The billion pound drop: the Blitz and agglomeration economies in London

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Abstract

We exploit locally exogenous variation from the Blitz bombings to quantify the effect of redevelopment frictions and identify agglomeration economies at a micro-geographic scale. Employing rich location and office rental transaction data, we estimate reduced-form analyses and a spatial general equilibrium model. Our analyses demonstrate that more heavily bombed areas exhibit taller buildings today, and that agglomeration elasticities in London are large, approaching 0.2. Counterfactual simulations show that if the Blitz had not occurred, the concomitant reduction in agglomeration economies arising from the loss of higher-density redevelopment would cause London's present-day gross domestic product to drop by some 10% (or £50 billion).

1. Introduction

Cities are the engines of economic growth. Scholars have long recognized that this enhanced productivity appears to be heavily dependent upon the built environment—particularly the scale and density of economic activity. However, once cities' spatial structures have been established, they are slow to adapt. This sluggishness of change reflects the presence of the so-called 'redevelopment frictions' which may arise from a variety of sources, including the inherent durability of the building stock and transaction costs. However, in many cities the primary redevelopment friction appears to be regulation.

Redevelopment regulations—particularly building height limits and floor-area restrictions—may not necessarily reduce social welfare, as they may be a means to mitigate various externalities such as traffic congestion and incompatible land uses (Brueckner, 2000). Redevelopment regulations may also protect amenities and increase the quality of the built environment, implying a positive effect on land prices. However, many planning regulations limiting density have grown historically and have not been responsive to changes in local demand (Cheshire, 2009). Therefore regulatory hurdles pose perhaps the greatest obstacle to more compact urban growth (Cheshire and Sheppard, 2002; Glaeser et al., 2005; Glaeser and Gottlieb, 2009; Hilber and Vermeulen, 2016; Brueckner et al., 2017). London, the city which we focus on in this article, is a particularly interesting case.

Cheshire and Hilber (2008) show that London can be considered the world's most restrictive major office market—and far more restrictive than any market in the United States. Yet, within London, there are substantial local differences in land-use restrictions. For example, London's West End submarket is much more restrictive than the City of London or Canary Wharf, ostensibly due to its history and abundance of cultural amenities. Consequently, employment densities in the West End are considerably lower than in London's other submarkets.

Redevelopment frictions in real estate markets generally constrain employment densities, which implies that the potential for workers to gainfully interact is lower than if there were no frictions prohibiting greater clustering. Agglomeration economies arise due to labor market pooling, input and output sharing and knowledge spillovers (Marshall, 1890), and appear to be highly dependent on the density of economic activity (Ciccone and Hall, 1996; Rosenthal and Strange, 2003; Ahlfeldt et al., 2015). These advantages seem to explain why rents for a unit of office space in elite global cities like London, New York and Tokyo are several multiples above their corresponding national averages. However, endogeneity issues make identification of the economic effects of density challenging. Both height constraints and density, for example, could be directly influenced by prices (see Hilber and Robert-Nicoud, 2013).

This article aims to investigate both (*i*) the effect of redevelopment restrictions on density and (*ii*) the impact of density on agglomeration economies. By linking these two relationships in a structural model, we can show that redevelopment frictions may strongly reduce the benefits of agglomeration and therefore have a profound impact on London's urban spatial structure and productivity. We address the potential endogeneity issue by using a quasi-experimental setting based on the Blitz bombings, which erased a substantial portion of London's building stock at the time.[1] Because more heavily bombed areas are more likely to lose historic buildings and amenities, the local concentration of bombs dropped during the Blitz provides an exogenous source of variation in the local permissiveness of present day regulation, which allows us to establish estimates for agglomeration economies at a micro-geographic scale. A concern with this methodology, however, is that the location of bombings may not be completely random over space, and may therefore be correlated with centrality or specific locational endowments. To address this concern, we present both anecdotal and rigorous statistical evidence that the locations of Blitz bombings were indeed random at our local scale of analysis.

We further adapt Ahlfeldt et al.'s (2015) quantitative spatial model of a city to predict the general equilibrium effects of the reduction in redevelopment frictions resulting from the Blitz. Because redevelopment frictions at one location may also impact location choices at another further away, for example, via commuting of workers and agglomeration economies, such a model is necessary to evaluate the overall effects of redevelopment frictions on London's entire urban spatial structure. We incorporate variation in Blitz bombings into the model in two ways. First, we allow redevelopment frictions, as proxied by bomb density, to lower the density of economic activities at a certain location. Second, we use Blitz bombings as an instrument for agglomeration to address potential endogeneity of agglomeration. Hence, this follows closely the main estimated reduced-form

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1   For instance, it is estimated that one third of the buildings in the City of London were severely damaged or destroyed (Marriott, 1989, 66).

equations. Using the recursive structure of the model, we estimate its structural parameters and calculate the effects of counterfactual experiments.

Our reduced-form results indicate that a standard deviation increase in Blitz bomb density is now associated with a 6.45% increase in local building height and that office rents increase by roughly 20% for each doubling in employment density. In addition, the structural parameters obtained from the quantitative spatial equilibrium model confirm the reduced-form evidence: density is positively related to bombings and the agglomeration elasticity is about 0.2, which is 2 to 10 times greater than estimates produced in prior research. Although these effects are large, we argue that they are consistent with the higher agglomeration economies thought to exist in elite global cities. These findings are robust to a wide range of sensitivity checks.

Related literature

This article makes a number of positive contributions to the literature on the economic effects of land-use regulation and our understanding of agglomeration economies. While the economies of the developed world have ostensibly been liberalized over the past several decades, land-use regulation has by contrast generally expanded and intensified (McLaughlin, 2012). Although the current empirical literature on the economic effects of land-use regulation focuses almost entirely on the housing market (see Turner et al., 2014; Siodla, 2015; Hornbeck and Keniston, 2017; Hsieh and Moretti, 2019), such restrictions would seem most important in the context of commercial property, whose high-rise office buildings dominate most CBDs.[2]

Although using wage data to measure productivity is most common, office rents are arguably the best economic manifestation of agglomeration economies arising from service industries in urban areas (Drennan and Kelly, 2011, 488). Similar to only a few recent studies on agglomeration economies, we employ actual transactions of commercial office rents for individual buildings as our dependent variable in the reduced-form analyses.[3] Related literature primarily proxies commercial transaction prices with either valuations, asking prices (Arzaghi and Henderson, 2008) or residential prices (Dekle and Eaton, 1999). In addition, we compare our results derived from office rents with those from the residential market. Furthermore, we examine London exclusively, and at a micro-geographic scale, thereby producing specific estimates for the level of agglomeration economies operative within one of the world's largest and most productive cities.

In addition, our results contribute to the still limited stream of research within the broader agglomeration literature that has employed exogenous sources of variation in employment density. However, unlike some previous research, we are able to objectively verify the exogeneity of our instrument: Blitz bombings. Employing historical war damage as a source of exogenous variation has become increasingly common in empirical work addressing challenging econometric questions. For example, using wartime bombings as a proxy for economic shocks, Davis and Weinstein (2002), Brakman et al. (2004) and Bosker et al. (2007) show that enduring location-based natural advantages maintain the relative economic status *between* cities over the long-run. Whereas, akin to this study, Koster et al. (2012), Redding and Sturm (2016) and Kappner (2018) investigate the long-run impacts of war damage *within* cities.

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2   As an illustration, of London's 10 tallest buildings only one is classified as primarily residential.
3   See, for example, Koster et al. (2014) and Liu et al. (2018).

Finally, we contribute to an emerging literature that estimates quantitative models to predict the general equilibrium effects of shocks to the economy. Hsieh and Moretti (2019), for instance, employ a Rosen–Roback style model to estimate the impact of housing supply constraints at the metropolitan area level, and show that relaxing land-use restrictions in New York, San Jose and San Francisco to the median level of restrictions in the United States would increase the growth rate of those cities by 36%. Whereas Ahlfeldt et al. (2015), whose model we follow closely, use the Berlin Wall as an exogenous shock to density to estimate the magnitude and scope of agglomeration economies. A recent paper by Brinkman and Lin (2019) has likewise adapted this model to measure the disamenity effects of highways and their impacts on the urban spatial structure.

This article proceeds as follows. In Section 2, we provide relevant background on redevelopment frictions in the London office market, the Blitz and the data. In Section 3, we discuss the econometric framework and the reduced-form results. In Section 4, we outline the structural model, estimate the parameters, conduct counterfactual simulations and frame our findings within the existing literature and Section 5 concludes.

2. Research context and data

2.1. Redevelopment frictions in London

Redevelopment frictions tend to reduce urban density and by consequence agglomeration economies. These frictions can arise from a variety of sources including; the durability of buildings (Wheaton, 1982), transaction costs (Buitelaar, 2004), strategic behavior (Munch, 1976; Dixit and Pindyck, 1994), idiosyncratic owner-value (Nedzell and Block, 2007) and planning regulations (Ball, 2011).

Although it is frequently not possible to isolate the effects of different redevelopment frictions (Brooks and Lutz, 2016), in the case of London, it is well-established that a principal redevelopment friction is planning regulation. London has one of the most extreme and long-standing regimes of building development control in the developed world, both in terms of the quantity of land made available for development and permissible building height (Cheshire and Hilber, 2008; Hilber and Vermeulen, 2016; Cheshire et al., 2018a). Between 1890 and 1956 near-absolute height limits preventing new development taller than existing structures operated continuously across London. Then from 1956, absolute height limits were replaced with plot ratio restrictions of only 2:1 to at most 5.5:1. In the 1980s and 1990s, however, local authorities gradually removed these in favor of the somewhat more discretionary planning system in use today (Kufner, 2011; Cheshire and Dericks, 2020). During the same period, additional layers of development control were progressively added and intensified, including development bans on conservation areas, listed buildings, greenbelts, protected viewing corridors and legal restrictions on land-use categories. The upshot of these 130 years of strict planning controls has been the preservation of urban densities in London more characteristic of the 19th rather than 21st century. For instance, the average building height in London's primary financial district, the City of London, is an anachronistic eight floors.[4]

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4 For more background information regarding redevelopment regulations in London, we refer to Supplementary Appendix A.1.

