Employment Density and Agglomeration Economies in Tall Buildings

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Abstract

This paper examines vertical patterns of employment density and agglomeration economies within tall buildings. Theory suggests that vertical density should depend on the interplay of street access, height-related amenities, and productivity. Based on suite level data, we show that density patterns are u-shaped, with high density at ground level and high floors. Furthermore, factors associated with productivity, including nearby employment and firm-specific characteristics, have positive effects on employment density. Vertical density patterns are consistent with productivity spillovers that are strongest on a company's floor and attenuate rapidly with vertical distance. Similar evidence is obtained based on sales for law firms.

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I. Introduction

Cities exist because density is valuable. Mills (1972) writes that, "[T]he purpose of urban areas, broadly interpreted, is to facilitate production and exchange by proximate locations of producers and consumers." A range of empirical contributions have documented the patterns of density observed in cities, and interpreted the results in ways that illuminated important socioeconomic phenomena, such as the decentralization that many cities experienced after World War II. Papers in this literature include Clark (1951), Muth (1961, 1969), and Mills (1970).[1]

One key element of the value of density is the positive relationship between density and productivity. See Rosenthal and Strange (2004), Behrens and Robert-Nicoud (2015) and Combes and Gobillon (2015) for reviews. A central question that this literature has begun to address is the spatial range of agglomeration effects. While most of the literature has employed fixed spatial units such as cities or metropolitan areas, a smaller but growing literature has focused on the attenuation of agglomeration effects, including Rosenthal and Strange (2001, 2003, 2005, 2008, 2019), Arzaghi and Henderson (2008), Baum-Snow (2011), and Ahlfeldt et al (2015). The key result is that the strongest agglomeration effects are highly localized. This literature has not considered vertical density within buildings or its relationship to agglomerative spillovers.

This paper considers the vertical structure of tall buildings, with a particular emphasis on vertical patterns of density and within-building agglomeration economies that contribute to urban productivity. In related work, Liu et al (2018a) consider vertical structure, but focus instead on the equilibrium rent relationship and sorting that takes place within a building. There is no paper in the literature that considers vertical density patterns and evidence of within building productivity spillovers, either theoretically or empirically. This paper does both.

The paper's theory shows that vertical density is sensitive to multiple forces. Ascher (2011), for instance, notes that one should expect lower density on a building's higher floors, since these locations have poor access and create demands on the elevator system. While it is surely true that access and vertical transportation play an important role in determining vertical spatial structure – as access and horizontal transportation do in determining horizontal structure – our theoretical analysis will show that there are other forces also at work. These other forces include the taste by commercial tenants or their customers for high locations. Our model will show that the simple prediction of a decreasing vertical density gradient fails to hold unambiguously in a model that considers these forces. This means that it is

[1]See Duranton and Puga (2015) for a recent review of the literature on urban land use that began with the classic contributions of Alonso (1964), Mills (1967), and Muth (1969). Unlike this paper's analysis, the traditional monocentric model is concerned largely with horizontal issues, however. For a recent synthesis of research on density, see Ahlfeldt and Pietrostefani (2019).

an empirical question whether vertical density rises or falls as one moves to a higher floor within a tall building.

Answering this empirical question involves considering the interplay of forces that determine vertical density. As noted above, access and height-based amenities are important. We will show later that sorting is also an important force impacting vertical density. We will also show that an increase in tenant productivity will encourage the hiring of more workers and increase density, *ceteris paribus*. This suggests that if localized agglomeration economies exist within buildings, as would be the case if companies care about the composition of establishments on nearby floors, then within-building agglomeration spillovers will tend to raise employment and density on floors with advantageous configurations of nearby companies. As with vertical density, these issues have never been considered within individual buildings.

To explore these ideas empirically, the paper makes use of two novel data sources. The first is a set of confidential offering memoranda (OM).[2] These data describe the complete set of commercial tenant locations within a building and details of their leases for all suites within 90 buildings located in 18 metropolitan areas. They also include information on the amount of space occupied by a tenant. The OM data do not however provide information on tenant employment. To address this, we make use of establishment-level Dun and Bradstreet data (D&B). These data provide information on establishment-level employment, establishment type, and other indicators of establishment productivity (e.g. sales).

Tenant-level data in D&B were matched by hand to the tenants in the OM data by searching for the unique D&B DUNS number associated with each establishment in the OM files. Combining suite-level information from the two data sources enables us to determine suite-level employment density at each site in a building. Details of the matching procedure are provided later. For now, it is sufficient to emphasize that it is only possible to study vertical density patterns if one has suite level data on both space occupied and employment. The matched OM/D&B data allow us to do this.

The empirical analysis of vertical density has several interesting findings. First, density varies vertically within a building in a complex way. There is always high density at the ground floor level where access is best. As one moves to higher floors, density initially changes relatively little, which suggests that some other mechanism is at work to offset the negative influence of access. High up in a tall building, where access is especially poor but amenity levels are high (e.g. Liu et al (2018a)), we see higher density. This result is especially strong for law firms, one of the most important tenant types for tall buildings. This gives a vertical density gradient that is u-shaped. This complex pattern is inconsistent with the notion that access alone drives a decreasing vertical density gradient.

[2] Offering memoranda are distributed by building owners to potential buyers when a building is put on the market.

Second, we typically see higher densities for establishments that are likely to be more productive. Specifically, we see higher density for older establishments and for headquarters compared to branch and single-site establishments. Liu et al (2018a) provide evidence that higher productivity companies tend to sort into higher locations in tall buildings. Higher productivity companies also tend to employ more workers which, all else equal, will increase density. Our findings support this prediction.

Third, we find a clear pattern that establishment productivity is sensitive to proximity to complementary companies within the building, even after controlling for vertical location and tenant attributes. Specifically, establishment density increases with proximity to other own-industry companies. The effect is most pronounced on the floor on which the establishment is located and mostly attenuates away within three floors distance. For law firms, the relationship is especially strong and is further confirmed using data on sales per square foot, a measure of productivity especially relevant for law firms given their focus on billable hours. These patterns suggest that micro-agglomerations of similar type companies increase tenant productivity within commercial buildings.

One reason that these results are important is that buildings are managed by profit-maximizing owners. The result on u-shaped density means that building owners should design, maintain, and allocate space in the building with this pattern in mind. This has implications for elevator management and for the allocation of complementary activities such as restaurants and health clubs. The result on agglomeration suggests that building managers should also consider the spatial decay of agglomeration effects. This has clear implications for the allocation of space within a building: building managers have incentives to create micro clusters of complementary establishments.

In addition to contributing to the literatures on agglomeration economies and urban spatial structure, the paper also contributes to a small but growing literature on tall buildings. The short literature on tall buildings deals primarily with building height. Sullivan (1991) models vertical transportation in a tall building. Helsley and Strange (2008) develop a game-theoretic model of a building height as an all-pay auction, where builders compete to construct the tallest building in a market. Ahlfeldt and McMillen (2018) show that the spatial dispersion of tall buildings in Chicago is consistent with the sort of competition at the heart of the Helsley and Strange model. Ahlfeldt and McMillen also document a relationship between building height and land rent consistent with the predictions of the monocentric model. Koster et al (2014) consider the parallel issue of the relationship of office rents to building heights in the Netherlands. Barr (2010, 2012) focuses on the forces that govern building heights in New York City. The only recent paper on tall buildings that focuses on internal spatial structure is Liu et al (2018a), but it does not deal with density, as noted above.

The remainder of the paper is organized as follows. Section II presents a theoretical model laying out the issues that govern vertical density. Section III sets out the data that we employ. Section IV presents the empirical analysis of vertical density patterns, Section V provides evidence of localized within building productivity spillovers. Section VI lays out the results of a number of robustness exercises. Section VI concludes.

II. A theory of vertical density

This section outlines our model of vertical density. We begin by highlighting the role of two fundamental forces, vertical access costs and height-based amenities. As developed in Liu et al (2018a), these forces drive vertical rent gradients and the vertical sorting of establishments by type and productivity within buildings. We extend this analysis to show how this affects patterns of vertical density, both directly and indirectly.

A. Primitives

There are three types of agents in the model: a firm, the workers it employs in its production, and the consumers who buy its output. The activities take place within a tall building, so the firms will also be referred to as tenants. A tenant's location in the building is denoted by its floor, z.

All agents are assumed to be small relative to the market in which they operate. In this setting, the firm/tenant can employ as many workers as it wants at the market wage. Similarly, the firm/tenant can sell as much output as it wants at the market price. The market wage and price will depend on vertical location in a manner that will be clarified below. We will begin with a model where the locations within a building differ only based on access.

B. Access-only model

The simplest version of the traditional horizontal model of a city treats locations as differentiated only in their accessibility to the city's downtown center of production. Differences in accessibility are manifested in equilibrium in differences in prices for land and space, differences in building heights, and (most importantly for our purposes) in differences in density.

We are interested here in the vertical allocation of commercial activities. Suppose for now that all commercial tenants are identical. Output commands a price of p^0 at the ground floor of a building. Above ground level, a client purchasing from a tenant on floor z incurs transportation costs equal to $\Phi + \tau^c z$. In this specification, all trips begin at the ground floor. A trip has both fixed costs (e.g., waiting for an elevator or finding a stairwell) and marginal costs (e.g., time cost). Labor commands a wage of w^0 at the ground floor. Above ground level, workers incur transportation costs equal to τ^w per floor. As noted above, both goods markets and labor markets are competitive in the sense that an employer at floor z must compensate both customers and workers for the transportation costs that they incur.[3] Specifically, we suppose that price at floor $z > 0$ is given by $p(z) = p^0 - \Phi - \tau^c z$, while on the ground floor we have $p(z) = p^0 - \tau^c z$. The wage on floor z is given by $w(z) = w^0 + \tau^w z$. These price and wage relations capture how access matters to customers and employees and so ultimately to the tenant.

Tenant output depends positively on the amount of labor that the firm hires, $\alpha f(n)$, where $\alpha > 0$ is a productivity shifter and where the production function f(-) is increasing and concave. A tenant occupies space s, which we take as given and normalize to unity. Rent on floor z equals r(z). There are no other inputs employed. In this case, a tenant's profit on floor z equals

$$\pi(z) = \alpha f(n)p(z) - w(z)n - r(z). \qquad \text{(II.1)}$$

The standard first order condition for tenant profit maximization is

$$\alpha p(z)f'(n) - w(z) = 0 \qquad \text{(II.2)}$$

The second-order condition is

$$\alpha p(z)f''(n) = \Delta < 0. \qquad \text{(II.3)}$$

Applying the implicit function theorem gives

$$dn/dz = -[\alpha p'(z)f'(n) - w'(z)] / [\alpha p(z)f''(n)]. \qquad \text{(II.4)}$$

This has the sign of $[\alpha p'(z)f'(n) - w'(z)]$. The access-only assumptions made above suffice to give $p'(z) < 0$ and $w'(z) < 0$. This in turn gives a negatively sloped density gradient, $dn/dz < 0$.

The level and slope of the equilibrium rent gradient are determined by competition for space. This competition results in rent adjusting to give zero profit:

$$r(z) = \alpha p(z)f(n) - w(z)n, \qquad \text{(II.5)}$$

where n is evaluated at (II.2). The rent-gradient is thus negatively sloped in the access only case.

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[3] One could instead assume that part or all of workers' vertical commuting takes place on company time, reducing output. Nothing substantial would change.

The access-only model gives the clear prediction that both rent and density will fall with reduced access. As demonstrated in Liu et al (2018a), above ground level, rent rises within tall buildings so the model's predictions fail to match data in an important way.[4] We must, therefore, move on to a richer model.

C. Access and amenities: simple model

In order to obtain the result that higher floors command greater rents in equilibrium, the model must be modified in a way that would result in greater profits on high floors. As noted in Liu et al (2018a), there are two possible channels. The first is that the tenant's customers are willing to pay more for the output of a firm occupying a high floor. It seems unlikely that this could be a pure consumption effect, one corresponding to the high price of residential units on high floors. A resident occupies a penthouse for a substantial amount of time, presumably enjoying the view over that time. A customer of a commercial tenant spends less time on the tenant's high floor, and this time is presumably devoted to business.[5] Instead, a price premium associated with high floors, if it should exist, seems more likely to be associated with some sort of signal.

The second channel by which some sort of amenity can impact tenant profits is through worker wages. Workers, like the residents of a penthouse, do spend considerable time at their desks. They thus probably do assign positive utility to a pleasant office environment, with a view being one possible element of this environment. In addition, a worker's office is a publicly observable status symbol, suggesting another reason why worker utility might increase with floor.

For now, we will capture these effects with simple modifications of the p(z) and w(z) functions introduced above. Specifically, we suppose that these functions include both the access effect introduced above and also the amenity effect introduced in this section. For transparency, we will specify these linearly. For price, let $p(z) = p^0 - \tau^c z + \phi^c z$, while for wage, let $w(z) = w^0 + \tau^w z - + \phi^w z$. Suppose that these amenity effects are large relative to the access effects:

$$\tau^c z < \phi^c z, \quad \text{(II.6a)}$$
$$\tau^w < \phi^w z. \quad \text{(II.6b)}$$

Under these conditions, differentiation of (II.5) shows that the rent gradient is positively sloped, consistent with observation. In this case, however, the density gradient in (II.4) is now also positively

[4]It is worth noting that the prediction of a negatively-sloped vertical rent gradient would probably have agreed with data in the pre-elevator era.
[5] An exception are restaurants high up where the view is a more integral part of the dining experience.

sloped, which does not agree with the patterns emphasized in the professional literature (e.g. Ascher (2011)).

