take sole responsibility for errors in this paper.
Takeda: Department of Economics, National University of Singapore, AS2, 1 Arts Link, Singapore, 117570 (Email: k.takeda@nus.edu.sg); Yamagishi: Department of Economics, Princeton University, Julis Romo Rabinowitz Building, Princeton NJ, USA, 08544 (Email: ayamagishi@princeton.edu).

1 Introduction

The evolution of city structure often, but not always, exhibits remarkable resilience after a devastating shock. Severely destroyed areas in cities following wars and natural disasters often exhibit quick and strong recovery, while such recovery is weaker in some cases, such as New Orleans after Hurricane Katrina (Glaeser 2022). What drives the quick and strong recovery after a large shock to city structure? Answering this provides insight into the future of cities that experienced a large negative shock, including the destroyed cities in Ukraine. More broadly, our analysis also sheds light on the effects of place-based policies, such as infrastructure investments and urban renewal, as they are also examples of shocks to city structure. However, investigating the resilience of cities has been challenging because (i) we rarely observe a large shock to city structure when we have rich spatially-granular data on economic activities and (ii) we lack a quantitative economic model that captures all the important determinants of the dynamics of city structure, which helps us assess the empirical importance of each determinant.

To investigate the resilience of city structure and its underlying economic mechanisms, we analyze the atomic bombing of Hiroshima, one of the most remarkable examples of resilience in human history. In particular, the atomic bombing drastically changed the spatial distribution of population and employment in the city by completely destroying the city center while sparing the city's outskirts, thereby providing a unique and interesting laboratory for studying the dynamics of city structure after a large shock. We consider three factors that are potentially important determinants of city structure and thus may have contributed to the rebuilding of central Hiroshima (Lin and Rauch 2022). The first consists of fundamentals such as transportation costs and natural amenities. The second factor is history, which influences the dynamics of city structure through the durability of investments and lock-in effects arising from spillover effects. Finally, although much less empirically studied, expectations regarding future city structure may also influence the dynamics through forward-looking location decisions (Krugman 1991; Matsuyama 1991). It is essential to identify these underlying mechanisms because they determine the extent to which government intervention can impact the city structure and welfare. We combine reduced-form and structural approaches to investigate which factor is the key contributor to the fast and strong recovery of central Hiroshima.

Our dataset consists of newly-collected granular historical data on population, employment, wartime destruction, and fundamental characteristics at the city block level within Hiroshima. Importantly, our novel dataset covers both the pre-bombing period and immediate post-bombing period, allowing us to investigate the speed and magnitude of the recovery of central Hiroshima. We find strong resilience in Hiroshima's recovery: the completely destroyed city center recovered just five years after the atomic bombing. In addition, our reduced-form analysis reveals that the fundamental location advantages of the city center, such as natural conditions and transportation access, cannot plausibly explain the recovery. Therefore, factors other than fundamental advantages played a role in the quick recovery of the city center.

To further understand the mechanism underlying the recovery of city structure, we develop and calibrate a novel dynamic quantitative urban model that incorporates forward-looking migration decisions, agglomeration forces, and heterogeneous fundamentals and history across locations. In the model, finitely-lived individuals can switch their residence and workplace while anticipating future productivity and amenities, subject to migration frictions and idiosyncratic taste shocks. We allow for the productivity and amenities at each location to be dependent on both the present and the past, as well as on fixed locational characteristics to account for arbitrary spatial heterogeneity. The calibrated model adequately explains the resurgence of population and employment in the city center after the bombing, and agglomeration forces are essential for making central Hiroshima again an attractive place to live and work. Furthermore, we demonstrate that expectations in the recovery are crucial for agglomeration in the city center to be realized in the sense that individuals would not have chosen to live and work in the city center if they had not expected the recovery. Taken together, our quantitative findings highlight the role of agglomeration forces and expectations in shaping the dynamics of city structure.

Section 2 describes the historical context and newly-collected data on the distribution of economic activities within Hiroshima. Hiroshima provides a unique case study for understanding the dynamics of city structure: the atomic bombing reversed the pre-war monocentric city structure. The majority of the administrative region of Hiroshima city as of 1945 lied within 6 kilometers of the city center. On August 6, 1945, almost all structures within 2 kilometers of the city center were destroyed by the atomic bomb, but many structures on the outskirts were not entirely destroyed. 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 can be viewed as an extremely large shock to city structure, leaving the pre-war city center with the lowest population and employment density.

In Section 3, our reduced-form analysis reveals that the city structure is resilient to the unprecedented shock. Our findings are twofold. First, the completely destroyed city center recovered within five years of the atomic bombing. This recovery result is consistent with historical-shock independence in the *across*-city distribution after bombing (e.g., Davis and Weinstein 2002) given that the effects of the atomic bombing on Hiroshima's city structure quickly disappeared in the post-war period. Notably, however, our recovery result is for the *within*-city population distribution, which in other empirical settings tends to show historical-shock dependence (see Lin and Rauch 2022 for a review). Second, our novel finding is that the recovery of central Hiroshima cannot be plausibly explained by the fundamental locational advantages of the city center relative to its periphery. In particular, the recovery of the pre-war city center is not explained by the observable location characteristics, and the recovery is observed even within a small and relatively homogeneous area of the city. We also look at Nagasaki, in which the periphery was completely destroyed in contrast to Hiroshima. We find that the destroyed areas in Nagasaki also recovered. Nagasaki's recovery suggests the limited importance of the locational fundamentals of the city center in driving the recovery: the destroyed peripheral areas of Nagasaki did not have the potential advantage of the pre-war city center and yet their recovery was similar to that of central Hiroshima.

In Section 4, we develop a novel dynamic quantitative urban model to investigate the underlying economic mechanisms of the recovery. Our model is the first quantitative spatial model that accommodates commuting, forward-looking location choice, and path-dependence in location decisions and fundamentals. First, a city has heterogeneous location-specific amenities and productivity, and people commute within a city. Second, individuals correctly anticipate the future path of the economy when making location decisions, and neighborhood amenities and productivity depend on population and employment density. Therefore, the location decisions of individuals hinge on their expectation on the evolution of population and employment distribution. Third, our model incorporates a perspective of backward-looking location decisions. In particular, amenities and productivity also depend on past population and employment density because the current and past situations of each block can affect its attractiveness (Allen and Donaldson 2022), and migration is subject to frictions (Caliendo, Dvorkin and Parro 2019). These model elements are necessary to capture all the potentially important determinants of the dynamics of city structure (Lin and Rauch 2022).

In Section 5, we calibrate our model and assess how well it explains the recovery of central Hiroshima. We calibrate our model using data 1950–1975, which spans the post-recovery period. Since our purpose is to examine how well our model can explain the recovery after the atomic bombing, we do not use the recovery period data (1945–1950) for calibration.[1] We leverage the structure of the model to estimate model parameters and compute unobserved location characteristics. Our key parameters are agglomeration forces in amenities and productivity that determine the value of future returns from location choices. We estimate them under the identification assumption that changes in the amenities and productivity of each block are explained by model endogenous forces while allowing for arbitrary heterogeneity in fixed amenities and productivity across blocks (c.f., Ahlfeldt, Redding, Sturm and Wolf 2015).

We find strong net agglomeration forces in both amenities and productivity. A high population and employment density today improves current amenities and productivity, respectively. In addition, a higher population density five years ago increases the current value of amenities, while a high employment density five years ago is negatively associated with the current level of productivity. Our estimates are broadly in line with Allen and Donaldson (2022) in the across-county setting of the US, except that the net agglomeration forces in amenities are positive in our within-city setting

[1] We also do not use for calibration the pre-war period data due to limited data availability.

due to the sufficiently strong contemporaneous agglomeration forces. We then assess the ability of our calibrated model to explain the data from 1945 to 1950 when people returned to the completely destroyed city center. We show that the endogenous mechanisms of our model successfully predict the resurgence observed in the data.

Section 6 highlights that both agglomeration forces and expectations in the recovery are key elements of the model that are needed to explain the quick recovery. The first counterfactual analysis investigates the importance of agglomeration forces. When we shut down agglomeration forces in amenities and productivity, the calibrated model fails to predict the recovery of the city center. This implies that the incentive to live and work in the city center after the bombing was driven by the expected high density of the city center rather than from location-specific amenities and productivity, consistent with our reduced-form results. Next, we show that expectations in recovery are essential to make the agglomeration forces work in the recovery. In particular, individuals coordinately anticipated the recovery of central Hiroshima when choosing their residence and workplace. We show this by presenting an alternative equilibrium of our model in which the city center does not recover. If the city center recovered because of sufficiently advantageous fundamentals, then such an equilibrium would not exist because people would have an incentive to live and work in the city center irrespective of their expectations of no recovery. Therefore, the existence of such a no-recovery equilibrium suggests that the incentive to live and work in the city center stems from the agglomeration forces that are expected to be realized. This result suggests that expectations in the recovery may become self-fulfilling, as discussed by Krugman (1991) and Matsuyama (1991). Lastly, although we remain agnostic about the origin of the expectations in the recovery and focus on showing their importance for accounting for the recovery given their emergence, we briefly discuss the possible causes of the expectations in the recovery. In particular, the presence of governmental recovery plans, the anchoring effect of the transportation network, property rights, and the popular narrative of rebuilding may have led to the formation of expectations of the recovery and thereby induced the recovery.

Overall, our analysis of the experience of Hiroshima highlights that agglomeration forces and expectations in recovery may play key roles in inducing recovery after the atomic bombing. Our study suggests that in considering future rebuilding of a city after a large shock, such as rebuilding cities in Ukraine and cities hit by natural disasters, it is important to build up expectations for the city's recovery because it may become self-fulfilling through agglomeration forces. More generally, a place-based policy, including infrastructure investment and urban renewal, may have a bigger effect on the evolution of city structure and welfare if the policy could successfully change individuals expectations about how cities will change in the future.

Related Literature. This paper contributes to the extensive literature on the determinants of the spatial distribution of economic activities. The first strand of research examines whether a historical event has a persistent impact on the spatial distribution of economic activities. Previous studies exploiting war-time destruction as a shock often discovered historical-shock independence (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). In particular, the seminal work by Davis and Weinstein (2002) finds that across-city population distribution of Japan after World War II converged to the pre-war trend, including Hiroshima and Nagasaki. Yet, historical-shock dependence has been found to arise depending on the historical event and the outcome variables of interest (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; See Glaeser 2022; Lin and Rauch 2022 for recent review). Our paper is distinctive from these studies in three important ways. First, we use new spatially granular data to analyze the intra-city spatial distribution of economic activities.[2] Second, we use the atomic bombing of Hiroshima as an exogenous and unprecedentedly large shock to the internal structure of the city. Finally and most importantly, we construct and apply a novel dynamic quantitative urban model to this historical shock to investigate why we observe the historical-shock independence in Hiroshima, highlighting the role of agglomeration forces and expectations in overcoming the catastrophic history.

Our paper also relates to the literature emphasizing fundamental locational characteristics, such as transportation costs and natural conditions, as a determinant of city structure. The theoretical literature dates back to, at least, the Alonso-Muth-Mills model (Fujita 1989) and the importance of fundamental locational characteristics has been empirically investigated (e.g., Anas, Arnott and Small 1998; Glaeser and Kahn 2004; Saiz 2010; Lee and Lin 2018; Harari 2020). Our paper accommodates the role of fundamental locational characteristics in determining city structure. Nevertheless, by showing that the rebuilding after the atomic bombing in Hiroshima is unlikely to be explained by locational fundamental characteristics alone, our paper suggests that factors other than locational fundamental characteristics, especially agglomeration forces and expectations, can also be important determinants of the city structure.

This paper also contributes to the discussion about the role of expectations in shaping the evolution of the spatial economy. Krugman (1991) and Matsuyama (1991) show that self-fulfilling

[2] As reviewed by Lin and Rauch (2022), the focus on the within-city setting is recent but growing (e.g., Ahlfeldt et al. 2015; Hornbeck and Keniston 2017; Brooks and Lutz 2019; Ambrus et al. 2020; Heblich et al. 2021; Yamagishi and Sato 2023). We investigate the atomic bombing, which is also analyzed by Davis and Weinstein (2002, 2008) in the across-city setting, by focusing on its effect on the city structure.

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.[3] A spatial economy with strong agglomeration forces is a primary example in which multiple equilibria and equilibrium selection matter because the positive agglomeration forces can lead to multiple equilibria (Fujita, Krugman and Venables 1999; Redding and Rossi-Hansberg 2017).[4] Combining our model and data, we empirically demonstrate that the dynamics of the city structure would be starkly different and the city center may not recover in an alternative equilibrium. In this sense, we provide new evidence of the potential importance of self-fulfilling expectations in the spatial economy based on a large historical shock and a structural model, which has been scarce as pointed out by Lin and Rauch (2022). Investigating the role of self-fulfilling expectations is policy-relevant because, if they matter, then even a small-scale policy can have a large welfare impact by affecting people's expectations (Kline and Moretti 2014).

Our structural analysis also relates to recent advancement of quantitative spatial models (Redding and Rossi-Hansberg 2017). Our model is the first quantitative urban model to incorporate the following three key components, which we argue are essential to capture important determinants of within-city structure (Lin and Rauch 2022). First, we incorporate commuting to account for differences in location as a residential place and a workplace within a city (Ahlfeldt et al. 2015; Dingel and Tintelnot 2020; Tsivanidis 2022). Second, individuals make forward-looking migration decisions with perfect foresight (Desmet, Nagy and Rossi-Hansberg 2018; Caliendo et al. 2019; Balboni 2021; Heblich et al. 2021; Allen and Donaldson 2022; Kleinman, Liu and Redding 2023) in order to account for expectations. Third, we include history-dependent amenities and productivity and migration frictions to account for the influence of history (Allen and Donaldson 2022).[5] Importantly, we integrate these elements into a single framework while keeping it parsimonious in other aspects since the data availability in our historical context is relatively limited. This parsimony may be particularly useful in applying our model to data-scarce environments.

Lastly, this paper is related to studies on the recovery of Hiroshima from the atomic bombing (Hiroshima City Government, 1971; 1983a). However, there is little econometric analysis on the distribution of economic activities within the city and what can account for the resurgence of the city

[3] Fukao and Bénabou (1993) corrects a mathematical problem in Krugman (1991). See, among others, Rauch (1993), Baldwin (2001), Ottaviano (2001), Oyama (2009), and Barreda-Tarrazona, Kundu and Østbye (2021) for further developments on the idea of Krugman (1991) and Matsuyama (1991) in economic geography.

[4] The self-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 insurances (Foley-Fisher, Narajabad and Verani 2020).

[5] In particular, our model extends Allen and Donaldson (2022) by introducing commuting to analyze the internal structure of a city. Furthermore, we set a much lower discount factor for future values compared to Allen and Donaldson (2022) so that expectations play a more important role. This reflects the difference in time horizon. We consider short periods (every 5 years), while Allen and Donaldson (2022) suppose 50 years for one period since their primary focus is on the long-run impact of history (i.e., the initial conditions).

center. Our paper formally analyzes the recovery pattern using newly-digitized granular historical data on population and employment. In addition, we develop and calibrate a novel quantitative economic model to understand the economic mechanisms behind the recovery of central Hiroshima.

This paper is structured as follows. Section 2 provides historical context and data. Section 3 introduces the reduced-form analysis and shows the fast and strong resurgence of central Hiroshima after the bombing. Section 4 presents our model. Section 5 calibrates the model and demonstrates that our model explains the recovery of central Hiroshima. In Section 6 we undertake the counterfactual analysis to show the role of agglomeration forces and expectations in the recovery. Section 7 concludes.

2 Historical Background and Data

This section briefly describes the historical context of Hiroshima City and the data of our study. 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 location characteristics of Hiroshima city. Section A of the online appendix provides further details, including summary statistics of the data.

2.1 Historical Background

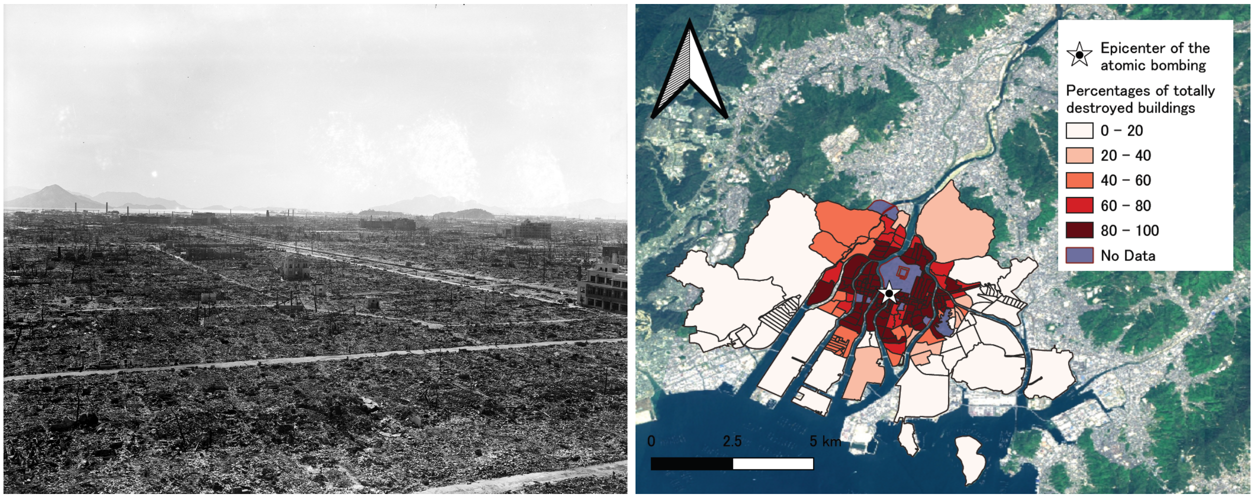
The development of Hiroshima city started in the late 16th century when Terumoto Mōri, a local samurai lord, built the Hiroshima castle. since then, Hiroshima has been a major city in the *Chugoku* region because it is close to the sea and rivers. Early in the 20th century, the city grew quickly. In 1935, 310,118 people lived in Hiroshima city, which made it the seventh-largest city in Japan by population. As Japan gradually transitioned to a total-war system following the Second Sino-Japanese War (1937-) and the Pacific War (1941-), growth slowed down and then turned around. 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. did not bomb Hiroshima on purpose because they desired to preserve Hiroshima as the "best laboratory" for demonstrating the effects of the atomic bomb.[6] 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.

[6] See "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 May 14, 2022).

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 the map of Hiroshima city 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). We overlay the area of our study on an aerial photograph. Since the old photographs right after the bombing are not of high image quality, we use the contemporary image for illustration.

The damage to people and buildings was unprecedentedly catastrophic.[7] The city government of Hiroshima estimates that 140,000 people died as a result of the atomic bombing by the end of 1945, although it is difficult to determine the exact number.[8] The death rate was exceptionally high nearing 100 percent for those within 1 kilometer from the epicenter. The bomb also destroyed a large number of buildings: 70,147 out of 76,237 buildings in Hiroshima city were destroyed in excess of fifty percent. The majority of buildings within two kilometers of the city center were completely destroyed. The situation where almost all buildings were destroyed can be seen in the photo Figure 1a, which was taken near the epicenter of the bombing. Consequently, the population of Hiroshima city dropped to 136,518 in November 1945, which is about one-third of the pre-war population.

In contrast to the total destruction in central Hiroshima, the outskirts of the city more than 2 kilometers away from the city center experienced relatively moderate destruction. Figure 1b shows the fraction of completely destroyed buildings at the block level (Hiroshima City Government 1971;

[7]This 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, the 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 May 13, 2022). While the absolute number is large in Tokyo, the destruction ratio in Hiroshima is substantially greater than in Tokyo due to its smaller population size.

[8]The real death toll is likely to be even higher than this because the atomic bombing caused severe injuries and diseases that killed many of the victims after 1945. Source: https://www.city.hiroshima.lg.jp/site/english/9803.html (last accessed on November 4, 2022).

Takezaki and Soda 2001). While nearly all buildings in the dark-colored areas close to the epicenter were destroyed, the majority of buildings in the light-colored areas away from the epicenter avoided complete destruction. As a result, the outskirts of Hiroshima experienced a significant increase in population as survivors from the city center escaped to them. Most notably, on November 1, 1945, areas beyond 3 kilometers from the epicenter had 142 percent of their pre-bombing population.

The war ended on August 15, 1945. People initially doubted whether Hiroshima could recover. Although people at that time had limited scientific knowledge, the radioactive contamination was a major concern immediately after the bombing. There were rumors circulated that "nothing will grow here for 75 years."[9] However, the serious radioactive contamination caused by the bombing decayed relatively rapidly with time.[10] 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 contaminated materials, bringing the level of radioactivity down to a safe level (Takahashi 2008). Given this evidence, we do not take into account the potential radioactive contamination in analyzing the recovery of Hiroshima because living in Hiroshima was unlikely to cause diseases after this typhoon.[11]

The city government of Hiroshima attempted some early public efforts to promote the recovery, but a shortage of resources prevented a large-scale action. There was no special aid from the central government for Hiroshima until 1949 despite the exceptionally severe damage. Notwithstanding the lack of strong public actions, Hiroshima city, including its city center, had started to recover strongly due to private efforts. In 1955, Hiroshima city had a population level of 357,287, which was already larger than the 1935 population. Hiroshima continued to grow and the city area expanded along the way. Today, Hiroshima city has a population of approximately 1.2 million in 2022, ranking it 10th among all Japanese municipalities and the largest in the *Chugoku* region of Japan.

2.2 Data

We have collected and, when necessary, digitized various information on the economic activity in Hiroshima before and after the war. Here, we provide a brief overview of the essential data used in this paper. See Section A of the online appendix for more details.

Spatial Units. The spatial unit of our analysis is mainly a city block (*cho-cho-moku*) in Hiroshima city. As our primary definition of city blocks, we use the GIS data of block boundaries as of the

[9]Source: https://www.bbc.com/news/world-asia-53660059 (last accessed on March 13 2022).

[10]According to the Hiroshima city government (https://www.city.hiroshima.lg.jp/site/english/9809.html, last accessed on November 4, 2022), the radiation level at the epicenter became 1/1,000th a day after the bombing and 1/1,000,000th a week later.

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

bombing constructed by Takezaki and Soda (2001). To make the comparison between the pre-war and the post-war period, we focus on areas that already belonged to Hiroshima city as of the bombing.[12] We additionally digitize the block boundaries as of 1966 and 1976 to account for revisions of the block boundaries by the government. 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. The block tends to be small near the city center. The average area size for blocks is 0.04 square kilometers within 1 kilometer of the CBD and 0.13 square kilometers within 3 kilometers from the CBD. In contrast, the average block area is 2.19 square kilometers among blocks more than 3 kilometers away from the CBD. The average block-level population in 1936 was 1,880 for all blocks and 1,642 for blocks within 3 kilometers from the CBD.

Destruction by the Atomic Bombing. Similar to Davis and Weinstein (2002) and Brakman et al. (2004), we primarily use the fraction of totally destroyed buildings as a severity measure of destruction. The block-level destruction rate is reported in Hiroshima City Government (1971). Building on the digitization by Takezaki and Soda (2001), we augment it by consulting Hiroshima City Government (1971) to correct typos in their data and obtain additional information on missing values. Figure 1b in the previous section illustrates the share of completely-destroyed buildings in each block on a map.