2.2. Blitz bomb strikes as a determinant of current redevelopment frictions

Although London was attacked periodically throughout WWII, the city was most intensively targeted during the 8-month period between 7 September 1940 and 11 May 1941 known as the Blitz. Arguably no other event has impacted London's modern-day built environment more. Hitler's explicit goal in the Blitz was to 'erase' London, and it was intended that these attacks would finally break the resolve of the defending population, as the Luftwaffe had recently achieved at Guernica, Warsaw and Rotterdam (Goss, 2010, 23). During the Blitz, the Luftwaffe dropped 18,291 tons of high explosives and countless incendiaries, destroying or damaging 576,947 homes and killing 19,622 of London's 4,013,400 residents (Ray, 1996, 264; London County Council, 2005, 22).[5]

Although the Blitz ended almost 80 years ago, we argue that the density of Blitz bombings is a suitable proxy for local redevelopment frictions today because greater local bombing leads to more permissive local regulation which then promotes higher local densities. This is because culturally significant locations are less likely to survive in areas that have been heavily bombed, and rebuilt buildings and surrounding areas are also less likely to later receive protection (Creigh-Tyte, 1998). A recent article from a popular UK newspaper entitled 'Blitzed, rebuilt and built again' underscores this point stating that:

> [I]t is astonishing how often the bomb site of 1940 is the building site of 2015. Developers and planners are still working round decisions made when London was rebuilt following the [Blitz] (Watts, 2015).

Panoramic inspection of London also supports this association, with the heavily bombed eastern portion of the City of London and the Docklands now featuring London's most permissive height restrictions.[6] More concretely, we further show in Supplementary Appendix A.6 that greater Blitz bomb density is associated today with more permissive local planning regulations as measured by London local planning authority permission refusal and delay rates.

Alternative explanations for the Blitz's effect on density also seem less than satisfactory. For instance, bomb-damaged sites may not in fact benefit from lower redevelopment frictions as a result of the Blitz's gratis demolition due to: greater clearing costs, more dangerous worksites, reduced scrap value and the need to repair damage to the integrity of the ground. More crucially, demolition costs are in fact de minimis in comparison to the cost of construction and the value of extra space. Data obtained from the construction cost consultants Gardiner and Theobald quote demolition costs for an eight-floor (i.e. average height) office building in the City of London of £54/m^2 versus total construction costs of £3,767/m^2 (for a building up to 22 floors). This compares with a value of extra space of some £14,000/m^2 (Cheshire and Dericks, 2020, 23). These price differentials imply that it could be money-making today to replace a modern eight-floor office building with another only three floors taller.[7] Therefore, even if immediately after the war it was indeed *only* profitable to build taller on Blitzed sites, such is the current value of space that essentially all buildings of that era in central London now share this incentive. Thus it is probable

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5 For more background information on the Blitz and the difficulties in achieving bombing accuracy in the night-time conditions representative of our sample, we refer to Supplementary Appendix A.2.

6 This relationship is even more striking in Rotterdam where, four months prior to the London Blitz, its city center was devastated by the Luftwaffe while surrounding areas went largely unscathed. Koster et al. (2012) observed that the boundaries of the now conserved—and hence lower density—areas are sharply delineated by the extent of this bombing.

7 i.e. $£14,000 \times 3 > £54 \times 8 + £3,767 \times 11$.

that a sizable fraction of non-Blitzed buildings would similarly have been rebuilt to higher densities today unless binding development controls had been in place since such redevelopment became profitable.

Finally, most alternative redevelopment frictions would apply only with respect to the 'own lot' of the building itself. Yet, our results are rather determined by the density of bombs falling within a building's general vicinity. Therefore, it is even more probable that the effects we observe are indeed driven by regulation. We explore additional evidence for the primacy of regulatory frictions in the redevelopment frictions currently operative in London in Supplementary Appendix A.1.

Nevertheless, as we cannot conclusively rule out the possibility that greater bombings capture still other important frictions, in the rest of the article, we will therefore refer more generally to the effect of the Blitz on 'redevelopment frictions'.

2.3. Data

We obtain the data from the Ordnance Survey on all buildings in Greater London and their corresponding building heights as of 2014. Using the Points-of-Interest data, we identify office buildings by selecting buildings that are occupied by commercial services.[8] We use the information on the postcode location of the building to link the building data to location attributes. We exclude observations for which the (maximum) building height is missing or <5 m, which refers to $\sim$1.5% of the data. Buildings with a footprint <25 m are excluded. We end up with information on 2,164,940 buildings, of which we classify 65,125 buildings as offices. We also gather data on geographic attributes, such as the distance to a park, open water, the Thames, as well as location attributes such as the distance to: highways, railway stations, tube stations and the nearest conservation area. Finally, we gather data on demographic attributes based on the 2011 Census at the Output Area level. For descriptive statistics on the building sample we refer to Table A2 in Supplementary Appendix A.3.

Rental data on office transactions consists of 9,202 leases signed in Greater London between 1997 and 2011 and was compiled by *Estates Gazette*. This data contains information on rents, floor space rented, year built or latest refurbishment year, the floor levels leased, total floor space in the building and total floors in the building. We also have information on the geographic location of the building leased at the address level. We take employment information from the 2011 Census, which is available at the Output Area level—the lowest geographical level at which census estimates are provided: the median size is only 0.0333 km^2.[9]

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8 The Points-of-Interest data classify four million places and real-world features in Great Britain by their use and function, also providing their postal address or location. Commercial services include; construction services; consultancies; employment and career agencies; engineering services; contract services; IT, advertising, marketing and media services; legal and financial services; personal, consumer and other services; property and development services; recycling services; repair servicing; research and design; transport, storage and delivery; and hire services.

9 To enrich the spatial content of the employment data even further, we only keep land that is occupied by buildings and then randomly distribute the number of jobs in each Output Area over all buildings in an Output Area. Preferably, one would have year-specific information on employment. Annual postcode area level employment is in principle available from the Business Structure Database Secure Access. However, after having digitally mapped this data, there were clearly some serious errors. For this reason, we have preferred the Census data. In the sensitivity analysis, we will also use building volume as an alternative proxy for agglomeration economies.

Table 1. Key descriptive statistics

	(1) Mean	(2) SD	(3) Min	(4) Max
Rent (in £/m²)	384.8	179.4	10.76	1,507
Agglomeration, $A(x)$, $\delta = 1.5$	130,400	47,559	695.9	198,939
Bomb density, $B(x)$, $\delta = 1.5$	215.0	43.52	0.124	269.2
Building site hit by bomb, $b(x)$	0.0709	0.257	0	1
Distance to river Thames (km)	1.320	1.291	0.00497	17.42
In conservation area	0.676	0.468	0	1
Size of the property (m²)	847.7	2445	17.19	65,032
Building size (m²)	6256	11,813	40.41	112,305
Number of floors in building	7.970	5.155	1	52
Floor of property	3.352	2.768	0	50
Building—newly constructed	0.0898	0.286	0	1
Building—refurbished	0.0916	0.288	0	1
Building—second hand	0.824	0.381	0	1

Note: The number of observations is 9202.

We gather data on an extensive number of location attribute controls, such as the distance to the nearest highway, tube station, railway station, open space, water, all based on open source GIS data. Information on historic amenities is obtained from the National Heritage List for the UK. Demographic characteristics are obtained from the 2001 census. Furthermore, we gather data on population per Parish in 1931, so before WWII. The median size of a Parish is 5.55 km². To enrich the spatial content of the population data, we only keep land that is currently occupied by buildings and then randomly distribute the number of people in each Parish over all buildings currently in a Parish.

For each location, we also calculate agglomeration, which is the spatially weighted number of employees. Following, among others, Lucas and Rossi-Hansberg (2002) we define:

$$A_i = \delta \sum_{j=1}^{S} \mathrm{e}^{-\delta d_{ij}} H_{Mj}, \qquad (2.1)$$

where H_{Mj} denotes the number of workers at location j.

Key descriptive statistics for the rental dataset are reported in Table 1. The average yearly rent for office space is £385/m², which confirms that London is among the most expensive office locations in the world. The average property is ∼850 m². About 7% of the observations are on building sites that were directly hit by a WWII bomb. The average distance to the River Thames of the leased buildings is only 1.3 km, which confirms that we mainly observe leases in Inner London. About 86% of the observations are in a conservation area, suggesting that although many areas had been bombed severely, many historic amenities still survived.[10]

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10 For the descriptive of the complete set of variables included in the regressions, we refer to Table A3 in Supplementary Appendix A.3. We also plot agglomeration over space, as well as historic population density in 1931.

Our data on the location of bombs dropped on London during the Blitz comes from Bomb Sight. This data originates from the WWII London bomb census, and contains the geographic locations of all the high explosive bombs that fell in London from piloted night-time raids between 7 October 1940 and 6 June 1941.[11] The locations where the much smaller and more numerous incendiaries fell were not recorded. One may argue that the bombs which fell in large water bodies or parks were less likely to have been reported, which implies measurement error. We address this issue in our research design.[12] We also digitize maps of the target areas (so-called '*zielraum*') used by German bomb crews during the Blitz because they could not deliberately hit individual targets. Their average size is $0.73\,km^2$, which is consistent with the argument that night-time bombings could not be very precise. We then divide Greater London into the so-called *zielraum×borough* areas which are determined based on the distance to the nearest *zielraum* and the borough in which a particular location is. We thereby subdivide Greater London into 232 *zielraum×borough* areas. The average (median) residential population of such an area is 35,379 (15,816) and the average (median) working population is 19,519 (7,773).

Finally, for the estimation of the structural model, we use data at the Mid-layer Super Output Area (MSOA) level. For Greater London, this means that we have 983 zones. The average (median) residential population of an MSOA is 8,321 (8,158) and the average (median) working population is 4,583 (2,441). Using 2011 Census data, we have information on commuting flows between each of the MSOAs. Geographic and location characteristics are calculated based on the centroid of each MSOA.