There is one additional comparative static that is worth discussing now:

$$dn/d\alpha = -[p'(z)f'(n)] / [\alpha p(z)f''(n)] > 0. \quad \text{(II.7)}$$

The sign of $dn/d\alpha$ is the sign of the term in brackets in the numerator, which is positive. An increase in productivity is associated with an increase in density. For instance, if agglomeration economies were present, then density would be greater. Even though the productivity change would allow the firm to produce the same output with fewer workers, the productivity increase leads to more employment, since the firm will choose to produce more output.[6]

In the meantime, the important point to restate is that simple models of access and amenities generate patterns of rent and density that are either globally upward sloping or globally downward sloping. Before turning to empirics, we will consider a richer model of amenities, one that accounts for complementarities between per worker space and height, in order to further investigate the relationship of rent and density.

D. Complementarities

The relationship of density to rent can be restated as follows: there must be an amenity of some sort in order for there to exist a positive commercial rent gradient, but the amenity raises the payoffs to density. It is our view – a view shared by every market participant with whom we have spoken – that worker amenities are a plausible explanation for the observed positive vertical rent gradient. In order to also obtain a decreasing vertical density gradient, one would need to have some additional force that results in more sparsely occupied offices at the high level.

There are two natural ways to incorporate such an additional force. The first is to suppose that vertical amenities depend jointly on floor height and on density, with density having a negative effect. Corner offices have prestige attached to them in part because they have more windows, and a high floor corner office can thus have especially impressive views. But such a corner office would seem likely to confer on its occupant less additional prestige if it were horribly cramped. More generally, if an employer

[6] It is possible the a tenant's floor directly impacts productivity because of abundant light and reduced noise. In this case, density would rise with floor through the productivity channel.

attempts to benefit from high floor views employing a large number of workers there, it seems reasonable to suppose that the cramped office will, at least in part, detract from the amenities associated with height.[7]

To capture this in the model, suppose that instead of being a linear function of floor, amenities for workers and customers include a complementarity between the space devoted to each worker, $\sigma = s/n$ and the worker's floor. Per worker space is, of course, the inverse of density. Let the relationship be given by $h(z,\sigma)$ for workers and by $g(z,\sigma)$ for consumers, with both functions increasing in both arguments. Cross-partials are assumed to be positive to capture complementarities. We also suppose also that $[\partial^2 g/\partial\sigma^2\ (\partial\sigma/\partial n) + \partial g/\partial n\ \partial^2\sigma/\partial n^2] < 0$ and $[\partial^2 h/\partial\sigma^2\ (\partial\sigma/\partial n) + \partial h/\partial n\ \partial^2\sigma/\partial n^2] < 0$, which is sufficient for the second order conditions to be met.

In this setup, the price equation then becomes $p(z) = p^0 - \tau^c z + \phi^c\ h(z,\sigma)$, while for wage, $w(z) = w^0 + \tau^w z - \phi^w\ g(z,\sigma)$. The first order condition for employment becomes

$$p(z)f'(n) - w(z) + f(n)\phi^c\ \partial h/\partial\sigma\ \partial\sigma/\partial n + n\phi^w\ \partial g/\partial\sigma\ \partial\sigma/\partial n = 0. \qquad \text{(II.8)}$$

The first two terms are as in (II.2). The second two depend on the complementarities in amenities production. The expression $\partial\sigma/\partial n = -s/n^2 < 0$; additional workers reduce the space per worker. Since $\partial h/\partial\sigma > 0$ and $\partial g/\partial\sigma > 0$, both expressions are negative. Firms tend to hire fewer workers because the marginal hire impacts price negatively and wage positively through the amenity channel.

The slope of the density gradient is given by

$$dn/dz = (-1/\Delta)\ [(-\tau^c + \phi^c\ \partial h/\partial z\ )f'(n) - (-\tau^w + \phi^w\ \partial g/\partial z) + f(n)\phi^c\ \partial^2 h/\partial\sigma\partial z + n\phi^w\ \partial^2 h/\partial\sigma\partial z], \qquad \text{(II.9)}$$

where

$$\Delta = p(z)f''(n) + f'(n)\ \phi^c\ \partial h/\partial\sigma\ \partial\sigma/\partial n + \phi^w\ \partial g/\partial\sigma\ \partial\sigma/\partial n + f(n)\phi^c[\partial^2 h/\partial\sigma^2\ (\partial\sigma/\partial n) + \partial h/\partial n\ \partial^2\sigma/\partial n^2] + n\phi^w\ [\partial^2 g/\partial\sigma^2\ (\partial\sigma/\partial n) + \partial g/\partial n\ \partial^2\sigma/\partial n^2] \qquad \text{(II.10)}$$

is negative by the second order condition. The sign of dn/dz equals the sign of the expression in square brackets. This latter expression is indeterminate. If we suppose that $(-\tau^c + \phi^c\ \partial h/\partial z)$ and $(-\tau^w + \phi^w\ \partial g/\partial z)$ are positive, then the amenity effects are large enough to ensure that $dr/dz > 0$. Density may rise or fall as one moves up within the building.

[7] Another way to capture this is to consider multiple types of tenant with a particular sort of differences in their demand for space and amenities. We will discuss this below in the extensions subsection.

In sum, a natural assumption of a complementarity between space per worker and floor level in the creation of amenities is sufficient to allow for the possibility that density falls with floor while rent rises. This will motivate the empirical analysis to follow. Before turning to this analysis, there are some corollaries to the vertical model presented here that are worth exploring.

E. Extensions

The key prediction so far is that density can potentially rise or fall vertically, with the slope of the density gradient being an empirical issue. There is no ambiguity with respect to productivity, however, with an increase in productivity being associated with an increase in density.

There are two important limitations of the model, and it is worth discussing how the model might be extended to deal with them. We will begin by relaxing the assumption that there is one type of tenant. Suppose that there are amenities as in Section C above. Suppose also that there are two types of tenant differentiated by the degree to which high locations are valued by workers. Specifically, for the workers hired by high-type tenants, amenities outweigh access, but for those hired by low-type tenants, the reverse is true. Suppose for simplicity that consumers assign no value to high locations for either type of tenant with output prices constant and identical for the two types. In this case, we have $\phi^{wH} > \tau^{wH}$ and $\phi^{wL} < \tau^{wL}$. It is easy to see that there will be sorting in a way discussed previously in Liu et al (2018a). The high-type tenants are amenity oriented, while the low-type tenants are access oriented. The former will have upward sloping bid-rent by floor, while the latter will have downward sloping bid-rent. If the low-types are able to outbid the high-type firms anywhere, it will be at the bottom of the building. This requires a low τ^{wL} relative to τ^{wH} and ϕ^{wH}.

In this situation, density will depend on both the access and amenities forces discussed above and also on sorting. The high-type tenants will have an upward sloping density gradient. The low-type tenants will have a downward sloping density gradient. The overall vertical pattern of density will aggregate the densities chosen by the two types of tenant.

Another limitation is that we have treated space demand as given. Suppose instead that there are variable factor proportions, with output now depending on both n and s. The first order conditions for n and s together give the familiar condition

$$(\partial f/\partial n)/(\partial f/\partial s) = w/r. \qquad \text{(II.11)}$$

This can be used in a natural way to see how density changes with floor level in the various scenarios discussed above. In the access-only case, wage rises with floor, and rent falls. Consequently, density falls as one moves up within a building. In the amenities case, when amenities dominate, rent rises with floor, and wage falls. This gives density rising within a building. Finally, if there are complementarities between height and space as in Section C, the standard condition (II.10) no longer holds since the choices must account for the effect on amenities. This tends to decrease n and raises s, lowering density everywhere. The effect on the gradient is, however, indeterminate. As with the fixed s case discussed above, with variable proportions, the density gradient is indeterminate.

III. Data

A. Overview

In order to consider vertical density, data on tenant employment, space occupied, and within-building location are required. In addition, examining the theory's predictions requires data on various tenant characteristics related to productivity. While standard data sets provide information on employment and tenant characteristics, they do not include information on space occupied or vertical location. In our view, the lack of this sort of data explains the absence of a literature on the internal structure of buildings. To address this, we make use of two data sources.

The first is a set of confidential offering memos (OM) that identify the complete set of tenants in a set of tall commercial buildings, their locations within the building, the rent that they pay, and the amount of space that they occupy.[8] With the exception of Liu et al (2018a), these microdata are new to the literature. The second is establishment level Dun and Bradstreet (D&B) data that provides information on employment and other characteristics of the company. These two data sources were matched at the suite level. This allows us to calculate suite-level employment density per square foot of space occupied, and to measure vertical patterns of employment density, the first such measures in the literature of which are aware.

B. Matching establishments in the OM and D&B data

The OM data are based on offering memos that are distributed to potential buyers when a commercial building is exchanged. We were provided with access to offering memos for 90 tall commercial buildings located in 18 U.S. metropolitan areas over the period 2004-2014.[9]

The D&B data are more familiar. A series of earlier papers by Rosenthal and Strange have drawn on D&B data aggregated to the 5-digit zipcode level.[10] More recently, Syracuse University has obtained a

[8] For all offering memos, we work with the Building Owners and Managers Association (BOMA) compliant reported value for floor area. See https://www.boma.org/BOMA/BOMA-Standards/Home.aspx. BOMA is an international trade association, and it has precise guidelines for calculating floor area. While such measurement has the potential for error, the precision of the BOMA measurement is meant to ensure true reporting, avoiding the "rubber ruler" problem of exaggerated suite sizes that is sometimes found in areas reported according to "local custom."

[9] The OM data were also used in the analysis in Liu et al (2018a).

site license that provides access to establishment level data. The D&B data cover close to the universe of establishments in metropolitan areas across the U.S, providing detailed information on employment and sales at an establishment's site (i.e. a tenant's suite), establishment type (i.e. single site, branch, headquarters), sales and employment of the overall firm for multi-site companies, and many other establishment attributes. Among these other features includes the establishment's SIC code which we draw upon at the 2-digit level.

Given our goal of measuring employment density at the suite level, matching of suite-level D&B data to suite-level OM data is crucial. This allows us to divide a suite's employment by the space occupied, creating a suite-level measure of employment density. The offering memos identify tenants by name and address only while D&B identifies tenants by name, address and their unique D&B DUNS number. To match OM and D&B tenant data, we searched the web by tenant name for each of the roughly 6,000 tenants in the offering memo data and determined the DUNS numbers for each establishment. This process was done by hand to ensure an accurate match.

When considering the matched data file, it is important to keep in mind the difference in timing associated with the OM and D&B data. The OM data represent the complete set of companies present in a building at the time that the offering memorandum was produced, ranging from 2004 to 2014 depending on the building in question. The D&B data were all obtained in 2016 and cover establishments present in that year. Because the D&B data are current at the time the data are observed, we do not have access to corresponding employment data at the time the offering memos were issued. The manner in which these differences in timing are addressed, both when cleaning the data and in the empirical work to follow, is described next.

C. Timing differences between the OM and D&B data

OM companies that went out of business prior to 2016 are not present in the D&B data. For these establishments it is not possible to observe employment. For other OM companies that relocated to a different building after the offering memo was issued, we do not observe the space they occupied in 2016. In both instances, it is not possible to develop a reliable measure of employment density, and, for that reason, both sets of companies were dropped from the estimating sample. This reduced the number of suites in our estimating sample from roughly 5,800 in the offering memos to roughly 2,800.

We address possible selection issues from this loss in sample in two ways. The first is to include a rich set of controls in our density models to capture the influence of establishment productivity, the value of street access, and amenities up high. These fundamental drivers of density are not directly observed. Instead, we rely on floor height, building fixed effects, age of establishment, etc. as proxies. If our

[10] See Rosenthal and Strange (2001, 2003, 2004, 2005 and 2012).

controls do a good job of capturing the underlying drivers of density, this will reduce correlation between the model estimation errors and unobserved factors that contribute to sample attrition. This will help to mitigate selection bias.[11]

We also estimate a series of models that check for robustness with regard to timing. Specifically, models are estimated in which the samples are restricted to successively more recent offering memos, up to just a few years prior to when the D&B data were obtained. These models also control for space vacated by establishments that left their buildings between the time the offering memos were issued and 2016. Estimates from these models are nearly identical to the full sample models, including also when controls for vacated space are omitted. These robustness checks are discussed in Section VI. For now, it is sufficient to emphasize that our results do not appear to be sensitive to temporal differences between the OM and D&B data. This is consistent with our model controls doing a good job of capturing the influence of unobserved factors. Bearing this in mind, those establishments that are retained in our primary estimating sample are all present in both the offering memos and in the D&B data for those same buildings in 2016.

D. Trimming outliers from the matched OM and D&B sample

In addition, the sample was trimmed to eliminate suites that exhibited extreme values for employment density. These suites were dropped to reduce the influence of outliers. Specifically, we dropped suites for which the reported level of space occupied was less than 200 square feet. Also dropped were suites for which employment density exceeded 25 workers per 1,000 square feet, or less than 40 square feet per worker. To put this in context, commercial real estate industry reports indicate that the average square feet per worker has mostly been between 190 and 200 over our same sample period.[12] Setting the threshold for suite employment density to 25 workers per 1,000 square feet causes the average space per worker to also equal roughly 200 square feet per worker, matching industry norms.[13] Trimming out observations in this manner further reduced the estimating sample to 2,291 establishments.