Population. We collect and digitize the population data at the block level. For the period 1933-1936, we refer to the Statistical Handbook of Hiroshima city (*Hiroshima-shi toukei sho*). For 1945-1953, we refer to the Statistical Abstract of Hiroshima city (*Hiroshima shisei youran*). From 1955, we exploit data from the Population Census. We address changes in the block boundaries by the areal weighting interpolation. For 1945–1950, population is reported in less geographically granular units than blocks, which we address by utilizing the best available block-level information to approximate the block-level population distribution. Figure 2a provides a visualization of the population in Hiroshima over time. The total population in Hiroshima increased prior to the atomic bombing and significantly dropped after the bombing. After WWII, the total population again increased over time. We also observe that the central area of Hiroshima showed a declining share of the population over time. This is suggestive of suburbanization and the development of the outer suburbs of the city that absorbed the population growth of the city, which was a general trend in cities during the post-WWII period. Note that the declining trend was already observed in the pre-WWII period,

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

suggesting that a lower population share of the center after the WWII does not necessarily mean that the recovery was incomplete.

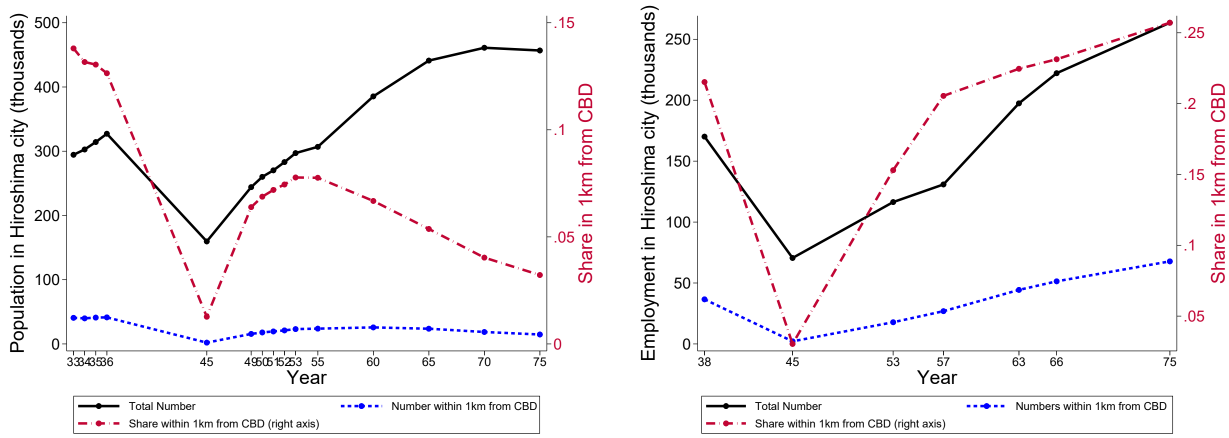
Employment. We collect and digitize employment data at the block level.[13] For the year 1938, we refer to the Survey of Commerce and Industry in Hiroshima city (*Hiroshima-shi shoukou-gyou keiei chousa*) that records the number of establishments at the block level. The number of commercial buildings right after the bombing is available in the Statistical Abstract of Hiroshima city (*Hiroshima shisei youran*). For 1953, we exploit the Survey on the Daytime Population of Hiroshima (*Hiroshima-shi chukan jinko chosa*). From 1957 to 1975, we use the Business Establishment Statistical Survey (*Jigyousho toukei chousa*). We address changes in the block boundaries by the area weighting interpolation. For 1953–1963, employment is reported in less geographically granular units than blocks, which we address by combining the best available block-level information to approximate the block-level employment distribution. Finally, when employment data is unavailable but establishment data is available, we follow Ahlfeldt et al. (2015) to assume that the number of establishments is proportional to the number of employment. Based on the data described above, we then approximate the block level employment every five years from 1950 to 1975 to match the years in which the population data is available. Figure 2b shows the change in employment in Hiroshima city. The total employment dropped significantly in 1945 after the bombing, but it increased again post-war, and the number of employed in the central area recovered to a similar level to the pre-war period. The share of employed in the central area had been increasing throughout the post-war period, implying the concentration of employment over time.

Commuting and Transportation Networks. We use the trip-level microdata from the 1987 Hiroshima City Person Trip Survey to analyze the commuting pattern, which collects the workplace, residence, and the representative travel mode for the commuting trip. We also collect and digitize road networks, bus networks, and train networks in Hiroshima city, and compute the bilateral travel time between blocks for each mode: walk, bike, car, bus, and train. Although the public transportation networks were generally stable after the war, there were some changes, notably the discontinuation of the *Ujina* line in 1966.[14] To address this, we use the public transportation networks of 1950 for years prior to 1966 and those of 1987 for later years.

[13]Throughout this paper, we focus on employment in manufacturing or service sectors and abstract from agricultural employment. This is a relatively moderate restriction because we focus on an urban area and the agricultural employment is small. Even in 1950, in which agricultural employment was large in the entire Japanese economy, the Population Census suggests that less than 10 percent of workers are in the agricultural sector in Hiroshima city.

[14]Two new lines (*Hijiyama/Minami line* and *Eba line*) opened in 1944 for military purposes, and these lines have been maintained even after the war.

Figure 2: Change in Population and Employment in Hiroshima City



(a) Population **(b)** Employment

Note: The total number of population and employment of the entire city and within one kilometer from the CBD (left axis), as well as the share of the population and employment within one kilometer from the CBD (right axis). See Section A of the online appendix for data construction.

Locational Characteristics. We collect various information on the locational characteristics of each block. In particular, we exploit data on altitude, ruggedness, soil condition, distance to train stations, distance to Hiroshima port (*Ujina* port), distance to water areas, and distance to cultural assets for each block.

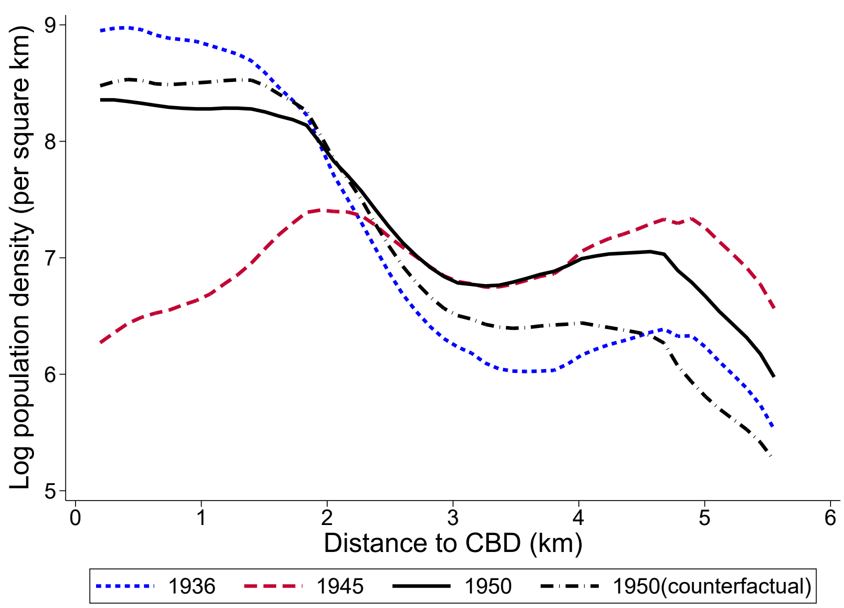
3 Reduced-form Evidence

In this section we analyze population density to illustrate the pattern of destruction and recovery in Hiroshima. Subsection 3.1 describes how the atomic bombing destroyed central Hiroshima and how the city recovered in its subsequent periods. In Subsection 3.2, we conduct a regression analysis of the changes in population distribution and argue that the fundamental advantages of central Hiroshima are unlikely to explain its recovery. Subsection 3.3 examines the case of Nagasaki, which is another city hit by the atomic bomb to discuss the external validity. Subsection 3.4 investigates the recovery as measured by the employment distribution and land prices, an alternative regression specification that explicitly considers the characteristics of neighboring blocks and the effects of public recovery policies.

3.1 Descriptive Evidence of the Destruction and Recovery within Hiroshima

In Figure 3 we non-parametrically plot the population density in the city of Hiroshima by the distance to the central business district (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 completely changed due to the atomic bombing but it 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 it decreased as one moved away from the center. This monocentric pattern had been completely reversed because the atomic bomb hit the most densely populated city center. Figure 3 shows that, after the bombing, the city center became totally destroyed and consequently had the lowest population density in the city. In contrast, areas that are about 2 kilometers away from the city center, which avoided the total destruction of buildings (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. Indeed, the outskirts experienced an increase in population density as many survivors in the city center escaped to the outskirts.

Figure 3: Population Density by the Distance to the City Center



Note: The figure shows the local polynomial regression of the log population density on the distance to the central business district (CBD) using the 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. Distances are calculated using the centroid of each block shape and CBD is defined as the mid-point of *Kamiya-cho* block and *Hacchobori* block, which are the two prominent areas in the CBD of Hiroshima city both in the pre and post-WWII. The counterfactual population distribution of 1951 is generated from the 1936 population distribution, assuming that each block has the annual population growth rate during 1933–1936.

Despite the "reversal" of the monocentric city pattern after the bombing, the monocentric city structure had already re-emerged in 1950, just five years after the bombing. This is quite surprising given that the city center, which was nearly completely destroyed, quickly became the most prosperous place again. While the recovery from the total destruction appears to be robust, the recovery may not be perfect, as the concentration of the 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 the similarity between the actual population distribution in 1950 and the counterfactual one, which was constructed by assuming that there was no atomic bombing and the pre-war population growth rate continued from 1936 until 1950.

If the initial population distribution immediately after the end of the war determined by the atomic bombing had a persistent impact, then we would expect a lower population density in the center and a higher population density in the outskirts. The recovery result is analogous to the path-independence result of Davis and Weinstein (2002) for *inter-city* population distribution of Japan after WWII. However, we obtain the recovery in a *within-city* setting of Hiroshima that experienced an extremely larger shock: the complete destruction of the city center.[15] The next section formalizes this point by a regression analysis, which allows us to consider statistical significance of our findings and various control variables.

3.2 Regression Analysis of the Recovery of Central Hiroshima

We now look at the magnitude of the resurgence at a spatially granular level of blocks. We estimate the following regression model analogous to Davis and Weinstein (2002):

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

where i is the block and t is the year, X_i is the vector of control variables and v_i is the error term. In this specification we regress the post-war log population density change rate on the log population change rate induced by the atomic bombing from 1936 to 1945. If $\gamma = 0$, the log post-war population density is proportional to the log population density right after the bombing, irrespective of the pre-war population density. This is consistent with historical-shock dependence: the historical shock by the atomic bombing is crucial in determining the population distribution. In contrast, if $\gamma = -1$, the population change due to the atomic bombing is completely negated. This is consistent with historical-shock independence: the historical shock of the bombing no longer matters. Therefore, the estimated coefficient of γ informs whether the data is better characterized by historical-shock dependence or independence. Throughout Section 3, we examine the correlation between the population growth rate after and during the war, implying that this regression does not necessarily have a causal interpretation.

We start with a simple case of no control variable. Figure 4 illustrates the relationship between the post-war population density growth rate and that during the bombing period for each block,

[15]Moreover, our results may differ from Davis and Weinstein (2002) in terms of the rate of recovery. In Davis and Weinstein (2002), it took approximately 20 years for the total population of Hiroshima to return to the level predicted by the pre-war trend. In our within-city case, it took just about five years conditional on the location characteristics (see Columns 2 and 3 of Table 1).

along with the regression line of (1). The first panel in Figure 4 shows that in 1950. The fitted line is somewhat less steep but already close to the slope of -1, implying that the strong resurgence of the destroyed areas had already occurred just five years after the bombing. The second panel 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. Columns 1 and 4 of Table 1 provide detailed regression results depicted in Figure 4. The coefficient is -0.712 in 1950 and -0.688 in 1960, both of which are statistically distinguishable from zero, thus the complete historical-shock dependence is rejected. Although we can also statistically reject $\gamma = -1$ (i.e., perfect historical-shock independence) in these regressions, the results suggest a strong recovery just within five years.

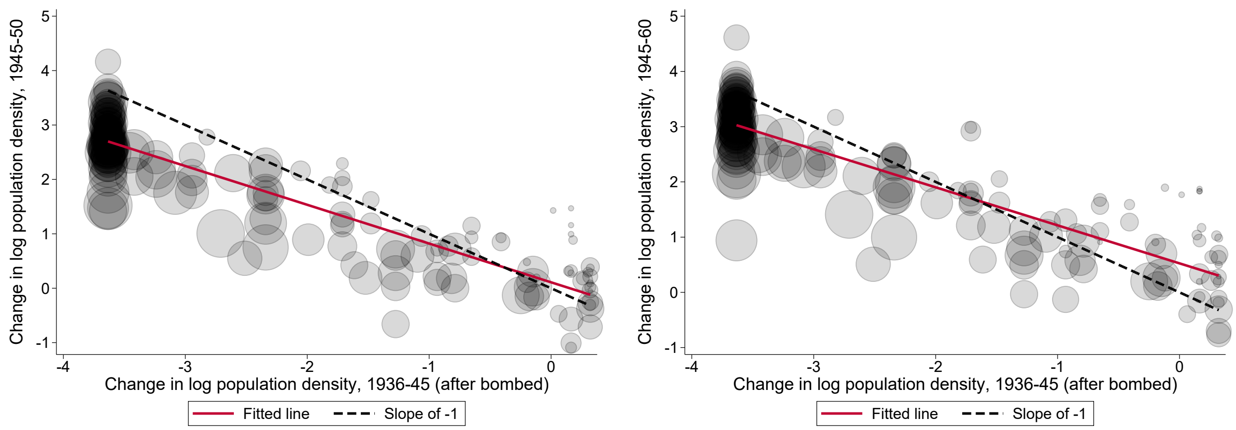
The regression specification (1) has been estimated in other contexts and our result is comparable to those estimates. The coefficient around -0.7 in our simple regression is larger in absolute value than Brakman et al. (2004) in their across-city analysis of Germany, suggesting that the recovery was stronger in our context. On the other hand, the coefficient is somewhat smaller in absolute value than some specifications of Davis and Weinstein (2002, Columns 1 and 3 of Table 3), suggesting that weak historical-shock dependence might be observed for the within-city population distribution of Hiroshima.[16] That said, we show in the next subsection that conditional on control variables, we also obtain a coefficient of around -1. The high R-squared despite the fact that we only include the population change from 1936 to 1945 as the explanatory variable implies a close relationship with the postwar population change. Overall, our results indicate the fast and strong resurgence of central Hiroshima.

Locational Advantages of the Central Hiroshima. Previous studies (e.g., Bleakley and Lin 2012; Schumann 2014; Lin and Rauch 2022) have argued that the spatial heterogeneity of geography in terms of climate and topography may be crucial in explaining the path-independence result of Davis and Weinstein (2002) for the across-city population distribution in post-WWII Japan. If the damaged locations were innately attractive, people would rebuild there. Although this may be a plausible explanation for the *across-city* population distribution in Davis and Weinstein (2002), we argue below that locational advantages do not appear to play a significant role in the resurgence of central Hiroshima *within* the Hiroshima city.

Before proceeding with the regression analyses, we discuss heuristically why the locational advantage of central Hiroshima does not appear to account for its resurgence. First, natural conditions within Hiroshima, conditions that are exogenous and difficult to change, are homogeneous. This is intuitive because our geographic scope is limited and most of the city area lies within up to 6 kilometers of the city center. The majority of Hiroshima city is located in the delta area of *Ota*

[16]Column 2 of Table 3 in Davis and Weinstein (2002) reports the coefficient of -0.759, which is close to -0.7.

Figure 4: Population Change due to the Atomic Bombing and the Subsequent Population Change



(a) Population Change in 1945-50

(b) Population Change in 1945-60

Note: The figures plot change in the log of population density from 1945 to 1950 or 1960 to 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 the slope of -1 (dashed line), which would be obtained if the population change during the bombing period is completely reversed in the post-war period.

river, which provides a flat terrain with loose soil. Moreover, the distance to the nearest water area is homogeneous within the city, reflecting the fact that the city is cut through by many branches of *Ota* river and faces the sea to the south.

Second, the key manmade advantages of central Hiroshima, conditions that may be changed through investment, were substantially damaged by the bombing. The city center of Hiroshima, areas around *Hacchobori* and *Kamiya-cho*, is located next to the Hiroshima castle, which had been a symbol of the city since the samurai period and a historical amenity. It was also adjacent to the former central area 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 convenient access to the tram network. These advantages were lost by the bombing. Hiroshima castle was totally destroyed and *Nakajima-cho* was also completely obliterated by the atomic bomb. Although the city center might retain some advantage in transportation access, the access to workers and jobs would have been substantially worsened as their neighborhoods were completely destroyed and other areas of the city may have had better conditions after the bombing.[17]

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 resurgence is not driven

[17] For instance, areas around Hiroshima station also provide convenient access to transportation but experienced much less destruction by the bombing, which may make Hiroshima station the potential new center of Hiroshima city. 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 the War-time Damage

	(1)	(2)	(3)	(4)	(5)	(6)
	Change in log population density 1945 - 1950			Change in log population density 1945 - 1960		
Change in log population density 1946–1945	-0.7124[a]	-0.9179[a]	-0.9787[a]	-0.6884[a]	-0.9323[a]	-1.0052[a]
	(0.0268)	(0.0960)	(0.0922)	(0.0304)	(0.1060)	(0.1120)
p-value from testing $\gamma = -1$	0.000	0.394	0.817	0.000	0.524	0.963
Control variables		✓	✓		✓	✓
Within 3 km from the city center			✓			✓
Number of blocks	174	174	158	174	174	158
R-squared	0.809	0.863	0.884	0.772	0.854	0.869

Note: We report the OLS estimation result of the equation (1). Fundamentals consist of the quadratics of the distance to the nearest station, the distance to Hiroshima port (*Ujina* port), the distance to the nearest cultural asset, the distance to the nearest water area, the altitude, and the slope. We also include a dummy for a bad soil condition. We also control for the quadratic of the pre-war (1933-1936) population growth rate, the fractions of the half-destroyed, moderately-destroyed, and intact buildings, and the geographical coordinates (the latitude, the longitude, and their interaction). In columns 3 and 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 1936 population distribution matters for the population in 1950 and 1960 but not the 1945 population distribution. Robust standard errors in parentheses.

by the fundamental advantages of central Hiroshima, the severity of destruction would retain its explanatory power and vice versa. We consider the following control variables: the quadratic form the distance to the nearest train station as of 1950, the distance to Hiroshima port, the distance to the nearest cultural asset, the distance to the nearest water area, the altitude and the ruggedness, an indicator for a bad soil condition and geographic coordinates. These variables capture the fundamental locational advantages of the city that can be considered as given after the WWII period.[18] Additionally, we control for the population growth rate from 1933 to 1936.[19] The pre-war growth trend is expected to capture the unobserved attractiveness of each location. We also control for the fractions of half-destroyed, moderately-destroyed, and intact buildings, which we expect to serve as proxies for the initial conditions of each location, such as the quality of the housing stock and infrastructure, immediately after the bombing.

Column 2 and 5 of Table 1 present the regression results of equation (1) for 1950 and 1960 with the rich set of control variables described above. Compared with columns 1 and 4, coefficient γ is now statistically indistinguishable from -1 even for 1950, suggesting the complete historical-shock independence. This result implies that if any, locations that grew more due to the attractive fundamental conditions might have experienced milder destruction from the atomic bombing, which is in contrast to the center having location advantages and experiencing rapid resurgence. Columns 2 and 5 thus imply that, conditional on observed fundamentals, the loss in population density due

[18]While most of the pre-war stations were restored by 1950, no new rails were constructed between 1945 and 1950.

[19]To avoid extreme values due to idiosyncratic reasons or measurement errors, we cap the annualized growth rate at 10 percent in absolute value.

to the atomic bombing completely recovered. This result suggests that the observed fundamental locational advantages of central Hiroshima do not explain its resurgence.

To further address the concern that the unobserved attractiveness of each location could drive the result, we restrict our sample to blocks within 3 kilometers of the city center. Since the edge of this circle was less damaged and had better access to the undamaged areas, it would be in a better position right after the bombing (see Figure 3). At the same time, these areas have more homogeneous natural conditions and transportation access as we have focused on a smaller area, leading to a smaller omitted variable bias.[20] Columns 3 and 6 of Table 1, however, show that, coefficient γ is statistically distinguishable from zero but not from -1. This result further suggests that fundamental locational advantages of the city center are unlikely to explain its resurgence.

3.3 When the Bomb Hit the Outskirts of the City: the Case of Nagasaki

Our findings regarding Hiroshima suggest that the recovery of central Hiroshima is attributed to the level of destruction caused by the atomic bomb; however, the fundamental location advantages do not appear to account for the recovery. To provide further support for this argument, we document the recovery from the bombing in Nagasaki, the second and last city in human history to be destroyed by an atomic bomb. In Section B of the online appendix we examine the population data in Nagasaki.

In Nagasaki, the atomic bomb hit the outskirts of the city (see Figure B.1a).[21] This is in contrast to Hiroshima, where the atomic bomb hit the city center. Consequently, the comparison with Hiroshima helps distinguish the fundamental advantages of the pre-war city center, some of which are potentially unobserved, from the level of destruction in explaining post-war population growth. Figure B.1b shows a fitted line from the regression of equation (1) for Nagasaki. It indicates that heavily destroyed areas on the outskirts of Nagasaki recovered strongly. The coefficient of our interest is around -0.88 and statistically indistinguishable from -1, suggesting historical-shock independence in population distribution within Nagasaki. Therefore, the recovery of the destroyed outskirts of Nagasaki suggests that locational advantages specific to the pre-war city center did not play a major role in the strong recovery of the destroyed area.

3.4 Further Discussions

Employment Distribution. We have looked at the evolution of the population distribution. However, due to commuting, the population distribution and employment distribution in a city may

[20] Table A.1 suggests that the standard errors of locational characteristics are smaller in this subsample. A similar idea has been invoked in Schumann (2014) in a different context.

[21] The US initially intended to bomb a city called *Kokura*, but it changed the target to the city center of Nagasaki due to the weather conditions. The weather condition also prevented attacking the city center of Nagasaki, and consequently the bomb was dropped onto the outskirt area of Nagasaki. See https://www.peace-nagasaki.go.jp/abombrecords/b020101.html (last accessed on June 30, 2023).

differ. As the city center is also the center of employment, the atomic bombing would also alter the employment distribution. In Section C of the online appendix we analyze the impact of the atomic bombing on the distribution of jobs using employment data for 1938, 1945, and 1966. We find that the number of jobs in central Hiroshima recovered, and the regression results are very similar to those for the population.

Land Prices. We also examine land prices. While we do not have comprehensive land price data during our sample period, we could investigate the location with the highest land price in the city, which could be interpreted as a central location of the city. Both in 1931 and 1959, the highest land price was observed in the block of *Hacchobori* area, the city center both before and after the war.[22] Thus, the resurgence of central Hiroshima is also observed in land prices.

Characteristics of Neighboring Blocks. In Section C of the online 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 its neighboring blocks. To consider the characteristics of neighbors, we adopt the so-called "SLX model" in spatial econometrics literature (Halleck Vega and Elhorst 2015) and add the spatial lags of the following three neighborhood characteristics to our main regression (1): (i) the population change rate by the bombing $\ln(\text{Popdens}_{i,1945}/\text{Popdens}_{i,1936})$, (ii) the locational characteristics X_i, and (iii) the population distribution right after the war, which is meant to capture market access after the bombing.[23] Table C.2 shows that including these spatial lag variables does not change our historical-shock independence result. Note that while this is a reduced-form approach to account for spatial interdependence across blocks, our theoretical model in Section 4 structurally incorporates it through transportation networks.

Timing of the Public Recovery Policies. As demonstrated in this section, our population data at the block level suggests that the recovery was complete by 1950. To shed additional light on when the recovery began, we use the population data for 1946, 1947, and 1948 from the Statistical Abstract of Hiroshima as reported by distance from the epicenter of the bombing. The rapid recovery began in 1946, as depicted in Figure A.4 in the online appendix. This finding may suggest that the direct impact of public recovery policies on the recovery was limited. In particular, the Hiroshima city government faced severe budget constraints when implementing a recovery plan. It was not until the enactment of the Hiroshima Peace Memorial City Construction Law in 1949 that Hiroshima could receive special recovery grants from the central government. Consequently, Hiroshima City was

[22]The 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).