MSOA travel time is calculated using information on the railway and underground network travel times from Transport for London. Because of the superb public transport network, distances and travel times are highly correlated ($\rho = 0.925$).

To obtain prices per meter square of floor space, we regress the rent per meter square of commercial properties on property controls and include MSOA fixed effects. The MSOA fixed effects are then used as the floor space prices if we have at least 20 observations. For the missing areas (80%), we use data from the Nationwide Building Society on housing transactions and regress prices per meter square on housing characteristics and MSOA fixed effects. We normalize prices and rents, by assuming that on average they are equal.[13]

3. Reduced-form analysis

3.1. Econometric framework

In the structural estimation to be discussed later on, there are two key equations to be estimated: (*i*) the effect of the Blitz bombings (as a proxy for redevelopment frictions) on the

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11 Since the final major daylight raid of the Blitz took place on 30 September 1940 and minor daylight raids were abandoned altogether by early October, the bomb location data used in this article exclusively comprises raids conducted under the less accurate night-time conditions.

12 For our purposes, to use information on the locations where bombs fell is preferable over the locations of actual Blitz damage because areas and buildings deemed 'significant' were heavily protected from incendiaries by dedicated fire crews who would have been able put out the majority of their fires before they could cause real damage. Moreover, low-quality buildings may have been less likely to survive the bombing and may not have been restored if damaged (see Hulten and Wykoff, 1981). Hence, measures of actual damage could be correlated with the quality of local buildings at that time. Moreover, the Blitz bomb location data are available for Greater London, while the damage maps are only available for Inner London.

13 Using different assumptions on the construction of floor space prices hardly changes our results. For example, if we entirely rely on residential floor space prices, the results are very similar (see Supplementary Appendix A.8.2).

density of development, and (*ii*) the impact of density on the productivity of firms, where we use exogenous variation in density provided by the conditionally random Blitz bombings.

Let h_i denote the height of a building i. A naive regression specification is given by:

$$\log h_i = \alpha_0 B_i + \alpha_1 b_i + \epsilon_{it}, \tag{3.1}$$

where α_0 is the parameter of interest and captures the effect of redevelopment frictions, proxied by bomb density B_i, which we define as follows:

$$B_i = \delta \sum_{j=1}^{S} e^{-\delta d_{ij}} b_j, \tag{3.2}$$

where j is another location and b_j is an indicator that equals one when location j was hit by a bomb. The distance in kilometers between i and j is d_{ij}, and δ is the decay parameter. In the reduced-form analysis, we set $\delta = 1.5$, which implies that most of the weight applies to bombs within 1 km of the firm location (see Figure A6 in Supplementary Appendix A.4 for more details). We show robustness to this assumption in the sensitivity analyses. Further, ϵ_{it} is an identically and independently distributed error term.

In these reduced-form estimations, we control for the effect of bombings that apply to the own lot, which captures the reduction in redevelopment frictions if a bomb falls within the parcel itself (Turner et al., 2014). In addition, redevelopment may be strongly spatially correlated because bombs near lot boundaries may also cause damage to other sites, and because redevelopment restrictions are often street or neighborhood-specific. So, we expect a higher bomb density in the neighborhood may also lead to taller buildings throughout.

It is unlikely that α_0 measures a causal effect of bombings on building height at this stage. The reason is that bombings are likely not random but based on both the population density before WWII commenced and the distance to the Thames (i.e. centrality). Furthermore, bomb strikes in water bodies and parks may not have been well recorded. To address these issues, we first include geographic control variables g_i, and *zielraum×borough* fixed effects $\eta_{i \in z}$, where z denotes a *zielraum×borough* area. Recall that '*zielraums*' were the discrete areas bomb-crews were instructed to target on Blitz raids.[14] In Supplementary Appendix A.5, we employ the point-pattern methodology from Duranton and Overman (2005) to verify that the location of our Blitz bomb data is indeed statistically random over space, conditional on all differences between *zielraum×borough* areas and geographic characteristics. As building and location attributes are not uniformly distributed over space (e.g. buildings in Inner London may be of higher quality), they may still be correlated with B_i. So we additionally control for building attributes, denoted by x_i, and location attributes l_i, such as the distance to the nearest tube station, and distance to open space. We then estimate:

$$\log h_i = \alpha_0 B_i + \alpha_1 b_i + \alpha_2 q_i + \alpha_3 g_i + \alpha_4 l_i + \eta_{i \in z} + \epsilon_i, \tag{3.3}$$

where α_2, α_3, α_4 and $\eta_{i \in z}$ are additional parameters to be estimated.

The second step in the reduced-form analysis is to measure the importance of agglomeration economies for office rents. The empirical literature cited in Section 1 provides

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14   We discuss further details in Supplementary Appendix A.2.

evidence that agglomeration economies exist within cities and decay within short distances, particularly for business services. Firms, therefore, cluster in dense central business districts and subcenters and are likely willing to pay higher rents in these locations. For this interpretation to be valid, there should be a positive effect of employment density (using Equation (2.1)) on office rents.

Agglomeration economies are likely endogenous and may be correlated to unobserved locational endowments. However, given that redevelopment frictions proxied by bombings (*i*) have an impact on building heights and (*ii*) are (conditionally) random; we can use B_i as an instrument for agglomeration economies.[15]

Hence, the first stage is given by:

$$\log A_{it} = \tilde{\gamma}_0 B_i + \tilde{\gamma}_1 b_i + \tilde{\gamma}_2 q_{it} + \tilde{\gamma}_3 g_{it} + \tilde{\gamma}_4 l_{it} + \tilde{\mu}_{i\in z} + \tilde{\mu}_t + \tilde{\epsilon}_{it}, \tag{3.4}$$

where γ's are coefficients to be estimated and the $\sim$ refer to first-stage coefficients. The second stage is given by:

$$\log r_{it} = \gamma_0 \log \hat{A}_{it} + \gamma_1 b_i + \gamma_2 q_{it} + \gamma_3 g_{it} + \gamma_4 l_{it} + \mu_{i\in z} + \mu_t + \epsilon_{it}, \tag{3.5}$$

where $\log \hat{A}_{it}$ is the fitted value obtained in Equation (3.4). Hence, we attempt to measure the effect of agglomeration economies on rents by using Blitz bomb density as an instrument for density. The key identifying assumption is then that bomb density only affects office rents through its effect on employment density. This assumption is unlikely to hold at the level of Greater London. However, note that we control for detailed location fixed effects.

The primary remaining potential unobservables that could be correlated to both rents and bomb density are the density of historic amenities—as a higher bomb density is associated with fewer historic amenities—and changes in the demographic composition of a neighborhood. We will therefore include 13 location attributes, including whether a transaction is in a preserved conservation area, and 10 demographic characteristics, including the share of council housing. The latter may capture the potential effects of re-building after the war, which often came in the form of council housing (Redding and Sturm, 2016). We show that the second-stage results are essentially unaffected.

3.2. Bombings and building height

We first report results with respect to the height of office buildings in Table 2. To further support the anecdotal evidence that bombings are correlated with redevelopment frictions discussed in Section 2, it is desirable to more formally test whether bombings are related to building height.

In Column (1), we estimate a naive regression of the building height of offices on bomb density, a dummy indicating whether the building was bombed and building

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15 However, one could argue that redevelopment frictions could also impact property values directly via increased costs for developers so that the instrument is invalid. Because we focus on the local effects of frictions and the *rental property market*, we do not consider this as a major problem here. More specifically, consider the case that a tenant faces two identical buildings: one in an otherwise identical but more stringent area with higher costs for developers, and another in an area with fewer restrictions. In a reasonably competitive market, developers cannot pass the costs of restrictions on to the tenant, because the tenant would always choose the building in the less restrictive area because it is cheaper. In particular, when we include detailed fixed effects, it seems very unlikely that our estimates capture a supply effect (Turner et al., 2014).

Table 2. Bombings and office building height (Dependent variable: the log of office building height in m)

	(1) OLS	(2) OLS	(3) OLS	(4) OLS	(5) OLS	(6) OLS
Bomb density, B_i, $\delta = 1.5$ (std)	0.1304[***]	0.1000[***]	0.0799[***]	0.0692[***]	0.0636[***]	0.0566[***]
	(0.0009)	(0.0014)	(0.0023)	(0.0032)	(0.0032)	(0.0032)
Building site hit by bomb, b_i	0.0488[***]	0.0526[***]	0.0521[***]	0.0510[***]	0.0495[***]	0.0548[***]
	(0.0151)	(0.0148)	(0.0142)	(0.0136)	(0.0134)	(0.0133)
Building—footprint (log)	0.1170[***]	0.1179[***]	0.1126[***]	0.1148[***]	0.1153[***]	0.1113[***]
	(0.0015)	(0.0015)	(0.0014)	(0.0014)	(0.0014)	(0.0014)
Building—listed	0.1126[***]	0.1011[***]	0.0463[***]	0.0375[***]	0.0279[***]	0.0262[***]
	(0.0067)	(0.0067)	(0.0064)	(0.0064)	(0.0064)	(0.0065)
Geographical attributes (10)	No	Yes	Yes	Yes	Yes	Yes
Borough fixed effects (33)	No	No	Yes	Yes	Yes	Yes
Zielraum×borough fixed effects (232)	No	No	No	Yes	Yes	Yes
Location attributes (10)	No	No	No	No	Yes	Yes
Neighborhood attributes (10)	No	No	No	No	No	Yes
Number of observations	65,125	65,125	65,125	65,125	65,125	65,125
R^2	0.4213	0.4389	0.5007	0.5200	0.5343	0.5508

Notes: Bomb density is standardized (std) to have mean zero and unit standard deviation. Geographic attributes include the log of distance to the River Thames, whether the property is within 125, 250 or 500 m of a park, within 125, 250 or 500 m of a large park and within 125, 250 or 500 m of a water body. Location attributes include dummy variables whether the property is within 125, 250 or 500 m of a highway, within 125, 250 or 500 m of a tube station, within 125, 250 or 500 m of a railway station, whether the property is in a conservation area or within 125, 250 or 500 m of a conservation area. Neighborhood attributes are the mean household size, the share of young (<25 years) people, elderly (>65 years), married, foreigners, unemployed, skilled occupations, highly educated, owner-occupied properties as well as the share of council housing. Standard errors are clustered at the building level and in parentheses; ***$p < 0.01$, **$p < 0.5$, *$p < 0.10$.

controls. The coefficient related to bomb density seems to suggest that an increase of one standard deviation in bomb density leads to an increase in height of 13%. Buildings that have been directly hit by a bomb are ($e^{0.0488} - 1 =$) 5.0% taller. The effects are very similar once we: control for geographic variables in Column (2); include borough fixed effects in Column (3); and use *zielraum×borough* fixed effects in Column (4). In Column (5), we further control for a host of location attributes and in Column (6), we add demographic controls. The coefficient of bomb density in the preferred specification in Column (5), Table 2, implies that a standard deviation increase in bomb density leads to buildings that are 6.45% taller. Furthermore, building sites that have been directly hit by a bomb have buildings on them that are 5.1% taller. This finding is consonant with Redding and Sturm (2016) who, using a distinct dataset from our own, also find that locations damaged in the Blitz now exhibit greater average building heights. These results support the inference that redevelopment frictions in London are weaker in areas that have been more heavily bombed.[16] We report similar results for non-office buildings in Supplementary Appendix A.7.1.