To assess the sensitivity of our estimates to the trimming procedure above, we estimated a series of models that imposed a range of employment density thresholds on the estimating sample. This

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[11] Phrased differently, suppose we estimated a Heckman selection model with a first stage sample attrition equation and a second stage density regression. If the errors in the density and sample attrition equations are uncorrelated, then the coefficient on the inverse Mills ratio in a second stage would be zero, and there will be no selection bias. We did not attempt to estimate a selection model because we have no obvious exclusion restrictions to aid in identification: controls that drive sample attrition but not density.

[12] See for example, "Why Space Matters: Density" by David Smith at Cushman and Wakefield. http://blog.cushwake.com/americas/why-space-matters-density.html.

[13] It is worth noting that some establishments may operate multiple shifts over a 24-hour period or have employees assigned to an office who are typically out in the field. This would produce large values for density relative to standard allocations of space to workers, leading us to set a high bar for removing outliers.

included thresholds from 50 workers per 1,000 square feet (20 square feet per worker) down to 15 workers per 1,000 square feet (67 square feet per worker). Results were quite robust over this range of thresholds. This suggests that outliers are not systematically located at different heights above ground level and that our estimates are robust for that reason. Patterns from these and other robustness checks are discussed later in Section VI.

E. Summary statistics

Table 1a provides broad summary statistics for the OM data. In Panel A, the cleaned data used in the regressions include 2,291 suites spread across 90 buildings in 18 cities. As described earlier, these data were coded from offering memos issued between 2004 to 2014 when the individual buildings were put up for sale. Panel B shows the distribution of floor heights associated with the individual suites and buildings. The buildings are all tall, with a minimum height of 16 floors, a median height of 28 floors, and 7.8 percent of buildings over 50 floors. Median suite height is floor 16, with 17.2 percent over floor 30, and 3.2 percent over floor 50. Thus, the OM sample is comprised exclusively of tall buildings, with some quite tall. The distribution of suite height is skewed towards lower floors since all buildings contribute suites to the sample up to floor 16.

Table 1b summarizes the industrial mix of tenants and the distribution of their employment density at different heights off the ground. Six industries are highlighted, including Retail, FIRE, Business Services (SIC 73), Advertising (SIC 7311, 7312, 7319), Law (SIC 81), and Engineering, Management and Accounting (SIC 87). A seventh, all other, category is also reported. Focusing first on the overall composition within the OM buildings (column 1), FIRE and Law are the most common occupants, accounting for 16.8 and roughly 19.0 percent of suites (384 and 436 suites), respectively, while Retail accounts for just 7.0 percent of suites overall (160 suites). Columns 2-5, however, show that the buildings are quite heterogeneous internally, with the composition of lower floors quite different than the composition of upper floors. Retail, is common at ground or concourse level (below ground), as seen in column 3, where it accounts for 45.8 percent of suites, while representing fewer than 3 percent of suites above ground level. For FIRE and Law the pattern is reversed. These industries account for 1.4 and 0.9 percent, respectively, of ground and concourse level suites but are roughly 22.10 and 37.8 percent of suites above floor 40 (column 5).

The right half of Table 1b reports density patterns. Grouping all industries together in the bottom row, density averages 5.0 workers per 1,000 square feet (column 6) taking all suites and buildings together.[14] Consistent with Ascher (2011), density is higher at ground and concourse level, averaging 5.6 workers per 1,000 square feet. Unlike Ascher (2011), we do not see a monotonic decline in density within a building. While density is comparatively low between floors 2 and 40, where it averages 4.6 workers per 1,000 square feet, it rises to an average of 8.0 workers per 1,000 square feet above floor 40. This u-shaped pattern will persist in most of the analysis to follow, including when all industries are pooled together and also when we examine patterns for Law separately. Overall, Table 1b shows that buildings are not internally homogeneous. There is variation in the type of establishments at different heights off the ground. There is variation in density as well. We next provide evidence on the nature and drivers of vertical density patterns.

IV. Vertical density patterns

Guided by Section II's theory, this section presents estimates of the density patterns present in tall commercial buildings. We will begin our analysis of the pattern of density within buildings by presenting a nonparametric specification estimated using kernel weighted local polynomial regression (Lpoly in Stata). This approach does not impose restrictions on the shape of the vertical density gradient or include controls. Figure 1a presents an Lpoly model based on a subsample of buildings over twenty-five floors. The figure then shows densities up to floor 25 to ensures that the same set of buildings are used to identify the pattern throughout the range of the figure.[15] The pattern displays sharply higher density at ground level, with a relatively flat pattern thereafter. The result that density is high at ground level is robust to every model estimated in the analysis to follow.

Figure 1b repeats the Lpoly model for the entire sample of buildings. This figure includes those lower than 25 floors, and densities are presented up to floor 50. Beyond this, there are too few suites to obtain reliable patterns.[16] The plot reveals high densities at the bottoms of buildings where access is good and also high densities on high floors where amenities are likely to be valuable. This finding of a u-shaped density gradient will also prove to be robust in the analysis that follows.

We now turn to parametric models of vertical density. We begin by outlining the general structure of our empirical model, variants of which are used in all of the regressions to follow. Estimates of the manner in which density changes with height off the ground are then presented. Discussion of the

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[14] This figure is broadly consistent with NAIOP's (National Association of Industrial and Office Park's) figure of roughly 200 square feet per worker. See https://www.naiop.org/en/Research-and-Publications/Magazine/2015/Spring-2015/Business-Trends/Trends-in-Square-Feet-per-Office-Employee.

[15] Figure 1a was produced using a Gaussian kernel function with 2 degrees of power and bandwidth and pwidth equal to 2.63 and 3.95, respectively, as selected by the default optimization routine in Stata.

[16] Figure 1b was also produced using a Gaussian kernel function with 2 degrees of power. In this instance the bandwidth and pwidth were set to 3.2 floors and 4.8 floors, respectively, using again the default optimization values in Stata.

influence of establishment productivity on density, including the effect of localized productivity spillovers within the building, are deferred to the following section.

A. Empirical model

As the theory makes clear, within-building suite density is impacted by various forces. The first is the tension between access and vertical amenities that varies with height off the ground. In our simplest model, we include height off the ground as $\delta_1 z_{concourse} + \delta_2 z_{ground} + \delta_3 z$. The variables $z_{concourse}$ and z_{ground} are 0-1 controls for concourse and ground level locations, respectively. They capture the fixed costs of moving up off the ground floor / concourse, where customers and employees typically enter the building. The third term, $\delta_3 z$, captures both access and amenities. If the former dominate, then $\delta_3 < 0$, while if the latter dominate, then $\delta_3 > 0$. In some specifications, we impose the constraint $\delta_1 = \delta_2 = 0$. In others, we replace the third term with a step function.

The second force is establishment productivity, which is expected to have a positive effect on density. Establishment *i*'s productivity depends on establishment specific attributes, denoted by $Estab_i$, and also on any agglomeration spillovers that depend on the establishment's location within the building, $Agglom_i$, described in further detail later in the paper. The establishments in building b have productivity that depends on the physical and other attributes of the building, denoted by Bld_b, and the building's location, Loc_b. The latter variables include agglomeration variables that operate at the neighborhood level (rather than within the building), including the level and composition of nearby employment along with other location specific conditions.

Collecting terms, the models to follow are all variants of the following form:

$$log(D_i) = \delta_1 z_{concourse} + \delta_2 z_{ground} + \delta_3 z + \theta_1 Estab_i + \theta_2 Agglom_i + \theta_3 Bld_b + \theta_4 Loc_b + \varepsilon_i \quad \text{(IV.1)}$$

where D_i gives the employment density for the tenant of suite *i*.

The model in (IV.1) does not control for rent. This requires an explanation, since all else equal, tenants should also use less space when rent is high. As shown in Liu et al (2018a), the systematic drivers of rent are the same as the drivers of density. These include height off the ground (which affects access and vertical amenities), a building's physical attributes, and the building's location specific attributes (including nearby employment), among other things. With rent omitted from the model, the model coefficients have a well-defined reduced form interpretation, reflecting both direct effects on density and indirect effects through rent. This is not a problem since we still are identifying the systematic effect of office and tenant attributes on density, our primary goal. Moreover, provided our model does a good job of capturing the systematic drivers of density, omitting rent from (IV.1) should not affect the other coefficients in the model since any residual component to rent should be uncorrelated with the model controls. Similarly, adding rent to the model should do little to improve ability to forecast density.

For these reasons, most of the models to follow omit the rent variable. This yields a slightly larger sample since rent is missing or not reliable in some instances. To confirm robustness, we will later report estimates from models that include rent but without any attempt to instrument. Consistent with the arguments above, adding rent has no effect on the other model coefficients and the rent coefficients are small and insignificant.[17]

B. Vertical patterns

Tables 2a and 2b present estimates from a series of models for which the dependent variable is the log of employment density at the suite level. In the first table, the sample includes companies from all industries. In the second table, the sample is restricted to just Law, an industry which accounts for more suites in our building than any other (436 as reported in Table 1b). Law is also an intensely information oriented industry and provides special opportunities to explore density patterns for reasons that will become apparent.

The structures of Tables 2a and 2b are identical. In both cases, additional controls are included in the model moving left to right, with the most complete specification in the far right column. Two sets of controls in the models are of particular interest. The first describes the vertical density gradient. The second appear in the lower portion of the table and include establishment-specific attributes that proxy for productivity.

We begin with Table 2a, which pools companies across industries. All of the columns except for column 1 include two-digit SIC industry fixed effects. Also, that columns 1-5 all enter height off the ground in a linear fashion, measured by floor number. In all five columns, the coefficient on floor number is positive and mostly shrinks in magnitude as one moves from left to right. The estimated floor number coefficients are also not significant, especially in the more fully specified models. In column 1, which controls for just floor number, the estimated coefficient is 0.004 with a t-ratio of 1.37. Adding industry fixed effects in column 2 hardly changes the effect of floor number. Column 3 adds controls for headquarter, branch or single-site status, and establishment age. This reduces the floor level coefficient to 0.0028. Controlling for building height and total square footage of office space in the building in column 4 reduces the floor coefficient yet again, to 0.0011 (with a t-ratio of 0.45). The coefficients on building

[17] We also estimated models in which the nonsystematic portion of rent only was included as a control. This was done by first regressing log rent on all of the model controls in (IV.1) and then including the residual in the density regressions. Estimates were identical to those reported later in the paper when rent is included directly in the density regressions.

height and floor area are also both small and insignificant. Column 5 adds 90 building fixed effects to the regression. This captures the influence of building-specific factors, which drop out of the model, while also taking account of all other time invariant building and location specific attributes. The floor number coefficient in this model remains small and insignificant, with a coefficient of 0.0016 and a t-ratio of 0.64.

Taken as a group, the models in columns 1 to 5 suggest that the vertical density profile is quite flat, on average. This is what one would expect given Figure 1a's depiction of a non-monotonic, u-shaped density pattern. To allow for a more flexible vertical density pattern, Columns 6 and 7 of Table 2a (and Table 2b) repeat the specifications in columns 4 and 5, respectively, but replace the floor number variable with a series of dummy variables for different floors: concourse level, ground level, floors 2-3, 4-9, 10-19 (the omitted category), 20-39, 40-59, and 60 and above. Specifying height in this fashion allows us to highlight the main features of the vertical density pattern revealed in Figures 1a and 1b, while conserving power given our relatively limited sample size and many fixed effects. Accordingly, we distinguish floors 2-3 from adjacent floors to capture the idea that floors 2 and 3 are less accessible than ground level but retain the possibility of access by walking up flights of stairs. Above floor 3, most individuals will use elevator transport and the floor groupings allow for the possibility of rising density as seen earlier.

In columns 6 and 7, u-shaped employment density pattern is evident, echoing the patterns in Figure 1. To see this, recall that the omitted height category is floor 10 through 19. Observe also that the density coefficients for floors 2-3 are negative, moderate in magnitude, and marginally significant, while the coefficients on floors 4-9 and 20-39 are close to zero and not significant, indicating a flat density pattern from roughly floors 5 to 40. Above floor 40, density increases sharply and is significantly higher than for the omitted category. As in Figure 1b, density displays a u-shaped pattern with high density both at ground level and above the 40^{th} floor. Different from before, the pattern in Table 2a persists after conditioning on a large number of other factors that affect density.

The magnitude of the density pattern is also important. We will focus on column 7, which is the more robust specification because of the building fixed effects. In this model, as with column 6, the concourse coefficient is not significant. The ground floor coefficient is large and significant, however, with a coefficient of 0.4074 and a t-ratio of 2.66. This indicates that ground level density is approximately 44 percent larger than density in the mostly flat range from roughly floors 4 to 40. Between floors 40 and 60, the point estimate suggests that density regains its ground level value. Relative to floors 4 to 40, density is about 44.69 percent higher, with a t-ratio of 3.77. Above floor 60, our estimates suggest some easing back on density, with density levels only about 25 percent higher than floors 5 to 40 (with a t-ratio of 1.69). We emphasize, however, that there are only three buildings in our sample above 60 floors. This results in a small number of suites above that level and reduces the precision of the estimate.

Figures 2 and 3 help to put the magnitude of the vertical density gradient in perspective. Figure 2 displays a heat map of employment density in Manhattan, for which density is clearly highest close to Grand Central Station. Figure 3 summarizes how density varies with distance from Grand Central. As reported in Figure 3, employment density at Grand Central is roughly double that of density levels one mile away. This is close to the same magnitude effect on density associated with moving up off of the ground floor in column 7, Table 2a.