[23]In particular, it 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 that the city center itself was totally destroyed.

only able to spend approximately 1.8 percent of the total rebuilding budget plan by August 1949 and 3.2 percent by May 1950 (Ohshima 1950). Such a serious budget shortage makes it difficult to attribute the early-stage rebuilding to the recovery plan. In addition, even the small budget spending did not seem to be a main factor in explaining the recovery. While the primary goal of the Hiroshima city government was to provide housing, the public sector provided less than 3,000 housing units by 1950.[24] This is a small fraction of the over 70,000 buildings that were at least partially destroyed by the atomic bombing. Consistently, we find that controlling for public housing has little effect on our regression results (see Section C of the online appendix). These suggest that the reconstruction policies had a limited direct impact on the recovery of central Hiroshima. Yet, we do not rule out the possibility of indirect effects of reconstruction policies to coordinate recovery expectations. We return to this discussion in Section 6.3.

In summary, our reduced-form analysis has revealed that the resurgence of central Hiroshima occurred within five years after the bombing. We have also demonstrated that it is difficult to explain the recovery through its fundamental location advantages. This raises the following question: why could central Hiroshima recover despite the destruction? We answer this question in the remainder of this paper by taking a structural approach and highlighting the role of agglomeration forces and expectations in recovery.

4 Theoretical Framework

In this section we present a novel dynamic quantitative spatial model to understand the mechanisms of the recovery, which we have seen in Section 3. The model has three key elements: heterogeneity in location fundamentals; the influence of history determining the initial conditions; and expectations about the future city structure. These elements are essential to account for all the potentially important determinants of the dynamics of city structure (Lin and Rauch 2022). First, individuals choose their residence and workplace that are potentially different, which define the equilibrium commuting patterns within a city as in Ahlfeldt et al. (2015). Second, finitely lived workers determine future residential places and workplaces in a forward-looking way, taking into account migration costs and future option values associated with each location. Third, the model incorporates amenities and productivity agglomeration forces that depend on population and employment density in the current period and in the past. With these externalities, there may exist the self-fulfilling

[24] Another primary expenditure was to rebuild damaged infrastructure, such as the water system and trains. While the rebuilding of the infrastructure is important, it did not appear to provide central Hiroshima with any particular advantages over the outskirts, as the outskirts already had comparable infrastructure. Moreover, our results do not change even if we focus on areas within 3km from the city center, which are expected to have more homogeneous infrastructure in the pre-war period.

prophecy and a multiplicity of transitions that hinge on both expectations and the past.[25] Our model is the first tractable dynamic quantitative model for the internal city structure that possesses these elements in a unified framework. In Section D of the online appendix we provide the details of derivations.

Time is discrete and indexed by t. We consider a single city $\mathcal{C}$ (Hiroshima City) embedded in a large economy $\mathcal{E}$ (Hiroshima Prefecture or Japan): $\mathcal{C} \subset \mathcal{E}$. The set of locations in a complementary set $\mathcal{O} = \mathcal{E} \backslash \mathcal{C}$ represents the outside of the city. The city $\mathcal{C}$ consists of a discrete number of locations indexed by i, j, n, ℓ. These locations correspond to blocks and they are differentiated by fundamental productivity, amenities, land endowment and geography. The fundamental productivity and amenities can change over time, while land endowment remains the same.

Individuals in the economy live for a finite time, T. The mass of the population in the economy ($\mathcal{E}$) is M and it is exogenous. We suppose that there is a potentially large number of people in the economy throughout time and M is constant. Instead, the total population of the city, which is embedded in the whole economy, 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 of the city ($\mathcal{O}$) are prohibited from commuting so individuals living outside of the city work there. Production occurs in every location in the economy and firms produce homogeneous tradable goods that can be freely traded across locations. In every period, an individual may have an opportunity to change their residential and workplace block in the economy ($\mathcal{E}$). In particular, individuals obtain their opportunity to change their locations with exogenous probabilities in every period and they decide their locations in a forward-looking way, correctly anticipating future economic conditions. Their location choice is based on their current real income and also an option value associated with that location. The forward-looking location choices allow us to characterize the transitions of population and employment distribution in the city that depends on their expectations.

4.1 Production

Firms in the economy are competitive and produce homogeneous tradable goods. Firms are myopic; therefore we do not formulate a dynamic problem for firms.[26] Production technology of a

[25] Allen and Donaldson (2022) introduces this type of local externalities to characterize historical-shock dependence in the spatial distribution of economic activities in the U.S. Kleinman et al. (2023) analyzes the properties of the spatial equilibrium when workers determine the future path of mobility in a forward-looking way, taking account of future shocks.

[26] Given 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.

representative firm in location $i \in \mathcal{C}$ is:

$$Y_{it} = A_{it} L_{it}, \tag{2}$$

where Y_{it} is production in location i, A_{it} is productivity and L_{it} is employment in location i at time t. Following Allen and Donaldson (2022), the productivity (A_{it}) depends on the current and past employment density in the location:

$$A_{it} = a_{it} \left(\frac{L_{it}}{S_i} \right)^{\alpha_1} \left(\frac{L_{it-1}}{S_i} \right)^{\alpha_2}, \tag{3}$$

where a_{it} represents the exogenous component in productivity and S_i is the area size of location i that is time-invariant. The parameter α_1 controls the contemporaneous productivity agglomeration forces with respect to employment density, and the parameter α_2 controls the effect of lagged employment density on productivity, such as durable investments. A positive value of α_1 implies a local agglomeration force that increases productivity, while α_2 captures the history dependence in productivity agglomeration forces.

In Section D.5 of the online appendix, we provide two different but related microfoundations of the agglomeration forces in productivity.[27] The first microfoundation introduces local capital in production, such as floor space, that augments labor productivity. The local capital is produced by using local public goods (e.g., roads and water facilities), final goods, and land. The current employment density is positively associated with the provision of local capital ($\alpha_1 > 0$). The supply of local public goods and land for local capital also depends on lagged employment density. In particular, when high employment density in the past induces the depreciation of local public goods and additional transaction costs in land supply, current local capital is negatively associated with lagged employment density ($\alpha_2 < 0$). The second microfoundation is the creation of ideas in production. Suppose incumbent workers with no opportunity to change their workplace between period $t-1$ to t engage in innovation to improve firms' productivity in period t. In period t, interactions with another worker with a novel idea allow incumbent workers to update their ideas, while ideas of the incumbent workers become obsolete without such interaction. Then, we show that a large number of current workers induce more successful knowledge spillovers ($\alpha_1 > 0$), and more incumbent workers make it difficult to find a worker to interact with for updating their ideas ($\alpha_2 < 0$). Note that, as exemplified by these microfoundations, (α_1, α_2) captures not only pure externalities but also other channels through which current or past employment density affects productivity, such as a floor space market.

Homogeneous goods are freely tradable in the economy and therefore we normalize their prices to one. The zero profit condition implies that the wage rate at location i in period t is $w_{it} = A_{it}$.[28]

[27] Allen and Donaldson (2022) provides different microfoundations for the formulation (3).

[28] Since firms obtain the zero profit at every location under this wage rate, no firm has an incentive to enter or exit in every location.

Therefore, the wage rate in any particular location is a function of exogenous productivity, contemporaneous employment density, and previous employment density in that location.

4.2 Preferences

Individuals live for finite periods, consume only homogeneous tradable goods, and inelastically supply one unit of labor. Their period utility of living in location n and working in location i at period t is

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

where B_{nt} is the common utility benefit from residential amenities at residential place n in period t, κ_{int} is the utility cost due to commuting from n to i, and w_{it} is labor earnings in workplace i.[29] The value of amenities in residential place (B_{nt}) depends on current and past population density:

$$B_{nt} = b_{nt} \left(\frac{R_{nt}}{S_n}\right)^{\beta_1} \left(\frac{R_{nt-1}}{S_n}\right)^{\beta_2}, \tag{5}$$

where b_{nt} is an exogenous component in the value of amenities for each location, R_{nt} is population of location n in period t and R_{nt-1} is that in period $t-1$.

In this specification two parameters (β_1, β_2) capture the strength of the net agglomeration effect in the residential place from the current and previous population density.[30] The former parameter (β_1) captures agglomeration forces in the residential place from the current population including housing prices and consumption amenities. The latter parameter (β_2) captures agglomeration forces from the past population including the effect of the stock of housing and amenities. In particular, we provide one microfoundation for both the current and lagged effects of agglomeration forces in amenities in Section D.6 of the online appendix, which introduces developers of floor spaces with adjustment costs in their investment. This microfoundation also highlights that similarly as the productivity parameters (α_1, α_2), (β_1, β_2) captures not only pure externalities but also other channels through which current or past population density affects amenities, such as residential floor space provision.

In any location outside of the city ($o \in \mathcal{O}$), individuals receive common utility u_{ot} in period t, which is exogenous in every period.

4.3 Forward-looking Location Choice

Workers are forward-looking in making migration decisions subject to the exogenous migration frictions. At the end of period t, the share $\theta_t \in (0, 1]$ of workers in the economy can change their location pairs and the share of $1 - \theta_t$ of workers will stay in the current location choices in the next

[29] In Section 5.1, we compute $\ln \kappa_{int}$ as the expected commuting cost in a travel mode choice model.
[30] Allen and Donaldson (2022) provides a different but related microfoundation for the formulation (5).

period $t+1$.[31] If $\theta_t = 1$, all workers are able to change their location pairs and a low value of θ_t leads to the stickiness of workers' mobility in the economy.[32] 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 the time-invariant independent Type-I extreme distribution $F(\varepsilon) = \exp(-\exp(-(\varepsilon+\Gamma)))$ where Γ is Euler-Mascheroni constant. At the end of period t, workers decide their residential place and workplace for the next period taking into account 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 in the next period, they solve the following problem of location choices:

$$v_{int}(\omega) = \ln u_{int} + \max\left\{\rho_{t+1}V_{j\ell t+1} + \sigma_{t+1}\varepsilon_{j\ell t+1}\ ;\ \rho_{t+1}V_{ot+1} + \sigma_{t+1}\varepsilon_{ot+1}\right\} \tag{6}$$

for $t = 1, 2, \cdots, T-1$. $V_{j\ell t+1}$ refers to the value function of choosing different pair of residential place ℓ and workplace j in period $t+1$ and V_{ot+1} is the option value of choosing to live in the outside of 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 $t+1$ expecting the path of the exogenous and endogenous variables. In particular, an individual correctly expects 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, bilateral mobility costs in a city are likely sufficiently small and homogeneous relative to inter-city migration costs. Therefore bilateral mobility costs are assumed away in our model.

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

$$V_{int} = \ln u_{int} + (1-\theta_{t+1})\rho_{t+1}V_{int+1} + \theta_{t+1}\sigma_{t+1}\ln \sum_{d\in\{\mathcal{C}\times\mathcal{C},\, o\}} \exp(V_{dt+1})^{\rho_{t+1}/\sigma_{t+1}} \tag{7}$$

The first term is the current utility from the location choice of residential place n and workplace i. The second term is the expected value of staying in the same location choices in the next period with non-migration opportunity $1-\theta_{t+1}$. The third term is the expected utility for future value when a worker is able to change the location pairs with probability θ_{t+1}. For workers who live outside of the city, we can express their option value for $t = 1, 2, ..., T-1$ by

$$V_{ot} = \ln u_{ot} + (1-\theta_{t+1})\rho_{t+1}V_{ot+1} + \theta_{t+1}\sigma_{t+1}\ln \sum_{d\in\{\mathcal{C}\times\mathcal{C},\, o\}} \exp(V_{dt+1})^{\rho_{t+1}/\sigma_{t+1}}. \tag{8}$$

[31] We allow people to choose the same pair of residence and workplace when they can choose other options.

[32] This Calvo-style migration friction is also adopted in other recent quantitative spatial models to capture the persistence of migration decisions (e.g., Caliendo et al. 2019 Section 5.3; Heblich et al. 2021).

When workers have an opportunity of migration, they can choose any location pairs in the economy and therefore the last term of the expected utility for future value is the same as in (7). Note that 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 dropped.

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

$$\lambda_{int+1} = \frac{\exp(V_{int+1})^{\rho_{t+1}/\sigma_{t+1}}}{\sum_{d \in \{\mathcal{C}\times\mathcal{C},\, o\}} \exp(V_{dt+1})^{\rho_{t+1}/\sigma_{t+1}}}, \quad i, n \in \mathcal{C}. \tag{9}$$

The probability λ_{int+1} characterizes the location dynamics of workers in the city for period $t+1$. Workers choose the pair of residential place and workplace with taking into account future changes in commuting costs, wages, and residential amenities. Since there is no location-workplace specific migration cost, equation (9) applies to all workers with the migration opportunity in period t. Further, the share of workers that live outside of the city in the period $t+1$ conditional on they can change their locations is given by probability $\lambda_{ot+1} = 1 - \sum_{(j,\ell)\in\mathcal{C}\times\mathcal{C}} \lambda_{j\ell t+1}$.

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

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

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 continue the same workplace and residence, and the second term is the total of workers who move from outside of the city and those who change their locations within the city. The commuting market clears in the city. Therefore, the mass of workers in workplace i becomes:

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

where a mass of workers in workplace i is the sum of workers who have no opportunity of changing locations and those who sort into the workplace in period t. Analogously, the mass of workers in residence n becomes:

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

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

Note that conditional on 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). Both a low degree of stickiness and more dispersion in idiosyncratic taste shocks in location choices increase workers' mobility in a city. However, we emphasize the difference in interpretations. The parameter of Calvo-style migration friction captures the immobility of workers even if they would like to change their locations. Intuitively, this reflects any physical 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 take account of both mobility constraints and the sorting of workers in their residence and workplace choices.

4.4 General Equilibrium

Having the assumptions in our model above, we now define a forward-looking competitive equilibrium in the economy. The economy starts with the initial distribution of the population (R_{i0}) and employment (L_{i0}). The exogenous variables of the model are fundamental productivity (a_{it}) and amenities (b_{nt}) of blocks, the area size of blocks (S_n), bilateral commuting costs in a city (κ_{int}), the path of stickiness in reallocation of workers (θ_t) and path of the utility outside of a city (u_{ot}). The economy-wide parameters in the model are agglomeration forces in productivity (α_1, α_2), agglomeration forces in amenities (β_1, β_2), 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 sequence of wages $\{w_{it}\}$, population $\{R_{nt}\}$, employment $\{L_{it}\}$, and value functions associated with location choices $\{V_{int}\}$ such that (i) 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) 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 transition equilibrium by population, employment, and value function adjusted by the value of outside of the city. Equations (3), (7), (8), (11), and (12) constitute $N^2 + 3N$ equations for each t, and that 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 option values associated with the pair of locations, and they determine the future path of location choices taking into account future shocks. In the present model, there are agglomeration forces in real income through productivity and amenities, as well as mobility frictions. With small mobility frictions and strong agglomeration forces, there may exist the self-fulfilling prophecy and multiplicity of transitions that hinges on the expectations of people. In particular, large values of the agglomeration forces in productivity (α_1) and amenities (β_1) and large mobility (θ_t) may lead to multiple equilibria.

We call an economy in a steady-state equilibrium if population and employment distributions are constant given the exogenous time-varying factors being constant. The steady state equilibrium in this economy exists, and it is unique when the net agglomeration forces are small in both productivity and amenities. We summarize these results in the following proposition:

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

Section D.3 of the online appendix 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 net agglomeration forces are negative: $\alpha_1 + \alpha_2 \leq 0$ and $\beta_1 + \beta_2 \leq 0$, which implies that the net dispersion forces dominate the agglomeration forces both in productivity and amenities. In this case, the economy will converge to the unique steady state in the long run, although there could be multiple paths toward the steady state. Second, there can be multiple steady states, which can happen when net agglomeration forces are positive according to Proposition 1 (iii). In this case, after a shock in the economy that affects the initial condition, either the initial condition or expectations about the future distribution of population and employment matters 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 the unique path to the steady state because it relies only on the observed equilibrium path and the steady state. This feature allows us to calibrate the model when there are multiple steady states so that different expectations may lead to different steady states. That said, the multiplicity of equilibrium, by its nature, may pose a challenge in some counterfactual analyses as we need to select one equilibrium out of multiple possible counterfactual equilibria (Redding and Rossi-Hansberg 2017).

5 Quantitative Analysis

Our goal in this section is to show how the present model can be matched to the observations in Hiroshima. The quantification proceeds in three steps and we discuss it step by step. Section E of the online appendix presents further details on 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 them using different information. The dispersion of idiosyncratic taste shocks (σ_t) is calibrated based on the commuting elasticity (ρ_t/σ_t) that we estimate a gravity equation of commuting and the calibrated discount factor (ρ_t). We infer the stickiness (θ_t) from additional data on the share of people who stayed in their residential places. We use the data to infer how persistent migration decisions were. 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 composite 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 option values associated with each location. The option values reflect the attractiveness of each location as a residential place or workplace, which is a function of location fundamentals and agglomeration. In Subsection 5.3, we estimate the key parameters that govern the strength of agglomeration forces in productivity (α_1, α_2) and amenities (β_1, β_2). We recover the unobserved fundamentals in productivity and amenities based on the recovered option values and variation of population density and employment density over time. For those fundamentals, we define the moment conditions and estimate the parameters. In the estimation, we use the data from 1950 to 1975.

Having fully quantified our model, in Subsection 5.4, we assess how endogenous mechanisms in the model can rationalize the recovery of population and employment in the city after the bombing during 1945-50. To this end, we first use the data on population and employment in 1945 and 1950 to back out the location advantages. We then decompose the 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 recovery only with the first model-based component. This is suggestive of model's performance in explaining the dynamics of city structure.

5.1 Step #1: Parameter Calibration (ρ_t, σ_t, κ_{int}, θ_t, u_{ot})

Travel Mode Choice and Commuting Costs (κ_{int}) To estimate commuting costs, we extend the model by incorporating the choice of travel modes following Tsivanidis (2022). In particular, we suppose that workers minimize their commuting costs by deciding their travel mode for commuting after their workplace and residence are determined. We solve the problem backward: first, we estimate the mode choice model of an individual given their workplace and residence. Second, we use the mode choice model to calculate the expected bilateral travel cost, which we use as the bilateral commuting cost in equation (4). We briefly describe the procedure here and more details are found in Section E.1 of the online appendix.

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. We assume that the idiosyncratic travel cost follows a Gumbel distribution with two nests: (i) public modes consist of walking, bus and train; and (ii) private modes consist of 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, given their workplace and residence.[33] We then estimate the overall expected travel cost for residence n and workplace i before the realization of the idiosyncratic travel costs, using the 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).

Gravity of Commuting (ρ_t/σ_t) A feature of our model is that the commuting pattern in the steady state is consistent with the gravity equation. We posit that the economy is approximated by a steady state in the last period and estimate the commuting elasticity of workers using the 1987 Hiroshima City Person Trip Survey. Plugging the average commuting time in 1987 that we computed above into the equilibrium commuting pattern in the steady state yields the gravity equation:

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

where $\bar{c}_{in}$ is the log bilateral commuting cost, $\mathbb{W}_i$ 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, which is decreasing in σ (the dispersion parameter of the idiosyncratic shock) and increasing in ρ (the discount factor) as lower σ and higher ρ imply the higher sensitivity of migration decisions to utility differentials. We replace workplace and residence indicators with fixed effects and estimate (13) using the Pseudo Poisson Maximum Likelihood (PPML). The main estimation shows that $\rho/\sigma = 8.019$, which is comparable to the estimates of Dingel and Tintelnot (2020) and Ahlfeldt et al. (2015). In the following, we set ρ_t/σ_t to be 8 for all t. See Section E.1 of the online appendix for detailed derivations and estimation results.

Discount Factor (ρ_t) We assume that the annual discount rate of around 8.5 percent, which is consistent with the discount rate widely used in the context of developing countries (e.g., Garcia-

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

Cicco, Pancrazi and Uribe 2010). Note that Japan's GDP per capita in 1950 was less than one-fifth of that of the U.S. 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 for the period t with probability θ_t. In our calibration, we consider 174 blocks in a city and idiosyncratic taste shocks. Therefore, we suppose that people would change their residence conditional on obtaining the migration opportunity and match the parameter of migration friction to the probability that people change their residence during five years, the length of one period in calibration. The 1960 Population Census shows that around 86 percent of people stayed in the same residence one year before. Then, we set the parameter $\theta_t = 1 - (0.86)^5 \simeq 0.53$ for all $t \geq 1955$.[34]

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 outside of 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 choice of the outside utility only affects the total population 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 the location. In this step we back out the option values by leveraging the population and employment dynamics of the model. Specifically, for $t = 1, 2, \cdots, T-1$, the option value of location n as a residential place can be summarized by the continuation value of amenities in the location:

$$\Xi_{nt} = b_{nt} \left(\frac{R_{nt}}{S_n}\right)^{\beta_1} \left(\frac{R_{nt-1}}{S_n}\right)^{\beta_2} \prod_{\tau=t+1}^{T} \left(b_{n\tau} \left(\frac{R_{n\tau}}{S_n}\right)^{\beta_1} \left(\frac{R_{n\tau-1}}{S_n}\right)^{\beta_2}\right)^{\prod_{s=t+1}^{\tau} \rho_s(1-\theta_s)} . \quad (14)$$

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

$$\Omega_{it} = a_{it} \left(\frac{L_{it}}{S_i}\right)^{\alpha_1} \left(\frac{L_{it-1}}{S_i}\right)^{\alpha_2} \prod_{\tau=t+1}^{T} \left(a_{i\tau} \left(\frac{L_{i\tau}}{S_i}\right)^{\alpha_1} \left(\frac{L_{i\tau-1}}{S_i}\right)^{\alpha_2}\right)^{\prod_{s=t+1}^{\tau} \rho_s(1-\theta_s)} . \quad (15)$$

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 past and future population and employment

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

density.[35] When $\theta_t = 1$ for all periods, these option values are reduced to values of amenities (B_{nt}) and productivity (A_{it}). Intuitively, all workers can change locations every period, and therefore, the future values of their choice are not attached to the current location choices. In contrast, a small value of the migration opportunity (θ_t) leads to more weight for the future evolution of amenities and productivity in the location since workers are less likely to change their locations. In sum, these option values reflect the value of amenities and productivity by locations when workers choose locations in a forward-looking way.

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

$$\begin{aligned} R_{nt} - (1-\theta_t)R_{nt-1} &= \sum_{i \in \mathcal{C}} \frac{K_{int}\Xi_{nt}^{\rho_t/\sigma_t}}{\sum_{j \in \mathcal{C}} K_{ijt}\Xi_{jt}^{\rho_t/\sigma_t}} \big(L_{it} - (1-\theta_t)L_{it-1}\big), \\ L_{it} - (1-\theta_t)L_{it-1} &= \sum_{n \in \mathcal{C}} \frac{K_{int}\Omega_{it}^{\rho_t/\sigma_t}}{\sum_{j \in \mathcal{C}} K_{jnt}\Omega_{jt}^{\rho_t/\sigma_t}} \big(R_{nt} - (1-\theta_t)R_{nt-1}\big), \end{aligned} \tag{16}$$

where K_{int} is the continuation value of commuting costs. Intuitively, equations (16) state 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 the period t ($L_{it} - (1-\theta_t)L_{it-1}$) and their conditional choice probability of location n as their residence ($K_{int}\Xi_{nt}^{\rho_t/\sigma_t}/(\sum_{j\in\mathcal{C}} K_{ijt}\Xi_{jt}^{\rho_t/\sigma_t})$). We solve the system of equations (16) for option values (Ξ_{nt}, Ω_{it}) conditional on observed population (R_{nt}), employment (L_{it}), commuting costs (K_{int}), and migration frictions (θ_t), and obtain the unique option values.[36] Therefore, we can recover (Ξ_{nt}, Ω_{it}) that rationalize the observed changes in the mass of workers without using any information on the unobserved characteristics. In addition, this step does not require the parameter values of agglomeration forces (α_1, α_2, β_1, β_2) despite that strong agglomeration forces may induce unobserved alternative equilibria. Therefore, the possibility of multiple equilibria does not invalidate this step.