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16 We further find that buildings with a larger footprint tend to be taller: a 1% increase in building footprint is associated with a 0.11% increase in building height. Somewhat surprisingly, one can see that listed buildings

In Supplementary Appendix A.6, we further show that a higher bomb density in local authorities is associated with a higher acceptance rate of commercial planning proposals, the latter being commonly used as a proxy for the restrictiveness of land-use policies (see e.g. Hilber and Vermeulen, 2016; Cheshire et al., 2018). Using Oster's (2019) methodology, we do not find that omitted variable bias is an issue. We consider this as another piece of suggestive evidence that restrictions are less pronounced in heavily bombed areas.

3.3. Agglomeration economies and rents

We have shown that bomb density is associated with taller buildings. Hence, lower redevelopment frictions appear to lead to higher densities, which should increase agglomeration economies and cause higher productivity and rents. We next test for the existence of a positive relationship between employment density and office rents.[17]

We start by reporting OLS results in Panel A, Table 3. Column (1) suggests that doubling employment density leads to an increase in rents of $(\ln 2 - \ln 1) \times 0.2058 = 14.26\%$. One may argue, however, that employment density is correlated with unobserved features of a location. We therefore control for geographic features in Column (2) and include borough fixed effects and *zielraum×borough* fixed effects in Columns (3) and (4), respectively. We add a host of location attributes, such as distance to highways, tube stations and proximity to historic amenities, and control for 10 additional demographic variables in Columns (5) and (6).[18] These additions hardly affect the results. In our full specification, results suggest that doubling agglomeration leads to a rent increase of about 32%. Hence, employment density seems to be a key determinant of office rents.

One may still suspect that employment density is endogenous, as otherwise more attractive locations are expected to draw more firms. This would imply that estimates of agglomeration economies are overstated. On the other hand, regulation may prevent firms from concentrating in otherwise attractive areas, which would lead to an underestimate. We therefore need to instrument for employment density. Blitz bombings are a suitable instrument for agglomeration since at local levels they are random, and are associated with higher employment densities. In addition, conditional on the dummy variable indicating whether a site has been bombed, we strongly suspect that agglomeration economies are essentially the only possible explanation for the positive effect observed for Blitz bomb density on contemporary rents, and therefore that bombings do not have a direct effect on rents other than via higher densities. Panel B in Table 3 reports the results for the IV estimates where we instrument agglomeration with bomb density.

We first make sure that the instrument is strong (the Kleibergen–Paap *F*-statistic is >200 in all specifications) and has the expected positive effect. In Table A11 in Supplementary Appendix A.7.4 we report first-stage estimates. The elasticities of

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tend to be taller than other buildings, although the effect is small once we include *zielraum×borough* fixed effects and controls. There are two reasons for this. First, larger and taller buildings are more likely to become listed: the most celebrated landmarks are hardly ever small. Furthermore, listed buildings often imply height constraints for nearby buildings (e.g. based on view corridors), so that listed buildings remain taller than surrounding buildings.

17 We also show in Supplementary Appendix A.7.2 the 'reduced-form' effect of bombings on rents.

18 One may be worried that the standard errors are clustered at the wrong level. In Table A10 in Supplementary Appendix A.7.3, we show that when we cluster at different spatial levels, such as output areas, wards or constituencies, the standard errors are slightly higher. On the other hand, the results remain statistically significant at the 1% level in all specifications.

Table 3. Results: agglomeration economies and rents *(Dependent variable: the log of rent/m²)*

Panel A: Ordinary least squares	(1) OLS	(2) OLS	(3) OLS	(4) OLS	(5) OLS	(6) OLS
Agglomeration, A_i, $\delta = 1.5$ *(log)*	0.2058***	0.2391***	0.2736***	0.3729***	0.3519***	0.3178***
	(0.0116)	(0.0150)	(0.0200)	(0.0280)	(0.0299)	(0.0306)
Building site hit by bomb, b_i	−0.0553	−0.0515*	−0.0466*	−0.0442*	−0.0444*	−0.0378*
	(0.0400)	(0.0299)	(0.0268)	(0.0237)	(0.0232)	(0.0225)
Building attributes (15)	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects (15)	Yes	Yes	Yes	Yes	Yes	Yes
Geographical attributes (10)	No	Yes	Yes	Yes	Yes	Yes
Borough fixed effects (33)	No	No	Yes	Yes	Yes	Yes
Zielraum×borough fixed effects (232)	No	No	No	Yes	Yes	Yes
Location attributes (13)	No	No	No	No	Yes	Yes
Neighborhood attributes (10)	No	No	No	No	No	Yes
Number of observations	9202	9202	9199	9186	9186	9186
R^2	0.2906	0.4309	0.5622	0.5920	0.5998	0.6053

Panel B: Two-stage least squares	(1) 2SLS	(2) 2SLS	(3) 2SLS	(4) 2SLS	(5) 2SLS	(6) 2SLS
Agglomeration, A_i, $\delta = 1.5$ (log)	**0.1920*****	**0.1852*****	**0.3296*****	**0.3577*****	**0.3108*****	**0.2873*****
	(0.0133)	**(0.0169)**	**(0.0350)**	**(0.0467)**	**(0.0556)**	**(0.0579)**
Building site hit by bomb, b_i	−0.0548	−0.0489	−0.0459*	−0.0439*	−0.0438*	−0.0372*
	(0.0399)	(0.0299)	(0.0269)	(0.0237)	(0.0233)	(0.0225)
Building attributes (14)	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects (15)	Yes	Yes	Yes	Yes	Yes	Yes
Geographical attributes (10)	No	Yes	Yes	Yes	Yes	Yes
Borough fixed effects (33)	No	No	Yes	Yes	Yes	Yes
Zielraum×borough fixed effects (232)	No	No	No	Yes	Yes	Yes
Location attributes (13)	No	No	No	No	Yes	Yes
Neighborhood attributes (10)	No	No	No	No	No	Yes
Number of observations	9202	9202	9202	9202	9202	9202
Kleibergen–Paap *F*-statistic	3279	2594	526.7	424.7	257.4	241.8

Notes: Bold indicates instrumented. Bomb density is standardized (std) to have mean zero and unit standard deviation. Geographic attributes include the log of distance to the River Thames, whether the property is within 125, 250 or 500 m of a park, within 125, 250 or 500 m of a large park (>10 ha) and within 125, 250 or 500 m of a water body. Location attributes include dummy variables whether the property is within 125, 250 or 500 m of a highway, within 125, 250 or 500 m of a tube station, within 125, 250 or 500 m of a railway station, whether the property is in a conservation area or within 125, 250 or 500 m of a conservation area. Neighborhood attributes are the mean household size, the share of young (<18 years) people, elderly (≥65 years), married, foreigners, unemployed, skilled occupations, highly educated, owner-occupied properties as well as the share of council housing. Standard errors are clustered at the building level and in parentheses; ***$p < 0.01$, **$p < 0.5$, *$p < 0.10$.

agglomeration with respect to bombing are ∼0.55 and reduce to ∼0.30 when adding controls and fixed effects.

In Column (1) in Panel B of Table 3, we show that the elasticity of agglomeration is very similar to the corresponding specification in Panel A. This also holds if we include geographic control variables, borough fixed effects, and *zielraum×borough* fixed effects in, respectively, Columns (2), (3) and (4). For example, the elasticity in Column (4) in Panel B, Table 3, implies that if we doubled agglomeration, rents would increase by 36%, which is statistically indistinguishable from the corresponding OLS specification. In line

with previous results, the coefficient becomes slightly lower in Column (6) if we include a set of location attributes and neighborhood controls. Here doubling agglomeration economies implies that rents would increase by ∼20%.

3.4. Sensitivity analysis

In Supplementary Appendix A.7, we investigate the robustness of the reduced-form results. We show in Supplementary Appendix A.7.1 that the effects of bombings on building heights also hold for non-office buildings although the effects are somewhat smaller. In Supplementary Appendix A.7.2, we report the 'reduced-form' effects of bomb density on office rents. We find strong positive effects in line with findings reported in Table 3. Supplementary Appendix A.7.3 shows that coefficients remain statistically significant at the 1% level if we cluster at different spatial levels, and Supplementary Appendix A.7.4 reports first-stage estimates.

Supplementary Appendix A.7.5 shows the results of a battery of other robustness checks. First, we employ an alternative proxy for agglomeration—office building volume in the vicinity—leading to nearly identical results. We also address potential firm sorting by including firm fixed effects, and control (more) flexibly for the population density in 1931 and the distance to the Thames. We also estimate regressions where we only include Inner London or exclude the City of London. We additionally make sure that the results are robust to different definitions of fixed effects (e.g. constituencies and 1931 Parishes). Finally, we provide support for the specific choice of our decay parameter, δ. Taken together, these various sensitivity checks validate our chosen methodologies and the robustness of our results.