Table 2b revisits the vertical density pattern, restricting the sample to just law firms. Because of the smaller sample size, there were no ground level law establishments in the sample, but concourse level establishments were present. This accounts for why the ground level control is omitted. Industry fixed effects are also omitted given the focus on Law. All other features of the specifications in Table 2b are as for the all-industry models in Table 2a.

As a broad characterization, the density patterns for Law in Table 2b are qualitatively the same as for the all-industry models, but the amplitude of the u-shaped pattern is more pronounced. This is evident in columns 5 and 6, which allow for non-linear density patterns. In column 6, which controls for building fixed effects, the concourse coefficient is especially large, 1.23 with a t-ratio of 7.95. The coefficients for floors 2 through 9 suggest a mostly flat density pattern up to about floor 20 (recalling that floor 10-19 is the omitted category). Above that level, density increases sharply and monotonically. The coefficient for floors 20-39 is 0.59, with a t-ratio of 4.04. For floors 40-59, the coefficient is 0.83 with a t-ratio of 3.42. Above floor 60 density is 1.33 with a t-ratio of 4.76. As discussed earlier in the paper, rising density high up off the ground can arise because of sorting and related mixing of different industries. The pattern in Table 2b, however, is obtained for a single industry but still yields a prominent u-shaped density function.

In sum, Tables 2a and 2b show that vertical density is more complicated than has sometimes been believed. Simple linear models suggest flat (Table 2a) or only modestly rising density (Table 2b) with floor height, on average. However, this result does not extend beyond a simple linear specification. Instead, density is highest at the bottom of tall commercial buildings, consistent with greater access and as suggested by Ascher (2011), but density is also high in the upper portion of tall buildings where vertical amenities are greatest. This is consistent with the forces that Section II's theory has identified. Without amenities, decreasing access should cause density to decrease vertically in a monotonic fashion, but allowing for amenities, one can generate the u-shaped pattern of densities that we see here.

V. Establishment productivity and within-building spillovers

The previous section established that vertical density patterns have a u-shaped structure, consistent with the joint influence of access and amenities. The first part of this section provides evidence that establishment productivity also contributes to greater density, *ceteris paribus*. The second part presents additional estimates consistent with localized productivity spillovers that affect density patterns within tall commercial buildings.

A. Establishment productivity

Consider the proxies for establishment productivity in the lower portions of Tables 2a and 2b. These include whether the establishment is a headquarters, branch, or single-site facility, where single-site is the omitted category. Also included are 1-0 dummy variables for whether the establishment was created prior to 1950, 1950 to 1979, 1980 to 1999, 2000 to 2009, and an omitted category of 2010 or later. We expect headquarter establishments to be more productive, all else equal. This is consistent with patterns in Liu et al (2018a) which confirm that headquarters tend to be located on higher floors.[18] We also expect older establishments to be more productive since they have survived and presumably gained skill over time. In both cases, higher productivity establishments are expected to grow and add more workers. Higher productivity establishments could also add more space. However, moving costs and idiosyncratic availability of vacant suites create frictions that increase the transaction costs of adding space. In contrast, companies can easily add office staff and use existing space more intensively, at least up to a point. For these reasons, productive companies will use existing space more intensively, as in Section II. This suggests that office suite employment density should be higher for older companies, on average.[19]

Consider first Table 2a, with all industries pooled together. The patterns in columns 3-7 support the priors above. Focusing on the building fixed effect specification in column 7, the coefficient on Headquarters is 0.64 with a t-ratio of 5.22. This suggests that employment density is roughly 64 percent higher at headquarter establishments relative to single-site establishments (the coefficient on branch facilities is much smaller and not significant). It is also clear that older companies exhibit higher density. For companies created prior to 1950, employment density is 1.43 log points higher than for companies established after 2009, with a t-ratio of 6.64. The age coefficient declines monotonically in magnitude as the year of origination becomes more recent. The coefficient on 2000-2009 origination, for instance, is 0.87 with a t-ratio of 5.83. These patterns for headquarter and age effects are extremely robust across the specifications in columns 3-7, including allowance for non-monotonic vertical density patterns in columns 6 and 7, and inclusion of building fixed effects in columns 5 and 7. [20]

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[18] It is true that headquarter establishments may require more support staff who tend to be allocated less space, and that this would contribute to higher density. However, additional support staff would be present as complements to higher level management activity and would be a reflection of the overall higher level of productivity in the suite.

[19] Because the sample of companies used for our estimation are all survivors at least to the date the D&B data were obtained (as described earlier), the temporal argument above is relevant to both headquarter establishments and older companies.

[20] The conclusion that employment density increases with establishment age is consistent with the view that, on average, surviving, older companies tend to be more productive, expand over time, and for these reasons use space more intensively than younger establishments. It is also possible that older, growing companies may relocate to

Consider next Table 2b, for law firms. Once again, headquarter establishments display higher density, with estimates that are quite similar across all specifications. These estimates also always show high t-statistics, for example 4.69 in Column 6. Older establishments also display significantly higher density. Together, these results and those in Table 2a confirm that higher productivity establishments display higher employment density.

B. Within building spillovers

Tables 3a and 3b extend the previous models by providing evidence of within building productivity spillovers. If the composition and level of nearby activity within the building generates spillovers that enhance a company's productivity, its density is expected to increase. If instead nearby space is used in a manner that impedes productivity, then density is expected to be lower. Drawing on this idea, eight "FLA" variables (standing for floor area) are added to the previous models from Tables 2a and 2b, and are designed to measure how space within three floors of an establishment is distributed between companies in and outside of its 2-digit SIC industry.

FLA variables with "own" suffix extensions measure space occupied by companies in the tenant's industry (in 1,000s of square feet) not including the tenant itself. FLA variables with "other" suffix extensions measure space allocated to tenants in other industries. For both types of variables, separate measures are provided for space on the establishment's floor (denoted "0"), one floor away, two floors away, and three floors away (noted, respectively, "1," "2," and "3"). These distances are close enough that an employee might walk to another office as part of the interaction process generating the spillovers. Beyond three floors away, employees are likely to take an elevator and further vertical distance would not mater very much. For these and related reasons, we expect that if localized productivity spillovers are present, they will attenuate rapidly with distance.

Our approach follows the agglomeration literature in distinguishing between own and other industry activity (localization and urbanization economies, respectively). See Rosenthal and Strange (2004), Combes and Gobillon (2015) for reviews. Having said this, our approach to measuring agglomeration economies is unique, and for this reason some further comment is in order. The essence of agglomeration spillovers is that they are external increasing returns. Somehow – and the theory literature has suggested a range of channels – nearby activity increases an establishment's productivity. The valued activity may be within an establishment's own industry, in some particular sector with which the establishment is linked, or simply the aggregate of all activity. In prior empirical work, nearby activity is nearly always measured by employment. Our approach is unique in that we measure nearby activity by

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other buildings in search of more space. We are not able to address this directly because our data do not follow establishments over time. To the extent that growing establishments relocate to obtain additional office space, the density-age pattern reported above will understate age-related productivity effects on office employment density.

the space occupied rather than by employment. We are able to do this because the OM data provide a detailed mapping of activities to locations within the buildings in our sample.[21]

Our approach is also distinctive in the short distance over which we measure proximity. Most often, proximity in the agglomeration literature has been measured at the metropolitan level (see Rosenthal and Strange (2004) and Combes and Gobillon (2015) for reviews). Exceptions include papers discussed in a recent review by Rosenthal and Strange (2019), along with related work by Rosenthal and Strange (2001, 2003, 2005, 2008, 2012) and Arzaghi and Henderson (2008). Rosenthal and Strange (2003, 2005) demonstrate that in a range of industries companies care more about the composition of activity within one mile than further away. Henderson and Arzaghi (2008) show that advertisers in Manhattan care about location within just one-quarter mile. More recent work by Liu et al (2018b) suggests that companies care about what building they locate in even on the same city block. Here we allow for the possibility that companies may benefit from the type of establishments just down the hall.

A few comments on identification are also in order. If high productivity companies are more likely to seek a suite with advantageous neighbors, the FLA measures could be endogenous. Other mechanisms, however, likely dominate and determine the floor on which a company locates, mitigating this concern. The influence of street access and vertical amenities, for example, drive broad patterns of location and rent in the building (e.g. Liu et al (2018a)).[22] Search frictions arising from the idiosyncratic presence and location of vacant suites would also make it difficult for unusually productive companies to select a specific floor (see Liu et al (2018b) for related discussion). Recall further that our model controls for building fixed effects, floor level, and establishment attributes that proxy for productivity (including industry, headquarter status and age). Any correlation between the FLA measures and the model error would have to occur conditional on these other controls. These considerations mitigate the potential for endogenous effects. Robustness checks to follow support this view.

Bearing these ideas in mind, Tables 3a and 3b are designed to provide estimates of the influence of the FLA variables on density while also providing evidence on robustness. In both tables, column 1 includes only the FLA measures as controls. Column 2 adds in building fixed effects while column 3 controls for establishment attributes (including industry type, headquarter status and age). Column 4 adds controls that allow for non-monotonic floor level effects but omits the FLA variables; this repeats the

[21] Recall as described earlier, that space is being measured using only companies that survive at least until 2016. However, results from a series of robustness checks to follow will show that the patterns in Tables 3a and 3b are robust to this feature of the data.

[22] The high weight that retail places on street access, for example, accounts for its strong tendency to locate at ground level. Liu et al (2018a) also provide evidence that high productivity office establishments tend to sort into higher locations in tall buildings, consistent with the idea that highly paid workers treat scenic views as normal goods.

specification in the far right columns of Tables 2a and 2b. Column 5 then adds back the FLA measures and provides our most fully specified model.

Consider now the FLA coefficients across the model specifications in Tables 3a and 3b. Looking from left to right, it is clear that localized concentrations of own- and other-industry establishments have a significant effect on density, and that the pattern of coefficients is quite robust to the different model specifications. Indeed, the FLA coefficients are nearly identical between column 1 – which only controls for the FLA variables – and column 5 – which is fully specified. This supports the idea that the FLA variables capture a different influence on density that is largely independent of the mechanisms captured by the other model controls. While this does not ensure that the FLA variables are exogenous, it is consistent with random assignment playing an important role in determining the specific floor on which a company locates, and that the FLA measures are at least approximately exogenous.

Other qualitative patterns also stand out. The first is that the coefficients on establishment attributes in the middle portion of the tables (headquarter status and age) are extremely robust to inclusion of the FLA measures. This reinforces earlier arguments that higher productivity tends to increase density. Observe also that there is compelling evidence of high density at ground and/or concourse level in columns 4 and 5 of both tables. However, with all industries grouped together (Table 3a), the upper portion of the u-shaped density function flattens in column 5 when the FLA measures are in the model. This is evident from the smaller coefficients on Floor 40-59 and Floor 60 and above in column 5 relative to column 4. An implication of this pattern is that some of the increased density up high (in column 4) that was previously ascribed to amenity effects appears to arise instead from productivity spillovers among companies that locate in the upper portion of tall buildings. This nuance, however, does not carry over to law firms in Table 3b. In that table, there is compelling evidence of a u-shaped vertical density pattern regardless of whether the FLA measures are included in the model. In fact, including the FLA measures in column 5 increases the slope of the density function above the 40^{th} floor so that all of the mechanisms discussed thus far are clearly at work.

The magnitude of the FLA coefficients is also important. To simplify, focus first on column 5 of Table 3a which pools across industries. The coefficient on FLA_own_0 is 0.0263 with a t-ratio of 5.24. This suggests that for every 1,000 square feet of own-industry space occupied on the same floor (not including the target suite), density in the target suite increases by roughly 2.6 percent. That effect attenuates rapidly, however. One floor away, the coefficient on FLA_own_1 falls to 0.0041 with a t-ratio of 1.92 while the coefficients for the corresponding measures 2 and 3 floors away are close to zero. The opposite pattern is present for the FLA_other variables. Here the own-floor coefficient is - 0.0137 with a t-ratio of -2.40, and then attenuates sharply with distance. The same qualitative pattern is present in Table 3b for Law. The primary difference is that the FLA_other coefficients, although initially negative, turn positive with distance while still remaining small in magnitude: The floor-0 coefficient is equal to -0.017 with a t-ratio of -2.72 while 3 floors away the coefficient becomes positive at 0.0076 with a t-ratio of 2.35.

The FLA_own patterns are consistent with the view that close proximity to companies in the own industry – defined here as being on the same floor – enhances productivity, causing density to increase. The need to walk stairs or take an elevator, even to just one floor away, appears to greatly dampen this effect. This echoes patterns elsewhere in the literature that close proximity matters (Rosenthal and Strange, 2005 and 2008). It is also worth noting that the negative effect on density from own-floor, other-industry activity (FLA_other_0) in both tables suggests that something else is going on that can impede productivity. One possibility is that more activity on your floor increases elevator congestion or somehow creates other forms of distraction.[23]

Summarizing, the evidence in Tables 3a and 3b indicates that localized productivity spillovers are present in tall commercial buildings, and that these effects attenuate rapidly. Companies appear to be notably more influenced by other establishments on their own floor than just a few floors away. These effects also appear to be distinct from the influence of an establishment's inherent level of productivity and technology (e.g. as proxied by industry type), and also the influence of street access and vertical amenities.

VI. Robustness

This paper has obtained three key results. First, the vertical density function is u-shaped, with highest densities at the top and bottom of buildings. Second, there is greater density in headquarter establishments and for firms that are younger, results consistent with productivity encouraging high density. Third, there are spatially attenuating productivity spillovers within buildings, with significant, positive effects of own establishment activity on the same floor that disappear once beyond plausible vertical walking distance (about three floors).