5.3 Step #3: Estimation of Agglomeration Parameters (α_1, α_2, β_1, β_2)

In the second step, we obtain option values such that observed changes in population and employment in the city are consistent with equilibrium. We can back out fundamental productivity (a_{it}) and amenities (b_{nt}) by using observed employment and population density, according to the definition of option values (Ξ_{nt}, Ω_{it}). In particular, for each period $t = 1955, 1960, \cdots, 1975$, we

[35] Equations (14) and (15) imply that our definition of the option values (Ξ_{nt}, Ω_{it}) of each location does not incorporate the convenience of commuting access to other locations. The importance of the commuting access in migration decisions enters in equations (16), which we use to back out (Ξ_{nt}, Ω_{it}).

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

derive unique values of fundamentals by location, and these fundamentals are structural residuals in our calibration for the observation to be equilibrium. We assume that the fundamentals consist of location-fixed components, time-trend components, and time-varying errors:

$$\begin{aligned} \ln a_{it} &= \ln a_i^F + \ln a_t^* + \ln a_{it}^{\text{Var}}, \\ \ln b_{nt} &= \ln b_n^F + \ln b_t^* + \ln b_{nt}^{\text{Var}}, \end{aligned} \tag{17}$$

where $\left(\{a_i^F\}, \{b_n^F\}\right)$ are location fixed productivity and amenities, $\left(\{a_t^*\}, \{b_t^*\}\right)$ are trend of productivity and amenities, and $\left(\{a_{it}^{\text{Var}}\}, \{b_{nt}^{\text{Var}}\}\right)$ are stochastic parts of fundamental productivity and amenities. The location-fixed productivity and amenities capture the fundamental advantages of locations and the trend of productivity and amenities reflects the change in their levels over time in the city. $\left(\{a_{it}^{\text{Var}}\}, \{b_{nt}^{\text{Var}}\}\right)$ are the structural residuals in our model in the sense that they allow us to perfectly match the observed population and employment distribution in the city. As such, they incorporate any factors affecting the attractiveness of each location but not in the model (see also Section 6.3 for more discussion).

Averaging out the trend terms and taking differences between two periods, we suppose the following moment conditions:

$$\begin{aligned} \mathbb{E}[\Delta \ln \widetilde{a}_{it} \times \mathbb{1}_i(k)] &= 0, \\ \mathbb{E}[\Delta \ln \widetilde{b}_{nt} \times \mathbb{1}_n(k)] &= 0, \end{aligned} \tag{18}$$

where $\Delta \ln \widetilde{a}_{it} = \Delta \ln \widetilde{a}_{it}^{\text{Var}}$ and $\Delta \ln \widetilde{b}_{nt} = \Delta \ln \widetilde{b}_{nt}^{\text{Var}}$ are changes in the idiosyncratic shocks in productivity and amenities adjusted with their geometric means. $\mathbb{1}_n(k)$ is an indicator such that location n is in the grid k. The grid is defined based on the distance from the CBD. Our identification assumption for using the moment condition is that any improvements or declines in the stochastic terms of fundamental productivity and amenities during any five-year period are not systematically correlated to the distance from the city center. While this moment condition accommodates arbitrary location-fixed amenities and productivity, it requires that the systematic change in the gradient of economic activity relative to the distance from the CBD is explained by the mechanisms of the model rather than by systematic changes in the pattern of structural residuals. This identification assumption seems plausible in post-recovery Hiroshima because the spatial extent of our study is small and all blocks in data would face similar changes in the economic and political environment.[37] Indeed, all blocks in our sample are located just within 6 kilometers from the CBD. To check its robustness, we also estimate the set of parameters using blocks in 3 kilometers to CBD, which are expected to face even more homogeneous conditions and so more likely to satisfy the moment conditions. We use the moment conditions (18) to estimate the set of parameters of agglomeration forces.[38]

[37]We also emphasize that the effect of radioactivity faded away quickly from 1945 (see Section 2.1), and it would be

Table 2: Generalized Method of Moments Estimates for Agglomeration Parameters

	(1)	(2)	(3)	(4)
	All blocks		Blocks in 3 km to CBD	
	Productivity	Amenities	Productivity	Amenities
Elasticity of employment density (α_1)	0.228		0.232	
	(0.0007)		(0.0002)	
Elasticity of past employment density (α_2)	-0.064		-0.064	
	(0.0005)		(0.0003)	
Elasticity of population density (β_1)		0.175		0.198
		(0.0011)		(0.0037)
Elasticity of past population density (β_2)		0.015		0.001
		(0.0010)		(0.0040)

Note: This table reports estimates of the generalized method of moments (GMM) using data for five periods (1955, 60, 65, 70 and 75) and 174 blocks (all blocks) or 158 blocks (blocks in 3 kilometers to CBD). In constructing the moment conditions (18), we divide the blocks into five grids according to the distance from the CBD. We use the two-step GMM estimation and the standard errors are in parentheses. In Column 1 and 2, we use all blocks and in Columns 3 and 4, we use blocks in 3 kilometers to CBD.

Table 2 reports the efficient GMM estimation results. Columns 1 and 2 report our baseline estimates of agglomeration parameters in productivity (α_1, α_2) and amenities (β_1, β_2) respectively. Overall productivity (A_{it}) in the workplace rises by 0.23 percent when current employment density increases by one percent, but falls by 0.06 percent when employment density increases by one percent in the previous period. The negative agglomeration forces from the past employment density may capture the congestion effects, such as depreciation in public goods, reduced land supply, and fewer successful matching to achieve innovation (see our microfoundations in Section D.5), implying the possibility of creative destruction (Hornbeck and Keniston 2017). Its magnitude is smaller than the positive agglomeration forces from the contemporaneous employment density. Turning to amenities, a one percent increase in current population density is associated with a 0.18 percent increase in the value of amenities, while a one percent increase in past population density is associated with a 0.02 percent increase in the value of amenities. The remaining columns 3 and 4 in Table 2 show estimates when we restrict locations within 3 kilometers in our estimation, and we find similar results. These estimates imply that strong contemporaneous externalities in both amenities and productivity may create a self-fulfilling prophecy, which leads to multiple equilibria. In addition, we also find some effects of past economic activities in both productivity and amenities, implying that a historical event may matter in determining the transition path of the economy.[39]

irrelevant for changes in amenities and productivity as our estimation data run from 1950.

[38] Figure E.2 graphically illustrates that under our GMM estimates, the moment conditions appear plausible regardless of the distance from the city center.

[39] Our estimates of agglomeration forces in productivity are broadly similar to those in Allen and Donaldson (2022) that uses long-run county-level data of the U.S. However, they find negative contemporaneous agglomeration forces in amenities. This difference may arise from the difference in spatial extent. As we discussed in the microfoundation

5.4 Accounting for the 1945–1950 Recovery

We are now in the position to assess how well our calibrated model explains population and employment changes during the recovery period (1945–1950), which are not used for calibration. To this end, we evaluate how the endogenous part of location advantages and time-invariant unobserved characteristics can account for population and employment changes during the recovery of the city from 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 calculate the predicted population and employment distribution using our calibrated model. We use equations (14) and (15) to construct the predicted option values of each location as residence $\{\Xi^f_{n,1950}\}$ and workplace $\{\Omega^f_{i,1950}\}$ and substitute them into equation (16) to solve for the predicted population and employment of each block in 1950. By construction, the option values in our model are a composite of (i) location-fixed advantages, (ii) endogenous terms of agglomeration forces, (iii) future option values associated with the location, and (iv) idiosyncratic shocks. Among them, factors (i) through (iii) capture the location advantages that our model and calibration can explain. In contrast, the idiosyncratic terms (iv), corresponding to $\left(\{a^{\text{Var}}_{it}\}, \{b^{\text{Var}}_{nt}\}\right)$ in equation (17), are structural residuals in the location advantages and absorb any other characteristics unrelated to the model specification. Note that while our model can perfectly match the observed population and employment distributions with structural errors (iv), it may no longer perfectly match it without the structural errors. Therefore, to evaluate how well our model can explain the recovery, we exclude the structural errors when constructing the model-predicted option values for residence $\{\Xi^f_{n,1950}\}$ and workplace $\{\Omega^f_{i,1950}\}$, respectively.[40]

In obtaining the predicted location decisions for the recovery period (1945-1950), we use the same parameter values as our main calibration with data from 1950-1975, with the exception of the migration probability for 1945-1950.[41] We set a higher migration opportunity $\theta_{1950} = 0.9$ because available evidence suggests the mobility rate was substantially higher, possibly for war-related reasons such as the loss of jobs or homes and the end of temporal reallocation during the war (see Appendix A for more details).

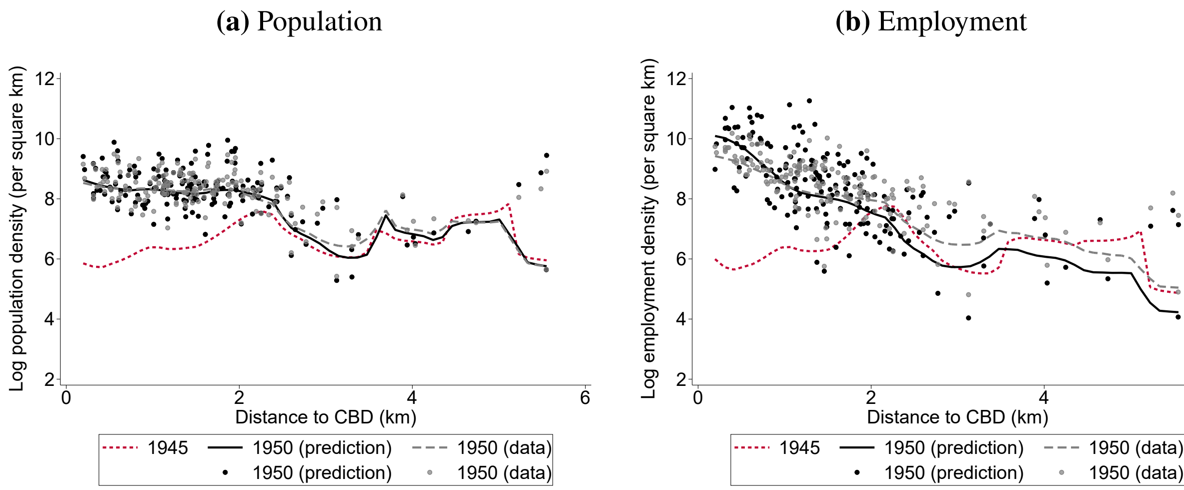
Figures 5a and 5b demonstrate the population and employment distribution predicted by our model for 1950. In Figure 5a, the predicted population density is plotted against the distance to the

(see Section D.6 of the online appendix), the negative agglomeration forces in amenities capture congestion in a local housing market. Our estimate implies that in our estimation sample, such congestion effects are dominated by positive agglomeration forces, including consumption externalities or neighborhood network effects. In a spatially-granular setting such as ours, those positive agglomeration forces are likely strong (see, for example Tsivanidis 2022).

[40]Note that this analysis is valid even under potential multiplicity of equilibria because while assuming the observed population and employment is coming from a forward-looking equilibrium, we examine how much of the migration incentives from 1945 to 1950 can be explained with the endogenous forces of the model, rather than structural errors.

[41]In particular, for the block fixed amenities and productivity, we substitute the average amenities and productivity during 1955-1975, our estimate of the block-fixed amenities and productivity, into (a_{i1950}, b_{n1950}).

Figure 5: Population and Employment Distribution Predicted by Our Model



Note: Each figure plots the results of local polynomial regressions of the log population density (Panel a) or employment density (Panel b) on the distance from the city center. We conduct three regressions separately for the 1945 population density in data (small dashed line), the 1950 population density in data (long dashed line), and the 1950 population or employment density under the counterfactual scenario in which we exclude structural errors of amenities and productivity (solid line).

CBD. The city center's recovery is predicted to have the highest population density, indicating the recovery. Figure 5b shows that this recovery result holds true for the employment distribution as well. Overall, our calibrated model successfully predicts the recovery of the city center, which we indeed observe in the data.

6 The Roles of Agglomeration Forces and Expectations in the Recovery

Having demonstrated that our calibrated model can account for the resurgence of central Hiroshima, we now evaluate the importance of expectations in the quick recovery. In particular, we focus on two elements: agglomeration forces and expectations for recovery. In Subsection 6.1 we undertake the counterfactual experiment in which we shut down agglomeration forces in both productivity and amenities. Comparing the counterfactual results and observations, we show that agglomeration forces are crucial to explain the quick recovery. Next, in Subsection 6.2, we solve the model for an alternative self-fulfilling equilibrium in which people expect a peripheral area will thrive in the future. We find that if the city center is not expected to recover, individuals do not choose to live and work in the city center because the expected low density of the center makes it an unattractive residence and workplace due to agglomeration forces. This suggests that the self-fulfilling nature of expectations is important in inducing the recovery of central Hiroshima. Note that throughout the analysis, we remain agnostic about why the expectations in the recovery emerged. Rather, we consider the emergence of expectations about the recovery as given and show how important they are in explaining the actual recovery. In Subsection 6.3 we briefly explore the potential factors contributing to the formation of expectations.

6.1 The Role of Agglomeration Forces

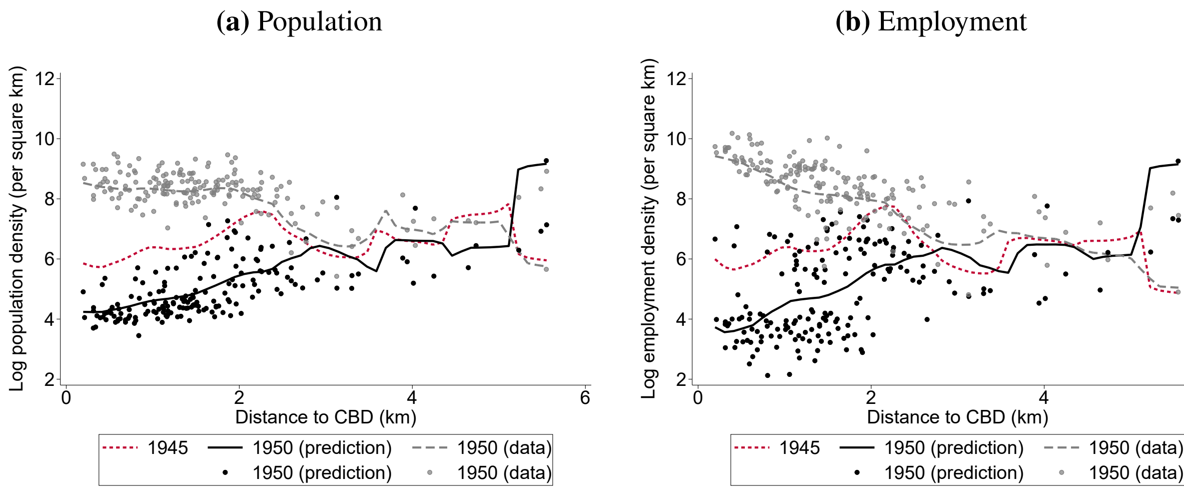
The recovery of the city center is achieved because individuals regard the city center as an attractive residence and workplace. We now show that strong agglomeration forces are the primary source of attractiveness and that regaining population and employment density enhances attractiveness through positive agglomeration forces. To formally investigate the importance of agglomeration forces, we compute the counterfactual population and employment distribution for 1950 based on the model. We follow the same procedure as in Subsection 5.4, but we turn off agglomeration forces by setting $\alpha_1 = \alpha_2 = \beta_1 = \beta_2 = 0$. [42] Individuals still make forward-looking migration decisions taking into account future fundamental productivity (a_{it}), amenities (b_{it}), and transportation access (κ_{int}). If the recovery of the city center is due to fundamental location advantages, solving the model without agglomeration forces would still result in the city center's recovery. Alternatively, if agglomeration forces are the key to making the centripetal force, then this counterfactual exercise would not be able to predict the recovery.[43]

Figures 6a and 6b show the counterfactual population and employment density in the absence of agglomeration force, respectively. The model no longer predicts the recovery of central Hiroshima in terms of both population and employment. This is in stark contrast to the result of our main calibrated model in Figures 5a and 5b. This contrast indicates that the presence of agglomeration forces are essential for the recovery of central Hiroshima, given that the only deviation from our main calibrated model is the shutdown of agglomeration forces. The result that the recovery cannot be explained by a model without agglomeration forces suggests that the recovery is not primarily driven by the fundamental locational characteristics of the city center. In Figure E.1 we demonstrate that, in our calibrated model, location-fixed amenities and productivity are generally homogenous in the distance to the city center. This implies that the fundamental advantages of the city center are unlikely to explain the recovery of central Hiroshima, consistent with our findings in Figure 5 and our reduced-form results. Instead, strong agglomeration forces enhance the attractiveness of the city center.

[42]The parameters (α_1, α_2, β_1, β_2) capture not only pure externalities of density but also other channels through which population or employment density affects productivity and amenities (see microfoundations for Section 4). In this counterfactual, we turn off all of these density effects simultaneously.

[43]To focus on the population and employment distribution within the city, we assume that the total population matches the observed data in both our main calibration and the absence of agglomeration forces.

Figure 6: Counterfactual Equilibrium: Population and Employment Distribution When No Agglomeration Forces



Note: Each figure plots the results of local polynomial regressions of the log population density (Panel a) or employment density (Panel b) on the distance from the city center. We conduct three regressions separately for the 1945 population density in data (small dashed line), the 1950 population density in data (long dashed line), and the 1950 population or employment density under the counterfactual scenario in which we shut down agglomeration forces in both productivity and amenities (solid line).

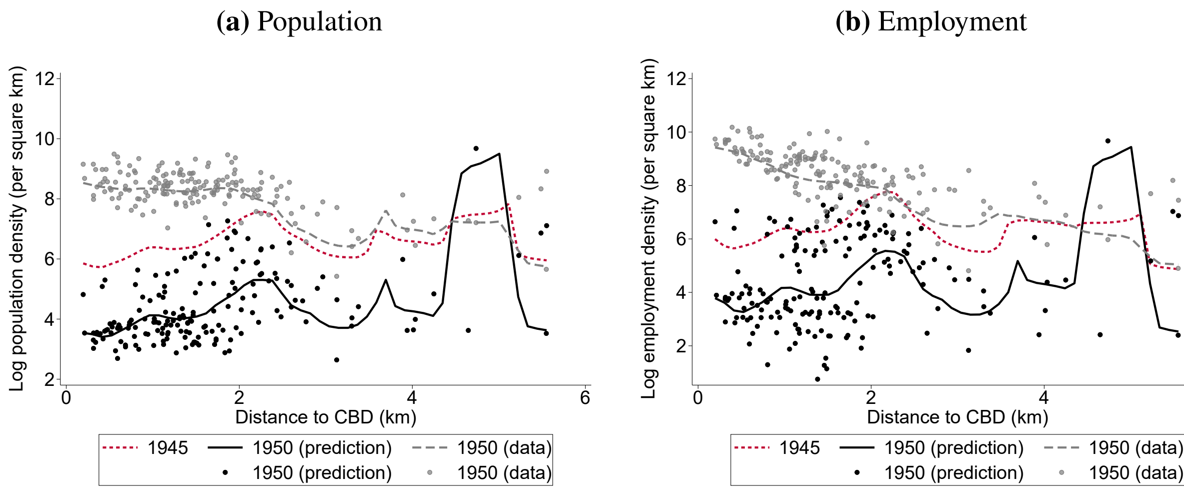
6.2 The Role of Expectations in the Recovery

Subsection 6.1 shows that agglomeration forces are important in driving the recovery of central Hiroshima. Yet, a key assumption is that individuals anticipated the recovery of the city center when choosing their residence and workplace for 1950. Intuitively, people may not choose to live and work in the city center if they do not expect the high density of the city center in the near future, as agglomeration forces make the city center unattractive.

To understand the role of expectations, we examine an alternative equilibrium of our model in which individuals do not expect the recovery of central Hiroshima. If the recovery of central Hiroshima is driven by fundamental locational advantages, we cannot find such an alternative equilibrium because individuals always have a strong incentive to live and work in the city center regardless of the expected path of population and employment. If, on the other hand, the recovery is driven by expectations that the city center would achieve high density, then we may find an alternative equilibrium in which the center does not recover and workers correctly expect no recovery. In order to focus on the population and employment within the city, we assume that the total population matches the observed data. We also use the values of parameters and fundamentals estimated in Section 5.[44]

[44]Contrary to Subsection 6.2, parameters (α_1, α_2, β_1, β_2) are the same as our main calibration.

Figure 7: An Alternative Equilibrium: Population and Employment Distribution When Individuals Expect No Recovery



Note: Each figure plots the results of local polynomial regressions of the log population density (Panel a) or employment density (Panel b) on the distance from the city center. We conduct three regressions separately for the 1945 population density in data (small dashed line), the 1950 population density in data (long dashed line), and the 1950 population or employment density in an alternative equilibrium when the city center does not recover and people correctly anticipate it (solid line).

Figure 7 provides a visualization of population and employment density in an alternative equilibrium, which we find numerically.[45] Figure 7a plots the population density obtained in the alternative equilibrium for 1950 against the distance to the city center. In contrast to the actual data, the monocentric city structure does not re-emerge. Figure 7b shows a similar pattern for employment. These results show that the different expectations of individuals lead to a completely different urban structure in dynamic equilibrium. In this counterfactual equilibrium, individuals believe that central Hiroshima would not recover and population and employment density would remain low, while they anticipate that locations less damaged by the atomic bombing would be prosperous. Given the positive contemporaneous agglomeration forces (i.e., $\alpha_1 > 0$ and $\beta_1 > 0$), the expectations keep the city center unattractive in 1950 and provide an incentive to live and work in the peripheral areas.

Our findings in the alternative equilibrium with no recovery suggest the importance of self-fulfilling nature of expectations in the spatial economy (Krugman 1991; Matsuyama 1991). Comparing Figure 5 and Figure 7 shows that the model predicts the recovery of the city center when

[45]Our numerical procedure is as follows: (i) As a guess, we simulate the population and employment distribution in 1975, assuming that people have a myopic expectation that the population and employment distribution in period $t+1$ will be the same as those in period t; (ii) Starting from the guessed 1975 distribution, we solve the path of population and employment consistent with equilibrium conditions back to 1945; (iii) We compare the obtained population and employment distributions for the 1945 solution and the 1945 data, and update our guess for the 1975 distribution. We repeat this procedure until the population and employment distributions obtained for 1945 are sufficiently close to the data.

individuals expect it and vice versa. In this sense, under the degree of agglomeration forces that we estimate, optimistic expectations about the future of central Hiroshima played a crucial role in inducing the recovery despite the initial low density due to the atomic bombing.

6.3 Discussion: Origins of Expectations in the Recovery

Our analysis has demonstrated that expectations for the recovery are essential for explaining the recovery of central Hiroshima. However, we have remained agnostic as to why individuals could believe in the recovery despite its catastrophic shock. In this subsection we discuss several factors that may have influenced the coordination of individuals' expectations.