Previous research on agglomeration economies has frequently proxied commercial rents with house prices because they are easier to obtain. We expect that residential house prices are most comparable to commercial rents in areas where there is relatively more employment (for a theoretical underpinning of this argument see Lucas and Rossi-Hansberg, 2002). As most of London has mixed land use, we might expect results using house prices to be similar to those using office rents.[19] For this analysis, we use data on house prices obtained from the Nationwide Building Society. The data provides information on 128,931 housing transactions, so the housing sample is substantially larger than the data on office rents and covers a much wider area of Greater London. The results in Supplementary Appendix A.7.6 show that the effects on house prices are lower in magnitude than the office market. However, the effects are most similar in areas in which the ratio of employment to households is above one.[20]

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19 As an illustration, in ∼50% of the output areas, the ratio of jobs to households is >0.25 and <2.5.

20 In a working paper, Redding and Sturm (2016) provide preliminary evidence that house prices within 200 m of areas heavily damaged by the Blitz are lower due to negative social interactions (e.g. more public council housing may have been built in heavily damaged areas after the war). We therefore include a control variable measuring the number of bombs within 200 m of the postcode, which should have a negative effect on house prices. In line with Redding and Sturm (2016), we also find negative house price effects on the number of bombs within 200 m. Per bomb, this price decrease is 0.3%. In heavily bombed areas, this implies a strong price effect of up to 15%. Note that we use data on bomb strikes, whereas Redding and Sturm (2016) use actual bomb damage data. The fact that we are able to replicate this result supports the validity of using bomb strikes in our estimations.

4. Structural model

Now that we have shown that redevelopment frictions have an economically and statistically significant impact on densities (proxied by building height) and on productivity (proxied by rents), in this section, we outline a structural model to analyze the general equilibrium effects of redevelopment frictions (as proxied by the Blitz bombings) on London's economy as a whole. Our contribution is that we adapt the model of Ahlfeldt et al. (2015) and embed redevelopment frictions into the model. Furthermore, we address the potential endogeneity of employment density using variation in local bomb densities. Here we restrict ourselves to a rather brief description of the model; for details we refer to their paper. We then proceed by estimating the model using bomb density as a (conditionally) exogenous source of variation. We close this section by analyzing the effects on London's urban spatial structure if (*i*) the Blitz had not taken place, and if (*ii*) the whole of Greater London had been bombed as heavily as Pimlico (Borough of Westminster): the most heavily bombed MSOA in Greater London. These counterfactuals serve to illustrate that redevelopment frictions have had an important impact on London's spatial structure and strongly reduce the benefits of agglomeration.

4.1. Model

4.1.1. Workers

There are $i = 1, \ldots, S$ locations in the city, each with land area L_i. Land may be used for residential purposes or may be used by businesses. A worker o that lives in i and commutes to j has preferences over consumption c_{ijo} and residential floor space ℓ_{ijo}. The worker also has an idiosyncratic preference for pair ij, denoted by ξ_{ijo}. The idiosyncratic component of utility is only revealed after the worker has moved to London. The utility is then given by:

$$U_{ijo} = \Psi_i \left(\frac{c_{ijo}}{\beta}\right)^\beta \left(\frac{\ell_{ijo}}{1-\beta}\right)^{1-\beta}, \tag{4.1}$$

where Ψ_i is the given amenity level of a location and $0 < \beta < 1$. The idiosyncratic component is drawn from a Fréchet distribution, so that $F(\xi_{ijo}) = e^{-\overline{\nu}_i \overline{v}_j \xi_{ijo}^{-\varepsilon}}$, where $\overline{\nu}_i$ and $\overline{v}_j$ denote the average utility of living in i and working in j, respectively, and ε governs the amount of commuting heterogeneity.

Workers earn a wage w_j, which is dependent on the place of work j. The workers budget constraint is given by $e^{-\kappa \tau_{ij}} w_j = p_i \ell_{ijo} + c_{ijo}$, where $e^{-\kappa \tau_{ij}}$ represents iceberg commuting costs, τ_{ij} is the travel time between location i and j and p_i is the price per unit of floor space. The indirect utility is then given by $u_{ijo} = \Psi_i e^{-\kappa \tau_{ij}} w_j p_i^{\beta-1} \xi_{ijo}$.

Note that a higher value of ε implies a smaller dispersion of wages. Given the Fréchet distribution of ξ_{ijo} we can determine the probability that a worker chooses to reside in i and work in j:

$$\pi_{ij} = \frac{\overline{\nu}_i \overline{v}_j \left(\Psi_i e^{-\kappa \tau_{ij}} w_j / p_i\right)^\varepsilon}{\sum\limits_{r=1}^{S} \sum\limits_{s=1}^{S} \overline{\nu}_r \overline{v}_s \left(\Psi_r e^{-\kappa \tau_{rs}} w_s / p_r\right)^\varepsilon}. \tag{4.2}$$

Let us define 'transformed' wages as $\omega_j = \bar{v}_j w_j^\varepsilon$. The probability that a worker works in j, conditional on living in i is then given by

$$\pi_{ij|i} = \frac{e^{-\kappa\varepsilon\tau_{ij}}\omega_j}{\sum\limits_{s=1}^{S} e^{-\kappa\varepsilon\tau_{is}}\omega_s}. \tag{4.3}$$

This leads to the *commuting market-clearing condition*:

$$H_{Mj} = \sum_{i=1}^{S} \pi_{ij|i}H_{Ri}, \tag{4.4}$$

which states that the number of workers (H_{Mj}) in j is the sum over the residential population (H_{Rj}) multiplied by the probability that they commute to j. The total floor consumption F_{Hi} at i is obtained by summing the floor space demand for all workers in a location:

$$F_{Hi} = \frac{(1-\beta)\sum\limits_{j=1}^{S} \pi_{ij|i}e^{-\kappa\tau_{ij}}w_j}{p_i}H_{Ri}. \tag{4.5}$$

We assume that workers obtain expected utility equal to a reservation utility $\overline{U}$ which is the same for everyone. Moving is costless and population mobility implies that:

$$\overline{U} = \mathbb{E}[u] = \Gamma\left(\frac{\varepsilon-1}{\varepsilon}\right)\left(\sum_{i=1}^{S}\sum_{j=1}^{S}\bar{v}_i\bar{v}_j\left(\frac{\Psi_i e^{-\kappa\tau_{ij}}w_j}{p_i^{1-\beta}}\right)^\varepsilon\right)^{\frac{1}{\varepsilon}}, \tag{4.6}$$

where $\Gamma(\cdot)$ is the Gamma function. From this condition, Ahlfeldt et al. (2015) show that one can determine residential amenities up to a normalization, denoted by $\tilde{\Psi}_i$, $\forall i$:

$$\tilde{\Psi}_i = \tilde{H}_{Ri}^{1/\varepsilon}\tilde{p}_i^{1-\beta}\tilde{W}_i^{-1/\varepsilon}, \tag{4.7}$$

where the $\sim$ denote variables normalized by their geometric mean (e.g. $(\prod\limits_{i}\Psi_i)^{1/S}$), and $W_i = \sum\limits_{j=1}^{S} e^{-\kappa\varepsilon\tau_{ij}}\omega_j.$[21]

4.1.2. Production

We now turn to production. Firms produce a single final good in a perfectly competitive market with constant returns to scale. Moreover, the final good is sold to the wider economy without costs. Production in location j, which is assumed to be Cobb–Douglas, is given by $Y_j = \Omega_j H_{Mj}^\alpha F_{Mj}^{1-\alpha}$, where Ω_j the final goods productivity at j, and F_{Mj} is the

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21 Note that we do not allow for residential externalities here. We will show in Supplementary Appendix A.8.2 that residential externalities are small and our counterfactuals are robust to the inclusion of residential externalities.

amount of floor space consumed by firms. Profit maximization implies that final goods productivity equals $F_{Mj} = [w_j/(\alpha\Omega_j)]^{1/(1-\alpha)}H_{Mi}$. Using the first-order conditions for profit maximization, 'innate' productivity of a location can be written as $\Omega_j = (1 - \alpha)^{\alpha-1}\alpha^{-\alpha}p_j^{1-\alpha}w_j^{\alpha}$.

We assume that productivity is partially exogenous and partially dependent on employment accessibility, as is common in the literature. In line with Equation (2.1), we then define:

$$\Omega_j = \breve{\Omega}_j \breve{A}\,(\delta)_j^{\gamma} = \breve{\Omega}_j (\delta \sum_{i=1}^{S} e^{-\delta\tau_{ij}}H_{Mi})^{\gamma}, \qquad (4.8)$$

where $\breve{\Omega}_j$ denotes the innate exogenous productivity of a location j and note that agglomeration is dependent on travel time (instead of Euclidean distance).

4.1.3. The land market and redevelopment frictions

We follow Ahlfeldt et al. (2015) in assuming that floor space F_i is supplied in a competitive construction market that uses land L_i and capital K_i as inputs. Using a Cobb–Douglas production function $F_i = K_i^{\mu}L_i^{1-\mu}$. Since the price for capital is assumed to be the same across all locations, hence it holds that $F_i = \Phi_i L_i^{1-\mu}$, where $\Phi_i = K_i^{\mu}$ is the density of development. Land market clearing then implies that $F_{Ri} + F_{Mi} = \Phi_i L_i^{1-\mu}$.