These results have already proven to be quite robust. As a range of additional controls are included, all of the key results continue to hold. This section presents a series of additional robustness checks. The key results are present in every one of these checks. This includes different degrees of trimming to remove possibly miscoded outliers from the sample (Part A), restricting the sample to more recently issued offering memos in order to improve suite-level matching of the OM and D&B data (Part B), and additional controls and sample restrictions designed to further explore potential effects from possible unobserved heterogeneity and/or model misspecification (Part C). Lastly, we also explore using a

[23] Positive spillovers from adjacent own-industry activity (FLA_own_0) appear to offset congestion effects. The positive spillovers should be weaker for other-industry neighbors (FLA_other_0), which would allow congestion effects to dominate as suggested by the estimates in Tables 3a and 3b.

direct measure of productivity as the dependent variable, sale per square foot (Part D). For these models, we focus only on the law firm sample for which sales are more reliably measured and assigned to the establishments.

A. Data trimming

As discussed in Section III, the data were trimmed in order to remove outlier observations with especially high density. Specifically, we included only observations with density less than or equal to 25 workers per 1,000 square feet. This is a maximum; most suites have much lower density, with the mean equaling 5 workers per 1,000 square feet and the median equaling 2.9 workers per 1,000 square feet. As noted above, these values are close to densities reported in industry publications.

Table 4a presents alternative density model estimates based on more and less stringent trimming of the data. In all cases, the estimates are based on the all-industries, fully specified model in column 5 of Table 3a. Each column then corresponds to a different estimating sample constructed with a different degree of trimming. The trimming criteria are indicated in the top rows of the table along with the associated sample mean and median number of workers per 1,000 square feet. Maximum allowable density based on workers per 1,000 square feet ranges from 50 in column 1, down to 25 (the preferred sample) in column 3, and down further to 15 in column 5. The corresponding mean densities vary from 7.1 down to 3.8 and the median densities from 3.2 down to 2.6. These latter summary measures indicate that trimming outliers has relatively little effect on median sample density but reduces mean density, as would be expected.

The results in Table 4a are entirely consistent with the key results emphasized at the beginning of this section. The density gradient remains u-shaped, headquarter and older establishments display greater density, and spatially attenuating productivity spillover effects are present. Moreover, not only do these qualitative patterns hold across the different samples, the magnitude of the estimated coefficients is also quite similar to those in column 3 for the preferred sample. These patterns suggest that outlier suites are not highly correlated with the model controls, which would account for the high degree of robustness in the table.

B. Data matching

Table 4b presents results of robustness exercises that restrict the sample to more recently issued offering memos in order to improve suite-level matching of the OM and D&B datasets. For this table, alternate samples are used to estimate the fully specified column 5 models for the all-industry and law samples in Tables 3a and 3b. In each case, those models are also augmented with a further set of floor area variables that measure the amount of space vacated prior to 2016 (FLA_vacated) based on companies present in the OM data but which are not present in the D&B data. As with the other FLA measures, FLA_vacated controls are included for the establishment's own floor as well as for space 1, 2 and 3 floors away.

Moving left to right in the table, the estimating samples are successively restricted to more recently issued offering memos, with all-industry samples in columns 1-4 and the Law-only models in columns 5-7. Observe that column 1 uses the full sample of offering memos issued 2004-2014, which duplicates the sample used earlier. Column 2 restricts the sample to memos issued 2007 to 2014; column 3 uses memos issued 2010-2014 and column 4 uses only memos issued 2013-2014. Columns 5-7 present analogous estimates for Law but without the 2013-14 sample as there were not enough observations.

Estimates in Table 4b indicate that the vertical density, FLA_own, and FLA_other coefficients are quite similar across the different columns and very close to estimates reported in Tables 3a and 3b for the analogous specifications. These findings confirm that the combination of building fixed effects, establishment age and the other model controls do a good job of addressing possible effects of sample attrition associated with timing differences between the OM and D&B data. Our core results appear to be robust to this issue.

C. Unobserved sample heterogeneity

Table 5 provides additional estimates of the column 5, Table 3a model (all-industries, fully specified) that allow for other possible sources of unobserved heterogeneity.

The first of these checks concerns the relationship of rent to density. As discussed earlier, our model controls capture the systematic drivers of both density and rent. For that reason, if our model is well specified, adding rent to the model should have little effect on the other coefficients in the model since. Estimates in columns 1 and 2 (for all industries and law, respectively), support this view. The estimates are nearly identical to those reported in Tables 3a and 3b. In addition, the coefficients on rent are small and not significant, suggestive that there is little new information being added to the model. Together, this pattern of results reinforces earlier arguments that the model controls largely capture the systematic drivers of rent. This also suggests that our estimates of density patterns within tall buildings are robust to possible confounding effects from rent.

The next two columns of Table 5 carry out a different sort of robustness check. The specifications estimated earlier in the paper are based on a sample of 18 cities. While these estimates include many controls, including building fixed effects in the preferred specification, there are differences between cities that have the potential to impact results. High floors might have a different amenity value in New York City than in a smaller city. In order to assess this, we separately estimate all-industry models for New York City and Chicago. These are the only two cities where we have enough data to carry out such estimation. The results are reported in columns 3 and 4 of Table 5. As is immediately apparent, the key results all continue to hold in these two individual city models.[24]

D. Sales per square foot

Table 6 presents our final set of robustness checks. In this instance, we focus only on law firms and use log sale per square foot as the dependent variable. The controls in the model, however, remain as before in Table 3b. Sale per square foot is a more direct measure of productivity than employment density. These models are therefore helpful in assessing whether our previous evidence of productivity effects is robust. This includes whether headquarters and older companies exhibit higher productivity. It also includes whether evidence of floor-level productivity spillovers persists based on the FLA variables. In adopting this approach, it is worth emphasizing that Law is especially oriented towards billable hours, making sales an appealing measure of productivity for this industry.

The regressions reported in Table 6 mirror the structure in the last three columns of Table 3b. Column 1 controls for establishment attributes and the FLA variables, but does not control for a suite's floor. Column 2 controls for floor and establishment attributes, but omits the FLA variables. Column 3 provides the full specification that includes all of the controls. For all three regressions, branch facilities are omitted from the sample because sales are only reported in D&B for headquarter and single site establishments.[25]

A careful review of the estimates confirms that all of the conclusions from the previous tables hold. As before, a sharp u-shaped pattern is present in columns 2 and 3, with higher sale per square foot near ground level and again above the 40^{th} floor. Establishment attributes that proxy for productivity point to higher sale per square foot, including headquarter and older establishments. Comparing estimates in columns 1 and 3, as before the qualitative pattern for the FLA coefficients is robust and provides strong evidence that proximity to other law firms on the same floor increases productivity. Quantitatively, the estimates in column 3 indicate that for every 1,000 additional square feet occupied by other law firms, sale per square foot increases by 5.6 percent with a t-ratio of 3.7. This effect also attenuates rapidly and is one order of magnitude smaller just three floors away. The coefficients on the FLA_other controls are

[24] We also estimated all-industry models that mirror those in Table 3a but which omitted the concourse and ground level suites from the sample. Results were largely the same as in Table 3a and are not reported.

[25] We also estimated the law firm models using only single-site companies to further ensure accurate assignment of sales to the target suite. This reduced the sample size to just 207 suites. Nevertheless, robust results include higher sale per worker among older companies and strong evidence of positive, own-floor own-industry (FLA_own_0) productivity spillovers that attenuate away within a few floors. The vertical pattern also indicates higher productivity up high, consistent with Liu et al (2018a). Given the limited sample size, we focus above on the large sample that includes multi-site law firms.

largely insignificant and/or negative. Overall, we see results for sale per worker that echo the density results presented above.

VII. Conclusions

It is well-known that density is fundamental to urban economics. Nearly universally, however, analysis of the determinants of density and its impact on local economies has focused on horizontal relationships, as between a city's central business district and its suburban satellites or the productivity gains from proximity to complementary firms and workers. This paper's key contribution is to analyze, for the first time, vertical density relationships and agglomerative spillovers within the tall commercial buildings that are so important to modern urban economies.

Our theory and empirical work both suggest that vertical density patterns are complex. It has been argued that density should decline monotonically with height off the ground because of increasing costs of street access. Consistent with this view, we find that ground floor density is double that of just a few floors above, about the same effect as moving one mile away from Grand Central Station, the economic center of Manhattan. However, we also document high levels of density on the upper floors of tall buildings, giving a u-shaped vertical density gradient. Our theory shows that tension between street access and vertical amenities (e.g. scenic views) can support this pattern, with access-oriented companies like retail sorting into locations down low and amenity-oriented companies such as high end law choosing to locate on high floors.

The paper also provides evidence of within-building productivity spillovers. The presence of complimentary establishments on a company's own floor is associated with higher density, and for law, higher sales per worker. These effects, however, attenuate rapidly and are much smaller just one floor away and nearly absent three floors away. Easy walking access, without stairs or elevator travel, appears to be an important factor governing the potential for valuable interactions within a commercial building.

Overall, our estimates and theory demonstrate that vertical density patterns in cities can be as complex as horizontal patterns. It is important to recognize, however, that unlike horizontal density configurations, vertical patterns occur within individual buildings that are entrepreneurially managed in the sense that they are managed with a goal of profit maximization. This has two implications. First, it speaks to the efficiency of resource allocation when there are agglomerative externalities. It has been established in many settings that profit maximization can potentially lead to the internalization of externalities (e.g., Henderson, 1974). In the case of within-building externalities, the difficulties of internalization of an entire city's externalities – as discussed in Helsley and Strange (1997) – are not obstacles to efficiency to the same degree. Second, the results also suggest that building owners should consider the economics of density in building design and tenanting. Specifically, the demand for density at the top of buildings means that buildings should be designed in ways that address this demand. This is relevant to elevators and other sorts of within-building infrastructure. With regard to tenanting, the paper's results imply that building managers should not simply consider how a tenant's presence enhances a building, but also how the tenant's location within the building matters. Analogous market based incentives are mostly not present when considering horizontal patterns of development. For these reasons, buildings play an important role in urban areas as distinct, market based spatial units that not only give cities their striking skylines but also contribute to urban productivity.

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Figure 1a: Log Employment Per 1,000 Square Feet – Buildings ≥ 25 Floors