First, the presence of the recovery plan by the government would have facilitated the formation of expectations, despite the fact that the plan was published in the midst of the recovery and was substantially underfunded (see Subsection 3.4).[46] Another possible factor is the tangible presence of infrastructure, particularly the train and tram systems. While the direct benefit of access to train stations does not appear to be crucial for the recovery (see Table 1 that controls for transportation access), the continuity of the pre-war train network may have anchored people's expectations for the reconstruction. Land ownership is a further consideration. People could reasonably anticipate the recovery if they believed that landowners had a strong attachment to the location and that some of them would return despite the miserable conditions. However, the direct effect of this channel may be limited in our context because of the low ownership rate. In particular, landownership rate in urban areas of pre-WW2 Japan was likely to be less than 10 percent (Kato 1988).[47] Moreover, unlike the case of conventional air-raid bombing, the atomic bombing had nearly 100% death rate near the epicenter, implying that the number of surviving landowners would be relatively limited.[48] Lastly, the narrative of "rebuilding from the atomic bombing" may have sounded like a compelling success story from the tragedy and been shared widely (Shiller 2017).[49] As long as individuals

[46]Zoning laws are a related factor, but their importance was limited in explaining the recovery because the first post-war zoning of Hiroshima was not published until 1949. The recovery was nearly complete by that point. In addition, there were only four types of zones (commercial, residential, industrial, and unspecified) and the zoning was not strict in that substantial mixed land-use was permitted (Asano 2012).

[47]The fraction of households owning a home was also quite low in urban areas of pre-WW2 Japan at around 25 percent (Hinokidani and Sumita 1988).

[48]Consistent with the limited importance of attachment due to property ownership, Hiroshima City Government (1983b) conducted a survey on tenure of current residence in 1965 and concluded that "many individuals settled in the current location after being forced to move by the bombing". Moreover, the turnover of business owners was also active. According to Hiroshima City Government (1983a), in 1958, approximately 28 percent of stores on a shopping street (*Hondori*) remained in the same location as during the pre-war period, while the remaining 72 percent started operating after the bombing. Although the majority of them were newcomers, land ownership may have influenced their expectations for the recovery of business activities.

[49]Although it is challenging to assess in data how powerful and widespread such a narrative was, the 1946 Statistical Abstract of Hiroshima was suggestive in stating '...rumors like "nothing will grow here for 75 years" immediately disappeared among people with their burning desire to rebuild...' (p4, translated by the authors). Consistent with the initial pessimism and the later optimism, Figure A.4 shows that the population growth of the center was slow for the

were aware that many others shared this narrative, they may expect that the city structure would look like the pre-war Hiroshima city in their memory, thereby inducing the recovery of the pre-war city center.[50]

These underlying factors may influence the attractiveness of each location through the direct channel and the expectations channel. In the expectations channel, these factors may alter people's expectations regarding the future population and employment distribution after the bombing, thereby affecting the attractiveness of each location via agglomeration forces. Our results in Subsection 6.2 have highlighted the importance of this expectation channel. For the direct channel, these factors may directly stimulate the recovery of central Hiroshima by increasing its attractiveness, which corresponds to an increase in location-specific amenities (b_{nt}) and productivity (a_{it}) in the model. However, our results in Subsection 5.4 imply the limited importance of this channel. First, Figure 5a highlights that agglomeration forces, not location-specific amenities and productivity, induced the recovery. Second, our estimates of location-fixed amenities and productivity, which may be higher in the city center if the bombing has made the city center attractive for some reason, are homogeneous with respect to the distance from the city center (see Figure E.1). Finally, Figure 5 shows that our model can explain the recovery without structural residuals of amenities and productivity, which may include the direct channel of the above-mentioned factors. In sum, although their direct impact on the attractiveness of each location would be limited in our context, the aforementioned factors may have a significant impact on the spatial distribution of economic activities by contributing to the formation of recovery expectations.

7 Conclusion

What are the underlying economic mechanisms in the resilience of city structure? This paper answers this question through the lens of the atomic bombing of Hiroshima, one of the most remarkable examples of urban resilience in human history. The atomic bombing was an unprecedentedly large exogenous shock to the city structure that completely destroyed the city center while sparing its outskirts. We newly digitize granular historical data of Hiroshima to investigate which factor is the key contributor to the recovery of central Hiroshima. We first provide reduced-form evidence for the fast

first eight months after the bombing, but accelerated afterwards. This pattern is also suggestive of the importance of expectations rather than fundamental advantages of the city center, as people would have an immediate incentive to return to the city center if it is inherently an attractive location.

[50]This relates to the idea of "memory-based expectations," in which people form expectations based on their past experiences (Malmendier and Wachter 2022). To gauge its potential importance, we calculate the predicted population and employment density when everyone has "purely memory-based expectations." Specifically, we can proceed with the model simulation as in Subsection 5.4, 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 close to rational expectations in our context.

and strong recovery of central Hiroshima. Then, we develop a dynamic quantitative urban model to disentangle three important determinants of city structure: locational fundamental characteristics, initial conditions determined by a historical shock, and forward-looking individuals' expectations regarding future city structure.

We first document the strong resilience in Hiroshima's recovery: the completely destroyed city center recovered just five years after the atomic bombing. Importantly, our reduced-form analysis reveals that the fundamental location advantages of the city center, such as natural conditions and transportation access, cannot plausibly explain the recovery. This is suggestive of additional mechanisms that contributed to the quick recovery of the city center. To further investigate the economic mechanism underlying the recovery, we develop and calibrate a novel dynamic quantitative urban model that incorporates important determinants of the dynamics of city structure: forward-looking migration decisions, agglomeration forces, and heterogeneous fundamentals and history across locations. Our calibrated model successfully explains the quick recovery of central Hiroshima, and agglomeration forces are essential in creating the incentive to rebuild the center. Moreover, expectations of recovery play a key role, as we show that an alternative equilibrium exists in which individuals do not expect recovery and it indeed does not occur. Overall, following the total destruction, people chose to live and work in central Hiroshima again because they could expect that it would again achieve high density in the near future, making the city center attractive in the presence of strong agglomeration forces. This result highlights the importance of agglomeration forces and expectations in determining the dynamics of city structure.

Agglomeration economies and expectations are likely important determinants of the dynamics of city structure also in other contexts. However, we note that a more systematic understanding of how expectations about the future spatial distribution of economic activities can emerge is necessary to determine which spatial equilibrium is realized in a particular context. We have pointed out in Subsection 6.3 that a combination of different factors may have contributed to forming expectations in the recovery of central Hiroshima. Since these factors are likely to be present in varying degrees in other contexts of wartime destruction, our findings suggest that individuals expectations may explain the recovery after wartime destruction that is frequently documented in empirical research (see Glaeser 2022 and Lin and Rauch 2022 for recent reviews). However, it would be important to better characterize how people form expectations about future changes in city structure, which is essential for understanding different patterns of the evolution of city structure beyond wartime contexts. Answering the question would be an important future research agenda.

References

Ahlfeldt, Gabriel M, Stephen J Redding, Daniel M Sturm, and Nikolaus Wolf, "The economics of density: Evidence from the Berlin Wall," *Econometrica*, 2015, *83* (6), 2127–2189.

Allen, Treb and Dave Donaldson, "Persistence and Path Dependence in the Spatial Economy," *mimeo*, 2022.

Ambrus, Attila, Erica Field, and Robert Gonzalez, "Loss in the time of cholera: long-run impact of a disease epidemic on the urban landscape," *American Economic Review*, 2020, *110* (2), 475–525.

Anas, Alex, Richard Arnott, and Kenneth A Small, "Urban spatial structure," *Journal of Economic Literature*, 1998, *36* (3), 1426–1464.

Arthur, W Brian, *Increasing returns and path dependence in the economy*, University of Michigan Press, 1994.

Asano, Jun-ichiro, "A Study on Method of the First Zoning Designation by the City Planning Law and the Building Regulation Law of 1919: In the Cases of 43 Small and Middle Scale Cities Where the City Planning Law was Enforced by the Taisyo Era," *Journal of Architecture Planning*, 2012, *77*, 2389–2398. (In Japanese).

Balboni, Clare, "In harm's way? infrastructure investments and the persistence of coastal cities," *mimeo*, 2021.

Baldwin, Richard E, "Core-periphery model with forward-looking expectations," *Regional Science and Urban Economics*, 2001, *31* (1), 21–49.

Barreda-Tarrazona, Iván, Tapas Kundu, and Stein Østbye, "On rational forward-looking behavior in economic geography: An experimental analysis," *Regional Science and Urban Economics*, 2021, *87*, 103654.

Bleakley, Hoyt and Jeffrey Lin, "Portage and path dependence," *The Quarterly Journal of Economics*, 2012, *127* (2), 587–644.

Bosker, Maarten, Steven Brakman, Harry Garretsen, and Marc Schramm, "Looking for multiple equilibria when geography matters: German city growth and the WWII shock," *Journal of Urban Economics*, 2007, *61* (1), 152–169.

Brakman, Steven, Harry Garretsen, and Marc Schramm, "The strategic bombing of German cities during World War II and its impact on city growth," *Journal of Economic Geography*, 2004, *4* (2), 201–218.

Brooks, Leah and Byron Lutz, "Vestiges of transit: Urban persistence at a microscale," *Review of Economics and Statistics*, 2019, *101* (3), 385–399.

_, Jonathan Rose, and Stan Veuger, "Destruction, Policy, and the Evolving Consequences of Washington, DC's 1968 Civil Disturbance," *FRB of Chicago Working Paper*, 2022.

Caliendo, Lorenzo, Maximiliano Dvorkin, and Fernando Parro, "Trade and labor market dynamics: General equilibrium analysis of the china trade shock," *Econometrica*, 2019, *87* (3), 741–835.

Davis, Donald R and David E Weinstein, "Bones, bombs, and break points: the geography of economic activity," *American Economic Review*, 2002, *92* (5), 1269–1289.

_ and _, "A search for multiple equilibria in urban industrial structure," *Journal of Regional Science*, 2008, *48* (1), 29–65.

Desmet, Klaus, Dávid Krisztián Nagy, and Esteban Rossi-Hansberg, "The geography of development," *Journal of Political Economy*, 2018, *126* (3), 903–983.

Diamond, Douglas W and Philip H Dybvig, "Bank runs, deposit insurance, and liquidity," *Journal of Political Economy*, 1983, *91* (3), 401–419.

Dingel, Jonathan I and Felix Tintelnot, "Spatial economics for granular settings," Technical Report, National Bureau of Economic Research 2020.

Feigenbaum, James, James Lee, and Filippo Mezzanotti, "Capital destruction and economic growth: The effects of Sherman's March, 1850–1920," *American Economic Journal: Applied Economics*, 2022, *14* (4), 301–42.

Foley-Fisher, Nathan, Borghan Narajabad, and Stéphane Verani, "Self-fulfilling runs: Evidence from the us life insurance industry," *Journal of Political Economy*, 2020, *128* (9), 3520–3569.

Fujita, Masahisa, *Urban economic theory*, Cambridge university press, 1989.

_ **, Paul R Krugman, and Anthony Venables**, *The spatial economy: Cities, regions, and international trade*, MIT press, 1999.

Fukao, Kyoji and Roland Bénabou, "History versus expectations: a comment," *The Quarterly Journal of Economics*, 1993, *108* (2), 535–542.

Garcia-Cicco, Javier, Roberto Pancrazi, and Martin Uribe, "Real business cycles in emerging countries?," *American Economic Review*, 2010, *100* (5), 2510–2531.

Glaeser, Edward L, "Urban resilience," *Urban Studies*, 2022, *59* (1), 3–35.

_ **and Matthew E Kahn**, "Sprawl and urban growth," in "Handbook of Regional and Urban economics," Vol. 4, Elsevier, 2004, pp. 2481–2527.

Halleck Vega, Solmaria and J Paul Elhorst, "The SLX model," *Journal of Regional Science*, 2015, *55* (3), 339–363.

Harari, Mariaflavia, "Cities in bad shape: Urban geometry in India," *American Economic Review*, 2020, *110* (8), 2377–2421.

Hayakawa, Kazuo and Michiko Nakaouji, "Toshi no jinko kibo to chika no kankei ni tsuite (On the relationship between population size and land prices)," *Nihon kenchiku gakkai ronbun houkoku shu*, 1965, *extra volume.* (In Japanese).

Heblich, Stephan, Alex Trew, and Yanos Zylberberg, "East-Side Story: Historical Pollution and Persistent Neighborhood Sorting," *Journal of Political Economy*, 2021, *129* (5), 1508–1552.

Hinokidani, Mieko and Shyoji Sumita, "Jutaku Syoyu Keitai No Henyo Katei Ni Kansuru Kenkyu (A Study on the Changing Process of Housing Tenure)," *Journal of Architecture and Planning*, 1988, *392*, 136–146. (The main text is in Japanese. The English title and abstract are included.).

Hiroshima City Government, "Hiroshima Genbaku Sensai-Shi (The Hiroshima Atomic Bombing Damage Records)," 1971. (In Japanese).

_ , "Hiroshima Shin-Shi: Chiri-hen (The New History of Hiroshima: The Geography)," 1983. (In Japanese).

_ , "Hiroshima Shin-Shi: Shimin-seikatsu-hen (The New History of Hiroshima: The Citizen's Life)," 1983. (In Japanese).

Hornbeck, Richard and Daniel Keniston, "Creative destruction: Barriers to urban growth and the Great Boston Fire of 1872," *American Economic Review*, 2017, *107* (6), 1365–98.

Inami, Etsuji, "Toshi Henbou ron Danshou: Hiroshima to Nagasaki no baai (Conditions of the reconstruction in the atombombed cities, Hiroshima and Nagasaki)," *Japanese Journal of Human Geography*, 1953, *5* (3), 195–204. (In Japanese. An English abstract is available).

Kato, Yuriko, "On the ownership of land and housing in pre-war Tokyo (Senzen no toukyou ni okeru tochi kaoku no shoyuu jyoukyou ni tsuite)," *Journal of Aoyama Gakuin Woman's Junior College*, 11 1988, *42*, 99–114. (In Japanese).

Kleinman, Benny, Ernest Liu, and Stephen J Redding, "Dynamic spatial general equilibrium," *Econometrica*, 2023, *91* (2), 385–424.

Kline, Patrick and Enrico Moretti, "People, places, and public policy: Some simple welfare economics of local economic development programs," *Annual Review of Economics*, 2014, *6* (1), 629–662.

Kocornik-Mina, Adriana, Thomas KJ McDermott, Guy Michaels, and Ferdinand Rauch, "Flooded cities," *American Economic Journal: Applied Economics*, 2020, *12* (2), 35–66.

Krugman, Paul, "History versus expectations," *The Quarterly Journal of Economics*, 1991, *106* (2), 651–667.

Lee, Sanghoon and Jeffrey Lin, "Natural amenities, neighbourhood dynamics, and persistence in the spatial distribution of income," *The Review of Economic Studies*, 2018, *85* (1), 663–694.

Lin, Jeffrey and Ferdinand Rauch, "What Future for History Dependence in Spatial Economics?," *Regional Science and Urban Economics*, 2022, *94*, 103628.

Malmendier, Ulrike and Jessica A Wachter, "Memory of Past Experiences and Economic Decisions," *Available at SSRN*, 2022.

Matsuyama, Kiminori, "Increasing returns, industrialization, and indeterminacy of equilibrium," *The Quarterly Journal of Economics*, 1991, *106* (2), 617–650.

Michaels, Guy and Ferdinand Rauch, "Resetting the urban network: 117–2012," *The Economic Journal*, 2018, *128* (608), 378–412.

Miguel, Edward and Gerard Roland, "The long-run impact of bombing Vietnam," *Journal of Development Economics*, 2011, *96* (1), 1–15.

Murphy, Kevin M, Andrei Shleifer, and Robert W Vishny, "Industrialization and the big push," *Journal of Political Economy*, 1989, *97* (5), 1003–1026.

Nozawa, Hiroshi, "Hiroshima-shi no Hattatsu to sono Zinbun Gensyo no Chiri-teki Kousatsu (A Geographical Consideration on the Development of Hiroshima city and its Humanilistic Issues)," *Chiri Ronso*, 1934, *5*, 47–91. (In Japanese).

Ohshima, Munao, "Fukkou no ashidori (The path of the recovery)," *Shin Toshi*, 1950, *4* (8), 6–13. (In Japanese. A special issue of Hiroshima Peace Memorial City Construction).

Ottaviano, Gianmarco IP, "Monopolistic competition, trade, and endogenous spatial fluctuations," *Regional Science and Urban Economics*, 2001, *31* (1), 51–77.

Oyama, Daisuke, "History versus expectations in economic geography reconsidered," *Journal of Economic Dynamics and Control*, 2009, *33* (2), 394–408.

Rauch, James E, "Does history matter only when it matters little? The case of city-industry location," *The Quarterly Journal of Economics*, 1993, *108* (3), 843–867.

Redding, Stephen J and Esteban Rossi-Hansberg, "Quantitative spatial economics," *Annual Review of Economics*, 2017, *9*, 21–58.

__ **, Daniel M Sturm, and Nikolaus Wolf**, "History and industry location: Evidence from German airports," *Review of Economics and Statistics*, 2011, *93* (3), 814–831.

Saiz, Albert, "The geographic determinants of housing supply," *The Quarterly Journal of Economics*, 2010, *125* (3), 1253–1296.

Schumann, Abel, "Persistence of Population Shocks: Evidence from the Occupation of West Germany after World War II," *American Economic Journal: Applied Economics*, 2014, *6* (3), 189–205.

Shiller, Robert J, "Narrative economics," *American Economic Review*, 2017, *107* (4), 967–1004.

Siodla, James, "Razing San Francisco: The 1906 disaster as a natural experiment in urban redevelopment," *Journal of Urban Economics*, 2015, *89*, 48–61.

Takahashi, Hiroko, "Genbaku touka ippungo: kesareta zanryuu housyasen no eikyou (One-minute after atomic bombing: The hidden effect of remaining radiation)," *Amerika kenkyuu*, 2008, *42*, 1–19. (In Japanese. An English abstract is available.).

Takano, Keisuke, "Path-dependence in the location of business agglomeration: The impact of the postwar land requisition in Yokohama," *mimeo*, 2022.

Takezaki, Yoshihiko and Ryoji Soda, *Hiroshima Genbaku Dezitaru Atorasu (The Digital Atlas of Atomic Bombing in Hiroshima)*, Research center for regional geography, Hiroshima University, 2001. (In Japanese).

Tsivanidis, Nick, "Evaluating the impact of urban transit infrastructure: Evidence from bogota's transmilenio," *mimeo*, 2022.

Yamagishi, Atsushi and Yasuhiro Sato, "Persistent Stigma in Space: 100 Years of *Japan's Invisible Race* and Their Neighborhoods," *mimeo*, 2023.

Yamasaki, Junichi, Kentaro Nakajima, and Kensuke Teshima, "From samurai to skyscrapers: How historical lot fragmentation shapes Tokyo," *mimeo*, 2022.

Online Appendix to: "The Economic Dynamics of City Structure: Evidence from Hiroshima's Recovery"

Kohei Takeda Atsushi Yamagishi

A Data Appendix

This section describes the details of data construction. Table A.1 provides summary statistics.

A.1 Basic Data

Maps (Spatial Units) and Sample Selection. We use the city block (*cho cho moku*) as 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 first 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

[1]We 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*.

[2]We drop *Hakushima kita-machi*, *Iwamiya-cho*, and *Toriya-cho*. Although we are not completely sure of why these there 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.

kilometers from the city center. 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 shiryou showa 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.

Destruction by the Atomic Bombing. The severity of destruction can be measured primarily in two ways: the destruction ratio of buildings and the kill ratio of people. Hiroshima City Government (1971), which is our key source of data on the bombing damage, provides both measures at the block level. However, 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. Indeed, Hiroshima City Government (1971) has many missing values for the kill ratio precisely because no reliable data on the kill rate was available. 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, but 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 many days, months, or even years after the bombing due to the atomic-bomb sickness caused by the radiation. Third, prior studies about the impact of bombing on the city population (Davis and Weinstein 2002; Brakman, Garretsen and Schramm 2004) note 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. The large heterogeneity within the city is apparent. Blocks within 2 kilometers of the CBD were quite severely destroyed, while those more than 2 kilometers away from the CBD tend to experience much less destruction. See also Figure 1b for the representation of a map. 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. The time-series data is summarized in Figure 2a. 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. We address these issues using various data and construct block-level population data that are comparable between 1933 and 1975.

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 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 regression model fits the data well. 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 ($\rho \simeq 0.86$) 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.[3] *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.[4] 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.

Employment. We collect and digitize block-level employment data. For 1938, we use the Survey of Commerce and Industry in Hiroshima City (*Hiroshima-shi shoukou-gyou keiei chousa*) that records the number of establishments (factories and commercial stores) at the block level. For 1946, we take from the Statistical Abstract of Hiroshima City (*Hiroshima shisei youran*) the number of buildings used for business purposes. For 1953, we use the Survey on the Daytime Population of Hiroshima (*Hiroshima-shi chukan jinko chosa*). 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 ignore agricultural employment. This is a relatively moderate restriction because we focus on an urban area throughout our sample period.[5] The time-series data is summarized in Figure 2b.

Three issues must be addressed to make the block-level employment data comparable between

[3]Similar 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.

[4]There 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.

[5]While most of our data already focus on non-agricultural employment, the 1953 data report total employment, including agricultural employment. To adjust for this, we estimate the number of agricultural workers in 1953 using the following procedure: First, we obtain the share of agricultural households from the 1950 Statistical Abstract of Hiroshima. Combined with the number of agricultural workers from the 1950 Population Census, we estimate that about half of the agricultural household members are counted as working. This allows us to calculate the fraction of agricultural workers in the overall population. We multiply it by the 1953 block-level population to approximate the block-level agricultural employment in 1953. This adjustment is of relatively minor importance because even in 1950, when agricultural employment was still significant in the Japanese economy, the Population Census suggests that less than 10 percent of workers are in the agricultural sector in Hiroshima city.

1938 and 1975. First, similar to population, the block boundary and the land area changed over time. Second, for 1945–1963, the employment information is available only 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, which is the time at which our first post-war population data is available. For this, we first take from the 1946 Statistical Abstract of Hiroshima City the number of buildings for shops, restaurants, banks, hotels, associations, and entertainment facilities before and after the bombing (August 1946). We also approximate the establishment distribution right after the bombing (August 1945) by multiplying the number of establishments before the bombing and the ratio of totally destroyed buildings.[6] Using linear interpolation, we can approximate the number of establishments for each distance bin as of November 1945 from the numbers as of August 1945 and 1946. Second, we regress the change rate of 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 exhibits a good fit. 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.[7]

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*).[8] 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,

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

[7]The predicted model yields a negative change rate in the number of establishments for a 100 percent total destruction rate. To address this, we use the change rate predicted for the 99 percent destruction rate for blocks with a 100 percent destruction rate.

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

which is 44.2 percent according to the 1936 Statistical Handbook of Hiroshima City (*Hiroshima-shi toukei sho*).[9]

A.3 Other Data

Commuting and Transportation Network. We use the trip-level microdata of the 1987 Hiroshima City Person-Trip Survey for residents of the Hiroshima metropolitan area. It was large-scale (about 7 percent of the population was surveyed) and representative. To further enhance the 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, it collects information on the origin, destination, and mode(s) of transportation. We use the representative mode of transportation in the trip: 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 it uses buses. We code trips that have not been coded as "car" if it uses a motorcycle or automobile. We code trips that have not been coded as "bicycle" if it uses a bicycle. Finally, we code it as "walk" if it uses walking.

Using the microdata of 1987 person-trip survey, we estimate the mode choice model using travels of workers from home to workplace.[10] 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.[11] Although public transportation networks 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.[12] We then calculate the travel times to the city center under these networks and compare

[9] In 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.

[10] As 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.

[11] We use QGIS to compute the travel time. Based on available evidence, we assume the following travel speeds: 5 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. In calculating the travel time by bicycle, car, bus, and train, we assume walking occurs outside its network.