As established in Section 3.2, bombings are associated with taller buildings nowadays due to redevelopment frictions. We therefore model:

$$\Phi_i = \breve{\Phi}_i e^{-\varphi\left(\frac{b_i}{L_i}\right)}. \qquad (4.9)$$

So the density of development depends on some innate initial conditions $\breve{\Phi}_i$ and on bomb density b_i/L_i in area i. Note that bombings are expected to reduce redevelopment frictions, hence φ is expected to be negative.[22]

4.2. Model estimation

We use the recursive structure of the model to solve for the parameters of interest $\{\kappa, \varepsilon, \varphi, \gamma, \delta\}$. We borrow the parameters $\{\alpha, \beta, \mu\}$ from Ahlfeldt et al. (2015). Based on the literature, they set the share of household's expenditure on floor space at $1 - \beta = 0.25$, the share of commercial expenditure on floor space at $1 - \alpha = 0.2$, and the share of land in construction costs at $1 - \mu = 0.25$. We estimate the model at the MSOA level, and obtain information on commuting flows for $983 \times 983 = 966,389$ bilateral commuting pairs.

Let us define $\varkappa = \kappa\varepsilon$. In the first step we estimate a gravity equation, by defining the following moment condition:

$$\mathbb{E}[\pi_{ij}H - e^{-\varkappa\tau_{ij}-\varsigma_i-\varsigma_j}] = 0, \qquad (4.10)$$

where H is the total population, $\varkappa$ is the commuting travel time elasticity, ς_i is a residential location fixed effect absorbing $\{\Psi_i, p_i, \overline{\nu}_i\}$, and ς_j is a workplace fixed effects absorbing $\{\overline{\nu}_j, w_j\}$ (see Equation (4.2)). Because the dependent variable $\pi_{ij}H$ has many zeroes, we estimate Equation (4.10) by a Poisson model with two-way fixed effects. In

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22 The more negative φ, the stronger the effect of bomb density, so the stronger the difference between areas which are restricted and the areas for which restrictions have been eased.

Supplementary Appendix A.8.1 we consider different estimation techniques to estimate $\varkappa$. Moreover, we consider the issue that travel times are endogenous: between locations where there is a higher commuting flow it is more likely that new transport infrastructure is provided, leading in turn to lower travel times. This endogeneity issue should lead to an underestimate of $\hat{\varkappa}$. We show in Supplementary Appendix A.8.1 that when instrumenting travel times with Euclidean distance, endogeneity hardly matters. Hence, in what follows, we treat travel times as exogenous.[23]

Using data on the (working) population H_{Ri}, $\forall i$, and the number of workers H_{Mj}, $\forall j$, and the estimated parameter $\hat{\varkappa}$, in the second step, we can recover transformed wages ω_j at each location j by solving:

$$\mathbb{E}\left[H_{Mj} - \sum_{i=1}^{S} \pi_{ij|i} H_{Ri}\right] = 0, \tag{4.11}$$

In the third step, we recover ε by using actual information on the distribution of household incomes in Greater London. We choose ε in such a way that it minimizes the squared differences between the variances across zielraum×borough areas of log-transformed wages in the model and log wages in the data:[24]

$$\mathbb{E}\left[\sigma^2_{\log w_i|z} - \left(\frac{1}{\varepsilon}\right)^2 \sigma^2_{\log \hat{\omega}_i|z}\right] = 0. \tag{4.12}$$

Using $\hat{\varepsilon}$, we obtain $\hat{\kappa} = \hat{\varkappa}/\hat{\varepsilon}$.

Fourth, using Equation (4.5), land market clearing and the estimated parameters $\{\hat{\kappa}, \hat{\varepsilon}\}$, we recover 'structural' density Φ_i. Let $\log \breve{\Phi}_i = \chi_3 g_i - \chi_4 l_i - \vartheta_{i\in z}$. We then identify the effect of bombings on density:

$$\mathbb{E}\left[\log \Phi_i + \varphi\left(\frac{b_i}{L_i}\right) - \chi_3 g_i - \chi_4 l_i - \vartheta_{i\in z}\right] = 0, \tag{4.13}$$

Hence, we identify the effect of redevelopment frictions as proxied by bomb density, conditional on *zielraum×borough* fixed effects and effects of geography g_i and infrastructure l_i.[25] To facilitate interpretation, we standardize b_i/L_i to have mean zero and unit standard deviation. Note here the similarity to the reduced-form Equation (3.3), where we measure the effect of bomb density on building height. The difference here is that we take the density obtained in the model as dependent variable.

Armed with estimates for transformed wages $\hat{\omega}$, $\hat{\kappa}$ and $\hat{\varepsilon}$ and data on H_{Ri}, H_{Mi} and floor space prices p_i, we can recover amenities $\check{\Psi}_i$ and productivity Ω_i up to a normalization. We define the following moment condition:

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23 Recall from Section 2 that we use data on travel times between MSOAs by public transport. Hence, issues related to traffic delays due to traffic congestion are unlikely to be an important issue.

24 We obtain data on estimated household incomes by MSOA in the Greater London Authority for 2011.

25 One may argue that the effect of bomb density on structural density may not be exactly linear. For example, particularly in places that are heavily bombed (i.e. the City of London), demand pressure was higher and so is the effect of loosening development restrictions. We therefore also considered non-linear effects of bomb density in Φ_i. However, this does not materially influence the effects of the counterfactual scenarios. Results are available upon request.

$$\mathbb{E}[\log \Omega_i - \gamma \log \breve{A}_i(\delta) - \zeta_3 g_i - \zeta_4 l_i - \mu_{i \in z}] = 0, \qquad (4.14)$$

where $\log \breve{A}_i = \delta \sum_{j=1}^{S} e^{-\delta \tau_{ij}} H_{Mj}$ and $\breve{\Omega}_i = \zeta_3 g_i + \zeta_4 l_i + \mu_{i \in z}$. The above equation shows that we control for geographical and location attributes as well as *zielraum×borough* fixed effects. We obtain $\hat{\gamma}$ and $\hat{\delta}$ by minimizing the mean squared error of Equation (4.14). Again, observe the similarity of Equation (4.14) to the reduced-form Equation (3.5), where we measure the effect of densities on rents. Instead of rents, we use Ω_i as the dependent variable, which is a composite of rents and wages, see Equation (4.8).

One may be worried that γ and δ are not causal parameters related to the elasticity and decay of agglomeration economies. We, therefore, instrument $\breve{A}_i$ with $\breve{B}_i = \delta \sum_{j=1}^{S} e^{-\delta \tau_{ij}} b_j$.

Like in the reduced-form analysis, the exclusion restriction requires that bombings are uncorrelated to unobserved locational endowments that are potentially related to agglomeration economies. We have provided support for this assumption by showing that bombings are conditionally random on *zielraum×borough* fixed effects. Moreover, we include geographical and location attributes (i.e. g_i and l_i) that should address residual concerns that the bombings could be correlated to current locational endowments.

We estimate the standard errors by bootstrapping all the steps, so we take into account the fact that errors are correlated between different equations.

4.3. Structural parameters

In Table 4, we report the results from estimating the parameters of interest. We find a commuting semi-elasticity of $\varkappa = \kappa \varepsilon$ with respect to flows that is essentially identical to Ahlfeldt et al. (2015).[26] The commuting heterogeneity parameter $\hat{\varepsilon}$ is about half of that of Ahlfeldt et al. (2015), but is in line with guesstimates from Brinkman and Lin (2019). It is also on the low side if compared to the range provided by Eaton and Kortum (2002), although we do not have clear priors as to whether heterogeneity in trade models are indeed comparable to urban economic models.

The redevelopment frictions parameter $\hat{\varphi}$ has the expected negative sign. It shows that a standard deviation decrease in bombings (so *increasing* redevelopment frictions) leads to a density that is 8.7% lower. This confirms the previous reduced-form findings in Section 3.2 that buildings are shorter when redevelopment frictions are more pronounced. One may be concerned that the impact of Blitz bombings on density depends on the overall level of bombings. That is, if bombings would have been more substantial, this may have impacted φ. This is because if fewer historic buildings would have remained, restrictions for the remaining buildings could have been even more substantial, so that φ would become more negative. This criticism is a possibility, but would likewise apply to any model that uses current data in attempt to estimate structural parameters. As we additionally do not find strong evidence for non-linear effects of redevelopment restrictions within London, this would appear to be a minor concern.[27]

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26 Again, we report a couple of different specifications to identify $\varkappa$ in Supplementary Appendix A.8.1 and allow for potential endogeneity of travel times. The results are robust.

27 The results of this exercise are available upon request.

Table 4. Structural parameters

	Baseline Specification (1)
Commuting time elasticity, $\hat{\kappa}\varepsilon$	0.1005***
	(0.0006)
Commuting heterogeneity, $\hat{\varepsilon}$	3.7979***
	(0.2864)
Redevelopment frictions, $\hat{\varphi}$	−0.0872**
	(0.0402)
Productivity elasticity, $\hat{\gamma}$	0.1960***
	(0.0391)
Productivity decay, $\hat{\delta}$	0.6626*
	(0.3997)
Geographical attributes (10)	Yes
Location attributes (13)	Yes
Zielraum×borough fixed effects (232)	Yes
Number of areas	983
Number of area pairs	966,289

Notes: We estimate the parameters using data at the MSOA. In Columns (1) and (2), we instrument agglomeration $\bar{A}_i$ with bomb density. Standard errors are bootstrapped (250 replications) and in parentheses; ***$p < 0.01$, **$p < 0.5$, *$p < 0.10$.

We further find evidence that agglomeration economies are very important, with an agglomeration economies elasticity of $\hat{\gamma} = 0.196$. This estimate is substantially higher than usually found in the literature. Our estimate $\hat{\delta}$ suggests a strong decay parameter of 0.663, although it is somewhat imprecisely estimated. In Section 4.5 we put these estimates in context with prior research.

In Supplementary Appendix A.8.2 we conduct a series of robustness tests including; (*i*) the estimation of residential externalities; (*ii*) controlling for population density in 1931; (*iii*) only controlling for geographical attributes and borough fixed effects; (*iv*) excluding employment in the own MSOA when calculating agglomeration measures; (*v*) not instrumenting for agglomeration; and (*vi*) using residential floor space prices only. Overall, the results are very robust, although for some specifications we do find a lower productivity elasticity (ranging from 0.05 to 0.25).