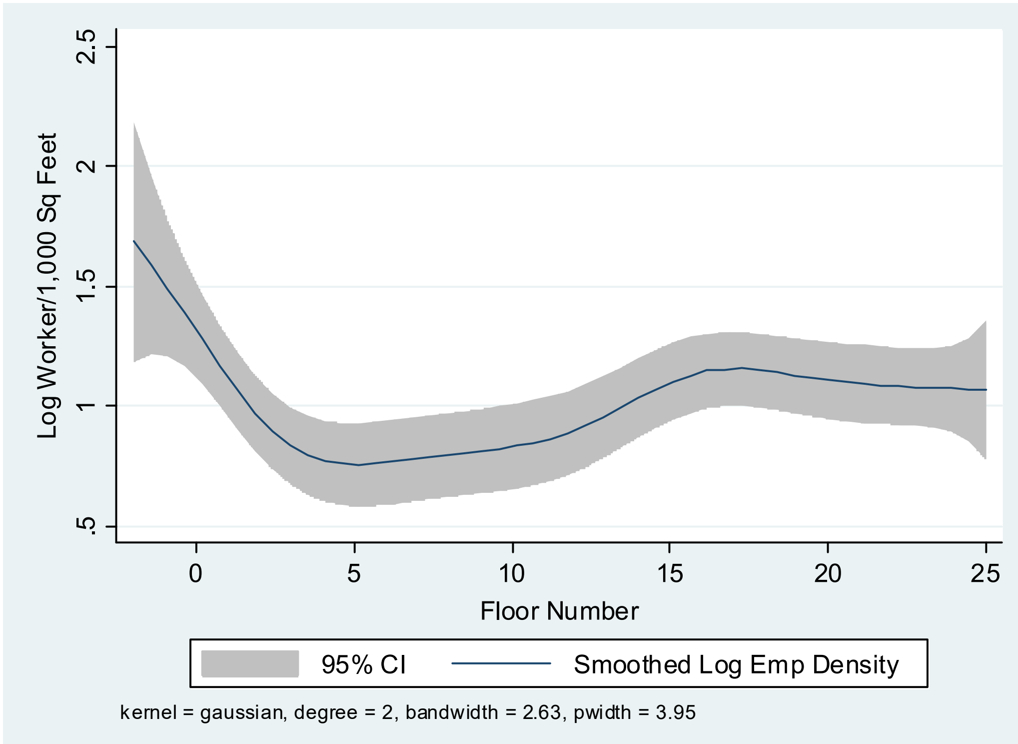

Figure 1b: Log Employment Per 1,000 Square Feet – All Buildings

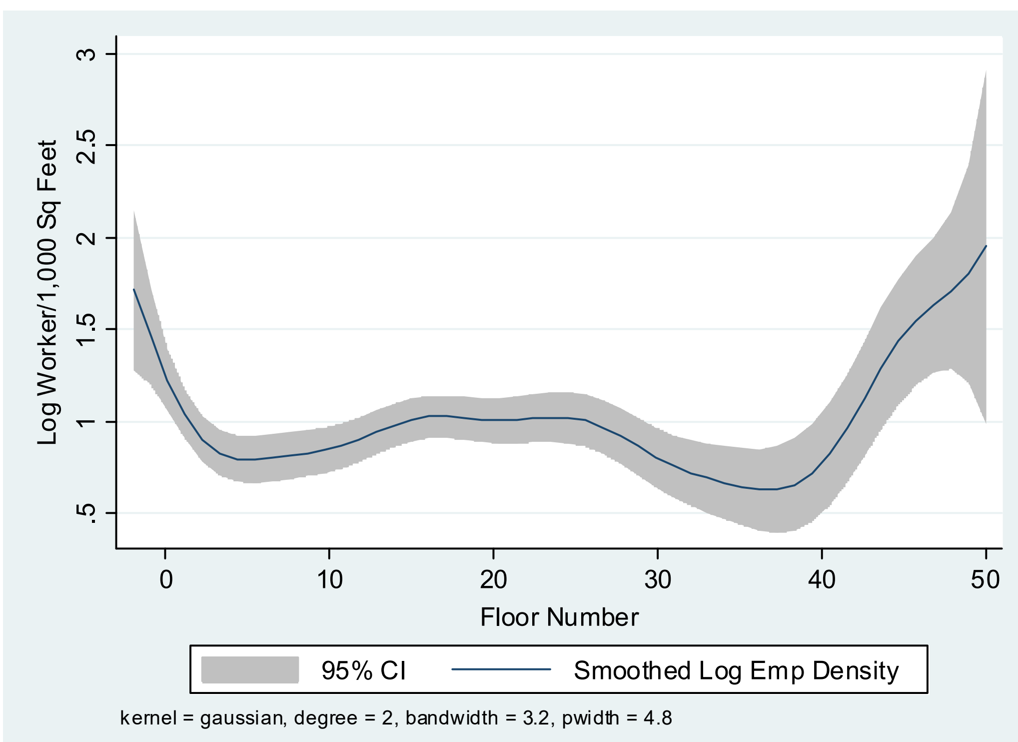

Figure 2: Employment Density in Manhattan

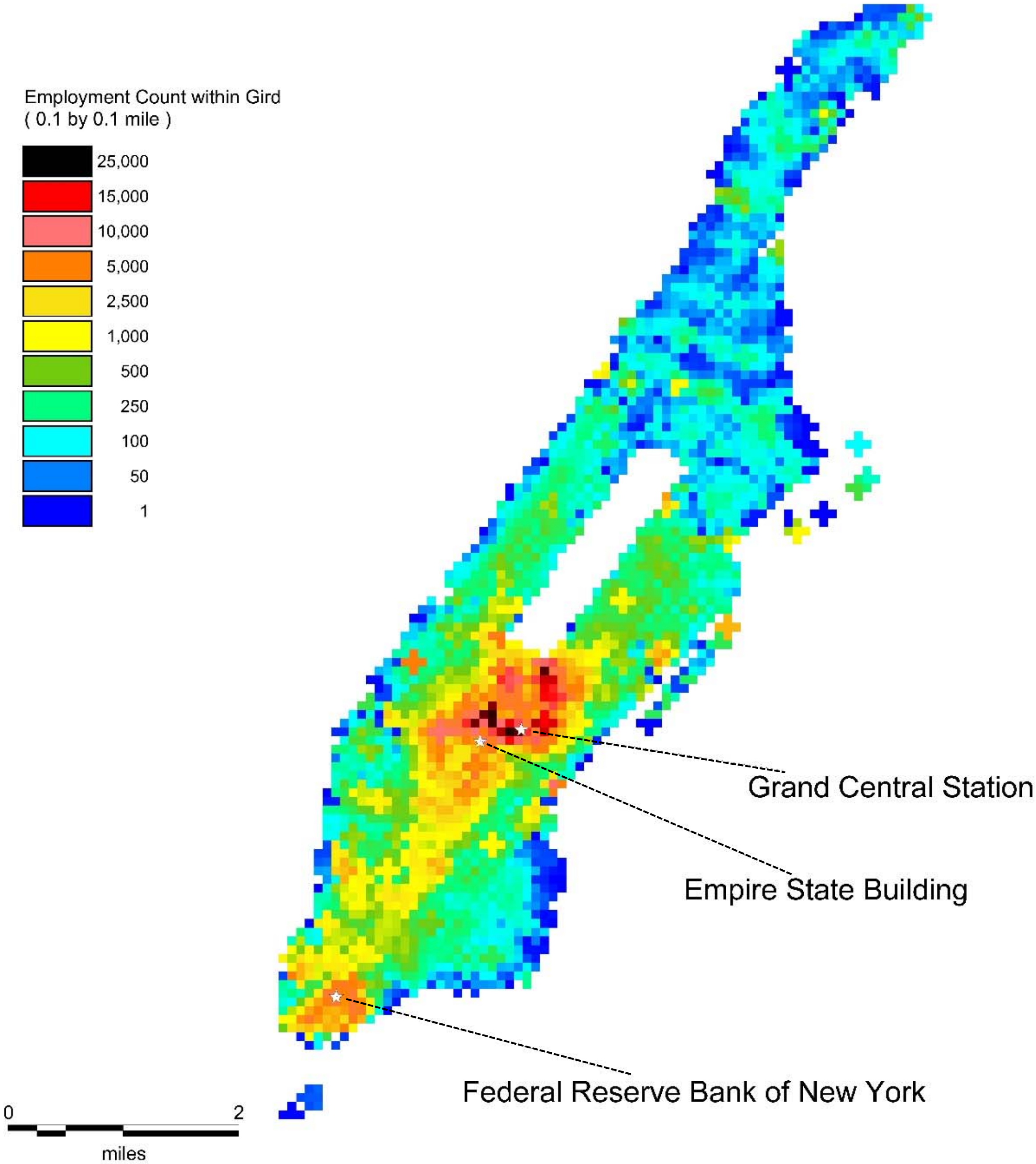

Figure 3: Employment Density Near Grand Central Station

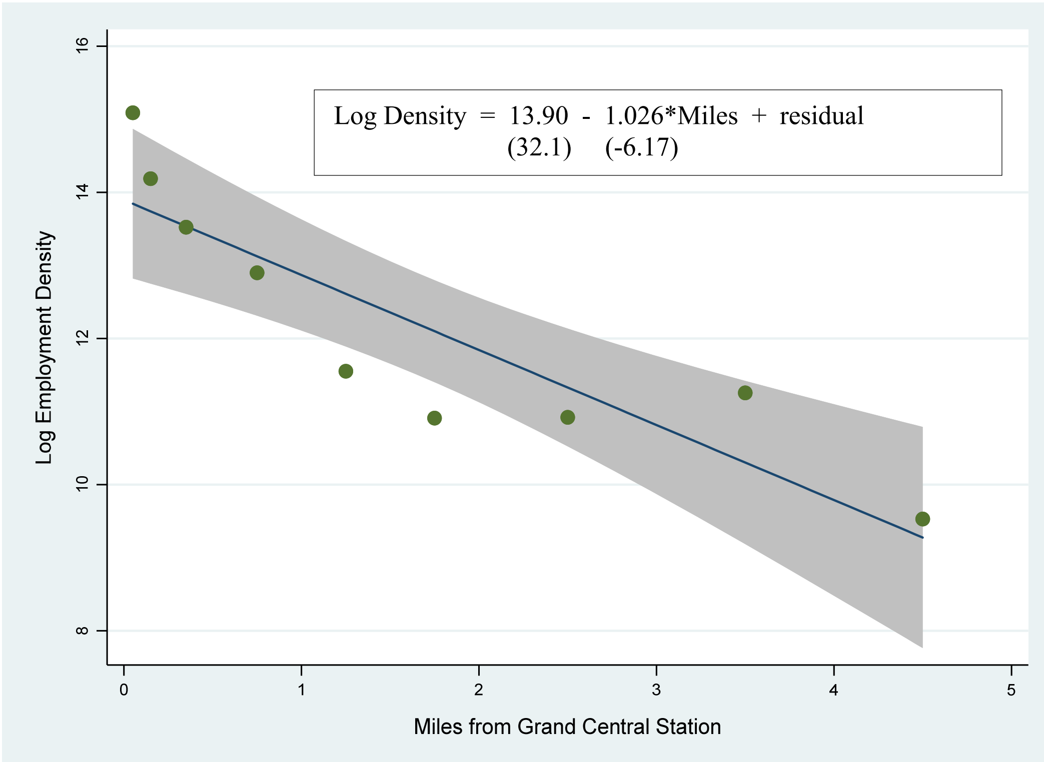

Table 1a: Offering Memo Data

Panel A: Sample Composition

Number of Buildings	90
Number of Tenant-Suite Observations	2,291
Number of Cities	18
Years offering memos issued	2004 - 2014

Panel B: Building and Suite Height (by floor)

	Average Floor Height	Median Floor Height	% Over Floor 30	% Over Floor 50	Minimum Floor	Maximum Floor
Buildings	32.9	28	46.7	7.8	16	109
Suites	18.3	16	17.2	3.2	-1	103

Panel C: Distribution of Buildings Across Cities

City	Number	Share
Atlanta	2	2.22
Boston	4	4.44
Chicago	11	12.22
Cleveland	1	1.11
Dallas	1	1.11
Denver	2	2.22
Houston	3	3.33
Irvine	1	1.11
Knoxville	1	1.11
Los Angeles	8	8.89
New York	40	44.44
Oklahoma City	3	3.33
Orlando	1	1.11
Philadelphia	1	1.11
Sacramento	1	1.11
San Diego	1	1.11
San Francisco	8	8.89
Seattle	1	1.11

Table 1b: Industry Composition and Employment Density

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	Number of Suites	**Industry Composition (Percent)**				**Density (Employment/1,000 square feet)**			
	All Floors	All Floors (2,291 Obs)	Ground Floor & Concourse (216 Obs)	Floor >= 2 and < 40 (1,903 Obs)	Floor >= 40 (172 Obs)	All Floors (2,291 Obs)	Ground Floor & Concourse (216 Obs)	Floor >= 2 and < 40 (1,903 Obs)	Floor >= 40 (172 Obs)
Retail (SIC 52-59)	160	6.98	45.83	3.00	2.33	6.34	6.61	5.50	11.51
FIRE (SIC 60-67)	384	16.76	1.39	18.02	22.09	4.94	5.57	4.63	7.63
Bus Serv (SIC 73)	160	6.98	4.17	7.09	9.30	4.46	2.68	4.16	8.02
Advertising (SIC 7311, 7312, 7319)	19	0.83	-	0.95	0.58	3.38	-	3.74	0.69
Law Offices (SIC 81)	436	19.03	0.93	19.39	37.79	5.94	12.11	5.03	10.90
Eng, Acc, Man (SIC 87)	21	0.92	-	1.05	0.58	6.47	-	6.76	0.61
Other Industries	1,111	48.49	47.69	50.50	27.33	4.45	4.68	4.43	4.24
All Industries	2,291	100.00	100.00	100.00	100.00	4.96	5.56	4.61	7.98

Table 2a: All Industries Nonlinear Vertical Density Gradient[a]

	Linear Vertical Density Gradient (Cols 1-5)					Nonlinear Vertical Density Gradient (Cols 6-7)	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	No Controls	Estab SIC2 Fixed Effects	More Estab Controls	Building Scale	Building Fixed Effects	No Building Fixed Effects	Building Fixed Effects
Floor Number	0.0040	0.0037	0.0028	0.0011	0.0016	-	-
	(1.37)	(1.40)	(1.41)	(0.45)	(0.64)	-	-
Concourse	-	-	-	-	-	0.0704	0.1157
	-	-	-	-	-	(0.38)	(0.66)
Ground Floor	-	-	-	-	-	0.3771	0.4074
	-	-	-	-	-	(2.89)	(2.66)
Floor 2 to 3[b]	-	-	-	-	-	-0.3023	-0.2497
	-	-	-	-	-	(-2.19)	(-1.69)
Floor 4 to 9[b]	-	-	-	-	-	-0.0192	-0.0376
	-	-	-	-	-	(-0.21)	(-0.37)
Floor 20 to 39[b]	-	-	-	-	-	-0.0053	0.0450
	-	-	-	-	-	(-0.07)	(0.53)
Floor 40 to 59[b]	-	-	-	-	-	0.3977	0.4469
	-	-	-	-	-	(3.43)	(3.77)
Floor 60 and above[b]	-	-	-	-	-	0.2916	0.2499
	-	-	-	-	-	(1.87)	(1.69)
Building Height (floors)	-	-	-	0.0026	-	0.0011	-
	-	-	-	(1.06)	-	(0.47)	-
Log building floor area	-	-	-	-0.0222	-	-0.0464	-
	-	-	-	(-0.24)	-	(-0.48)	-
Headquarters	-	-	0.7522	0.7538	0.6355	0.7521	0.6420
	-	-	(6.25)	(5.89)	(5.20)	(5.93)	(5.22)
Branch	-	-	-0.0312	-0.0347	0.0658	-0.0052	0.0870
	-	-	(-0.17)	(-0.19)	(0.34)	(-0.03)	(0.47)
Yr orig < 1950[b]	-	-	1.5142	1.5203	1.4351	1.5118	1.4341
	-	-	(6.85)	(6.87)	(6.57)	(6.81)	(6.64)
Yr orig 1950 to 1979[b]	-	-	1.4485	1.4468	1.3760	1.4724	1.4135
	-	-	(8.85)	(8.88)	(9.02)	(8.92)	(9.14)
Yr orig 1980 to 1999[b]	-	-	1.2496	1.2502	1.1923	1.2583	1.2120
	-	-	(9.06)	(9.04)	(8.90)	(9.29)	(9.35)
Yr orig 2000 to 2009[b]	-	-	0.8614	0.8584	0.8576	0.8737	0.8740
	-	-	(4.82)	(4.84)	(5.57)	(5.04)	(5.83)
Number of SIC 2 FE	-	60	60	60	60	60	60
Number of Bldg FE	-	-	-	-	90	-	90
Observations	2,291	2,291	2,291	2,291	2,291	2,291	2,291
Within R-squared	-	-	-	-	0.256	-	0.270
Total R-Squared	0.002	0.171	0.322	0.322	0.303	0.336	0.315

[a] Dependent variable is log of employment density at the individual suite level. Robust t-statistics in parentheses.
[b] Omitted categories are floor 10 through 19 and suite originated 2010 to 2014.