[12] For 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.

them with the travel time under the 1987 road network. 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 collect various information on the locational characteristics of each block. We first explain the natural locational characteristics: altitude, ruggedness and soil condition. The altitude and the ruggedness are taken from the Digital National Land Information.[13] For each 250 m $\times$ 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.[14] 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 locational characteristics. We collect information on the location of train stations in 1950 from the Digital National Land Information.[15] The location of Hiroshima port (*Ujina* port) is taken from Google Map as (34.352167, 132.455119). The list of cultural assets (*bunkazai*) in the city is taken from the Hiroshima Metropolitan Area and Hiroshima Prefecture Open Data Portal Site.[16] 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*).[17] The data cover all public housing units constructed in Hiroshima from 1946 to 1950.

Land Prices. We obtain the location with the highest unit land price within Hiroshima city.[18] For 1931, this is reported in the 1931 Statistical Yearbook of Hiroshima City. For 1959, the National Tax Agency reports the location with the highest land price in each prefecture.[19] Since the highest land price in Hiroshima prefecture was in Hiroshima city, we know that this place also had the highest land price in Hiroshima city.

Migration Rate. In order to assess the degree of mobility friction, we use information on migration rates. Our primary data source is the 1960 population census. It asks whether a respondent

[13]Source: https://nlftp.mlit.go.jp/ksj/gml/datalist/KsjTmplt-G04-d.html, in Japanese. Last accessed on September 9, 2022

[14]Source is 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 September 7, 2022.

[15]Source: https://nlftp.mlit.go.jp/ksj/gml/datalist/KsjTmplt-N05-v1_3.html, in Japanese. Last accessed on September 7, 2022.

[16]Source: https://hiroshima-opendata.dataeye.jp/resources/9843, last accessed on September 9, 2022.

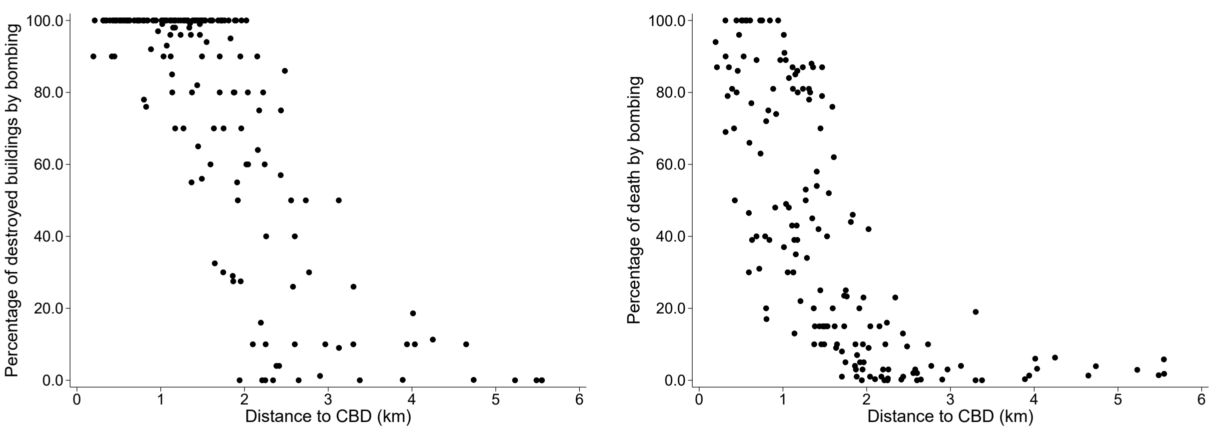
[17]In some cases, the location information in the data does not allow us to uniquely identify the block the public housing is located in. We still assign the single block based on our best guess on the location of that public housing.

[18]In 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).

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

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.[20] 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 of 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 migration and inter-city migration right after the war is similar to that in 1960.[21] Then, 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.

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



(a) Damage to Buildings

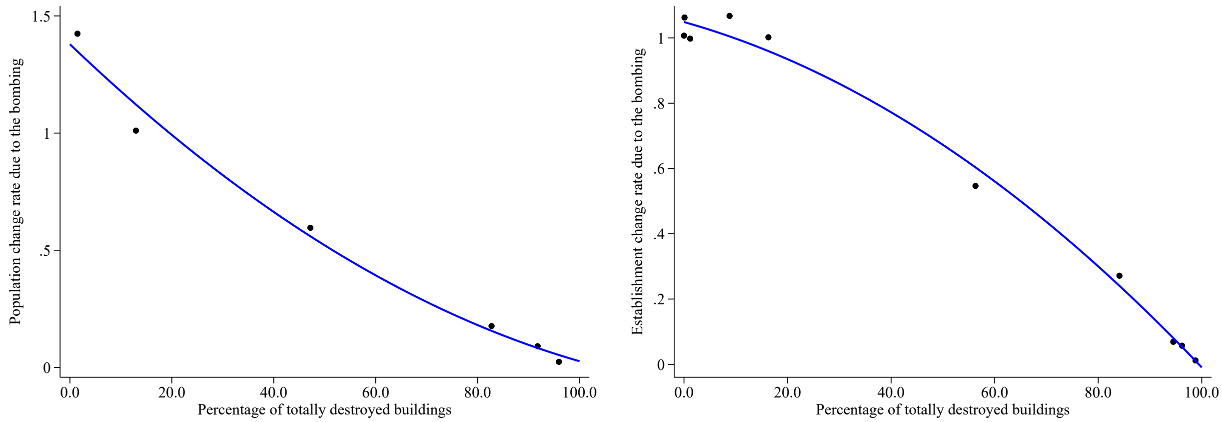
(b) Death Rate of People

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).

[20]The 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 September 8, 2022.

[21]For 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.

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

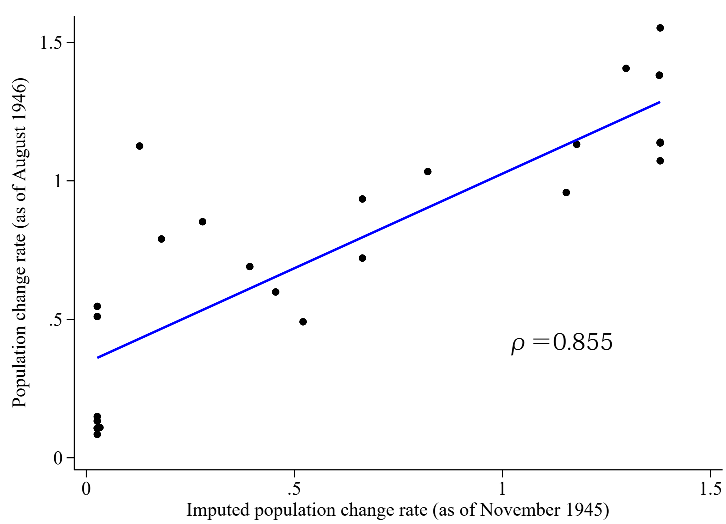


(a) Population change

(b) Establishment change

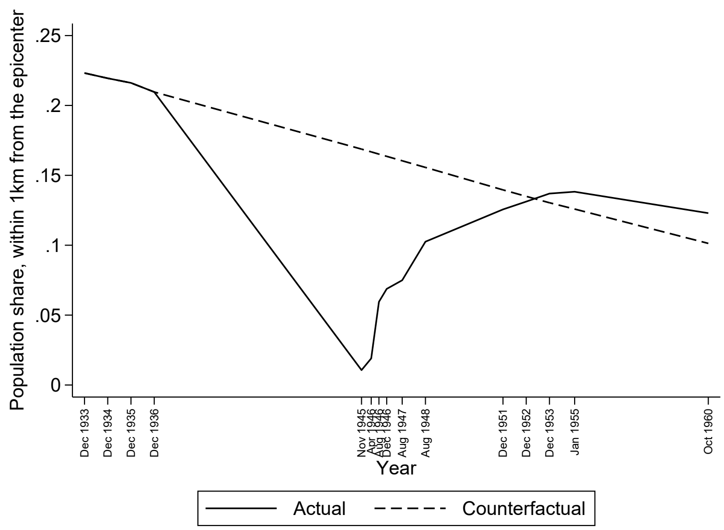
Note: The left panel shows the scatter plot of the percentage of totally destroyed buildings and the population change rate due to the bombing for distance categories from the epicenter (within 1km, 1-1.5km, 1.5-2km, 2-2.5km, 2.5-3km, more than 3km away). The population change is from the 1946 Statistical 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.

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



Note: This figure shows the population share of areas within 1 kilometer of the epicenter of the atomic bombing. 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 counterfactual population share extrapolates the pre-war linear trend to the post-WWII period, analogous to Figure 2 of Davis and Weinstein (2002).

Table A.1: Summary Statistics

	Full sample			Within 3km from the CBD		
	mean	sd	count	mean	sd	count
Population 1936	1880	2153	174	1642	1103	158
Population 1936 per $1km^2$	23761	14104	174	25752	13138	158
Population 1945	917	2927	174	459	916	158
Population 1945 per $1km^2$	3566	5496	174	3374	5158	158
Population 1950	1495	2683	174	1026	1091	158
Population 1950 per $1km^2$	11877	6616	174	12583	6374	158
Population 1960	2215	3648	174	1537	1689	158
Population 1960 per $1km^2$	16725	8548	174	17737	8188	158
Population 1975	2625	5423	174	1501	2694	158
Population 1975 per $1km^2$	12758	5046	174	13065	4906	158
Employment 1938	978	835	174	949	626	158
Employment 1938 per $1km^2$	42517	41449	174	46512	41422	158
Employment 1945	405	1056	174	259	420	158
Employment 1945 per $1km^2$	5507	8035	174	5602	8072	158
Employment 1953	669	965	174	505	465	158
Employment 1953 per $1km^2$	7358	6083	174	7909	6099	158
Employment 1966	1277	1516	174	1060	792	158
Employment 1966 per $1km^2$	18499	17408	174	20111	17463	158
Employment 1975	1515	1880	174	1211	993	158
Employment 1975 per $1km^2$	21017	21948	174	22821	22243	158
Block area (km^2)	.321	.971	174	.132	.39	158
Distance to the CBD (km)	1.66	1.06	174	1.4	.652	158
Distance to Hiroshima port (km)	4.74	1.08	174	4.72	.985	158
Distance to the nearest station (m)	336	319	174	285	232	158
Distance to the nearest water area (m)	248	229	174	226	185	158
Distance to the nearest cultural asset (m)	808	637	174	684	412	158
Altitude (m)	5.91	14.4	174	4.25	7.56	158
Average slope (degree)	.814	2.4	174	.611	2.07	158
Dummy of bad soil condition	.96	.197	174	.981	.137	158
Latitude	34.4	.0104	174	34.4	.00917	158
Longitude	132	.0167	174	132	.0123	158
Annual population growth rate 1933–1936	1.03	.0355	174	1.03	.0344	158
Rate of total destroyed Building	74.5	35.4	174	81.1	29.8	158
Rate of half-damaged buildings	18.6	26	174	15.2	23.6	158
Rate of mildly-damaged buildings	6.65	17.7	174	3.38	12.1	158
Rate of intact building	.685	3.99	174	.316	1.66	158
Observations	174			158		

B Nagasaki

Throughout the paper, we focus on Hiroshima: the first city hit by the atomic bomb in our history. Our focus on Hiroshima is motivated by better data availability and city size: Hiroshima was about twice as large as Nagasaki in the pre-war period. That said, this section analyzes Nagasaki, the second and last city that experienced an atomic bombing as of the time this paper is written, based on available data.

The case of Nagasaki is useful to distinguish the role of war-time destruction from the locational fundamentals because the atomic bomb hit a different part of the city. In Hiroshima, we have shown in Section 3 that the atomic bombing of Hirohsima results in a populaton decline in the city's core, while the city's outskirts experienced an increase in population. In contrast, as shown in the damage map of Nagasaki in Figure B.1a, the atomic bomb hit the outskirts of Nagasaki and the epicenter is more than 2 kilometers away from the city center, where the Nagasaki City Hall and the Nagasaki Prefectural Office are located. Consequently, the city center of Nagasaki, areas to the south-east of Nagasaki station, was damaged relatively mildly. Some of the outskirts of Nagasaki experienced destruction and a decrease in population, while the center, which experienced less destruction, experienced an increase in population as people escaped into the center (Inami 1953). Therefore, in contrast to Hiroshima where the monocentric city structure was reversed, the concentration in the center was augmented by the bombing in Nagasaki. This contrasting pattern of population change after the atomic bombing allows us to distinguish between the importance of the destruction due to the bombing and its fundamental characteristics. If the destruction rate determines the post-war population growth, then the outskirts should experience a substantial increase in population. In contrast, if being the (pre-war) city center is what matters in explaining the post-war population growth of central Hiroshima, then we would not expect the recovery of the pre-war population distribution on the outskirts of Nagasaki.

To investigate the post-war population growth in Nagasaki after the bombing, we use the population data in May 1945 (pre-bombing), October 1945 (post-bombing), and March 1954 at the school district level, taken from Nagasaki City Government (1983). We estimate the following equation similar to equation (1):

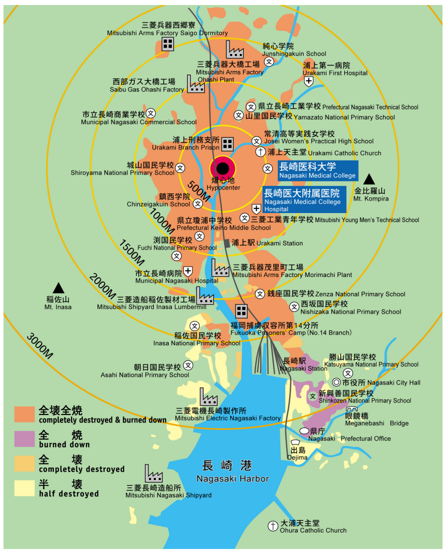
$$\ln\left(\frac{\text{Popdens}_{i,1954}}{\text{Popdens}_{i,1945\text{ Oct}}}\right) = \gamma \ln\left(\frac{\text{Popdens}_{i,1945\text{ Oct}}}{\text{Popdens}_{i,1945\text{ May}}}\right) + v_i. \quad \text{(B.1)}$$

The unit of observation is the school district i and there were 24 school districts.[22]

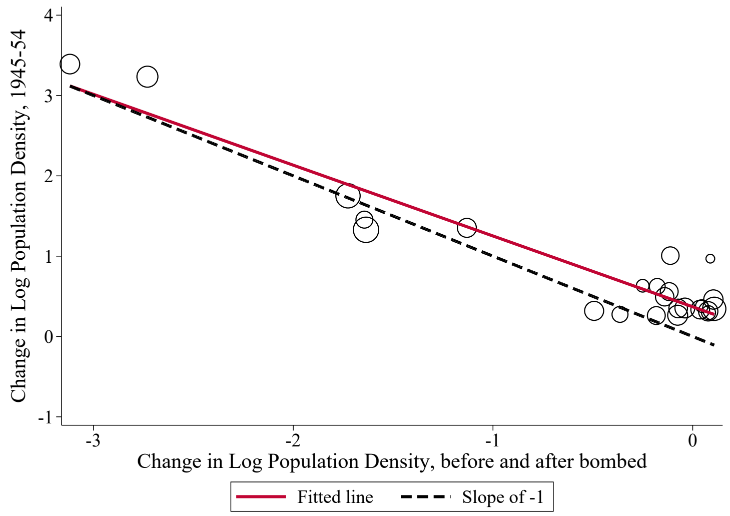
[22] Strictly speaking, we cannot calculate population density because we have no information on the size of each school district. However, this does not prevent us from implementing (B.1) as long as the size does not change throughout our sample period. We do not include control variables because Nagasaki City Government (1983) does not show a map of school districts and we could not collect precise locational characteristics.

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 of 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. We plot the (unweighted) linear fit between these two variables (solid line) as well as the slope of -1 (dashed line).

Figure B.1b shows the estimation result. Despite the fact that the atomic bomb hit a different part of the city, the figure looks very similar to the case of Hiroshima in Figure 4. The estimated slope of the fitted line is -0.882 with a standard error 0.101. While we can strongly reject the null of $\gamma = 0$, we cannot reject the null of $\gamma = -1$ at the conventional level. Therefore, similar to Hiroshima, we obtain evidence of the historical-shock independence within Nagasaki. This evidence from Nagasaki suggests that the population distribution in the city would resemble the pre-war one, even if the atomic bomb hit a different place within the city. Combined with the result from Hiroshima, it is difficult to attribute the recovery to the fundamental advantages of particular locations within a city.

C Additional Reduced-form Evidence

Employment. We repeat the same reduced-form analysis as Section 3 for employment data in 1938, 1945, and 1966. Figure C.1 shows the scatter plot of the log employment change rates in the same way as Figure 4 for population data. Similar to the population, we find those areas that experienced a significant decline in employment due to the bombing had a high employment growth rate in the post-war period. Table C.1 reports the regression results of the equation (1) for employment, in the same manner as Table 1 for population. Column 1 reports the result of the simple regression in Figure C.1. We find the coefficient around -0.86, which indicates a stronger recovery than the case of the population in Table 1 (around -0.7). Adding control variables, column 2 shows that the coefficient is now almost -1, i.e., the historical-shock independence. The historical-shock independence result after adding control variables is the same as in the case of the population. Finally, column 3 shows that focusing on blocks within 3 kilometers of the epicenter, which is expected to have more homogeneous locational characteristics, still implies historical-shock independence. This is again similar to the pattern of the population in Table 1.

Characteristics of Neighboring Blocks. We suppose that post-war population growth of block i may depend not only on own characteristics but also on the characteristics of neighboring blocks $j \neq i$. To consider the characteristics of neighbors, we adopt the so-called "SLX model" in spatial econometrics literature (Halleck 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 locational 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 that are 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 in Table 1. Table C.2 shows that the inclusion of these spatial lag 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 historical-shock independence ($\gamma = -1$) in all specifications. Overall, the results suggest that considering the characteristics of neighboring blocks does not change our historical-shock independence result.

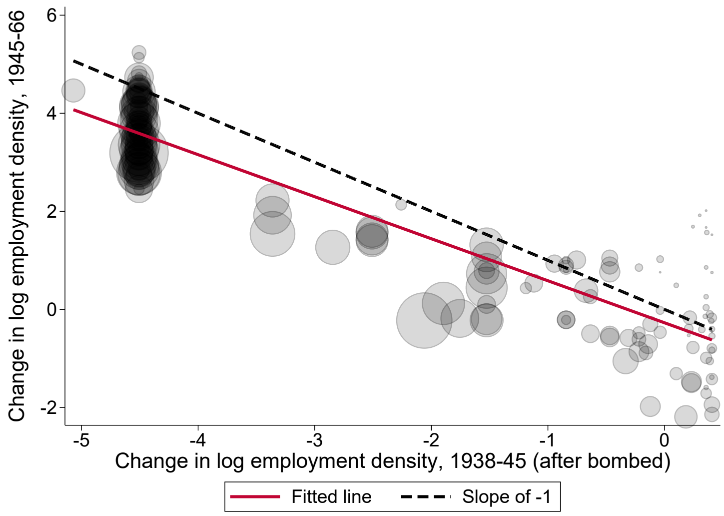
Public Housing. To assess how much the recovery of central Hiroshima was driven by governmental policies, we explore the role of public housing, which was a primary policy target right after the war. To investigate whether the provision of public housing directly leads to the recovery, we control for the number of public housing units on top of our main reduced-form regressions in Table

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

[24]We 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 (Takeda and Yamagishi 2023). We have also tried an alternative market access term that is the sum of the spatial lag and the population level of the own block as of 1945. The result hardly changes.

1. Table C.3 reports the results, showing that controlling for public housing does not change our conclusion.[25]

Figure C.1: Change in Employment Density



Note: This figure plots the log employment change rate from 1938 to 1945 against the log employment change rate from 1945 to 1966. Each circle represents a block (i.e., an observation), where the size of the circle is proportional to the employment density in 1938. We plot the (unweighted) linear fit between these two variables (solid line) as well as the slope of -1 (dashed line).

[25]The result that public housing provision does not explain the recovery of central hiroshima is natural because we find that public housings were more likely to be supplied in locations away from the CBD.

Table C.1: Change in Employment Density

	(1)	(2)	(3)
	Change in log employment density 1945-66		
Change in employment density 1938–1945	-0.8571[a]	-1.0090[a]	-0.9347[a]
	(0.0324)	(0.0610)	(0.0578)
p-value from testing $\gamma = -1$	0.000	0.882	0.261
Control variables		✓	✓
Within 3km from the city center			✓
Number of blocks	174	174	158
R-squared	0.828	0.896	0.921

Standard errors in parentheses

[c] $p < 0.1$, [b] $p < 0.05$, [a] $p < 0.01$

Note: We report the OLS estimation result of the equation (1) for employment density. Fundamentals consist of the quadratics of the distance to the nearest station, the distance to Hiroshima port (*Ujina* port), the distance to the nearest cultural asset, the distance to the nearest water area, the altitude, and the slope. We also include a dummy for a bad soil condition. We also control for the quadratics of the pre-war (1933-1936) population growth rate, the fractions of the half-destroyed, moderately-destroyed, and intact buildings, and the geographical coordinates (the latitude, the longitude, and their interaction). In columns 3, we confine the sample to blocks within 3km from the city center, in which fundamental conditions are more homogeneous. We also test the null that $\gamma = -1$ (i.e., the complete historical-shock independence) and report its p-value. Robust standard errors in parentheses.

Table C.2: Controlling for Characteristics of Neighboring Blocks

	(1)	(2)	(3)
	Change in log population density 1945-50		
Change in log population density 1936–1945	-0.9291[a]	-0.9470[a]	-0.9298[a]
	(0.0991)	(0.0941)	(0.0988)
p-value from testing $\gamma = -1$	0.475	0.574	0.478
Control variables (block characteristics)	✓	✓	✓
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			✓
N	174	174	174
R^2	0.864	0.906	0.864

Standard errors in parentheses

[c] $p < 0.1$, [b] $p < 0.05$, [a] $p < 0.01$

Note: We report the OLS estimation result of the equation (1) for population density, while controlling for a spatial lag of dependent variables based on geographic distances between centroids of blocks. As control variables, we include the quadratics of the distance to the nearest station, the distance to Hiroshima port (*Ujina* port), the distance to the nearest cultural asset, the distance to the nearest water area, the altitude, and the slope. We also include a dummy for a bad soil condition. We also control for the quadratics of the pre-war (1933-1936) population growth rate, the fractions of the half-destroyed, moderately-destroyed, and intact buildings, and the geographical coordinates (the latitude, the longitude, and their interaction). 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 also test the null that $\gamma = -1$ (i.e., the complete historical-shock independence) and report its p-value. Robust standard errors in parentheses.

Table C.3: Change in Population Density (Controlling for Public Housing)

	(1)	(2)	(3)
	Change in log population density 1945-50		
Change in log population density 1936–1945	-0.7270[a]	-0.9357[a]	-0.9762[a]
	(0.0270)	(0.0952)	(0.0951)
p-value from testing $\gamma = -1$	0.000	0.501	0.803
Control variables (other than public housing)		✓	✓
Within 3km from the city center			✓
Number of blocks	174	174	158
R-squared	0.816	0.866	0.880

Standard errors in parentheses
^{c} $p < 0.1$, ^{b} $p < 0.05$, ^{a} $p < 0.01$

Note: We report the OLS estimation result of the equation (1) for population density while controlling for the number of units of public housing in each block for all specifications. Fundamentals consist of the quadratics of the distance to the nearest station, the distance to Hiroshima port (*Ujina* port), the distance to the nearest cultural asset, the distance to the nearest water area, the altitude, and the slope. We also include a dummy for bad soil conditions. We also control for the quadratics of the pre-war (1933-1936) population growth rate, the fractions of the half-destroyed, moderately-destroyed, and intact buildings, and the geographical coordinates (the latitude, the longitude, and their interaction). In column 3, we confine the sample to blocks within 3 kilometers from the city center, in which fundamental conditions are more homogeneous. We also test the null that $\gamma = -1$ (i.e., the complete historical-shock independence) and report its p-value. Robust standard errors are in parentheses.