4.4. Counterfactual scenarios

Given the estimates of structural parameters, we can perform counterfactual simulations in order to investigate how important redevelopment frictions are for London's economy. We consider two experiments. Using the estimate for redevelopment frictions $\hat{\varphi}$, we estimate what would happen to Greater London's density of development $\hat{\Psi}_i$ if (*i*) the Blitz had not taken place ($b_i/L_i = 0, \forall i$) and if (*ii*) all of Greater London had been as bombed as heavily as Pimlico (Borough of Westminster), the most heavily bombed MSOA ($b_i/L_i = \max_i(b_i/L_i), \forall i$). We refer to this second scenario as 'full bombings'. Given $\{\hat{\kappa}, \hat{\varepsilon}, \hat{\varphi}, \hat{\gamma}, \hat{\delta}\}$, we describe in Supplementary Appendix A.8.3, the procedure used to estimate the counterfactuals. Using the population mobility condition Equation (4.6), so

holding utility constant for different scenarios, we calculate changes in the population for different counterfactual scenarios.

For the first 'no Blitz' scenario, so when redevelopment frictions would be more pronounced, London's total population would decline by 9% (due to emigration). Effects on the city center would be even more pronounced. In the main financial center, the City of London, the population would decrease by 25%. Due to the resultant fall in employment density, we estimate that London's total output would decline by ∼18%. Given that the population has simultaneously declined by 9%, this implies a London-wide drop in per capita income of ∼10%.[28] Given a total annual economic output of £506.5 billion in 2011 denotes an annual deadweight loss to London's economy of ∼£50 billion/year.[29] Assuming any reasonable discount rate implies that the capitalized present value loss would approach £1 trillion.

By contrast, in the 'full bombings' scenario where redevelopment frictions are eased even more than at present, London's population would increase by ∼27% to 6.3 million. While London's total economic output would increase by roughly 36% to £689 billion/year, implying ∼7% increase in London-wide per capita income.[30]

It is also interesting to study changes in the spatial distribution of the residential and working populations as well as wages and floor space prices within London. We report the results for the first 'no Blitz' counterfactual scenario in Figure 1. We see from Figure 1(A) that without the Blitz London's city center would lose a substantial fraction of its working population, up to 25% in some areas. These workers would then find jobs outside Inner London. In Figure 1(B), we observe a similar, perhaps somewhat stronger, pattern for the residential population. Because space becomes more scarce in Inner London, floor space prices generally go up (see Figure 1(C)). These effects can be large; up to 20%. The pattern for wages net of commuting costs is in line with expectations: wages go down because households in the city center generally have longer commutes and because of a loss in agglomeration economies throughout the city (see Figure 1(D)). These results clearly highlight that the Blitz has had a profound impact on London's urban structure by reducing redevelopment frictions, thus allowing the city to be substantially more concentrated than it otherwise would have been.

We consider the second 'full bombings' counterfactual scenario in Figure 2, where each and every MSOA location would have been as intensely bombed as Pimlico. We observe less clear-cut patterns than in the first scenario. We generally see that areas around Southbank would see a fall in both workers and residents, whereas Westminster and peripheral areas would witness an increase (see respectively, Figure 2(A,B)). Looking at land rents (Figure 2(C)), we observe that in all areas floor space prices go down (on average 16%) ostensibly due to greater supply. In Figure 2(D), we show that wages go up on average by ∼2%. Juxtaposing these two scenarios, it is reassuring that the effects of the 'no Blitz scenario' are visually more pronounced in the urban core of London where economic activity is most concentrated, whereas the effects of the 'full bombings' scenario are most evident in London's periphery.

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28    $1 - [(1 - 18\%)/(1 - 9\%)] = 9.89\%$.

29   Data source is the 2011 Eurostat 'Gross domestic product (GDP) at current market prices by metropolitan regions', rescaled into GBP using the average 2011 EUR/GBP exchange rate provided by the European Central Bank.
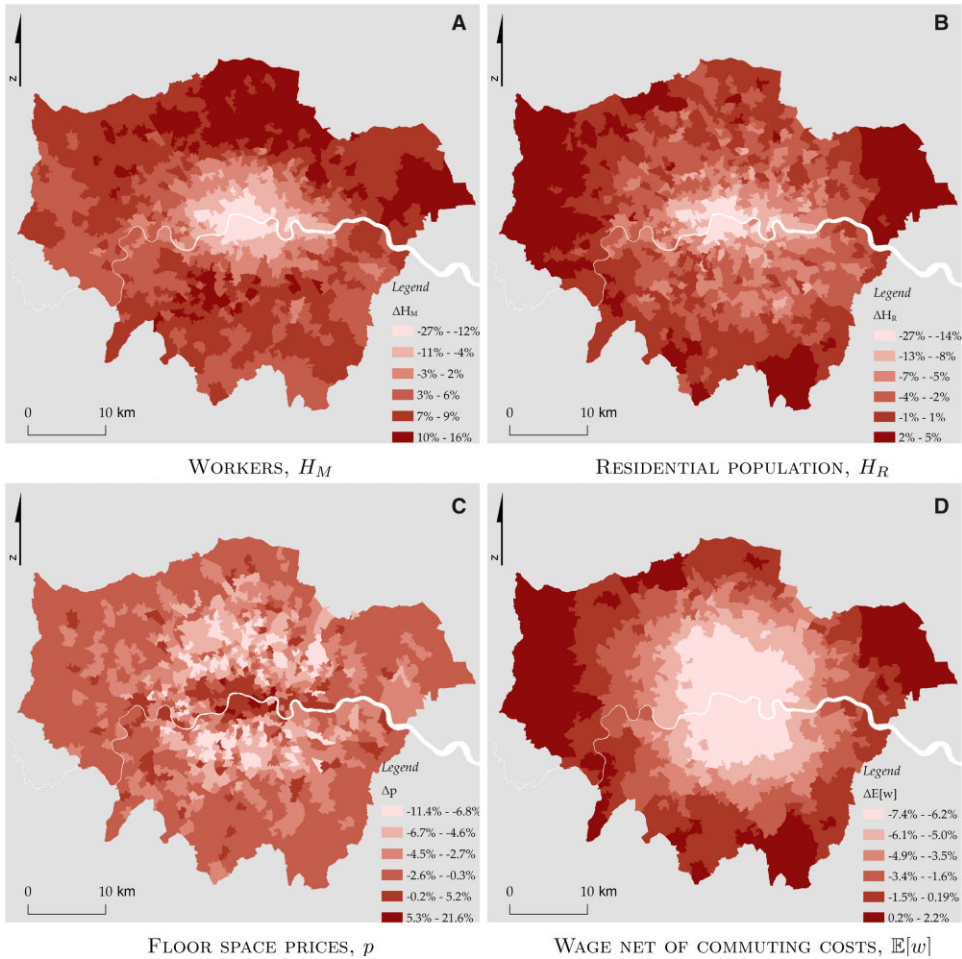
30   i.e. $(1 + 36\%)/(1 + 27\%) - 1 = 7.1\%$.

Figure 1. Counterfactual scenario 1: no Blitz.

4.5. Discussion

We find evidence that within-city service industry agglomeration economies in primate cities are large. The productivity elasticity is about 0.2 and remains robust to extensive sensitivity analyses. As previous research has found that the elasticity of agglomeration is typically between 0.02 and 0.10 (see Melo et al., 2009), our results point toward elasticities in London from 2 to 10 times larger. Using a similar model, Ahlfeldt et al. (2015) for instance find an agglomeration elasticity for Berlin of just 0.071. Although patently large, our findings are not unprecedented. Arzaghi and Henderson (2008), for example, find an agglomeration elasticity in New York of 0.13–0.40 for firm births within 250 m of existing firm locations, though this only applied to firms within the same industrial sector (i.e. advertising agencies). In a somewhat more similar analysis studying vertical agglomeration economies in a sample of nearly 20 US metropolitan areas, Liu et al. (2018) find that doubling zip-code employment is associated with a 10.7% increase in office rent, which implies an elasticity of ∼0.15. This again is comparable to our estimates.
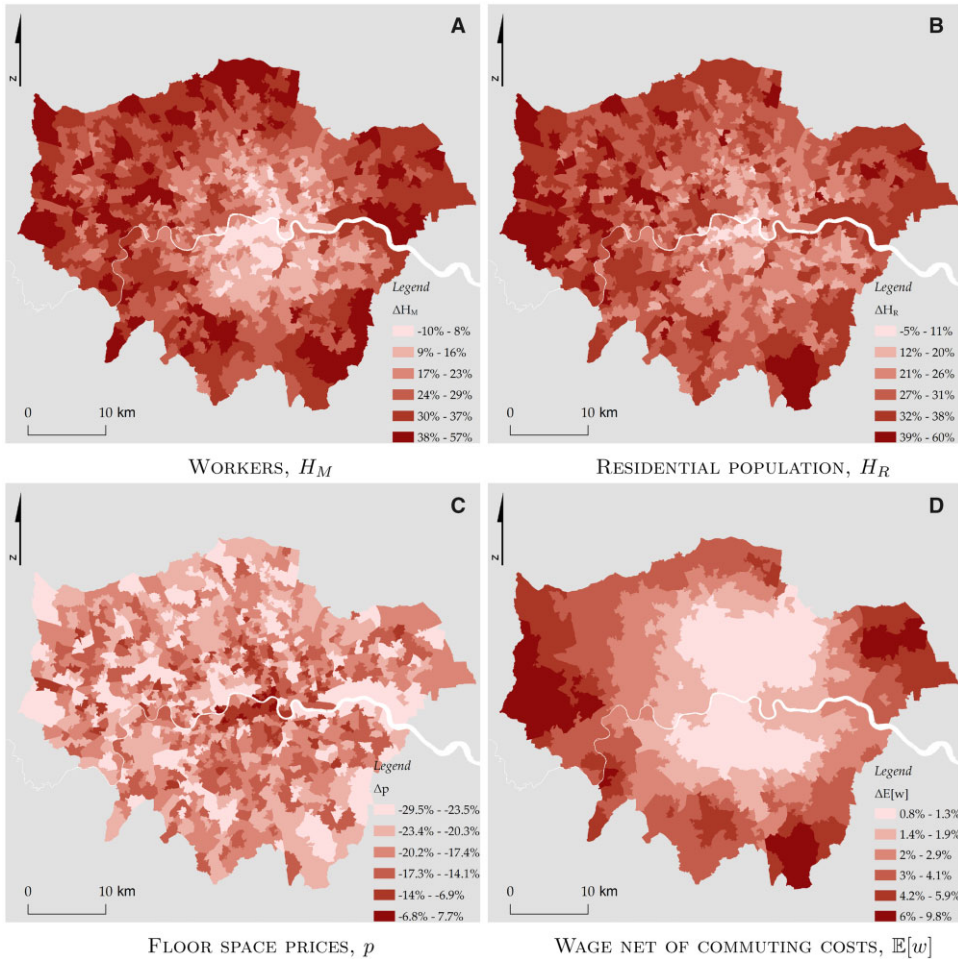
Figure 2. Counterfactual scenario 2: full bombings.