Table 2b: Law Firm Nonlinear Vertical Density Gradient[a]

	Linear Vertical Density Gradient (Cols 1-4)				Nonlinear Vertical Density Gradient (Cols 5-6)	
	(1)	(3)	(3)	(4)	(5)	(6)
	No Controls	Estab Controls	Building Scale	Building Fixed Effects	No Building Fixed Effects	Building Fixed Effects
Floor Number	0.0162	0.0090	0.0122	0.0158	-	-
	(3.31)	(2.48)	(2.75)	(3.89)	-	-
Concourse	-	-	-	-	0.7291	1.2301
	-	-	-	-	(4.25)	(7.95)
Floor 2 to 3[b]	-	-	-	-	0.1248	-0.0203
	-	-	-	-	(0.19)	(-0.06)
Floor 4 to 9[b]	-	-	-	-	-0.0173	0.0984
	-	-	-	-	(-0.12)	(0.75)
Floor 20 to 39[b]	-	-	-	-	0.2295	0.5905
	-	-	-	-	(1.69)	(4.04)
Floor 40 to 59[b]	-	-	-	-	0.6064	0.8276
	-	-	-	-	(2.29)	(3.42)
Floor 60 and above[b]	-	-	-	-	1.4597	1.3347
	-	-	-	-	(3.20)	(4.76)
Building Height (floors)	-	-	-0.0083	-	-0.0126	-
	-	-	(-1.28)	-	(-1.72)	-
Log building floor area	-	-	0.2023	-	0.2245	-
	-	-	(1.41)	-	(1.50)	-
Headquarters	-	0.8028	0.7773	0.7267	0.7662	0.7257
	-	(5.60)	(5.70)	(4.67)	(5.79)	(4.69)
Branch	-	0.0618	0.0467	0.0205	0.0933	0.0287
	-	(0.23)	(0.19)	(0.07)	(0.36)	(0.09)
Yr orig < 1950[b]	-	1.6560	1.5951	1.2162	1.5431	1.2872
	-	(3.63)	(3.42)	(2.39)	(3.24)	(2.50)
Yr orig 1950 to 1979[b]	-	1.4416	1.4155	1.0279	1.3719	1.0942
	-	(3.25)	(3.09)	(2.08)	(2.92)	(2.21)
Yr orig 1980 to 1999[b]	-	1.3215	1.2879	0.8593	1.2831	0.9501
	-	(3.16)	(2.99)	(2.13)	(2.92)	(2.24)
Yr orig 2000 to 2009[b]	-	0.7539	0.7764	0.5026	0.8093	0.6421
	-	(1.80)	(1.84)	(1.19)	(1.83)	(1.42)
Number of Bldg FE	-	-	-	68	-	68
Observations	436	436	436	436	436	436
Within R-squared	-	-	-	0.197	-	0.230
Total R-Squared	0.055	0.302	0.310	0.283	0.326	0.267

[a] Dependent variable is log of employment density at the individual suite level. Robust t-statistics in parentheses.
[b] Omitted categories are floor 10 through 19 and suite originated 2010 to 2014.

Table 3a: All Industries Floor Level Spillover Effects[a]

	(1)	(2)	(3)	(4)	(5)
	Floor Level Scale Effects	Building Fixed Effects	Estab Controls	Nonlinear Vertical Gradient	Full Model
Concourse	-	-	-	0.1157	-0.0641
	-	-	-	(0.66)	(-0.33)
Ground Floor	-	-	-	0.4074	0.4487
	-	-	-	(2.66)	(3.11)
Floor 2 to 3[b]	-	-	-	-0.2497	-0.2532
	-	-	-	(-1.69)	(-1.63)
Floor 4 to 9[b]	-	-	-	-0.0376	-0.0381
	-	-	-	(-0.37)	(-0.37)
Floor 20 to 39[b]	-	-	-	0.0450	-0.0045
	-	-	-	(0.53)	(-0.05)
Floor 40 to 59[b]	-	-	-	0.4469	0.2977
	-	-	-	(3.77)	(3.07)
Floor 60 and above[b]	-	-	-	0.2499	0.1048
	-	-	-	(1.69)	(0.58)
Headquarters	-	-	0.6416	0.6420	0.6413
	-	-	(4.95)	(5.22)	(4.91)
Branch	-	-	0.0019	0.0870	0.0160
	-	-	(0.01)	(0.47)	(0.08)
Yr orig < 1950[b]	-	-	1.5243	1.4341	1.5294
	-	-	(6.56)	(6.64)	(6.60)
Yr orig 1950 to 1979[b]	-	-	1.4063	1.4135	1.4448
	-	-	(8.80)	(9.14)	(9.00)
Yr orig 1980 to 1999[b]	-	-	1.2283	1.2120	1.2463
	-	-	(9.15)	(9.35)	(9.55)
Yr orig 2000 to 2009[b]	-	-	0.8663	0.8740	0.8881
	-	-	(5.52)	(5.83)	(5.85)
FLA_own_0[b]	0.0258	0.0223	0.0272	-	0.0263
	(4.16)	(3.46)	(5.04)	-	(5.24)
FLA_own_1 [b]	0.0056	0.0045	0.0027	-	0.0041
	(1.98)	(1.53)	(1.21)	-	(1.92)
FLA_own_2 [b]	0.0017	0.0018	0.0012	-	0.0015
	(0.58)	(0.65)	(0.60)	-	(0.78)
FLA_own_3 [b]	-0.0020	0.0004	-0.0006	-	-0.0000
	(-0.60)	(0.12)	(-0.24)	-	(-0.02)
FLA_other_0 [b]	-0.0063	-0.0098	-0.0135	-	-0.0137
	(-1.21)	(-1.48)	(-2.11)	-	(-2.40)
FLA_other_1 [b]	-0.0002	-0.0024	-0.0002	-	0.0013
	(-0.10)	(-0.81)	(-0.08)	-	(0.57)
FLA_other_2 [b]	-0.0007	-0.0004	-0.0020	-	-0.0016
	(-0.39)	(-0.21)	(-1.35)	-	(-1.03)
FLA_other_3 [b]	-0.0030	-0.0038	-0.0020	-	-0.0014
	(-1.58)	(-1.98)	(-1.18)	-	(-0.82)
Number of SIC 2 FE	-	-	60	60	60
Number of Bldg FE	-	90	90	90	90
Observations	2,291	2,291	2,291	2,291	2,291
Within R-Squared	-	0.0602	0.314	0.270	0.326
Total R-Squared	0.046	0.0426	0.357	0.315	0.372

[a] Dependent variable is log of employment density at the individual suite level. Robust t-statistics in parentheses.
[b] FLA variables measure the square footage of space (in 1,000s) occupied on the own floor (_0) and also 1, 2, and 3 floors away for own 2-digit SIC industry ("own") and establishments outside of the own industry ("other").

Table 3b: Law Firm Floor Level Spillover Effects[a]

	(1) Floor Level Scale Effects	(2) Building Fixed Effects	(3) Estab Controls	(4) Nonlinear Vertical Gradient	(5) Full Model
Concourse	-	-	-	1.2301	0.9733
	-	-	-	(7.95)	(3.36)
Floor 2 to 3[b]	-	-	-	-0.0203	0.5427
	-	-	-	(-0.06)	(1.33)
Floor 4 to 9[b]	-	-	-	0.0984	0.2327
	-	-	-	(0.75)	(1.59)
Floor 20 to 39[b]	-	-	-	0.5905	0.5818
	-	-	-	(4.04)	(3.68)
Floor 40 to 59[b]	-	-	-	0.8276	0.8638
	-	-	-	(3.42)	(2.97)
Floor 60 and above[b]	-	-	-	1.3347	1.9188
	-	-	-	(4.76)	(5.71)
Headquarters	-	-	0.7729	0.7257	0.7922
	-	-	(3.92)	(4.69)	(4.10)
Branch	-	-	-0.0605	0.0287	0.0621
	-	-	(-0.18)	(0.09)	(0.19)
Yr orig < 1950[b]	-	-	1.2964	1.2872	1.2700
	-	-	(2.46)	(2.50)	(2.39)
Yr orig 1950 to 1979[b]	-	-	1.0067	1.0942	0.9948
	-	-	(2.10)	(2.21)	(1.86)
Yr orig 1980 to 1999[b]	-	-	0.7739	0.9501	0.8383
	-	-	(2.07)	(2.24)	(1.85)
Yr orig 2000 to 2009[b]	-	-	0.3791	0.6421	0.5288
	-	-	(0.93)	(1.42)	(1.07)
FLA_own_0[b]	0.0259	0.0210	0.0251	-	0.0304
	(1.61)	(1.10)	(1.63)	-	(2.42)
FLA_own_1 [b]	0.0080	0.0094	0.0062	-	0.0075
	(2.07)	(2.25)	(1.51)	-	(2.17)
FLA_own_2 [b]	0.0082	0.0040	0.0038	-	0.0054
	(1.78)	(1.10)	(0.94)	-	(1.38)
FLA_own_3 [b]	-0.0010	0.0003	0.0017	-	0.0026
	(-0.21)	(0.07)	(0.49)	-	(0.76)
FLA_other_0 [b]	0.0024	-0.0102	-0.0188	-	-0.0173
	(0.24)	(-1.15)	(-2.84)	-	(-2.72)
FLA_other_1 [b]	-0.0052	-0.0032	-0.0013	-	-0.0001
	(-1.15)	(-0.52)	(-0.22)	-	(-0.02)
FLA_other_2 [b]	-0.0027	-0.0030	-0.0032	-	0.0008
	(-0.61)	(-0.67)	(-0.86)	-	(0.21)
FLA_other_3 [b]	0.0004	-0.0003	0.0041	-	0.0076
	(0.11)	(-0.11)	(1.68)	-	(2.35)
Number of Bldg FE	-	68	68	68	68
Observations	436	436	436	436	436
Within R-Squared	-	0.133	0.304	0.230	0.367
Total R-Squared	0.174	0.150	0.374	0.267	0.318

[a] Dependent variable is log of employment density at the individual suite level. Robust t-statistics in parentheses.
[b] FLA variables measure the square footage of space (in 1,000s) occupied on the own floor (_0) and also 1, 2, and 3 floors away for own 2-digit SIC industry ("own") and establishments outside of the own industry ("other").

Table 4a: All Industries – Restricted Sample Trimming by Workers Per Square Foot[a]

	(1)	(2)	(3)	(4)	(5)
Mean/Median Wrkr/1,000 SqFt	7.1/3.2	6.0/3.1	5.0/2.9	4.5/2.8	3.8/2.6
Maximum Wrkr/1,000 SqFt	50 Emp	35 Emp	25 Emp	20 Emp	15 Emp
Concourse	-0.0858	-0.0700	-0.0641	-0.0819	0.0104
	(-0.43)	(-0.34)	(-0.33)	(-0.48)	(0.06)
Ground Floor	0.5149	0.5111	0.4487	0.4958	0.4475
	(3.63)	(3.40)	(3.11)	(3.57)	(3.30)
Floor 2 to 3[b]	-0.2854	-0.3021	-0.2532	-0.2523	-0.2091
	(-1.76)	(-1.95)	(-1.63)	(-1.67)	(-1.43)
Floor 4 to 9[b]	-0.0313	-0.0452	-0.0381	-0.0258	-0.0046
	(-0.31)	(-0.45)	(-0.37)	(-0.26)	(-0.05)
Floor 20 to 39[b]	-0.0784	-0.0539	-0.0045	-0.0061	0.0490
	(-0.77)	(-0.60)	(-0.05)	(-0.08)	(0.61)
Floor 40 to 59[b]	0.2218	0.2282	0.2977	0.2930	0.2077
	(1.62)	(2.08)	(3.07)	(3.15)	(2.06)
Floor 60 and above[b]	-0.0900	0.0508	0.1048	0.1882	-0.0268
	(-0.47)	(0.26)	(0.58)	(1.08)	(-0.15)
Headquarters	0.7295	0.7712	0.6413	0.6170	0.5616
	(5.16)	(5.36)	(4.91)	(4.79)	(4.50)
Branch	-0.0605	-0.1177	0.0160	0.0230	0.2885
	(-0.30)	(-0.59)	(0.08)	(0.12)	(1.74)
Yr orig < 1950[b]	1.6916	1.6852	1.5294	1.4775	1.1755
	(6.99)	(7.10)	(6.60)	(6.45)	(6.28)
Yr orig 1950 to 1979[b]	1.5206	1.4415	1.4448	1.4023	1.3551
	(9.45)	(8.65)	(9.00)	(8.74)	(8.63)
Yr orig 1980 to 1999[b]	1.2571	1.2672	1.2463	1.2085	1.1755
	(9.39)	(9.47)	(9.55)	(9.15)	(9.10)
Yr orig 2000 to 2009[b]	0.9776	0.9197	0.8881	0.8845	0.8643
	(6.44)	(5.98)	(5.85)	(5.95)	(5.93)
FLA_own_0[b]	0.0280	0.0275	0.0263	0.0246	0.0202
	(5.75)	(5.47)	(5.24)	(4.92)	(3.91)
FLA_own_1 [b]	0.0039	0.0040	0.0041	0.0043	0.0040
	(1.88)	(1.95)	(1.92)	(2.01)	(1.91)
FLA_own_2 [b]	0.0008	0.0004	0.0015	0.0017	0.0009
	(0.35)	(0.19)	(0.78)	(0.86)	(0.45)
FLA_own_3 [b]	0.0007	0.0006	-0.0000	0.0004	0.0004
	(0.28)	(0.24)	(-0.02)	(0.18)	(0.16)
FLA_other_0 [b]	-0.0184	-0.0161	-0.0137	-0.0128	-0.0119
	(-3.04)	(-2.84)	(-2.40)	(-2.31)	(-2.47)
FLA_other_1 [b]	0.0007	0.0007	0.0013	0.0015	0.0024
	(0.28)	(0.31)	(0.57)	(0.66)	(1.06)
FLA_other_2 [b]	-0.0032	-0.0023	-0.0016	-0.0014	-0.0012
	(-2.17)	(-1.51)	(-1.03)	(-0.89)	(-0.77)
FLA_other_3 [b]	-0.0012	-0.0010	-0.0014	-0.0006	-0.0003
	(-0.58)	(-0.57)	(-0.82)	(-0.34)	(-0.17)
Number of SIC 2 FE	60	60	60	60	60
Number of Bldg FE	2,471	2,399	2,291	2,232	2,115
Observations	90	90	90	90	90
Within R-Squared	0.338	0.344	0.326	0.326	0.302
Total R-Squared	0.372	0.395	0.372	0.367	0.336

[a] Dependent variable is log of employment density at the individual suite level. Robust t-statistics in parentheses.
[b] FLA variables measure the square footage of space (in 1,000s) occupied on the own floor (_0) and also 1, 2, and 3 floors away for own 2-digit SIC industry ("own") and establishments outside of the own industry ("other").