D Theoretical Appendix

This section provides detailed derivations in the model.

D.1 Value Function

When an individual ω 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:

$$F(\varepsilon) = \exp(-\exp(-(\varepsilon + \Gamma))), \quad f(\varepsilon) = \exp(-(\varepsilon + \Gamma))F(\varepsilon)$$

where Γ is Euler-Mascheroni constant: $\Gamma \equiv -\int_0^\infty \ln x e^{-x} dx$. For $d \in \{\mathcal{C} \times \mathcal{C}, o\}$, we have distribution functions:

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

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

$$V^*_{t+1} \equiv \max\left\{\rho_{t+1}V_{j\ell t+1} + \sigma_{t+1}\varepsilon_{j\ell t+1}\ ;\ \rho_{t+1}V_{ot+1} + \sigma_{t+1}\varepsilon_{ot+1}\right\}$$

Then, we have

$$H_{t+1}(s) = \text{Prob}[V^*_{t+1} \leq s] = \prod_{(j,\ell)} G_{j\ell t+1}(s) \times G_{ot+1}(s)$$

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

$$\mu_{t+1} = \mathbb{E}_{t+1}[s] = \sigma \ln\left(\sum_{(j,\ell)} \exp\left(V_{j\ell t+1}\right)^{\rho_{t+1}/\sigma_{t+1}} + \exp\left(V_{ot+1}\right)^{\rho_{t+1}/\sigma_{t+1}}\right) \tag{D.1}$$

Therefore, for $d \in \{\mathcal{C} \times \mathcal{C}, o\}$, we have value functions (7) and (8) in the main text.

D.2 Location Choice

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

$$\lambda_{int+1} =$$

$$\int_{-\infty}^{\infty}\left(\prod_{(j,\ell)} \exp\left(-e^{-\frac{1}{\sigma_{t+1}}\left(z_{t+1} + \rho_{t+1}V_{int+1} - \rho_{t+1}V_{j\ell t+1}\right)}\right) \exp\left(-e^{-\frac{1}{\sigma_{t+1}}\left(z_{t+1}+\rho_{t+1}V_{int+1} - \rho_{t+1}V_{ot+1}\right)}\right)\right) \frac{1}{\sigma_{t+1}} e^{-\frac{z_{t+1}}{\sigma_{t+1}}} dz_{t+1}$$

$$= \int_{-\infty}^{\infty} \exp\left(-e^{-z_{t+1}/\sigma_{t+1}} \sum_{d \in \{(j,\ell),o\}} e^{-\frac{1}{\sigma_{t+1}}\left(\rho_{t+1}V_{int+1} - \rho_{t+1}V_{dt+1}\right)}\right) \frac{1}{\sigma_{t+1}} e^{-z_{t+1}/\sigma_{t+1}} dz_{t+1}$$

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

$$\begin{aligned}
\lambda_{int+1} &= \int_0^\infty \exp\left(-s_{t+1} \sum_{d\in\{(j,\ell),o\}} \exp\left(-\frac{1}{\sigma_{t+1}}(\rho_{t+1}V_{int+1} - \rho_{t+1}V_{dt+1})\right)\right) ds_{t+1} \\
&= \left[\frac{\exp\left(-s_{t+1}\sum_{d\in\{(j,\ell),o\}} \exp\left(-\frac{1}{\sigma_{t+1}}(\rho_{t+1}V_{int+1} - \rho_{t+1}V_{dt+1})\right)\right)}{-\sum_{d\in\{(j,\ell),o\}} \exp\left(-\frac{1}{\sigma_{t+1}}(\rho_{t+1}V_{int+1} - \rho_{t+1}V_{dt+1})\right)}\right]_0^\infty \\
&= \frac{\exp\left(V_{int+1}\right)^{\rho_{t+1}/\sigma_{t+1}}}{\sum_{d\in\{(j,\ell),o\}} \exp\left(V_{dt+1}\right)^{\rho_{t+1}/\sigma_{t+1}}}
\end{aligned} \tag{D.2}$$

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

$$\lambda_{ot+1} = \frac{\exp\left(V_{ot+1}\right)^{\rho_{t+1}/\sigma_{t+1}}}{\sum_{d\in\{(j,\ell),o\}} \exp\left(V_{dt+1}\right)^{\rho_{t+1}/\sigma_{t+1}}} \tag{D.3}$$

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):

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

and

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

The total population of the city is

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

D.3 Equilibrium

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

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

Iterating this, we obtain

$$
\begin{aligned}
\widetilde{V}_{int} &= \ln \widetilde{u}_{int} + \sum_{\tau=t+1}^{T} \left\{ \prod_{s=t+1}^{\tau} \rho_s (1-\theta_s) \right\} \ln \widetilde{u}_{in\tau} \\
&= \ln \left\{ \widetilde{u}_{int} \prod_{\tau=t+1}^{T} \left(\widetilde{u}_{in\tau} \right)^{\prod_{s=t+1}^{\tau} \rho_s (1-\theta_s)} \right\} \\
&= \ln \left\{ \frac{a_{it} b_{nt}}{\kappa_{int} u_{ot}} \left(\frac{L_{it}}{S_i} \right)^{\alpha_1} \left(\frac{L_{it-1}}{S_i} \right)^{\alpha_2} \left(\frac{R_{nt}}{S_n} \right)^{\beta_1} \left(\frac{R_{nt-1}}{S_n} \right)^{\beta_2} \right. \\
&\quad \left. \times \prod_{\tau=t+1}^{T} \left(\frac{a_{i\tau} b_{n\tau}}{\kappa_{in\tau} u_{o\tau}} \left(\frac{L_{i\tau}}{S_i} \right)^{\alpha_1} \left(\frac{L_{i\tau-1}}{S_i} \right)^{\alpha_2} \left(\frac{R_{n\tau}}{S_n} \right)^{\beta_1} \left(\frac{R_{n\tau-1}}{S_n} \right)^{\beta_2} \right)^{\prod_{s=t+1}^{\tau} \rho_s (1-\theta_s)} \right\}
\end{aligned} \tag{D.7}
$$

The probability (D.2) can be expressed as

$$
\lambda_{int+1} = \frac{\exp\left(\widetilde{V}_{int+1}\right)^{\rho_{t+1}/\sigma_{t+1}}}{\sum_{j,\ell} \exp\left(\widetilde{V}_{j\ell t+1}\right)^{\rho_{t+1}/\sigma_{t+1}} + 1} \tag{D.8}
$$

Therefore, we obtain the population in location n:

$$
R_{nt+1} = (1-\theta_{t+1}) R_{nt} + \theta_{t+1} \sum_i \frac{\exp\left(\widetilde{V}_{int+1}\right)^{\rho_{t+1}/\sigma_{t+1}}}{\sum_{j,\ell} \exp\left(\widetilde{V}_{j\ell t+1}\right)^{\rho_{t+1}/\sigma_{t+1}} + 1} M \tag{D.9}
$$

and employment in location i:

$$
L_{it+1} = (1-\theta_{t+1}) L_{it} + \theta_{t+1} \sum_n \frac{\exp\left(\widetilde{V}_{int+1}\right)^{\rho_{t+1}/\sigma_{t+1}}}{\sum_{j,\ell} \exp\left(\widetilde{V}_{j\ell t+1}\right)^{\rho_{t+1}/\sigma_{t+1}} + 1} M \tag{D.10}
$$

The equilibrium is characterized by $\{R_{nt}, L_{it}\}$ solving (D.7), (D.9) and (D.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 $(1-\theta_{t+\tau})\rho_{t+\tau} \to 0$ 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:

$$
\begin{aligned}
R_{nt+1} &= (1-\theta_{t+1}) R_{nt} + \sum_i \frac{\mathcal{X}_{int+1} R_{nt+1}^{\beta_1 \varkappa_{t+1}} R_{nt}^{\beta_2 \varkappa_{t+1}}}{\sum_\ell \mathcal{X}_{i\ell t+1} R_{\ell t}^{\beta_1 \varkappa_{t+1}} R_{\ell t}^{\beta_2 \varkappa_{t+1}}} \left(L_{it+1} - (1-\theta_{t+1}) L_{it} \right), \\
L_{it+1} &= (1-\theta_{t+1}) L_{it} + \sum_n \frac{\mathcal{X}_{int+1} L_{it+1}^{\alpha_1 \varkappa_{t+1}} L_{it}^{\alpha_2 \varkappa_{t+1}}}{\sum_j \mathcal{X}_{jnt+1} L_{jt+1}^{\alpha_1 \varkappa_{t+1}} L_{jt}^{\alpha_2} \varkappa_{t+1}} \left(R_{nt+1} - (1-\theta_{t+1}) R_{nt} \right),
\end{aligned} \tag{D.11}
$$

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 $\boldsymbol{X} = (\boldsymbol{R}, \boldsymbol{L})$ be a vector of population and employment and we define the operator $J(\boldsymbol{X})$ such that ι-th element $J_\iota(\boldsymbol{X})$ corresponds to the right-hand side of (D.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 $L_{it+1} \geq (1-\theta_{t+1})L_{it}$.

D.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:

$$\lambda^L_{i|n} = \frac{\lambda_{in}}{\sum_{j\in\mathcal{C}} \lambda_{jn}} = \frac{\mathcal{A}_{in} L_i^{\alpha\varkappa}}{\sum_{j\in\mathcal{C}} \mathcal{A}_{jn} L_j^{\alpha\varkappa}}$$

where we let $\alpha \equiv \alpha_1 + \alpha_2$, $\varkappa \equiv \rho/\sigma$ and $\mathcal{A}_{in} \equiv (a_i/\kappa_{in})^{\rho/\sigma} > 0$ summarizes the time-invariant fundamental productivity consistent with the steady-state. Analogously the conditional probabilities that workers live in n given workplace i become:

$$\lambda^R_{n|i} = \frac{\lambda_{in}}{\sum_{\ell\in\mathcal{C}} \lambda_{i\ell}} = \frac{\mathcal{B}_{in} R_n^{\beta\varkappa}}{\sum_{\ell\in\mathcal{C}} \mathcal{B}_{i\ell} R_\ell^{\beta\varkappa}}$$

where $\beta \equiv \beta_1 + \beta_2$ and $\mathcal{B}_{in} \equiv (b_n/\kappa_{in})^{\rho/\sigma} > 0$. In sum, the steady state equilibrium is characterized by variables $\{R_n, L_i, \Phi_i, \Upsilon_n\}$ solving the system of equations:

$$\begin{aligned} R_n^{1-\tilde{\beta}\varkappa} &= \sum_i \mathcal{B}_{in} \Phi_i^{-1} L_i, \quad \Phi_i = \sum_n \mathcal{B}_{in} R_n^{\beta\varkappa}, \\ L_i^{1-\tilde{\alpha}\varkappa} &= \sum_n \mathcal{A}_{in} \Upsilon_n^{-1} R_n, \quad \Upsilon_n = \sum_i \mathcal{A}_{in} L_i^{\alpha\varkappa} \end{aligned} \tag{D.12}$$

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:

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

Matrix $\mathbf{C}$ is a diagonal matrix and invertible when $\alpha \neq 1/\varkappa$ and $\beta \neq 1/\varkappa$, and steady state equilibrium exists when these conditions hold. Then, we define matrix $\boldsymbol{\Gamma} = |\mathbf{D}\mathbf{C}^{-1}|$. 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 $\boldsymbol{\Gamma}$ are no larger than one. In our case the sufficient conditions for a unique up-to-scale solution are:

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

These conditions hold if and only if:

$$\beta = \beta_1 + \beta_2 \leq 0, \quad \alpha = \alpha_1 + \alpha_2 \leq 0 \tag{D.13}$$

The net agglomeration in productivity ($\alpha_1 + \alpha_2$) and net neighborhood externality in amenities ($\beta_1 + \beta_2$) 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.

D.5 Microfoundations of Productivity Agglomeration Forces

In this section we present two different microfoundations of productivity agglomeration forces. The first subsection considers the local production capital and the second subsection discusses the innovation by local firms.

D.5.1 Local Production Capital

Capital in Final Good Production. The production function is given by $y_{it} = k_{it}^{\nu_1} l_{it}$ with a parameter $\nu_1 \in (0, 1)$. k_{it} stands for local production capital (e.g., floor space) and ν_1 governs the decreasing returns to scale in its contribution to labor productivity. The technology is linear in its labor, so the equilibrium wage $w_{it} = k_{it}^{\nu_1}$.[26] Firms also choose their local capital input taking its unit price p_{it} as given, leading to $p_{it} = \nu_1 l_{it} k_{it}^{\nu_1 - 1}$. Since the production technology is linear in labor, at this profit maximizing point, firms that earn negative profits may stop operating if the cost of local capital is incurred by them. To simplify the discussion, we assume that firms do not exit, possibly because they receive a lump-sum transfer from the government or other sources that cover the cost of local capital.[27]

[26] Due to the linear technology both in tradable final goods production and capital production, the wage rate must be equalized across both sectors for both sectors to be active. We focus on such a situation and assume as a tie-breaking rule that a fixed $\varrho \in (0, 1)$ fraction of L_{it} workers work in the capital sector and the remaining work in the final goods sector.

[27] Alternatively, firms may earn positive profits in equilibrium and have no incentive to exit when they can exert a monopsony power in the labor market and set a lower wage than the marginal revenue: $w_{it} = k_{it}^{\nu_1}/(1 + m_{it})$, which is isomorphic to the perfect competition case multiplied by $1/(1 + m_{it})$. In particular, since the local labor supply curve has the iso-elastic form with elasticity ρ_t/σ_t when $\theta_t = 1$, m_{it} equals ρ_t/σ_t so that markup rate is constant and common across all locations.

Local Capital Supply. Capital is supplied locally in each location. The production technology of the supplier is Cobb-Douglas technology: $k_{it} = e_{it} n_{it}^{\nu_2} \bar{S}_{it}^{1-\nu_2}$, where e_{it} is the efficiency of production of local capital, n_{it} is input of numeraire (final goods) and $\bar{S}_{it}$ is land used for business. The supplier of local capital decides input of numeraire given commercial land ($\bar{S}_{it}$). The local capital supplier bid for commercial land and absentee land owner extract all profit from the suppliers, implying that firms earn zero profit in equilibrium. In equilibrium market clearing condition for the local capital leads to:

$$k_{it} = \bar{k}_0 e_{it}^{\lambda_1} (A_{it} l_{it})^{\lambda_2} \bar{S}_{it}^{\lambda_1 - \lambda_2},$$

where $\bar{k}_0$ is a constant, $\lambda_1 \equiv 1/(1 - \nu_1 \nu_2)$ and $\lambda_2 \equiv \nu_2/(1 - \nu_1 \nu_2)$.

We now specify the efficiency of local capital supply (e_{it}) and land allocation for commercial use ($\bar{S}_{it}$). First, efficiency is related to the infrastructure invested by the government. If infrastructure depreciates more when firms use it intensively in period $t-1$, while infrastructure increases more when the government's investment is increasing based on production in period $t-1$. The time difference is intuitive since replacing infrastructure takes time. Then, we can argue $e_{it} = \bar{e}_{it} L_{it-1}^{\psi_1}$, where $\bar{e}_{it}$ is fundamental quality. Next, commercial land use is also related to land allocation by the government or absentee landowners based on economic activities in the previous period. On the other hand, land for commercial use can be negatively associated with employment in the previous period through lot size adjustment costs (Yamasaki, Nakajima and Teshima 2022). More workers in period $t-1$ may imply a smaller lot size and that increases development costs or adjustment costs of land for large-scale construction, limiting the efficient land allocation toward business. In sum, we can write: $\bar{S}_{it} = S_i L_{it-1}^{\psi_2}$ where ψ_2 can be negative or positive.

Equilibrium Wages. Combining them, we can represent the wage equation in location i:

$$w_{it} = k_{it}^{\nu_1} = \bar{A}_{it} L_{it}^{\tilde{\lambda}_2} L_{it-1}^{(\psi_1+\psi_2)\tilde{\lambda}_1 - \psi_2 \tilde{\lambda}_2} S_i^{\tilde{\lambda}_1 - \tilde{\lambda}_2},$$

where $\bar{A}_{it}$ conflates fundamentals, $\tilde{\lambda}_1 = \lambda_1 \nu_1$ and $\tilde{\lambda}_2 = \lambda_2 \nu_1$. Manipulating this, we have:

$$w_{it} = A_{it} \left(\frac{L_{it}}{S_i} \right)^{\tilde{\lambda}_2} \left(\frac{L_{it-1}}{S_i} \right)^{(\psi_1+\psi_2)\tilde{\lambda}_1 - \psi_2 \tilde{\lambda}_2}, \tag{D.14}$$

where A_{it} absorbs fundamentals. The wage is increasing in current employment density (L_{it}/S_i). The effect of previous employment density (L_{it-1}/S_i) depends on the sign of parameters. Assuming that the firm profit goes outside of the economy, the rest of the model behaves the same as our main model in Section 4 with A_{it} is given by the right-hand-side of (D.14).

D.5.2 Innovation by Incumbent Workers in Local Firms

The technology of final good producers is linear in labor, $y_{it} = A_{it}L_{it}$ where L_{it} is total employment. Productivity of firms in location i is determined by:

$$A_{it} = (\phi_{it} - \delta_A){L_{it}}^{\chi}\bar{A}_{t-1}, \tag{D.15}$$

which has three different components. First, productivity grows at rate $\phi_{it} - \delta_A$. ϕ_{it} is innovation between period $t-1$ and t and δ_A is the obsolescence rate of previous idea. Second, there is scale effects in innovation and parameter χ captures the return to employment size in knowledge spillovers. Third, all firms can access the productivity frontier of the last period, $\bar{A}_{t-1} = \max_i A_{it-1}$. In the following, we discuss how we determine innovation, ϕ_{it}.

The innovation ϕ_{it} is equal to the average units of a blueprint of innovators in location i. In period t, only incumbent workers who stay in the location from the period $t-1$ can do innovation since it requires experience in the local firms. Among workers in i at period t, incumbent workers who do not have an opportunity of moving are $(1-\theta_t)L_{it-1}$. Each incumbent workers have one unit of the blueprint of ideas at the end of period $t-1$, $z^{\text{Old}}_{it-1} = 1$.

At the beginning of period t, all workers in location i draw new blueprints from Pareto distribution with support $[1, \infty)$. Specifically, units of blueprints are drawn from $1 - z^{-\varrho}$ and its average is $\frac{\varrho}{\varrho-1}$. Intuitively, all workers of L_{it} in location i including both incumbent and movers have new ideas relative to the incumbent ideas, and they acquire the average size of innovating ideas $z^{\text{New}}_{it} = \frac{\varrho}{\varrho-1}$.

Incumbent workers of $(1-\theta_t)L_{it-1}$ can update their ideas or keep their obsolete ideas. To update their ideas, they need to meet workers who draw new ideas and their matching function is given by:

$$\mathcal{P}((1-\theta_t)L_{it-1}, L_{it}) = e_{it}((1-\theta_t)L_{it-1})^{\varpi_1}(L_{it})^{\varpi_2}, \tag{D.16}$$

where e_{it} controls matching efficiency and parameters are $\varpi_1 \in (0,1)$ and $\varpi_2 \in (0,1)$ as in standard matching function. Then, the share of incumbent workers who update their blueprints is:

$$s^{\text{New}}_{it} = \frac{\mathcal{P}((1-\theta_t)L_{it-1}, L_{it})}{(1-\theta_t)L_{it-1}} = e_{it}((1-\theta_t)L_{it-1})^{\varpi_1-1}(L_{it})^{\varpi_2}$$

Then, the average units of blueprints per incumbent worker become:

$$\phi_{it} = s^{\text{New}}_{it} z^{\text{New}}_{it} + (1 - s^{\text{New}}_{it}) z^{\text{Old}}_{it-1} = 1 + \frac{e_{it}}{\varrho - 1}((1-\theta_t)L_{it-1})^{\varpi_1-1}(L_{it})^{\varpi_2}$$

Plugging this into (D.15) and setting $\delta_A = 1$, we obtain productivity in location i:

$$A_{it} = \frac{e_{it}}{\varrho - 1}((1-\theta_t)L_{it-1})^{\varpi_1-1}(L_{it})^{\varpi_2+\chi}\bar{A}_{t-1} \tag{D.17}$$

Productivity depends on matching efficiency (e_{it}), the number of incumbent workers who have blueprints for innovation, a mass of workers in period t and the technology frontier in the previous period ($\bar{A}_{t-1}$). In particular, this is decreasing in the number of incumbent workers since they are imperfectly updating their obsolete blueprints and more incumbent workers lead to a small share of updating their blueprints. In contrast, this is increasing in the current number of workers since more workers lead to a large number of matching for updating blueprints of incumbent workers and directly increase productivity through scale effects. Lastly, matching efficiency can absorb any characteristics in location i. Among them, it is natural to assume that a small area is associated with higher matching efficiency. Therefore, we can write the right-hand side of (D.17) as a function of employment density.

D.6 Microfoundation of Amenity Agglomeration Forces

We consider local investment in housing. In each location there are homogeneous developers or absentee landlords and each of them develops local amenities including housing or general amenities for residents. In location n, they solve:

$$\max_{c_{nt}, c_{nt+1}, X_{nt+1}, H_{nt+1}} v(c_{nt}) + \rho v(c_{nt+1})$$

subject to

$$H_{nt+1} \leq \left(\frac{S_n}{H_{nt}}\right)^{\delta_H} \left(\frac{(1-\varsigma_n)H_{nt}}{\eta}\right)^{\eta} \left(\frac{X_{nt+1}}{1-\eta}\right)^{1-\eta}, \quad \eta \in (0,1)$$

$$c_{nt} + \frac{c_{nt+1}}{1+r_{t+1}} + \mathcal{O}(X_{nt+1}, H_{nt})H_{nt} \leq \frac{Q_{nt+1}H_{nt+1}}{1+r_{t+1}}$$

Developers consume numéraire and $v(\cdot)$ is a CRRA utility function. The stock of floor spaces for residents at period t is H_{nt}. The developers live for two periods and choose consumption (c_{nt}, c_{nt+1}) and investment in the first period (X_{nt+1}). We assume that the housing market is competitive so that developers take the housing price Q_{nt+1} as given.[28] In the budget constraint investing X_{nt+1} units of numéraire requires adjustment costs $\mathcal{O}(X_{nt+1}, H_{nt})$ per unit of the current stock of housing. Specifically, we posit the function for the investment and adjustment costs:

$$\mathcal{O}(X_{nt+1}, H_{nt}) = \left(\frac{X_{nt+1}}{\psi H_{nt}}\right)^{\psi}, \tag{D.18}$$

where we assume that $\psi > 1$ so that the investment costs are convex function of investment. This is a traditional functional form of investment costs in macroeconomics (see, for example Baxter and Crucini 1993). The production technology of floor space exhibits decreasing returns to investment. Housing is durable with depreciation rate ς_n and more housing stocks in the period t (H_{nt}) save the

[28]Perfect competition in the housing market seems a reasonable assumption because there were many small developers in Hiroshima city after WW2. For example, the 1948 Statistical Abstract of Hiroshima City documents that there were 1057 establishments classified as “construction industry” and the average number of workers per establishment was about 9.

required investment to provide a given amount of housing units in period $t+1$. The additional term $(S_n/H_{nt})^{\delta_H}$ reflects the idea that available land measured by the land endowment per residential floor space may affect the housing production cost. In particular, $\delta_H > 0$ may hold if more available land reduces the development cost.[29]

We suppose that $(1+r_{t+1})\rho = 1$ and consumption is constant over time. First order conditions for the problem imply:

$$Q_{nt+1} = \frac{1}{\rho(1-\eta)} \left(\frac{\psi H_{nt}}{X_{nt+1}} \right)^{1-\psi} \frac{X_{nt+1}}{H_{nt+1}} \tag{D.19}$$

Manipulating this, we obtain:

$$Q_{nt+1} = \bar{k}_n \left(\frac{S_n}{H_{nt}} \right)^{\delta_H \tilde{\psi}} (H_{nt})^{1-\tilde{\psi}} (H_{nt+1})^{\tilde{\psi}(1-\psi(1-\eta))}, \tag{D.20}$$

where $\bar{k}_n$ is constant and we define $\tilde{\psi} \equiv \psi/(1-\eta) > 1$.