Studies that also rely on quasi-experimental variation in densities generally find stronger elasticities. Kline and Moretti (2014), for example, find an elasticity of ∼0.45, and Greenstone et al. (2010) likewise find large effects for manufacturing plant openings in the USA. More crucially, aggregate average elasticities such as those cited by Melo et al. (2009) are perforce primarily derived from the manufacturing industry, yet comparative research has shown that agglomeration effects in business services can be several multiples larger (Mun and Hutchinson, 1995). Our result is also consistent with previous research demonstrating that greater agglomeration elasticities may exist in large cities (Combes et al., 2012). For instance, Drennan and Kelly (2011), find that their measured effect of agglomeration more than doubles when they restrict their US sample to only the largest metropolitan areas.

In this regard, London is obviously an extreme case. As perhaps the world's premier commercial center, London is not only a major host to industries which greatly benefit from higher local densities, but also to some of the world's most innovative firms and people. Furthermore, in London's major service industries, personal relationships are a

fundamental requirement for the establishment of trust, the production of knowledge and the completion of complex transactions which require the input of many suppliers (Taylor et al., 2003). Thus proximity may be a key driver of competitive advantage. It is well-known that London has distinct office submarkets which cater to specific industries, for instance, banking and finance firms congregate in the City of London, law and publishing in Midtown, and private equity in the West End. However, even within these submarkets, specific industrial subsectors commonly co-locate. For example, the eastern core of the City of London is the prime location for the major insurance houses, and in the West End the elite hedge funds cluster just east of Hyde Park. Furthermore, many of these clusters have been in existence for centuries and have only been displaced in exceptional circumstances.[31] The ubiquity and sustained historical presence of such clusters suggests that agglomeration economies in London may exert an exceptionally strong influence on productivity, and by implication that redevelopment frictions there may exact extraordinary economic costs. Taken together, we interpret our large measured elasticity as a valid reflection of the level of agglomeration economies operative within one of the world's largest and most productive cities.

In addition to the agglomeration elasticity, the rate of agglomeration decay is also important in understanding the overall impact of agglomeration economies. As shown in Figure 3, our estimate of the decay parameter implies that after 3 min travel time (∼1 km straight-line distance), agglomeration economies decline by about 86%. Unfortunately, there are few studies whose decay parameters are directly comparable to ours. Rosenthal and Strange (2008), for example, focuses on the attenuation of agglomeration using variation in densities between US cities, whereas Dekle and Eaton (1999) employs Japanese prefectures as the unit of analysis. However, in Figure 3, we juxtapose our decay parameter with previous estimates from Ahlfeldt et al. (2015) and Arzaghi and Henderson (2008). Visual inspection confirms that while Ahlfeldt et al.'s (2015) decay parameter (ranging from 0.36 to 0.92) for Berlin is somewhat more forgiving than ours over greater distances, Arzaghi and Henderson's (2008) estimate for New York is in contrast more severe.[32] While these two estimates conveniently 'bookend' our own, these results may also suggest that where agglomeration elasticities are largest, their rate of decay over distance may simultaneously be greatest.

In the presence of such potentially large agglomeration economies, it has been suggested that governments should encourage rather than prohibit the greater clustering of firms within cities (Rossi-Hansberg, 2004). At the very least, an understanding of the economic effects of density in these high productivity locations is essential to beginning the policy debate. In an ideal world, planners would calibrate the stringency of development controls so that society makes the most efficient trade-off between the costs and benefits of greater worker densities. However, in order to make this judgment, at the very least planners require accurate information on both these costs and benefits. What our research now shows is that for the case of London, and perhaps other global cities such as New York and Tokyo, the costs of restricting worker density appear to be much greater than previously surmised. Consequently, if welfare maximization is indeed city-planners' social

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31 Severe local damage from the Blitz, for instance, is known to have caused the permanent relocation of some long-lived commercial clusters (Marriott, 1989, 69).

32 To scale the estimate of Arzaghi and Henderson (2008) to be comparable to ours, we assume that people travel 160 m/min. We further fit an exponential decay function to the coefficients for different rings.
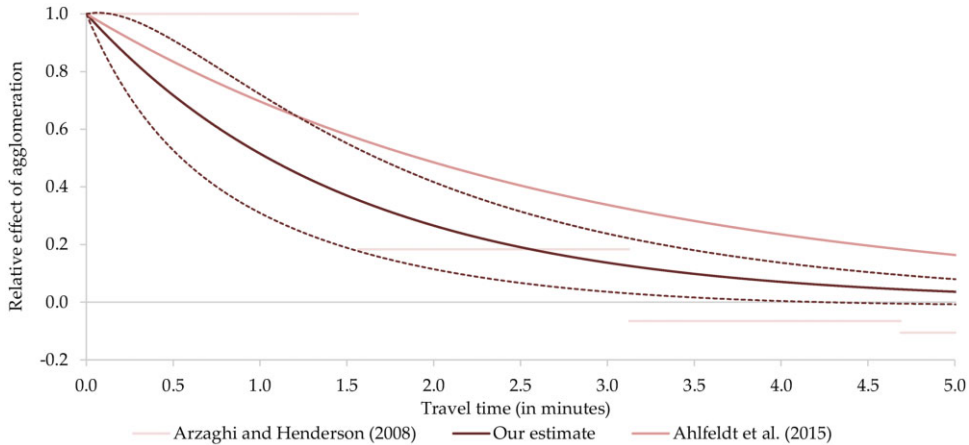
Figure 3. Decay of agglomeration economies.
Note: The dotted lines denote 95% confidence bands.

imperative (Ben-Shahar et al., 1969), then planners in such cities at least should now review the stringency of their development controls.

Our results additionally provide further evidence that a key redevelopment friction in London arises due to planning regulation. Although we are convinced that planning regulation is the dominant redevelopment friction in London (see Supplementary Appendix A.1), we cannot conclusively prove that the effect we observe from the Blitz bombings is not simultaneously caused by other important frictions. Nevertheless on the same token, planning regulation may in fact also be the driving force behind other supposedly different redevelopment frictions. For example, planning regulation may itself increase transaction and redevelopment costs, and lead to strategic behavior (see Cheshire and Dericks, 2020).

Our counterfactual simulations show that if the Blitz had not occurred, London's present day annual economic output could now be some 10% (or £50 billion) lower. However, a plausible alternative to this scenario is that absent the Blitz, rather than observing the local differences in planning permissiveness that we currently do, overall planning regulations could be more uniform, yet just as permissive *on average*. Such a scenario would not imply declines in London's population, but would still negatively affect local concentration and therefore output. A further relevant qualification of our results is that, since we do not simultaneously take into account potential benefits of the planning system (such as the preservation of historic amenities), it is not appropriate to interpret this loss as representative of *net* welfare costs.

5. Conclusion

This article exploits locally exogenous variation in the location of bombs dropped during the London Blitz to investigate how redevelopment frictions affect the urban spatial structure and agglomeration economies in an elite global city. Our results indicate that the Blitz bombings have lowered arguably the principal redevelopment friction in London: planning regulations, thereby increasing local employment density. More precisely, our reduced-

form results indicate that a standard deviation increase in Blitz bomb density is now associated with a 6.45% increase in local building height and that office rents increase by roughly 20% for each doubling in employment density. In addition, the structural parameters obtained from the quantitative spatial equilibrium model confirm the reduced-form evidence: density is positively related to bombings and the agglomeration elasticity is about 0.2, which is 2–10 times greater than estimates produced in previous research. These findings are robust to a wide range of sensitivity checks. Although these effects are large, we argue that they are consistent with the higher agglomeration economies thought to exist within the business services sector in elite commercial centers. Within London, these positive externalities seem to extend materially to around 1 km (or 3 min travel-time), which is in line with previous literature.

Counterfactual experiments employing a spatial general equilibrium model find that if the Blitz had not occurred, the resulting increase in redevelopment frictions in present day Greater London would cause its total population to fall by ∼9%, and would decrease employment concentration in the city center. As a consequence, we estimate that if the Blitz had not occurred, the annual per capita economic output of present day Greater London would now be about 10% (or £50 billion in aggregate) lower. It is important to qualify that these findings are speculative, and represent *gross* rather than *net* welfare losses because we do not take into account potential benefits of planning regulation. We also cannot definitively attribute the specific source of these redevelopment frictions, though we do provide substantial suggestive evidence that planning regulation is—at least in London—the dominant type.

Notwithstanding these limitations, our results nonetheless illuminate the large impact that redevelopment frictions have had on London's urban structure, both in restraining agglomeration and suppressing productivity. Our research indicates that in London, and perhaps other global cities such as New York and Tokyo, the costs of constraining worker density appear to be much greater than previously surmised. While the Blitz was an unquestionably tragic episode in London's history, for all its human cost, the peculiarly positive long-run economic impact wrought from this destruction further speaks to a remarkably resilient and dynamic city.

Supplementary material

Supplementary data for this article are available at *Journal of Economic Geography* online.

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