Table 4b: Restricted Sample by Year Offering Memo Issued with Controls for Vacated Space[a]

	All Industries				Law Firms		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Vertical Density Gradient	Full Sample	OM Issued 2007-2014	OM Issued 2010-2014	OM Issued 2013-2014	Full Sample	OM Issued 2007-2014	OM Issued 2010-2014
Concourse	-0.0469	-0.0589	-0.1179	0.1126	1.2158	1.2214	-
	(-0.24)	(-0.28)	(-0.44)	(0.30)	(2.67)	(2.29)	-
Ground Floor	0.4229	0.4799	0.6026	0.8324	-	-	-
	(2.84)	(3.33)	(4.10)	(5.20)	-	-	-
Floor 2 to 3	-0.2474	-0.2535	-0.0266	-0.0578	0.5665	1.0352	1.0813
	(-1.58)	(-1.54)	(-0.14)	(-0.27)	(1.41)	(7.49)	(6.95)
Floor 4 to 9	-0.0401	-0.0558	0.0622	0.1144	0.3533	0.3892	0.4310
	(-0.40)	(-0.55)	(0.55)	(0.67)	(2.41)	(2.34)	(2.12)
Floor 20 to 39	-0.0003	-0.0044	0.0621	0.2325	0.5571	0.5853	0.5950
	(-0.00)	(-0.05)	(0.67)	(1.24)	(3.53)	(3.67)	(3.18)
Floor 40 to 59	0.3054	0.3067	0.3927	0.4805	0.8839	0.9174	0.8401
	(3.14)	(3.14)	(3.59)	(2.32)	(2.91)	(3.05)	(3.18)
Floor 60 and above	0.1228	0.1618	0.2628	0.4243	1.9046	1.9647	1.9072
	(0.68)	(0.86)	(1.29)	(1.21)	(5.94)	(6.03)	(6.24)
Own-Industry Spillovers							
FLA_own_0	0.0263	0.0262	0.0287	0.0230	0.0209	0.0260	0.0053
	(5.11)	(4.97)	(4.94)	(3.44)	(1.79)	(2.07)	(0.25)
FLA_own_1	0.0043	0.0047	0.0059	0.0063	0.0088	0.0078	0.0053
	(1.97)	(2.15)	(2.55)	(1.83)	(2.55)	(2.13)	(1.80)
FLA_own_2	0.0015	0.0017	0.0037	0.0047	0.0060	0.0079	0.0088
	(0.79)	(0.88)	(1.48)	(1.38)	(1.66)	(2.18)	(2.34)
FLA_own_3	0.0000	-0.0001	0.0011	0.0002	0.0030	0.0031	0.0051
	(0.00)	(-0.05)	(0.51)	(0.06)	(0.86)	(0.76)	(1.53)
Other-Industry Spillovers							
FLA_other_0	-0.0137	-0.0132	-0.0106	-0.0237	-0.0280	-0.0292	-0.0439
	(-2.32)	(-2.32)	(-1.91)	(-4.13)	(-4.81)	(-5.62)	(-2.54)
FLA_other_1	0.0014	0.0018	0.0018	-0.0042	0.0013	0.0014	-0.0240
	(0.61)	(0.76)	(0.87)	(-1.06)	(0.26)	(0.28)	(-3.93)
FLA_other_2	-0.0015	-0.0014	-0.0005	0.0034	-0.0002	-0.0009	0.0071
	(-1.01)	(-0.89)	(-0.30)	(0.72)	(-0.06)	(-0.23)	(0.84)
FLA_other_3	-0.0012	-0.0013	-0.0017	0.0049	0.0109	0.0124	0.0169
	(-0.73)	(-0.74)	(-0.89)	(2.08)	(3.09)	(3.30)	(2.82)
Vacated Space Since OM Issued							
FLA_vacated_0	0.0088	0.0088	0.0089	-0.0067	-0.0205	-0.0248	-0.0148
	(3.04)	(2.97)	(3.11)	(-0.23)	(-0.65)	(-0.58)	(-0.14)
FLA_vacated_1	-0.0054	-0.0054	-0.0011	-0.0067	-0.0047	0.0149	0.0205
	(-1.87)	(-1.66)	(-0.30)	(-0.55)	(-0.30)	(0.72)	(0.35)
FLA_vacated_2	0.0000	-0.0000	-0.0036	0.0318	-0.0267	-0.0527	-0.0285
	(0.00)	(-0.01)	(-0.88)	(1.25)	(-1.37)	(-2.12)	(-0.53)
FLA_vacated_3	0.0012	0.0013	0.0008	-0.0322	0.0286	0.0385	0.0131
	(0.42)	(0.46)	(0.31)	(-1.81)	(1.47)	(1.65)	(0.30)
Estab Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Num SIC 2 FE	60	60	56	36	-	-	-
Num Bldg FE	90	85	63	18	68	63	46
Observations	2,291	2,189	1,728	489	436	415	349
Within R-Squared	0.327	0.323	0.338	0.472	0.383	0.393	0.433
Total R-Squared	0.374	0.373	0.360	0.474	0.327	0.355	0.364

[a] Dependent variable is log of employment density at the suite level. Robust t-statistics clustered at the building level in parentheses. All models are the same specifications as in column 5 of Tables 3a and 3b.

Table 5: Robustness Checks[a]

	(1)	(2)	(3)	(4)
	Include Rent Full Sample	Include Rent Law Sample	NYC Full Sample	Chicago Full Sample
Log rent/sq ft (2014$)	-0.0089	0.1052	-	-
	(-0.08)	(0.33)	-	-
Concourse	-0.0390	1.0414	0.2447	-0.0478
	(-0.19)	(2.94)	(0.84)	(-0.16)
Ground Floor	0.3889	-	0.4058	0.7553
	(2.56)	-	(2.15)	(2.46)
Floor 2 to 3[b]	-0.2250	0.5392	-0.4229	0.0916
	(-1.40)	(1.38)	(-1.63)	(0.39)
Floor 4 to 9[b]	-0.0340	0.2415	-0.2162	0.1237
	(-0.32)	(1.61)	(-1.20)	(0.80)
Floor 20 to 39[b]	0.0196	0.5865	0.0642	0.1743
	(0.24)	(3.79)	(0.47)	(1.16)
Floor 40 to 59[b]	0.3102	0.8043	0.3199	0.3163
	(3.29)	(2.67)	(2.39)	(1.61)
Floor 60 and above[b]	0.1988	1.8357	-	0.5146
	(1.16)	(4.98)	-	(1.56)
Headquarters	0.6536	0.7579	0.6405	0.4237
	(5.01)	(4.11)	(2.58)	(3.55)
Branch	0.0196	-0.0396	-0.2508	-0.2321
	(0.10)	(-0.13)	(-0.82)	(-0.85)
Yr orig < 1950[b]	1.5315	1.4285	1.6327	1.6107
	(6.42)	(2.83)	(5.65)	(4.43)
Yr orig 1950 to 1979[b]	1.4216	1.0202	1.4870	1.6247
	(8.43)	(1.89)	(6.21)	(7.23)
Yr orig 1980 to 1999[b]	1.2441	0.8165	1.1942	1.4954
	(8.71)	(1.81)	(7.67)	(9.36)
Yr orig 2000 to 2009[b]	0.9079	0.5679	0.8843	0.8834
	(5.82)	(1.15)	(3.80)	(3.71)
FLA_own_0[b]	0.0262	0.0303	0.0131	0.0442
	(5.03)	(2.67)	(2.39)	(8.81)
FLA_own_1 [b]	0.0041	0.0078	0.0062	0.0097
	(1.80)	(2.07)	(2.90)	(3.16)
FLA_own_2 [b]	0.0016	0.0049	0.0021	0.0073
	(0.78)	(1.15)	(0.89)	(1.57)
FLA_own_3 [b]	0.0002	0.0029	0.0026	-0.0052
	(0.07)	(0.71)	(0.79)	(-0.91)
FLA_other_0 [b]	-0.0142	-0.0168	-0.0215	0.0006
	(-2.38)	(-2.67)	(-5.95)	(0.21)
FLA_other_1 [b]	0.0014	0.0010	0.0078	-0.0001
	(0.63)	(0.19)	(2.80)	(-0.04)
FLA_other_2 [b]	-0.0016	0.0024	-0.0040	0.0026
	(-1.10)	(0.71)	(-1.78)	(1.02)
FLA_other_3 [b]	-0.0012	0.0073	-0.0017	0.0005
	(-0.76)	(2.09)	(-0.67)	(0.17)
Number of SIC 2 FE	60	-	60	60
Number of Bldg FE	2,206	422	854	515
Observations	90	67	40	11
Within R-Squared	0.327	0.375	0.367	0.425
Total R-Squared	0.369	0.309	0.423	0.407

[a] Dependent variable is log of employment density at the individual suite level. Robust t-statistics in parentheses.

[b] FLA variables measure the square footage of space (in 1,000s) occupied on the own floor (_0) and also 1, 2, and 3 floors away for own 2-digit SIC industry ("own") and establishments outside of the own industry ("other").

Table 6: Law Firm Sales Per Square Foot of Office Space[a]

	(1)	(2)	(3)
	Establishment Controls	Nonlinear Vertical Gradient	Full Model
Concourse	-	2.3037	1.9410
	-	(21.13)	(4.86)
Floor 2 to 3[b]	-	-0.8203	-0.7957
	-	(-4.33)	(-2.77)
Floor 4 to 9[b]	-	0.0614	0.2098
	-	(0.32)	(1.15)
Floor 20 to 39[b]	-	0.6640	0.6417
	-	(4.31)	(3.39)
Floor 40 to 59[b]	-	0.5992	0.1863
	-	(1.07)	(0.27)
Floor 60 and above[b]	-	1.0396	1.6784
	-	(2.26)	(2.57)
Headquarters	1.3401	1.2816	1.4163
	(5.89)	(7.28)	(6.11)
Yr orig < 1950[b]	1.5434	1.6460	1.6265
	(2.83)	(3.14)	(3.03)
Yr orig 1950 to 1979[b]	1.1553	1.3796	1.2036
	(2.34)	(2.91)	(2.57)
Yr orig 1980 to 1999[b]	1.0596	1.3286	1.2518
	(2.73)	(3.36)	(2.98)
Yr orig 2000 to 2009[b]	0.4557	0.8201	0.6559
	(1.20)	(2.02)	(1.47)
FLA_own_0[b]	0.0381	-	0.0555
	(1.68)	-	(3.68)
FLA_own_1 [b]	0.0038	-	0.0038
	(0.77)	-	(0.89)
FLA_own_2 [b]	0.0047	-	0.0070
	(1.10)	-	(1.68)
FLA_own_3 [b]	-0.0002	-	0.0003
	(-0.05)	-	(0.07)
FLA_other_0 [b]	-0.0105	-	-0.0050
	(-1.16)	-	(-0.57)
FLA_other_1 [b]	-0.0061	-	-0.0016
	(-0.72)	-	(-0.20)
FLA_other_2 [b]	-0.0077	-	-0.0046
	(-1.13)	-	(-0.79)
FLA_other_3 [b]	0.0053	-	0.0078
	(1.07)	-	(1.42)
Number of Bldg FE	61	61	61
Observations	292	292	292
Within R-Squared	0.485	0.425	0.554
Total R-Squared	0.543	0.500	0.513

[a] Dependent variable is log sales per square foot of office space at the suite level. Robust t-statistics in parentheses.

[b] FLA variables measure the square footage of space (in 1,000s) occupied on the own floor (_0) and also 1, 2, and 3 floors away for own 2-digit SIC industry ("own") and establishments outside of the own industry ("other").