We suppose that each household requires one unit of floor space: therefore in equilibrium, $H_{nt+1} = R_{nt+1}$ and $H_{nt} = R_{nt}$. Using them, we can express the value of amenities in n at period $t+1$ by:

$$Q_{nt+1} = \bar{k}_n S_n^{(1-\tilde{\psi})+\tilde{\psi}(1-\psi(1-\eta))} \left(\frac{R_{nt}}{S_n} \right)^{(1-\tilde{\psi})-\delta_H \tilde{\psi}} \left(\frac{R_{nt+1}}{S_n} \right)^{\tilde{\psi}(1-\psi(1-\eta))}. \tag{D.21}$$

If the share of input in development $(1-\eta)$ is relatively small, the supply of residential amenities is inelastic and the price (Q_{nt+1}) is increasing with population density in period $t+1$ due to congestion in the housing market. In contrast, if δ_H is sufficiently small, the price is decreasing in population density in period t. Intuitively, the large stock of housing in period t leads to a lower marginal cost of investment in period $t+1$. This turns out to be the positive spillover effects of current population density (R_{nt}/S_n) on the benefits from the local amenities. When we relate this microfoundation to our representation in amenities and calibration results, this property is consistent with the positive coefficient, $\beta_2 > 0$. In contrast, our estimation of $\beta_1 > 0$ suggests that housing and amenity supply is likely relatively elastic.

E Calibration Appendix

We follow multiple steps to estimate structural parameters in the model. This section provides details for Section 5 in the main text.

[29] Several mechanisms can rationalize $\delta_H > 0$. First, more land availability may imply lower land prices for developers due to a larger amount of land supply. Second, the availability of a large land plot may facilitate a large-scale development project through reduced transaction costs (Yamasaki et al. 2022).

E.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 κ_{int}^m in travel mode m is given by $\kappa_{int}^m \equiv \exp(c_{int}^m) > 0$ with (an inverse of) mode-specific travel cost:

$$-c_{int+1}^m \equiv -\delta\tau_{int+1}^m + \gamma^m + s_{int+1}^m(\omega),$$

where τ_{int+1}^m is the travel time in minutes between i and n in period $t+1$, δ captures the marginal increase in travel cost when the travel time increases by one minute, γ^m is the mode-specific fixed cost such as transfers and parking, and $s_{int+1}^m(\omega)$ 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 $-c_{int+1}^m$).

Assume that $s_{int+1}^m(\omega)$ 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 while the latter does. Using the well-known log-sum formula (Train 2009), we can write the expected commuting cost as

$$\bar{c}_{int+1}^{\text{car}} = -\ln\left(\exp(-\bar{c}_{int+1}^{\text{pub}}) + \exp(-\bar{c}_{int+1}^{\text{pri}})\right), \quad \bar{c}_{int+1}^{k} \equiv -\nu_k \ln \sum_{m\in\mathcal{B}_k} e^{-(\delta\tau_{int+1}^m - \gamma^m)/\nu_k}$$

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 Section 4. 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 p_{car} based on the car ownership rate in Japan: 0.1 in 1950, 0.2 in 1955, 0.3 in 1960, 0.4 in 1965, 0.5 in 1970, and 0.7 in 1975. Note 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. 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 was 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:

$$L_{in} = \lambda_{in} M = \frac{\bar{u}_{in}^{\rho/\sigma}}{\sum_d \bar{u}_d^{\rho/\sigma}} M$$

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

$$\ln L_{in} = \frac{\rho}{\sigma}\left(\ln B_n + \ln w_i - \ln \bar{\kappa}_{in}\right) + \ln \bar{M} \tag{E.1}$$

where $\ln \bar{M} \equiv \ln M - \ln \sum_d \bar{u}_d^{\rho/\sigma}$ and

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

This corresponds to the gravity equation (13) in the main text.

Table E.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 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 Tenreyro 2006) and we set $\rho_t/\sigma_t = 8$ in our calibration.

Table E.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	-3.976	-5.758	-3.931	-8.019	-7.031
	(0.156)	(0.170)	(0.179)	(0.169)	(0.195)	(0.215)
Estimation	OLS		OLS		PPML	
Number of observations	2,473	1,635	4,356	1,635	4,290	1,635
More than 20 commuters		✓		✓		✓
R-squared or Pseudo R-squared	0.543	0.522	0.551	0.521	0.764	0.729

Note: We report estiamtes of gravity equation (13) for commuting by OLS in Columns 1 and 2. In Columns 3 and 4, we use OLS but with adding 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.

E.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 (D.8) becomes: $\lambda_{int} = \lambda_{ot} \exp(\widetilde{V}_{int})^{\rho/\sigma}$. Then, (D.9) and (D.10) can be expressed by:

$$R_{nt} - (1-\theta_t)R_{nt-1} = \lambda_{ot}\theta_t \left[\sum_i \exp\left(\widetilde{V}_{int}\right)^{\rho_t/\sigma_t}\right] M \tag{E.2}$$

$$L_{it} - (1-\theta_t)L_{it-1} = \lambda_{ot}\theta_t \left[\sum_n \exp\left(\widetilde{V}_{int}\right)^{\rho_t/\sigma_t}\right] M \tag{E.3}$$

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

$$K_{int} \equiv \kappa_{int}^{-\rho_t/\sigma_t} \left\{ \prod_{\tau=t+1}^{T} \kappa_{in\tau}^{-\prod_{s=t+1}^{\tau} \rho_s(1-\theta_s)} \right\}^{\rho_t/\sigma_t},$$

$$v_t \equiv u_{ot}^{-\rho_t/\sigma_t} \left\{ \prod_{\tau=t+1}^{T} u_{o\tau}^{-\prod_{s=t+1}^{\tau} \rho_s(1-\theta_s)} \right\}^{\rho_t/\sigma_t}$$

for values of commuting costs and outside options.[30] Then, (E.2) and (E.3) become:

$$R_{nt} - (1-\theta_t)R_{nt-1} = \lambda_{ot}\theta_t v_t M \Xi_{nt}^{\rho_t/\sigma_t} \sum_{i \in \mathcal{C}} K_{int} \Omega_{it}^{\rho_t/\sigma_t}, \tag{E.4}$$

$$L_{it} - (1-\theta_t)L_{it-1} = \lambda_{ot}\theta_t v_t M \Omega_{it}^{\rho_t/\sigma_t} \sum_{n \in \mathcal{C}} K_{int} \Xi_{nt}^{\rho_t/\sigma_t}. \tag{E.5}$$

for periods $t = 1, 2, \cdots, T$. Substituting (E.5) into (E.4) 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.

E.3 Step # 3: Estimation of Parameters $(\alpha_1, \alpha_2, \beta_1, \beta_2)$

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

$$\Xi_{nT} = b_{nT} \left(\frac{R_{nT}}{S_n} \right)^{\beta_1} \left(\frac{R_{nT-1}}{S_n} \right)^{\beta_2} \tag{E.6}$$

Given the observation of population (R_{nT}, R_{nT-1}), block size S_n and parameters $(\alpha_1, \alpha_2, \beta_1, \beta_2)$, we can invert this for fundamental amenities $\{b_{nT}\}$ in period T. In period $T-1$ we have:

$$\Xi_{nT-1} = b_{nT-1} \left(\frac{R_{nT-1}}{S_n} \right)^{\beta_1} \left(\frac{R_{nT-2}}{S_n} \right)^{\beta_2} \Xi_{nT}^{\rho_T(1-\theta_T)} \tag{E.7}$$

Given population density in period $T-1$ and $T-2$, parameter ρ_T, migration friction θ_T and option value $\{\Xi_{nT}\}$, we can invert this for the fundamental amenities in the previous period.[31] We continue this process and obtain the sequence of fundamental amenities: $\{b_{nt}\}_{t=1,\cdots,T}$. For the productivity,

[30] For 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: $K_{in,50} = \kappa_{in,50}^{-\rho_{50}/\sigma_{50}} (K_{55})^{\rho_{55}(1-\theta_{55})\frac{\sigma_{55}}{\sigma_{50}}}$.

[31] For instance, fundamental amenities in period $t = 75$ are given by: $b_{n,75} = \Xi_{n,75} \left(\frac{R_{n,75}}{S_n}\right)^{-\beta_1} \left(\frac{R_{n,70}}{S_n}\right)^{-\beta_2}$. And for period $t = 70$, $b_{n,70} = \Xi_{n,70} \left(\frac{R_{n,70}}{S_n}\right)^{-\beta_1} \left(\frac{R_{n,65}}{S_n}\right)^{-\beta_2} \Xi_{n,75}^{-\rho_{75}(1-\theta_{75})}$.

we can decompose $\{\Omega_{it}\}_{t=1,2,\cdots,T}$ to obtain the sequence of fundamental productivity $\{a_{it}\}_{t=1,\cdots,T}$ in analogous way.

The fundamental amenities and productivity $\{a_{it}, b_{nt}\}_{t=1,\cdots,T}$ are uniquely given. These fundamentals are structural residuals in our calibration for the observation to be equilibrium. We assume that the fundamentals consist of location fixed components, time fixed components and variant terms:

$$\begin{aligned} \ln a_{it} &= \ln a_i^F + \ln a_t^* + \ln a_{it}^{\text{Var}}, \\ \ln b_{nt} &= \ln b_n^F + \ln b_t^* + \ln b_{nt}^{\text{Var}} \end{aligned} \tag{E.8}$$

where ($\{a_i^F\}$, $\{b_n^F\}$) are location fixed productivity and amenities, ($\{a_t^*\}$, $\{b_t^*\}$) are trend of productivity and amenities and ($\{a_{it}^{\text{Var}}\}$, $\{b_{nt}^{\text{Var}}\}$) are stochastic part of fundamental productivity and amenities. The location fixed productivity and amenities capture the first nature advantages of locations and trend of productivity and amenities reflect the change in levels over time.

Averaging out the trend yields:

$$\begin{aligned} \ln \tilde{a}_{it} &\equiv \ln a_{it} - \frac{1}{N}\sum_i \ln a_{it} = \ln \tilde{a}_i^F + \ln \tilde{a}_{it}^{\text{Var}}, \\ \ln \tilde{b}_{nt} &\equiv \ln b_{nt} - \frac{1}{N}\sum_n \ln b_{nt} = \ln \tilde{b}_n^F + \ln \tilde{b}_{nt}^{\text{Var}}, \end{aligned}$$

where $\tilde{a}_i^F \equiv a_i^F/\bar{a}^F$, $\tilde{b}_n^F \equiv b_n^F/\bar{b}^F$, $\tilde{a}_{it}^{\text{Var}} \equiv a_{it}^{\text{Var}}/\bar{a}_t^{\text{Var}}$ and $\tilde{b}_{nt}^{\text{Var}} \equiv b_{nt}^{\text{Var}}/\bar{b}_t^{\text{Var}}$ are variables adjusted with geometric mean. Then, taking the difference between periods and we suppose the following moment conditions:

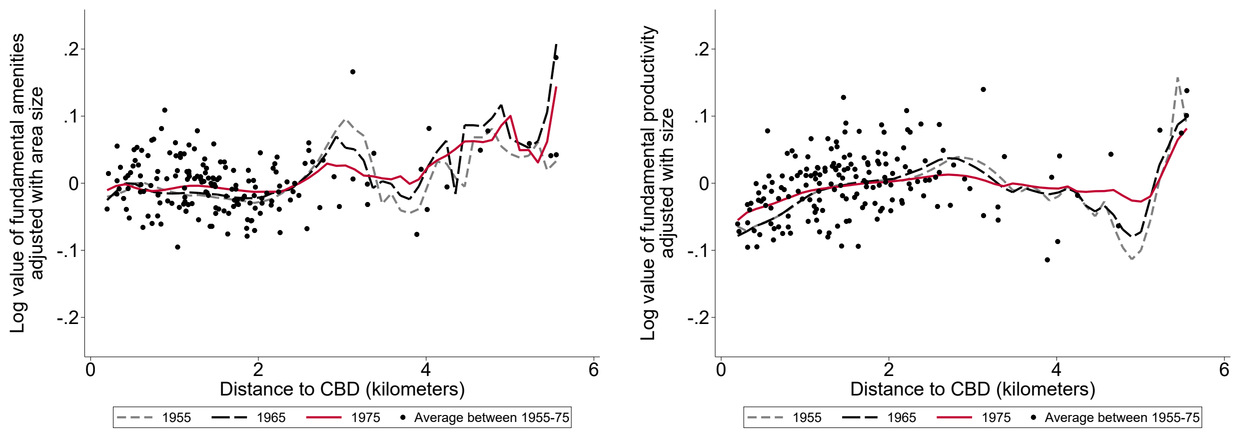
$$\begin{aligned} \mathbb{E}\left[\Delta \ln \tilde{a}_{it} \times \mathbb{1}_i(k)\right] &= 0, \\ \mathbb{E}\left[\Delta \ln \tilde{b}_{nt} \times \mathbb{1}_n(k)\right] &= 0, \end{aligned} \tag{E.9}$$

where $\Delta \ln \tilde{a}_{it} = \Delta \ln \tilde{a}_{it}^{\text{Var}}$ and $\Delta \ln \tilde{b}_{nt} = \Delta \ln \tilde{b}_{nt}^{\text{Var}}$ are change in the idiosyncratic shocks in productivity and amenities between period $t-1$ and t and $\mathbb{1}_n(k)$ is an indicator such that location n is in the grid k. The grid is defined based on the distance from CBD as in Ahlfeldt et al. (2015). Our identification assumption is that any improvements or declines in the stochastic shocks of productivity and amenities over any six years period are unrelated to the distance from the city center. We use the moment conditions (E.9) to estimate the set of parameters of agglomeration forces (α_1, α_2, β_1, β_2).

E.4 Calibrated Amenities and Productivity

We present additional discussions on the amenities and productivity in our calibration. Figure E.1 presents the estimated location-specific amenities and productivity. We adjust for the block size since the fundamental amenities and productivity tend to be mechanically undervalued for a smaller block (see Train 2009). 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, the 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 the location-specific productivity and amenities on the log of area size, and we plot the residuals from the regressions.[32] Figure E.1a and E.1b show the result for amenities and productivity, respectively. Both are not strongly related to the distance from the CBD and if any, amenities and productivity are relatively lower in areas closer to the CBD.

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



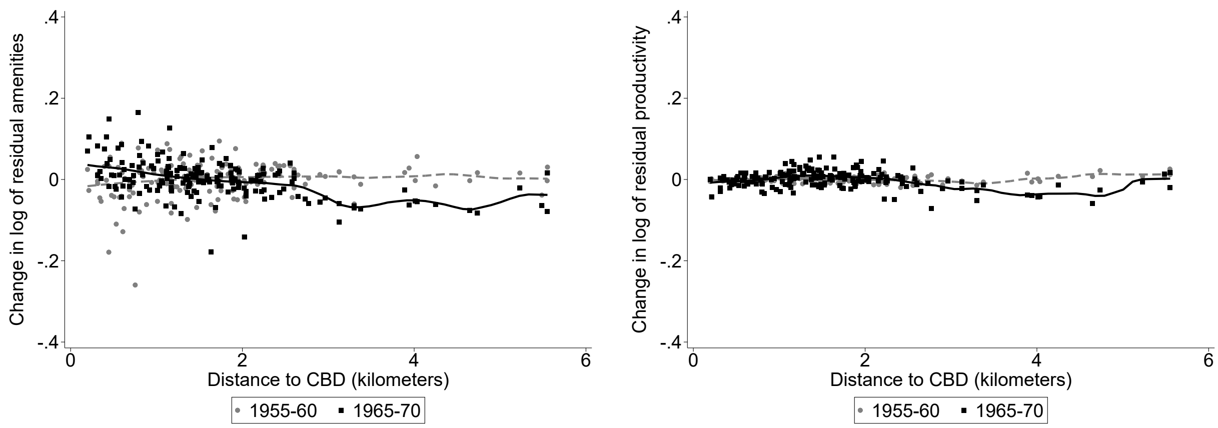
(a) Amenity **(b)** Productivity

Note: These figures display fundamental productivity ($\bar{a}_i$) and amenities ($\bar{b}_n$) in our calibration, after netting out the block size using the residual of the linear regression of the fundamentals on the log block size. Each line shows a local polynomial fitted line.

Figure E.2 displays the changes in residuals of fundamental amenities ($\Delta \ln \tilde{b}_{nt}$) and productivity ($\Delta \ln \tilde{a}_{it}$) for different periods, 1955-60 and 1965-70. During the early period, the changes exhibit small variations across locations in the city and this confirms that the idiosyncratic part of the fundamental location advantages in amenities is less important to explain the population changes during this period. In the later period, 1965-70, we observe some increase of the residuals in the area close to CBD while dropping in the periphery. This is consistent with the suburbanization that proceeds not because of the fundamental locational advantages in the periphery but the expectation of moving toward the periphery. 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 of employment distribution in the city and this is reassuring for our identification assumption.

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

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



(a) Change in Fundamental Amenities **(b)** Change in Fundamental Productivity

Note: These figures show changes in fundamental amenities ($\Delta \ln \tilde{b}_{nt}$) and productivity ($\Delta \ln \tilde{a}_{it}$) for two periods, 1955-60 and 1965-70. Each point represents different blocks and lines are local polynomial regressions.

E.5 Simulating Population and Employment Density for 1945-1950.

Having estimated model parameters (α_1, α_2, β_1, β_2) by exploiting the data from 1950 to 1975, we can evaluate how much the model explains the population and employment change from 1945 to 1950 after the atomic bombing. We compare the distribution of population and employment between observations and simulated ones in 1950 when we abstract the structural errors. In particular, we solve the system of equations:

$$\begin{aligned} R_{n,50} &= (1-\theta_{50})R_{n,45} + \sum_i \frac{K_{in,50}\left(\widetilde{\Xi_{n,50}}\right)^{\rho_{50}/\sigma_{50}}}{\sum_j K_{ij,50}\left(\widetilde{\Xi_{j,50}}\right)^{\rho_{50}/\sigma_{50}}}\left(L_{i,50}-(1-\theta_{50})L_{i,45}\right) \\ L_{i,50} &= (1-\theta_{50})L_{i,45} + \sum_n \frac{K_{in,50}\left(\widetilde{\Omega_{i,50}}\right)^{\rho_{50}/\sigma_{50}}}{\sum_j K_{jn,50}\left(\widetilde{\Omega_{j,50}}\right)^{\rho_{50}/\sigma_{50}}}\left(R_{n,50}-(1-\theta_{50})R_{n,45}\right). \end{aligned} \tag{E.10}$$

where we use

$$\begin{aligned} \widetilde{\Xi_{n,50}} &\equiv \widetilde{b}_n \left(\frac{R_{n,50}}{S_n}\right)^{\beta_1}\left(\frac{R_{n,45}}{S_n}\right)^{\beta_2} \Xi_{n,55}^{\rho_{55}(1-\theta_{55})}, \\ \widetilde{\Omega_{i,50}} &\equiv \widetilde{a}_i \left(\frac{L_{i,50}}{S_i}\right)^{\alpha_1}\left(\frac{L_{i,45}}{S_i}\right)^{\alpha_2} \Omega_{i,55}^{\rho_{55}(1-\theta_{55})} \end{aligned} \tag{E.11}$$

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 (E.8). Importantly, using ($\widetilde{a}_i$,

$\widetilde{b}_n$) eliminates the idiosyncratic structural errors in amenities and productivity $a_{it}^{\text{Var}}, b_{it}^{\text{Var}}$.[33] 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 of the model and structural errors in predicting the recovery by comparing the observed population and employment distribution and its prediction from equations (E.10) and (E.11).

We can similarly obtain the model prediction when there are no agglomeration forces by setting $\alpha_1 = \alpha_2 = \beta_1 = \beta_2 = 0$ in equation (E.11).[34] The comparison of model predictions with and without agglomeration forces indicates their importance in accounting for the recovery of central Hiroshima.

References for the Appendix

Ahlfeldt, Gabriel M, Stephen J Redding, Daniel M Sturm, and Nikolaus Wolf, "The economics of density: Evidence from the Berlin Wall," *Econometrica*, 2015, *83* (6), 2127–2189.

Allen, Treb, Costas Arkolakis, and Xiangliang Li, "On the equilibrium properties of network models with heterogeneous agents," Technical Report, National Bureau of Economic Research 2020.

Baxter, Marianne and Mario J Crucini, "Explaining saving–investment correlations," *The American Economic Review*, 1993, pp. 416–436.

Brakman, Steven, Harry Garretsen, and Marc Schramm, "The strategic bombing of German cities during World War II and its impact on city growth," *Journal of Economic Geography*, 2004, *4* (2), 201–218.

Correia, Sergio, Paulo Guimarães, and Tom Zylkin, "Fast Poisson estimation with high-dimensional fixed effects," *The Stata Journal*, 2020, *20* (1), 95–115.

Davis, Donald R and David E Weinstein, "Bones, bombs, and break points: the geography of economic activity," *American Economic Review*, 2002, *92* (5), 1269–1289.

Hiroshima City Government, "Hiroshima Genbaku Sensai-Shi (The Hiroshima Atomic Bombing Damage Records)," 1971. (In Japanese).

Nagasaki City Government, "Nagasaki Genbaku Sensai-Shi Dai 5-kan Shiryouhen (The Nagasaki Atomic Bombing Damage Records: Volume 5 Data)," 1983. (In Japanese).

Santos Silva, J.M.C. and Silvana Tenreyro, "The log of gravity," *The Review of Economics and Statistics*, 2006, *88* (4), 641–658.

Takeda, Kohei and Atsushi Yamagishi, "History versus Expectations in the Spatial Economy: Lessons from Hiroshima," *Mimeo*, 2023.

Takezaki, Yoshihiko and Ryoji Soda, *Hiroshima Genbaku Dezitaru Atorasu (The Digital Atlas of Atomic Bombing in Hiroshima)*, Research center for regional geography, Hiroshima University, 2001. (In Japanese).

[33] The year-fixed amenities and productivity $(\bar{a}_t^*, \bar{b}_t^*)$ in (E.8) are also excluded from (E.11), but this does not affect the model prediction because they appear both in the denominator and the numerator of (E.10).

[34] Note that using equation (E.6) and (E.7), we also eliminate the agglomeration forces included in the future term $\Xi_{n,55}$. The same applies for $\Omega_{n,55}$.

Train, Kenneth E, *Discrete choice methods with simulation*, Cambridge university press, 2009.

Tsivanidis, Nick, "Evaluating the impact of urban transit infrastructure: Evidence from bogota's transmilenio," *mimeo*, 2022.

Yamagishi, Atsushi and Yasuhiro Sato, "Persistent Stigma in Space: 100 Years of *Japan's Invisible Race* and Their Neighborhoods," *mimeo*, 2023.

Yamasaki, Junichi, Kentaro Nakajima, and Kensuke Teshima, "From samurai to skyscrapers: How historical lot fragmentation shapes Tokyo," *mimeo*, 2022.